BEFORE THE OHIO POWER SITING BOARD

In the Matter of the Application	**)**	
of Champaign Wind LLC for a	**)**	
Certificate to Install Electricity	**)**	**Case No. 12-0160-EL-BGN**
Generating Wind Turbines in	**)**	
Champaign County	**)**	

DIRECT TESTIMONY OF RICHARD R. JAMES ON BEHALF OF INTERVENORS UNION NEIGHBORS UNITED, INC., ROBERT AND DIANE McCONNELL, AND JULIA F. JOHNSON

Q.1. Please state your name and business address.

A.1. My name is Richard R. James. My business address is P.O. Box 1129, Okemos, MI 48805.

Q.2. What is your occupation?

A.2. I am a practicing acoustical engineer. A true and accurate copy of my resume is attached as Exhibit A.

Q.3. What types of work do you perform as an acoustical engineer?

A.3. My particular roles as an acoustical engineer can best be summarized as: 1) noise measurement, 2) noise control, and 3) techniques for predicting sound levels as a tool for guiding the design of new or retrofit facilities.

My work in the first part of my career was directed towards the use and interpretation of engineering procedures and methods so that I could assist my clients, who operated manufacturing facilities. This involved the design and operation of industrial facilities for in-plant communication, and protecting workers against hearing loss as well as designing new facilities so as to maintain compatibility with existing uses. In addition, I also addressed community noise complaints about sounds from their facilities and for new facilities worked with my client's new facility design team to prevent community noise problems for new facilities. In my work I viewed my role as an advisor to my clients to protect the health of their workers and the community near their facilities. This required working with medical professionals and specialists to understand the impact of sound on people. In pursuing this line of consulting, I have been interested since my earliest years in the application of computers to model sound propagation and to display acoustical data, the best example of which are contour maps.

The combination of these interests, computer modeling, measurement procedures, and the resulting effects of the sounds on people led to my work applying them to evaluate the impact that sound emissions from industrial machines on people both inside the facility and on the adjacent communities. My experience in this area ranges from the relatively simple cases of neighbors complaining about the sounds of dogs barking at neighboring animal kennels or of a noisy air-conditioning unit on a commercial building to the projects involving modeling of complete automotive manufacturing sites (inside and outside the buildings) in my work for U.S. automobile and other large manufacturers in the USA, Canada, and Europe.

Q.4. How many years of experience do you have as an acoustical engineer?

A.4. I conducted my first sound study before 1970. Its purpose was to document sound levels inside and outside a large metal stamping facility and was conducted in my role as noise engineer for Chevrolet Division of General Motors. I formed my first company in 1973 and have been an independent consultant since that time. Therefore, I have been an acoustical engineer for about 42 years.

Q.5. Please describe your educational background.

A.5. I obtained my Bachelor's Degree in Mechanical Engineering in 1971 from Kettering Institute (then General Motor's Institute) in the sub-category of applied acoustical engineering. I have since attended numerous seminars and short classes on various aspects of my profession. In addition, I have been a Full Member of the Institute of Noise Control Engineers since 1973, shortly after its formation.

Q.6. Please provide an overview of your occupational experience.

A.6. From 1968 to 1972 I was the noise control engineer for the Chevrolet Division of GM headquartered out of the Flint Metal Fabricating Plant. In this capacity I also participated on GM's Central Noise Committee which was responsible for setting standards for all GM facilities regarding in-plant and community noise.

From 1973 through 1983, I was Principal Consultant, Vice President and co-owner of Total Environmental Systems.

From 1983 through 2006 I was Principal Consultant, President and co-owner of James, Anderson & Associates, Inc. (JAA).

Q.7. What were your duties as a noise control engineer in the Chevrolet Flint Metal Fabricating Plant?

A.7. My duties were to assess sound levels inside and outside Chevrolet facilities, develop noise controls for equipment and processes that caused unacceptable levels of sound either for a worker or the adjacent community, and to represent my host facility and Division on the GM Central Noise Committee for internal standards and guidelines.

Q.8. Who started Total Environmental Systems and what types of work did this company do?

A.8. Total Environmental Systems, Inc. was started by me and Mr. Robert Anderson who was also a noise engineer working for GM. The services we offered were similar to those I describe for my work as a Chevrolet noise engineer plus I was also able to pursue my interests in developing and using computer applications for sound propagation models and contour mapping of the model results.

Q.9. What were your duties in your position as a Principal Consultant with Total Environmental Systems from 1972 to 1983?

A.9. I was responsible for all projects conducted by TES and its staff. I was also responsible for all technical development of procedures and software used by TES for its work.

Q.10. Please describe some of the major noise control projects that you performed in your capacity as a Principal Consultant with Total Environmental Systems.

A.10. During the first year or two of TES's history, most of the work was similar to what I described as my role for Chevrolet, except that it was applied to other non-automotive clients involved in metal stamping, forging, foundries, and other businesses. During these years I was also working on the software that would become SOUND6, which is TES's acoustic modeling application. It was in my role as Principal Consultant for TES that I used that software to develop the first large scale acoustical model of an industrial facility for GM. This model was used by the auto industry (through its trade associations and the Chamber of Commerce) in testimony during the 1976 Hearings held by OSHA on its proposal to drop the action level for worker hearing health from 90 dBA to 85 dBA. Subsequent to the 1976 hearings TES used its software to model in-plant and community noise for GM Assembly Division's new series of assembly plants and other types of plants for other divisions of GM, Ford and others. Along with this work I continued my work on noise measurement and noise controls for in-plant and community noise for a variety of clients. This work involved community noise problems faced by my clients at their facilities in the US, Canada, Europe, and Indonesia. Clients included the major automotive manufacturers, Goodyear Tire and Rubber Company, Armstrong Tire, and to a lesser extent companies involved in food processing and other types of industry.

The SOUND6 software permitted modeling of both community noise and noise inside manufacturing facilities. It was early in this period when I also developed the use of contour maps to depict sound measurement data. This concept was presented by me to others in my field at the INCE conference in the early 1970's. The combination of the SOUND6 software and contour maps was used to assess compatibility with host communities for many new facilities for clients in the automotive, tire, and other types of manufacturing operations.

Q.11. Who started the firm of James, Anderson & Associates, Inc.?

A.11. James, Anderson and Associates, Inc (JAA) was started by me and Mr. Robert Anderson.

Q.12. What types of work did this company do?

A.12. We continued the work of TES and its clients and expanded our client base to include many other manufacturing companies including automotive transplants like Toyota, Mazda, and Mitsubishi, and other firms such as John Deere and Co., Navistar, and Anheuser-Busch. In addition to expanding our client base, we developed partnerships with many of our clients that put JAA in the position of handling all noise related problems, in and outside of facilities on a sole-source (e.g. First Tier Partner) status. During this time I also expanded my work with the tire industry to include audits and other work for their European facilities in Italy, France, Germany, Luxembourg, and the U.K. This gave me broad exposure to the community noise standards and the enforcement practices in the European Union to add to my experiences in Canada, Mexico and the U.S.

JAA also focused more on the use of small acoustical models instead of the larger models that TES constructed. This was a result of our experience with the difficulty of accurately portraying the interactions between noise sources and the various real-world situations using general purpose sound propagation models that often needed to be considered for specific projects. When using spreadsheet software and the manual methods for prediction upon which the larger models were based, it was more effective to construct a model that represented a specific situation than it was to try to use SOUND6, our general purpose model. This problem still exists with modern commercial software packages like Cadna/A.

Q.13. What were your duties as a Principal Consultant for, and President of, James, Anderson & Associates, Inc. (JAA) from 1983 to 2006?

A.13. I was responsible for all projects deemed too complex for other members of my staff (which included acoustical engineers and industrial hygienists with Master's degrees) as well as the daily operation and management of a company that had between 25 and 45 employees. My work in this capacity with JAA built upon the work started in TES and expanded to include a much larger client base and higher levels partnerships with my clients. During this period my work continued, but I also took on more management responsibilities as my company grew. The types of problems my clients faced also became more complicated, because the easier problems had already been solved. It was during this time that my involvement with, audiologists, medical researchers and medical doctors increased and my relationship with NIOSH and other government agencies involved with worker and public health became more involved.

Q.14. Please describe some of the major noise-related projects that you performed in your capacity as a Principal Consultant with James, Anderson & Associates, Inc.

A14. During this period JAA took on First Tier Partner responsibility for the noise control programs at its clients. This meant that JAA operated as a replacement for our clients' in-house staffs. Through this out-sourcing arrangement, JAA was responsible for annual or bi-annual auditing all of its client's facilities for upper management reporting, maintaining on-going noise control activities, assessing new problems related to community noise complaints, and all other activities not associated with our clients' facilities. In the early 1990's JAA had over 750 individual manufacturing facilities, primarily located in the U.S., Canada and Mexico for which it was responsible. The exposure that this caused was the basis for the start of our relationship with NIOSH. Our NIOSH related collaborations included the epidemiological database discussed earlier and a separate project under the title of "Safe@Work" formed to assist a software developer who was converting his DOS based software to Windows. NIOSH's interest in this software was that it would form the basis for its internal storage of occupational noise and health data for workers in the U.S.

Q.15. What training and experience do you possess concerning the annoyance and sleep disturbance caused by noise?

A. 15. The primary reason why my profession exists is because there is a linkage between noise and health. However, as an engineer, my interests are as a consumer of medical research that establishes the boundaries of what levels and types of noise are safe and which are not. Thus, my training in the late 1960's as an acoustical engineer included courses on the effects of noise on people both as a cause of hearing loss and as a cause of other pathologies such as those attributed to sleep disturbance, annoyance, and other factors. This aspect of my work has allowed me to work with some of the top medical researchers in occupational hearing health and with the occupational medical doctors that managed the medical programs for my clients.

My training continued with the seminars and conferences held annually by the Institute of Noise Control Engineers (INCE) and the American Industrial Hygiene Association. I have also participated in conducting training on the topics of noise and health to members of these associations and to my client's engineering, medical and safety staff's since the early 1980's.

In the late 1980's and early 1990's I engaged in several collaborations with the National Institute of Occupational Safety and Health (NIOSH) to assess whether the presumptions built into the Occupational Safety and Health Act of 1972 regarding human response to noise were correct. This included a contract with NIOSH to construct a database of worker hearing test results, noise exposures, and hearing protection devices that could be used by their epidemiology staff to re-evaluate these assumptions based on the records of a major automotive company and a major food processing company.

With specific reference to wind turbine noise and its potential for adverse health effects on people living in or near the footprint of modern industrial scale upwind wind turbines I have collaborated with a number of medical professionals since 2006. These include collaboration with medical professionals including, Dr. Robert McMurtry (former Dean of a prestigious Ontario Medical School), Dr. Chris Hanning (British Sleep Specialist), Dr. Alec Salt (Medical researcher into cochlear function for NIDCD and others), and Dr. Michael Nissenbaum (Radiologist from Northern Maine Medical Institute who has been studying people in Maine living near wind turbines). I am a Director of the Society for Wind Vigilance, an international organization of medical and acoustical professionals who formed to advocate the need for independent, peer reviewed, health studies to address the complaints of adverse effects from living proximate to industrial scale wind turbines made by people in countries around the world. As a result of these collaborations I have a working knowledge of the medical issues involved with how people react to wind turbine noise.

Q.16. Who started the firm of E-Coustic Solutions?

A16. I started E-Coustic Solutions as the sole owner in 2006 after my JAA partner Robert Anderson and I decided to close JAA due to the economic uncertainties in our client base.

Q17. What types of work does your firm do?

A.17. E-Coustic Solutions focuses on much of the same work as I did with JAA but with more emphasis on community noise than in-plant noise. When JAA was closed, the contracts it held were passed forward to the new companies formed by each of its partners with E-Coustic Solutions taking the community noise aspects of the work and Mr. Anderson taking the in-plant portion of the services.

Q18. What are your duties with E-Coustic Solutions?

A.18. I am its sole full time employee and as such have responsibility for all of its work.

Q.19. Have you been a member of any professional organizations related to noise?

A.19. Yes. These organizations include the American National Standards Institute (ANSI), the Institute of Noise Control Engineers (INCE), American Industrial Hygiene Assoc (AIHA), and the National Hearing Conservation Assoc (NHCA). Each of these associations are stakeholders in the health effects of sound on people and their members interface with acoustical engineers and medical researchers relevant to each one's focus. AS stated above, I am also a member of the Society for Wind Vigilance and one of its founding members.

Q.20. Do you have any experience as a member of the faculty for any educational institutions?

A.20. Yes. My academic credentials include current appointments as Adjunct Professor and Instructor to the Speech and Communication Science Departments at Michigan State University and Central Michigan University.

For 12 years, from the mid 1980's to late 1990's) I conducted courses for Masters level audiology students on noise control and hearing conservation for audiologists at Michigan State University. More recently this program has been dropped by my department. I now act as an advisor to the staff and professors in the Department on matters related to test equipment and procedures and in that capacity have been a co-author of papers on the effects of personal entertainment devices on listener hearing health and have acted as co-advisor for students required to conduct research projects involving acoustical testing. This has involved a student's study of wind turbines in Michigan and preparation of a presentation for an upcoming conference of the America Speech-Language-Hearing Association (ASHA) titled: " What you can't hear can hurt you." with Professor Jerry Punch. This presentation is to alert ASHA professionals to the problems being identified with wind turbine noise.

I am currently working with a grad student and Dr. Michael Stewart at Central Michigan University to study a community in Michigan that is hosting a number of wind turbines (Repower MM92) where one or more families have experienced adverse health reactions to the operation of the wind turbines.

Q.21. What training and experience do you possess concerning noise from wind turbines?

A.21. I first took interest in wind turbines as a potential source of community noise in late 2002 through 2005. As a result of a viral infection in my heart causing complete heart failure in late 2001, I had been directed by my medical advisors to take a leave of absence from my duties at JAA and to do nothing that would stress my heart for a recovery period of two years. During this time, I conducted research using reports and studies available on the internet into the types of problems that were occurring in Europe, the United Kingdom, and elsewhere as the 1.5 MW and larger wind turbines were being installed.

It was clear to me that the U.S. would also be considering use of these modern industrial scale upwind turbines in the near future and I wanted to make sure that my company would be in a position to service clients and communities where they may be hosted. As the new projects came online in the U.S., such as Mars Hill, Maine and in Canada, New Zealand, and other countries, I used internet technology to obtain the siting studies and also the follow-up studies that were conducted to validate the siting studies or address post-construction complaints. I also started to collect research papers from consultants to the wind turbine manufacturers, developers and others to give me insight into the mechanisms involved in wind turbine sound generation. I have continued this research until the present. Now, papers are routinely presented at national and international conferences held on the topic of wind turbine noise.

I returned to my regular JAA duties in late 2004 but this sabbatical allowed me to conduct an in depth look at the issues that provided an excellent foundation for my present work on wind turbine siting criteria and noise impact on host communities.

Q.21. Have you authored any papers or made presentations at professional conferences on the topic of noise and health related to the operation of industrial scale wind turbines?

I have authored or co-authored four papers covering topics such as how to set criteria to protect public health, and others demonstrating that wind turbine sound emissions are predominantly comprised of infra sounds (*i.e.*, sounds that that are between 0 and 20 Hz, such that they are often "felt" and not heard).

I am the author (or co-author) of “Simple guidelines for siting wind turbines to prevent health risks,” "The 'How To' Guide To Siting Wind Turbines To Prevent Health Risks From Sound," "Wind Turbine Noise, What Audiologists should know," "Dynamic measurements of wind turbine acoustic signals, employing sound quality engineering methods considering the time and frequency sensitivities of human perception," and “Wind Turbine Infra and Low Frequency Sound: Warning Signs that were not Heard” and several other publications, fact-sheets whitepapers, and reports regarding wind turbine noise, and its impact on residential land-use and people. A list of these papers is attached hereto as Exhibit B.

I have made presentations on wind turbine noise and its impact on people and other topics related to the proper siting of wind turbines if risks to public health are taken into consideration at the INCE conference NoiseCon 2010 held in Detroit, MI (“Simple guidelines for siting wind turbines to prevent health risks”) and at a number of public venues in a less technical form ("The 'How To' Guide To Siting Wind Turbines To Prevent Health Risks From Sound").

I coauthored a paper describing the analysis of wind turbine noise measured and recorded at a residential home located approximately 1350 feet from the closest wind turbine using methods that can resolve the short duration, high amplitude pulsations that characterize the bursts of infra and low frequency sound emitted by wind turbines due to commonly occurring weather conditions. This paper: "Dynamic measurements of wind turbine acoustic signals, employing sound quality engineering methods considering the time and frequency sensitivities of human perception," was presented at the 2011 NoiseCon Conference by my coauthor, Wade Bray, of HEAD Acoustics, Brighton, MI. The paper demonstrated that acoustic energy in the very low frequency range produced by wind turbines during commonly occurring weather conditions were sufficiently strong to be perceived by 10% or more of the general population.

I have recently had a peer reviewed paper published in the April 2012 Journal of the Bulletin of Science, Technology and Society, titled: “Wind Turbine Infra and Low Frequency Sound: Warning Signs that were not Heard” that compares the characteristics of acoustical emissions from industrial scale wind turbines of the type located in the proposed project to the sounds of other large machines with slowly rotating blades such as the fans used in high rise office buildings for heating and ventilating that were found to be the cause of noise induced Sick Building Syndrome. Dynamic modulation (pulses) of infra and low frequency sound that were generally inaudible to occupants of these buildings caused adverse health effects of the type reported by people living near industrial scale wind turbines.

This paper also demonstrates that the acoustical experts commonly hired by the wind industry were aware of, and in some cases participated in, the studies that led to solving the question of what was causing noise induced Sick Building Syndrome. It also demonstrates that some of these same experts have other experience with noise sources emitting similar types of noise as wind turbines where the modulating infra and low frequency noise was found to cause adverse health effects. Finally, it reviews the history of a ten year study of wind turbine noise conducted for the DOE/NASA during the 1980's that reported that industrial scale modern upwind wind turbines of the type proposed for the Champaign project (Buckeye Wind) would be expected to produce these very low frequency sounds and that such sounds would be a source of problems for people if wind turbine were located too close to their homes. It also anticipated that the problem would be worse inside homes than outside them as a result of the way the building structure interacted with the wind turbine noise.

Q.22. On how many occasions have you testified as an expert in administrative hearings concerning noise?

A.22. I provide consulting services for municipalities and the private sector on wind turbine issues related to the installation and siting of industrial scale modern upwind wind turbines; assist in conducting reviews of proposed wind turbine utility projects and the documents submitted by the developer when applying for permits and other permissions; and adoption of zoning ordinances regulating the same. The focus is on whether the proposed or anticipated wind turbine project's noise, audible and inaudible sound, is a potential source of annoyance; sleep disturbance; or other adverse health effects such as vestibular disturbances, mood changes, headaches; and ear, head, and body sensations, etc..

I have testified in approximately 10 to 15 administrative hearings as an expert in acoustical engineering on behalf of such companies as General Motors, Ford, and Chrysler held by the Occupational Safety and Health Administration. The purpose of my testimony in those cases was directed towards the limits of feasibility of engineering controls and to establish that my clients were taking the necessary administrative and medical/safety precautions to protect their employees from the adverse health effects of occupational noise exposure.

Since forming E-Coustic Solutions in 2006, I have worked with clients in the U.S. and Ontario who are experiencing adverse health effects that started when wind turbines in their communities started operation. Specific to wind turbine noise, I have worked for clients in over 60 different communities. I have provided written and oral testimony in approximately 30 of those instances.

I have testified in approximately 30 administrative hearings considering applications by wind power companies to install wind powered electrical generating utilities. The subject matter of my testimony in these cases was to review and comment upon the noise studies conducted on behalf of the wind developer by its acoustical consultants, to present my research and recommendations for whether the wind project would result in nighttime sleep disturbance and other adverse health effects from the turbine's noise emissions, and to state my recommendations for criteria that would limit wind turbine noise to a level that would not be likely to cause adverse health effects.

Q.23. Have you reviewed the portions of Champaign Wind's application in this proceeding related to the noise impacts of its proposed wind turbines?

A.23. Yes.

Q.24. Do you hold an opinion as to what sound levels will cause annoyance or sleep disturbance?

A.24. Yes. One of the fundamental "rules of thumb" used by acoustical engineers since the 1970's and early 1980's when portable lab grade measurement instrumentation capable of performing calculations on the incoming data stream made it possible to study sound using statistical descriptors is that when the noise from a new source of sound is less than 5 decibels (dB) louder than the pre-existing background sound level (measured as the L90 dBA sound level) it is generally found to be unnoticed to tolerable. When it exceeds the naturally occurring sound levels in the receiving community (referred to as the "background" sound level) by more than five decibels, it becomes intrusive. Recent guidance from the World Health Organization states that 40 dBA sound levels outside a home at night is the threshold for adverse health effects for traffic, airport, and general industrial sounds that are not dominated by low frequency acoustic energy. When the new noise source will operate during night time hours, this intrusiveness will lead to sleep disturbance. Daytime conditions in many communities are much more noisy than nighttime. Thus, wind turbine noise during the daytime hours is more of a problem of annoyance than it is of sleep disturbance. This, of course, assumes that one is not trying to sleep during daytime hours. It should be noted that in this context "annoyance" is an indicator of adverse health effects if it is continued for long periods of time.

Q. Why is the background sound level important in predicting whether a new sound will be intrusive in a community?

A. The basic principle is that an increase of community sound levels of 5 dB is generally noticeable, but is not a sufficient increase to cause objections. This presumes that the characteristics of the new noise source are not particularly disturbing. That is, they blend with the other community sounds and do not have tones, non-steady sounds (fluctuating sound levels) and mechanical sounds like gear-box noise, whistles, etc.. The concept is that the other community sounds will help to mask the sound of the new noise source. This is where wind turbine noise has a potential to be a source of objections even if only 5 dBA louder than the pre-operation background sound levels during the quietest time of operation (nights when the surface level winds are calm and the upper level winds are adequate to power the wind turbines). The sounds of blade swish and the other non-steady sounds from wind turbines can often be heard as distinct noises from the turbines that do not get masked with other community sounds because of the rhythmic swishing sound and low frequency rumble and roar of the large blades moving through the air. Several studies have shown that it is not possible to mask the wind turbine sounds due to these characteristics. One study looked at wind turbines placed near a busy highway[1]. It found that the highway noise needed to be about 20 dBA higher than the sound from the wind turbines before people considered the sounds to be masked. This is relevant to this case because the premise of the Hessler report is that the sounds of community activities and noise induced by wind moving over the surface of the ground, leaf rustle, and around structures and objects will mask the sound of the wind turbines. Studies and my personal experience show that the unique mechanical, rhythmic nature of wind turbine noise makes it clearly distinguished even during periods of high winds. The sound that wind makes does not mask the sound of wind turbines.

Further, for people inside their homes the lower frequency sound from the wind turbines not effectively blocked by the walls, roofs and windows of homes. This leads to a situation where one study[2] found that when the sound level is 45 dBA (Leq) outside a home roughly 33% of the people inside the home found the wind turbine noise audible and annoying. 18% found it highly annoying.

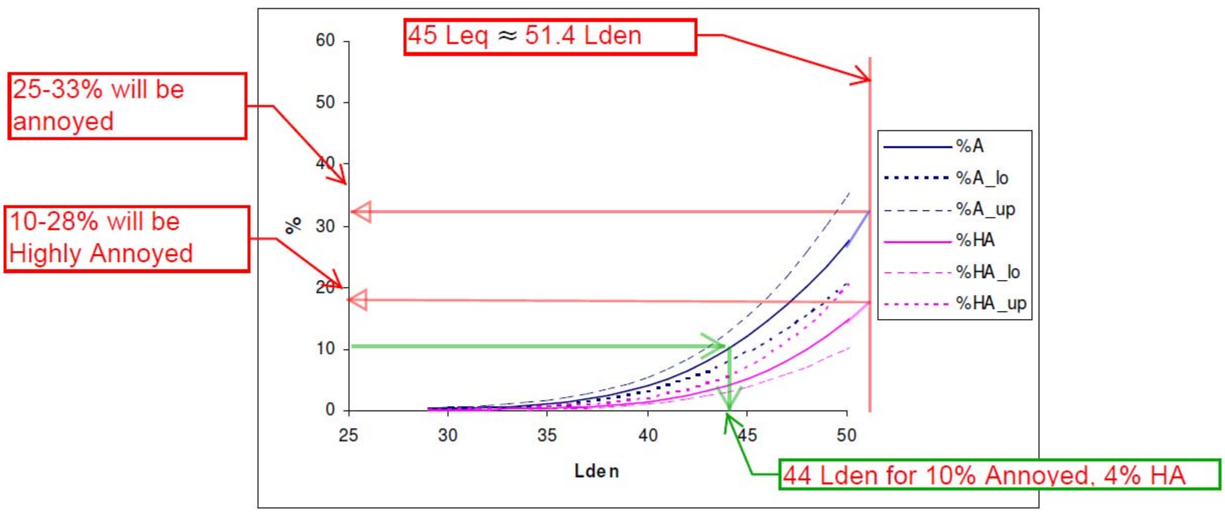

Figure 2 – Expected percentages annoyed (*%A*) and highly annoyed (*%HA*) indoors by wind turbine noise, with 95% confidence intervals.

Q. To what extent does the background sound level in a community mask the noise from wind turbines?

[1] Pedersen E, van den Berg GP (Fritz), Why is Wind Turbine Noise Poorly Masked By Road Traffic Noise, Invited Paper, InterNoise 2010, June 2010, Portugal

[2] Janssen SA, Vos H, Eisses AR, Pedersen E, "Predicting Annoyance by Wind Turbine Noise," Invited paper to InterNoise 2010, June 2010, Portugal

A. Wind turbine noise is sound produced by a machine that has a specific rhythm (related to hub rpm), strong low frequency components, and other characteristics that make it clearly identifiable when other natural sounds of community activity (urban hum) and wind induced sounds are present. Masking of a new sound by other sounds only works if the characteristics of both sounds are similar. In the case of wind turbine noise, it is not similar to the other sounds that would be potential masking agents. Further, the masking sounds must be as loud or louder than the sound to be masked. During nights when the sound of community activity abates the distinctive sounds of wind turbine operation are even more clearly distinguished. For evenings and nights with little or no surface level winds to produce any "wind noise" (referred to as stable atmospheric conditions) the upper level winds where the blades are located can have strong winds that are sufficient to power the wind turbines.

Papers have demonstrated that the conditions favorable for wind turbine operation during periods of low or calm surface level winds occur often during warm weather months. These are times when there is little or no potential for any masking of wind turbine noise. A paper by Cliff Schneider[3], found that: "Stable conditions occurred in 67% of nights and in 30% of those nights, wind velocities represented worst-case conditions where ground level winds were less than 2 m/s and hub-height winds were greater than wind turbine cut-in speed, 4 m/s." See Exhibit C. Van den Berg reported in his thesis that these conditions were present in temperate zones as often as 2 out of every three nights. See Exhibit D.

Further, night time upper level winds are often more turbulent and have speed differences that change dramatically from the point of lowest reach of a blade to the height of the blade at the top of the rotation. This leads to the situation where the control circuits that adjust blade angle for optimum energy production cannot find a blade position that is suitable for all of the various wind conditions from the top to the bottom of the rotation. When the blade is not properly aligned to the in-flow air stream the energy production drops and the noise emissions increase. Thus, studies have shown that at night wind turbine noise can be 6 to 15 dBA higher than during the day.[4]

It for the above reasons, and others that will be mentioned later in my testimony that the proper assessment of background sound levels is to measure the background sound during the quietest time when the wind turbines can operate (night without surface level winds) and that the measurement be based on the L90 sound level, not the Leq. These sound levels are shown in the graphs of Mr. Hessler's reports as the lowest points along the trace of L90 sound levels for each measurement site.

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[3] Schneider, CP, "Measuring background noise with an attended, mobile survey during nights with stable atmospheric conditions," InterNoise 2009, August 23-26, 2009, Ottawa Canada.

[4] Van den Berg, GP, "The Sounds of High Winds," Graduate Thesis May 12, 2006 and numerous other papers prior to and subsequent to the thesis.

It is worth noting that in a paper by Mr. Hessler's father, George, it is noted that when assessing the background sound in quiet rural areas: "LAeq is the poorest metric for measurement in quiet areas."[5] (Exhibit E)

In spite of the valid reasons for using the L90 measured for the quietest time of the night, without surface winds, insect noise, traffic, etc. as the basis for the evaluation of the background plus 5 dB rule of thumb for new projects, acknowledged in both the original Hessler study for Buckeye I and Champaign Wind (Buckeye II), Mr. Hessler diverges from this basic protocol, claiming instead that the Leq should be used and that the transient noise of from traffic and other human activity, wind induced noise, and other sounds not normally considered part of the residual or background sound in a community is the proper metric. This claim is clearly motivated by the fact that if he was to have used the L90 sound levels for the quiet nights with low surface level winds, the project's design goal would have been 35 dBA or less. Indeed, in the Hessler report for Buckeye I he states that the L90 for those conditions was approximately 29 dBA leading to a design goal of 34 dBA. It is obvious, that had Mr. Hessler used the commonly accepted L90 metric he would have had to conclude that the project was not compatible with the adjacent community.

Q. What are the bases of your opinion that noise higher than five decibels above background sound levels will cause annoyance or sleep disturbance?

A. This is a basic formula. It is presented as a rule in most modern textbooks that address community noise and is used either directly or as the basis for not-to-exceed limits in community noise standards worldwide. For example, L_{A90} +5 dBA (A-weighted decibels) is used in standards for the United Kingdom., Ireland, New Zealand, France (night L_{A90} +3 and +5 daytime). Other locations, such as Germany and the Netherlands (rural night 30 dBA), have set upper limits based on the use of this formula. The German rural residential night limit is 35 dBA. It should be noted that Germany and the Netherlands are also major users of wind turbines as part of their electric utility system. It is also incorporated directly into many U.S. state and community standards, such as New York’s or in modified forms in other communities. It is referenced in both the original noise study by Hessler for Buckeye I and in the recent study for Champaign Wind (Buckeye II). It is also the basis for recommendations I made in my 2008 presentation at Noise-Con 2008 (Detroit, MI) " Simple guidelines for siting wind turbines to prevent health risks,"[6]

Q. What is the reason for using five decibels above background as the standard?

A. The goal of the 5 decibels over background rule is to prevent community noise complaints as well as to prevent nighttime sleep disturbance. This principle was

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[5] Hessler GF Jr., "Measuring ambient sound levels in quiet environments," InterNoise 2009, August 23-26, 2009 Ottawa Canada.

[6] Kamperman GW, James RR, " Simple guidelines for siting wind turbines to prevent health risks," NoiseCon 2008, July 28-31, Detroit Michigan.

developed in studies of noise sources, such as highways, rail, air and industrial noise sources which are common to suburban and urban communities where background sound levels at night range from 35 to 45 dBA in the residential areas. The purpose of these studies was to establish the relationship between annoyance and absolute sound level. These studies confirmed that as the background sound levels increased, the tolerance for nighttime noise also increased. The relationship of L90 + 5 applied to these situations, too.

Q. Are there any other standards that are commonly used to establish allowable noise levels?

A. Yes. In the early 1970's the US EPA issued a guidance document that set out limits for day and night noise in different types of communities in the US. This document, referred to as the "Levels Document" specified that for urban communities with prior experience to high noise from traffic, aircraft and/or industry a daytime level of 55 dBA and a nighttime level of 45 dBA was the upper limit. But, it also addressed rural communities that had no prior experience with noise. For those communities, the EPA recommende3d that the day and night levels for urban noise be reduced by 15 dB. This makes their recommendation 40 dBA day and 30 dBA night.

For the purpose of establishing community noise limits for common community noise sources, it was deemed to be politically acceptable to set the limits at the point where 10% of the exposed population would be ”annoyed.” Similar studies conducted in the European Union for existing wind turbine utilities show that the absolute sound level where 10% of the population reports the noise as “annoying” is approximately 10 dBA lower for wind turbines than it is for the other noise sources. The most recent study of this type is titled: “WindFarm Perception” sponsored by the University of Groningen and Göteborg University. This study involved a review of operating wind utilities where the turbines ranged from smaller under 1MW models to the larger types proposed for the Champaign Wind project. It reports that the sound level at which 10% of the population is “very annoyed” is 30 to 35 dBA. At these sound levels sleep disturbance was reported by 25% of the population. This increased sensitivity to noise over what would be expected from other common community noise sources has been identified in many other studies.

Q. Have you reviewed the information and representations about turbine noise made in Champaign Wind’s application in this proceeding study, including the statements on pages 67-80 of the application and the report of David Hessler that is labeled as Exhibit O?

A. Yes.

Q. Does Champaign Wind’s application contain any statements indicating that the noise from wind turbines should not exceed five decibels above the background sound level?

A. Yes, It discusses the use of L90 as the basis for this assessment on page 68 of the application:

> The Leq is literally the average sound level over each measurement interval. This measure can be influenced and elevated by sporadic, short-duration noise events, such as cars passing by, and is therefore often unrepresentative of the quietest periods between these events. The L90 statistical sound level is commonly used to conservatively quantify background sound levels. The L90, or residual sound level, is the sound level exceeded during 90% of the measurement interval (i.e., it is louder than the L90 level most [90%] of the time). This measure has the quality of filtering out relatively loud, sporadic, short-duration noise events thereby capturing the quiet lulls between such events. It is this consistently present, near-minimum "background" level that forms a conservative basis for evaluating the audibility of a new source.

And at the bottom of page 72 it states:

> as the noise conditions imposed under the Timber Road I, Timber Road II and Black Fork wind projects. Those projects include a Facility-related noise limitation at non-participating residences of 5 dBA over the nighttime average Leq background level unless the validly measured ambient Leq

Continuing at the top of the next page with:

> at the location of the complaint plus 5 dBA is greater.

It is my position that the use of Leq is not appropriate for the background sound metric and should have instead used the L90 for the quietest time of the night. However, the Application does accept the basic formula of L90 + 5 being based on the residual sound and instead substitutes the average sound level (Leq).

Q. Are you aware of any other instances in which David Hessler has indicated that the noise from wind turbines should not exceed five decibels above the background sound level?

A. Mr. Hessler's first report for Buckeye Wind I states: "A design goal of limiting the project sound level to 5 dBA over the background strikes a reasonable balance between these extremes. This approach is commonly used in siting analyses for all types of new infrastructure projects and is currently being used for numerous wind energy projects in New York State, for example, per a set of guideline recommendations [Ref. 10] promulgated by that State's Department of Environmental Conservation (NYSDEC)." (top of page 22)

And,

"Because a nighttime L90 of only 29 dBA was measured during critical 5 m/s wind conditions the nominal impact threshold is about 34 dBA. Because there are a number of homes with predicted sound level of more than 34 dBA some adverse reaction to Project noise appears to be possible during these particular conditions." (page 27 bottom)

In the report for Champaign Wind (Buckeye Wind II), Mr. Hessler uses the rule of background plus 5 dB as a design goal. However, he now uses Leq measurements for background sound instead of the generally accepted L90:

Again it should be noted that the substitution of Leq for the generally accepted L90 metric as a measure of background sounds is not appropriate as discussed in other parts of this testimony.

Mr. Hessler is also the author of a guide developed for the Minnesota Public Utility Commission under funding from DOE. In that document he states:
"As a general rule of thumb, an increase of up to 5 dBA above the pre-existing LA90 sound level is usually found to be acceptable whereas greater increases should be avoided. This design approach only holds for background levels of about 35 dBA or above. When lower background sound levels are found a design goal of 40 dBA or less at all residences should be sought." (page 3)[7]

Again we see that Mr. Hessler acknowledges the concept of background plus 5 where the L90 sound level from the quietest time the wind turbines will be operating is the appropriate measure for a design goal. Then, he introduces his argument that this rule must be ignored because it interferes with locating wind turbines in quiet rural areas near homes. This argument is without foundation and is purely an economic argument to justify the installation of wind turbines against the best practices of acousticians for all other types of noise sources. It also fails to address the need of public authorities like the OPSB and Minnesota PUC to protect public health. When a noise source does not meet the criteria for safe installation the proper response is that it does not belong at that location, not that the people who will be exposed to the higher noise must learn to cope with it as though the communities are sacrifice zones and the health of the public is expendable, they are "collateral damage," if necessary to promote the interests of the State or the developer.

The proper application of the standard rule of thumb limiting new noise sources to no more than 5 dB above the L90 for the quietest time is the appropriate metric and as a Professional Engineer and Member of INCE, Mr. Hessler's professional obligation is to disclose these risks to the developer and OPSB not try to mask them with cleaver words and charts that are really little more than junk science.

[7] Hessler, DM, "Best Practices Guidelines for Assessing Sound Emissions from Proposed Wind Farms and Measuring the Performance of Completed Projects," Oct. 13, 2011 for the National Association of Regulatory Utility Commissioners (NARUC), Washington, DC.

Q. Do you have any opinions on whether any of the information and representations about turbine noise in Champaign Wind's application are erroneous?

A. Some of the errors in the application include the following:

1. Errors in protocol for background noise testing including but not limited to: location of the test sites, instrumentation techniques, metrics, and presentation.
2. Errors in the protocol for computer modeling of the sound propagation from the wind turbines to noise receptors including but not limited to: use of input data that reflects daytime noise from wind turbines not the higher nighttime noise associated with complaints; use of input settings that presume the ground will attenuate the sounds instead of assuming that the ground is reflective as would be appropriate for winter conditions; use of a model that is not designed or intended to be used for noise sources that are high in the atmosphere while the receptors are at or near ground level and that assumes a slight downwind condition not one with wind speeds of 10 mph and higher; failure to disclose and apply known tolerances for model algorithm and measurement errors, use of a model that predicts long term average sound levels hiding the fluctuating nature of wind turbine noise in an average value, presentation of the model results as contour maps and reported values with sound levels at integer increments implying that the results are accurate to that level of precision, and failure to include disclosure of these deviations from acceptable practice and the consequences of them in the report.
3. Conclusions about the impact on people from the wind turbine noise, both audible and inaudible, that assert there will be little or no impact when projects that Mr. Hessler has been involved in previously have resulted in reports of nighttime sleep disturbance, annoyance, and adverse health effects including health effects that are related to exposure to dynamically modulated infra and low frequency sound on the vestibular and auditory systems.

   Further, the noise study provided by Mr. Hessler does not even follow the recommendations he makes in the Minnesota PUC Guidelines for how to present the contour maps and other information. The PUC Guidelines had been published in 2011 while the Champaign Wind (Buckeye 2) report was submitted in 2012. Many of these deviations make it harder for reviewers to understand the results of his background and model work. For example, in the PUC Guidelines he recommends that the contour maps project the sound levels out to at least 35 dBA and the region between the 35 dBA Leq contour line and the 40 dBA Leq contour line be shaded green to clearly delineate this region. On page 20 of the PUC document he states in reference to Figure 4.1.5.1: "The green region between 40 and 35 dBA generally represents the area where in all likelihood project noise would still be readily audible some of the time, if not much of the time, but at a fairly low magnitude."

Q. Have you reviewed the sound measurements conducted by Mr. Doss for the OPSB?

A. Yes, I will address that document in my amended testimony.

Q. Have you reviewed the Staff report with respect to noise?

A. Yes, I will address that document in my amended testimony.

Q. Have you any further comments on the Application and Noise reports for Champaign Wind (Buckeye 2)?

A. Yes, I will address them in my amended testimony

Q. Do you have any recommendations for the OPSB as to proper criteria for Champaign Wind (Buckeye 2)?

A. Yes, I will summarize them here and will address them in more detail in my amended testimony.

1. The OPSB should adopt the use of L90 as the appropriate measurement metric for establishing the residual background sound level in a community targeting the conditions of winds at the surface of 2.2 meters per second or less to represent the sounds present during a nighttime stable atmosphere.

2. The OPSB should adopt the use of LA90 + 5 dB as the limit for the new noise source on any receiving property.

3. The OPSB should adopt a low frequency noise criteria limit of not to exceed 50 dBC as the limit for the new noise source on any receiving property.

4. The OPSB should adopt the use of the property line as the boundary for these decisions in order to avoid a creating an uncompensated noise easement across the property of non-participating residents.

Conclusion

Q. Do you hold all of the opinions expressed in this testimony to a reasonable degree of engineering certainty?

A. Yes.

Q. Does this conclude your direct testimony?

A. I request that I be allowed to expand upon and amplify the points I have made in this testimony in a second submittal to be provided by COB on Tuesday, Nov. 6, 2012.

CERTIFICATE OF SERVICE

I hereby certify that, on November 5, 2012, a copy of the foregoing was served by electronic mail on M. Howard Petricoff (mhpetricoff@vorys.com); Michael J. Settineri (mjsettineri@vorys.com); Miranda Leppla (mrleppla@vorys.com); Chad Endsley (cendsley@ofbf.org); Nick Selvaggio (nselvaggio@champaignprosecutor.com); Jane Napier (jnapier@champaignprosecutor.com), Stephen Reilly (Stephen.Reilly@puc.state.oh.us), Devin Parram (Devin.Parram@puc.state.oh.us); Kurt P. Helfrich (Kurt.Helfrich@ThompsonHine.com); Philip B. Sineneng (Philip.Sineneng@ThompsonHine.com); Ann B. Zallocco Ann.Zallocco@ThompsonHine.com); G.S. Weithman (diroflaw@ctcn.net).

*s/ Jack A. Van Kley*____________________
Jack A. Van Kley

EXHIBIT A

BIOGRAPHICAL SKETCH

NAME	POSITION TITLE	BIRTHDATE
Richard R. James	Principal Consultant, E-Coustic Solutions	3/3/48
	Adjunct Instructor, Michigan State University Adjunct Professor, Central Michigan University	

EDUCATION

INSTITUTION	DEGREE	YEAR	FIELD OF STUDY
General Motors Institute, Flint, MI	B. Mech. Eng.	1971	Noise Control Engineering

RESEARCH AND PROFESSIONAL EXPERIENCE:

Richard R. James has been actively involved in the field of noise control since 1969, participating in and supervising research and engineering projects related to control of occupational and community noise in industry. In addition to his technical responsibilities as principal consultant, he has developed noise control engineering and management programs for the automotive, tire manufacturing, and appliance industries. Has performed extensive acoustical testing and development work in a variety of complex environmental noise problems utilizing both classical and computer simulation techniques. In 1975 he co-directed (with Robert R. Anderson) the development of SOUND™, an interactive acoustical modeling computer software package based on the methods that would be later codified in ISO 9613-2 for pre and post-build noise control design and engineering studies of in-plant and community noise. The software was used on projects with General Motors, Ford Motor Company, The Goodyear Tire & Rubber Co., and a number of other companies for noise control engineering decision making during pre-build design of new facilities and complaint resolution at existing facilities. The SOUND™ computer model was used by Mr. James in numerous community noise projects involving new and existing manufacturing facilities to address questions of land-use compatibility and the effect of noise controls on industrial facility noise emissions. He is also the developer of ONE*dB(tm) software. He was also a co-developer (along with James H. Pyne, Staff Engineer GM AES) of the Organization Structured Sampling method and the Job Function Sound Exposure Profiling Procedure which in combination form the basis for a comprehensive employee risk assessment and sound exposure monitoring process suitable for use by employers affected by OSHA and other governmental standards for occupational sound exposure. Principal in charge of JAA's partnership with UAW, NIOSH, Ford, and Hawkwa on the HearSaf 2000tm software development CRADA partnership for world-class hearing loss prevention tools.

1966-1970	Co-operative student: General Motors Institute and Chevrolet Flint Metal Fabricating Plant.
1970-1971	GMI thesis titled: "Sound Power Level Analysis, Procedure and Applications". This thesis presented a method for modeling the effects of noise controls in a stamping plant. This method was the basis for SOUND™.
1970-1972	Noise Control Engineer-Chevrolet Flint Metal Fabricating Plant. Responsible for developing and implementing a Noise Control and Hearing Conservation Program for the Flint Metal Fabricating Plant. Member of the GM Flint Noise Control Committee which drafted the first standards for community noise, GM's Uniform Sound Survey Procedure, "Buy Quiet" purchasing specification, and guidelines for implement-ing a Hearing Conservation Program.
1972-1983	Principal Consultant, Total Environmental Systems, Inc.; Lansing, MI. Together with Robert R. Anderson formed a consulting firm specializing in community and industrial noise control.
1973-1974	Consultant to the American Metal Stamping Association and member firms for in-plant and community noise.
1973	Published: "Computer Analysis and Graphic Display of Sound Pressure Level Data For Large Scale Industrial Noise Studies", Proceedings of Noise-Con '73, Washington D.C.. This was the first paper on use of sound level contour 'maps' to represent sound levels from computer predictions and noise studies.
Nov. 1973	Published: "Isograms Show Sound Level Distribution In Industrial Noise Studies", Sound&Vibration Magazine
1975	Published: "Computer Assisted Acoustical Engineering Techniques", Noise-Expo 1975, Atlanta, GA which advanced the use of computer models and other computer-based tools for acoustical engineers.
1976	Expert Witness for GMC at OSHA Hearings in Washington D.C. regarding changes to the "feasible control" and cost-benefit elements of the OSHA Noise Standard. Feasibility of controls and cost-benefit were studied for the GMC, Fisher Body Stamping Plant, Kalamazoo MI.
1977-1980	Principal Consultant to GMC for the use of SOUND(tm) computer simulation techniques for analysis of design, layout, and acoustical treatment options for interior and exterior noise from a new generation of assembly plants. This study started with the GMAD Oklahoma City Assembly Plant. Results of the study were used to refine noise control design options for the Shreveport, Lake Orion, Bowling Green plants and many others.

1979-1983	Conducted an audit and follow-up for all Goodyear Tire & Rubber Company's European and U.K. facilities for community and in-plant noise.
1981-1985	Section Coordinator/Speaker, Michigan Department Of Public Health, "Health in the WorkPlace" Conference.
1981	Published: "A Practical Method For Cost-Benefit Analysis of Power Press Noise Control Options", Noise-Expo 1981, Chicago, Illinois
1981	Principal Investigator: Phase III of Organization Resources Counselors (ORC), Washington D.C., Power Press Task Force Study of Mechanical Press Working Operations. Resulted in publishing: "User's Guide for Noise Emission Event Analysis and Control", August 1981
1981-1991	Consultant to General Motors Corporation and Central Foundry Division, Danville Illinois in community noise citation initiated by Illinois EPA for cupola noise emissions. Resulted in a petition to the IEPA to change state-wide community noise standards to account for community response to noise by determining compliance using a one hour L_{eq} instead of a single not-to-exceed limit.
1983	Published: "Noise Emission Event Analysis-An Overview", Noise-Con 1983, Cambridge, MA
1983-2006	Principal Consultant, James, Anderson & Associates, Inc.; Lansing, MI. (JAA), Together with Robert R. Anderson formed a consulting firm specializing in Hearing Conservation, Noise Control Engineering, and Program Management.
1983-2006	Retained by GM Advanced Engineering Staff to assist in the design and management of GM's on-going community noise and in-plant noise programs.
1984-1985	Co-developed the 1985 GM Uniform Plant Sound Survey Procedure and Guidelines with James H. Pyne, Staff Engineer, GM AES.
1985-Present	**Adjunct Instructor, Michigan State University, Department of Communicative Sciences and Disorders**
1986-1987	Principal Consultant to Chrysler Motors Corporation, Plant Engineering and Environmental Planning Staff. Conducted Noise Control Engineering Audits of all manufacturing and research facilities to identify feasible engineering controls and development of a formal Noise Control Program.
1988-2006	Co-Instructor, General Motors Corporation Sound Survey Procedure (Course 0369)
1990	Developed One*dB$^{(tm)}$, JAA's Occupational Noise Exposure Database manager to support Organizational structured sampling strategy and Job Function Profile (work-task) approach for sound exposure assessment.
1990-1991	Co-developed the 1991 GM Uniform Plant Sound Survey Procedure and Guidelines with James H. Pyne, Staff Engineer, GM AES. Customized One*dB$^{(tm)}$ software to support GM's program.
1990-2006	Principal Consultant to Ford Motor Company to investigate and design documentation and computer data management systems for Hearing Conservation and Noise Control Engineering Programs. This included bi-annual audits of all facilities.
1993-2006	GM and Ford retain James and JAA as First-Tier Partners for all non-product related noise control services.
1993	Invited paper: "An Organization Structured Sound Exposure Risk Assessment Sampling Strategy" at the 1993 AIHCE
1993	Invited paper: "An Organization Structured Sound Exposure Risk Assessment Database" at the Conference on Occupational Exposure Databases, McLean, VA sponsored by ACGIH
1994-2001	Instructor for AIHA Professional Development Course, "Occupational Noise Exposure Assessment"
1996	Task Based Survey Procedure (used in One*dB$^{(tm)}$) codified as part of ANSI S12.19 Occ. Noise Measurement
1995-2001	Coordinate JAA's role in HearSaf 2000^{tm} CRADA with NIOSH, UAW,Ford, and HAWKWA
1997-Present	Board Member, Applied Physics Advisory Board, Kettering Institute, Flint Michigan
2002-2006	Member American National Standards Accredited Standards (ANSI) Committee S12, Noise
2005-Present	Consultant to local communities and citizens groups on proper siting of Industrial Wind Turbines. This includes presentations to local governmental bodies, assistance in writing noise standards, and formal testimony at zoning board hearings and litigation.
2006	Founded E-Coustic Solutions
2008	Paper on "Simple guidelines for siting wind turbines to prevent health risks" for INCE Noise-Con 2008, co-authored with George Kamperman, Kamperman Associates.
2008	Expanded manuscript supporting Noise-Con 2008 paper titled: "The "How To" Guide To Siting Wind Turbines To Prevent Health Risks From Sound"
2009	"Guidelines for Selecting Wind Turbine Sites," Kamperman and James, Published in the September 2009 issue of Sound and Vibration.

2010 Punch, J., James, R., Pabst, D., "Wind Turbine Noise, What Audiologists should know," Audiology Today, July-August 2010

2011 Jerry L. Punch, Jill L. Elfenbein, and Richard R. James , "Targeting Hearing Health Messages for Users of Personal Listening Devices," Am J Audiol 0: 1059-0889_2011_10-0039v1

2011 Bray, W., HEAD Acoustics, James, R., "Dynamic measurements of wind turbine acoustic signals, employing sound quality engineering methods considering the time and frequency sensitivities of human perception," invited paper for Noise-Con 2011, Portland OR

2012 James, R., "Wind Turbine Infra and Low Frequency Sound: Warning Signs that were not Heard," April 2012, Bulletin of Science, Technology and Society

2012 Appointed to a three year position as Adjunct Professor in the Department of Communication Disorders at Central Michigan University.

Professional Affiliations/Memberships/Appointments

Research Fellow - Metrosonics, Inc.		American Industrial Hygiene Association (through 2006)
National Hearing Conservation Association (through 2006)		Institute of Noise Control Engineers (Full Member)
American National Standards Insititute (ANSI) S12 Working Group (through 2006)		Founder and Board Member of the Society for Wind Vigilance, Inc.
Adjunct Professor, CMU 2012-2015		Adjunct Instructor, MSU 2011-2014 (since 1985)

EXHIBIT B

E-Coustic Solutions

Noise Control ● Sound Measurement ● Consultation
Community ● Industrial ● Residential ● Office ● Classroom ● HIPPA Oral Privacy
P.O Box 1129, Okemos, MI, 48805
rickjames@e-coustic.com Fax: (866) 461-4103

Richard R. James
Principal
Tel: 517-507-5067

List of Recent Publications

Oct. 8, 2012

2008 Paper on "Simple guidelines for siting wind turbines to prevent health risks" for INCE Noise-Con 2008, co-authored with George Kamperman, Kamperman Associates.

2008 Expanded manuscript supporting Noise-Con 2008 paper titled: "The "How To" Guide To Siting Wind Turbines To Prevent Health Risks From Sound"

2009 "Guidelines for Selecting Wind Turbine Sites," Kamperman and James, Published in the September 2009 issue of Sound and Vibration.

2010 Punch, J., James, R., Pabst, D., "Wind Turbine Noise, What Audiologists should know," Audiology Today, July-August 2010

2011 Jerry L. Punch, Jill L. Elfenbein, and Richard R. James , "Targeting Hearing Health Messages for Users of Personal Listening Devices," Am J Audiol 0: 1059-0889_2011_10-0039v1

2011 Bray, W., HEAD Acoustics, James, R., "Dynamic measurements of wind turbine acoustic signals, employing sound quality engineering methods considering the time and frequency sensitivities of human perception," invited paper for Noise-Con 2011, Portland OR

2012 James, R., "Wind Turbine Infra and Low Frequency Sound: Warning Signs that were not Heard," April 2012, Bulletin of Science, Technology and Society, http://bsts.sagepub.com, DOI:10.1177/0270467611421845

EXHIBIT C

Ottawa, Canada
INTERNOISE 2009
Scheduled for August 23-26 2009

Measuring background noise with an attended, mobile survey during nights with stable atmospheric conditions

Clifford P. Schneider[a]- Retired
Cape Vincent Fisheries Station
New York State Department of Environmental Conservation
PO Box 165
Cape Vincent, New York 13618

ABSTRACT

In response to sound studies from commercial wind developers, a series of background noise surveys were conducted in Cape Vincent, NY between May and July 2008. The survey approach included sampling at night under stable atmospheric conditions and systematically selecting monitoring stations at 1.6 km intervals. Stable conditions occurred in 67% of nights and in 30% of those nights, wind velocities represented worst-case conditions where ground level winds were less than 2 m/s and hub-height winds were greater than wind turbine cut-in speed, 4 m/s. The median A-weighted $L_{90A,9\text{-}hr}$ sound pressure level was 25.7 dBA for five, fixed monitoring stations. For two mobile surveys, the medians ($L_{90A,5\text{-}min}$) were comparable, 25.5 and 26.7 dBA. C-weighted SPLs from the two mobile surveys were 40.0 dBC and 43.9 dBC. Assuming 45 dBA background noise, developers of the St. Lawrence Wind Farm predicted noise impacts would not exceed local and New York guidelines. However, assuming worst-case conditions using 25.6 dBA background noise, nearly all residences within range of the St. Lawrence Wind Farm exceeded New York guidelines and more than half would have noise levels considered "objectionable" to "intolerable."

1. INTRODUCTION

The impetus for this study began in 2007, shortly after AES-Acciona Energy submitted a sound study for their proposed St. Lawrence Wind Farm Project located in the town where I reside, Cape Vincent, New York USA (Figure 1). By the end of 2007, another wind developer, BP Alternative Energy, also completed a series of studies in support of their proposed Cape Vincent Wind Power Facility Project (Figure 1). Collectively, the two wind energy projects plan to erect nearly 200 wind turbines (1.5 turbines/km^2) within the Town of Cape Vincent. The sound studies submitted by the two developers had a number of deficiencies. AES-Acciona was directed by the Town of Cape Vincent's Planning Board[b] to conduct an accurate assessment of background noise in lieu of assuming 45 dBA as typical of rural environments.[1] BP's sound study[2] had issues related to monitoring sites and estimating background levels that were identified by the Town's acoustic consultant[3].

[aa] Lake Ontario Unit Leader - Retired, Cape Vincent Fisheries Station, Division of Fish and Wildlife, email address clif.schneider@gmail.com
[b] http://www.stlawrencewind.com/pdf/planning_comments_061507.pdf

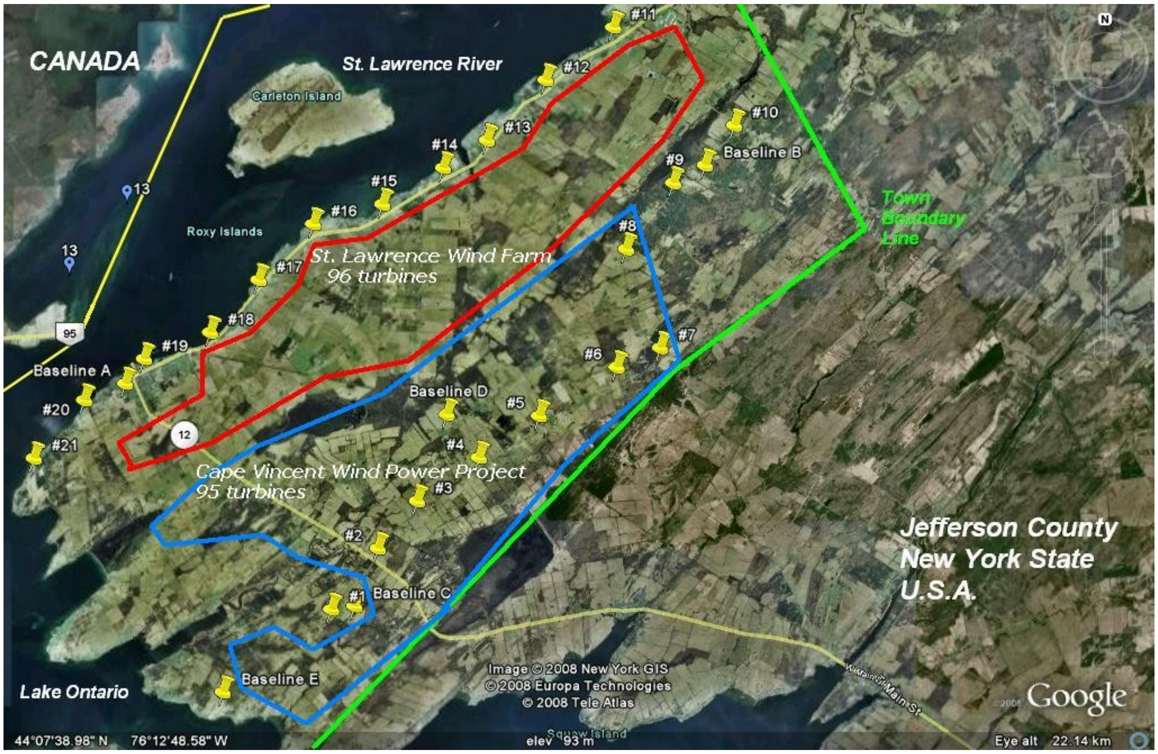

Figure 1. Map of the Town of Cape Vincent, NY showing the location of two proposed wind power projects, NYS Rte 12E road-based survey route(yellow pins no. 11-21), Burnt Rock Road road-based survey route (yellow pins no. 1-10), and location of baseline, night-time monitoring sites (yellow pins letters A-E.

In addition, the two Cape Vincent commercial wind developers neglected to consider night-time, worst-case wind conditions and noise impacts. Swedish and Dutch residents who live near wind farms described wind turbine noise as much louder and more perceptible during evenings and night, and they also reported excessive noise annoyance was associated with sleep disturbance[4,5]. In a study of the noise immissions from the Rhede Wind Park along the Dutch-German border, most of the complaints about noise focused on evenings and night-time, and wind turbine noise was found to be greater than predicted due to stable atmospheric conditions[6]. Stable atmospheric conditions occur when land begins to cool with the setting sun and calm ground level winds become de-coupled from winds aloft. Calm winds at ground level provide no masking sounds thereby making wind turbine noise more noticeable. The term worst-case has been commonly used by New York wind developers modeling noise impacts[1,7,8,9,10]. Yet, in none of their assessments have they completed an analysis of noise impacts during evenings and nights with stable atmospheric conditions, when wind turbine noise will be most noticeable and the worst-case impact will occur[11].

In this study I attempt to address some of these concerns related to site selection and atmospheric stability. A major problem with arbitrary site selection, the industry norm, is that it does not provide a means for establishing accuracy[12]. Probability sampling, on the other hand, allows the calculation of sample error and understanding the degree to which the sample differs from actual community levels. Systematic sampling is a form of probability sampling that uses a random start and a predetermined sample interval for site selection.[12] For this study I used systematic sampling by measuring sound pressure levels (SPL) at regular intervals along secondary rural roads. These roads are little traveled, particularly at night, concurring with the suggestion by van den Berg,[11] "*in order to reduce wind induced sound, it helps to measure over a low roughness surface and in a stable atmosphere, as both factors help to reduce* *turbulence*[11]."

Specific objectives of this study were to answer the following questions: 1)How common is atmospheric stability in Cape Vincent, and under these conditions, how often will winds be strong enough at hub-height to operate commercial wind turbines, 2) what background noise level is typical during stable nights in Cape Vincent, and do levels vary much within the Town, 3) how will predicted wind turbine noise levels exceed estimated background noise and how will these exceedences compare with the Town's and New York State guidelines[13], and 4) how practical is a night-time, mobile survey and how will results compare with a fixed-station survey?

2. METHODS

I collected wind velocity data using two Inspeed Vortex anemometers with Madgetech Pulse data loggers. One anemometer was located on a mast 10 m above ground level and the other 1.3 m above ground on a portable mount. I field calibrated the anemometers by comparing wind speed with a newly calibrated HOBO weather station. Wind velocity was collected for 10-minute sampling intervals and then averaged for day, evening and night periods, 07:00-18:00, 18:00-22:00 and 22:00-07:00 hours, respectively. I used night-time average wind speed at 10-m (V_{10}) and average percentage cloud cover from the Watertown, NY weather station to categorize Pasquill stability classifications for each night, using the criteria outlined in Table 1. For each stability classification I assigned an associated wind shear exponent (*m*) and then calculated hub-height wind velocities (80-m) according to van den Berg[11]:

$$V_{80\text{-m}} / V_{10\text{-m}} = (h_{80\text{-m}} / h_{10\text{-m}})^{m} \quad (1)$$

For the 140-night study period, there were 21 nights with no cloud cover information. For 17 of these nights I calculated wind shear using 10-m and 1.3-m wind speeds:

$$m_{h1,h2} = \ln(V_{h2}/V_{h1})/\ln(h_2/h_1) \quad (2)$$

The adjusted database provided complete data for 135 of the 140 nights.

Table 1: Pasquill stability class observational criteria[c] and associated wind shear exponents[11].

Wind speed	DAY Incoming solar radiation			NIGHT Cloud Cover		Pasquill Class	Name	*m*
(m/s)	Strong	Moderate	Slight	>50%	<50%	A	Very unstable	0.09
< 2	A	A – B	B	E	F	B	Moderately unstable	0.20
2-3	A – B	B	C	E	F	C	neutral	0.22
3-5	B	B – C	C	D	E	D	Slightly stable	0.28
5-6	C	C – D	D	D	D	E	stable	0.37
> 6	C	D	D	D	D	F	very stable	0.41

During sound measurements, the portable anemometer was located at the same height as the sound level meter (e.g., 1.3 m above ground level), but approximately 15 meters away. Noise measurements were made with a Quest Model 2900 Type II Integrated and Logging Sound Level Meter. An annual factory calibration of the sound meter and the field calibrator was completed in Arpil 2008, prior to data collection. The meter was fitted with a ½ inch Electret Microphone and a 75 mm diameter, open-cell wind screen.

[c] U.S. National Oceanic & Atmospheric Administration. Air Resources Laboratory. http://www.arl.noaa.gov/READYpgclass.php

I used two methods to collect A-weighted background noise data in Cape Vincent. First, five fixed-unattended monitoring sites were sampled. Sound pressure levels were collected for L_{90A}, L_{EQA}, and L_{10A} metrics. Three different methods were used to summarize the SPL in order to examine recommended approaches for assessing the quietest period. Two methods were based on recommended procedures submitted to the Town of Cape Vincent: the lowest 1-hr mean SPL of 10-min sample intervals[14], and the lowest 10-min SPL for a continuous night-time series[15]. The third method measured sound metrics for approximately a 9-hr period. I chose monitoring sites much the same as developer's consultants chose their sites, I picked them arbitrarily (Figure 1). I did not, however, place the sound level meter close to roads, homes and other buildings. Instead, I kept my meter at least 50 m from these locations and chose sites more in line with the Town of Cape Vincent's zoning guidelines, which called for measuring noise impacts at the property lines. I surveyed only nights when the atmosphere was calm and stable.

For the mobile survey, I employed a systematic sampling methodology with a random start. I selected two routes that ran along the longitudinal axis of the town and the two proposed wind projects (Figure 1). Survey nights were selected to coincide with forecasts for stable atmospheric conditions, i.e., calm winds and a clear sky. One survey ran along Burnt Rock Road on May 29-30, and a second along NYS Rte 12E on June 13 (Figure 1). Combined, twenty-one sites were sampled for approximately 10 minutes each. I randomly selected a starting point on the route near the end of the project boundaries, but then systematically chose the next site along the path by traveling 1.6 km (1 mile), as measured on my vehicle's odometer. Both A-weighted and C-weighted noise measurements were recorded in 1-second intervals for approximately 5 minutes for each weighting. The noises associated with walking to and from the sound level meter and passing vehicles did not influence L_{90} levels, but they did affect L_{EQ} and L_{10} levels. Therefore, L_{EQ} and L_{10} levels were recalculated for the two mobile surveys after removing 30 seconds each from the start and finish of A and C-weighted data collection and removing infrequent passing vehicle noise.

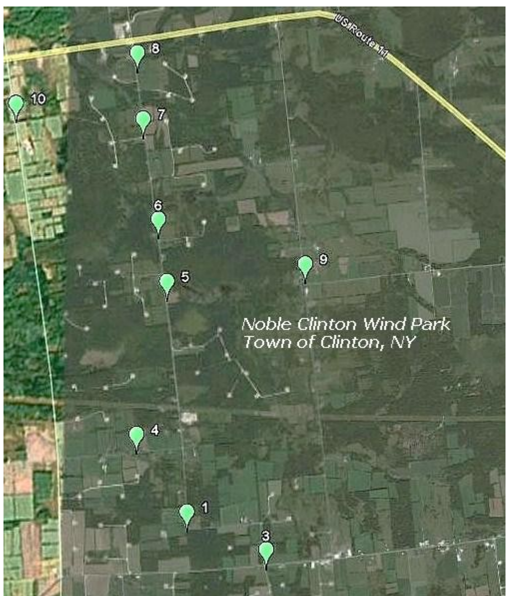

Figure 2: Mobile survey of Clinton Wind Park. Town of Clinton. NY

I also conducted a mobile survey at the Clinton Wind Park in the Town of Clinton, NY on June 24-25 (Figure 2). The monitoring stations were not systematically selected along every mile (1.6 km) of roadway. Rather, I chose stations near non-participating landowner residences, similar to what might be done with a compliance survey. Nevertheless, the sample sites were uniformly distributed. Atmospheric conditions were stable, winds at ground level were less than 1 m/s, but all wind turbines within view were operating.

I used Microsoft Excel to consolidate and summarize the wind and noise data. I did not edit the data files to remove anthropogenic (man-made) noise. I used the statistical software program MyStat and relied on simple statistical tests for normality and nonparametric procedures to establish differences in sample distributions.

3. RESULTS

A. Prevalence of atmospheric stability:

Stable night-time atmospheric conditions (classes E and F) predominated from June through October in Cape Vincent (Table 2). The prevalence of stable (E) and very stable (F) conditions occurred 22.2% and 45.2% of nights; the overall average was 67.4% for both classes; higher rates occurred in July and August. Although 67.4% of summer night conditions were classified as stable, not all of these nights had sufficient winds at hub-height (e.g., 80 m) to operate commercial wind turbines. I examined a subset of the data filtering two variables. First, I limited 1.3-m wind speeds to 2 m/s and less, knowing that winds this calm would provide very little leaf and grass rustle and that background noise levels under these conditions were usually very quiet. Next, I filtered 80-m wind speed to allow only those nights where velocities exceeded 4 m/s, which is a typical cut-in speed for commercial wind turbines. For an area with an operational wind farm, this represents a worst-case condition where ground level winds are calm yet wind turbines are fully operational, generating both electricity and noise.

Overall, 29.6% of the nights between June 10 and October 27 had worst-case conditions where wind turbine noise would have been dominant (Table 2). In June and July, wind turbine noise would have been more problematic with worst-case conditions occurring more than 40% of summer nights.

Table 2: Prevalence of Pasquill stability classification and worst-case noise impact conditions for nights in Cape Vincent, NY from June 10-October 27, 2008. Worst-case conditions were those stable nights with calm ground level winds ($\leq$2 m/s) and hub-height winds at or above cut-in speed ($\geq$4m/s).

STABILITY	JUN		JUL		AUG		SEP		OCT		JUN-OCT	
CONDITIONS	No.	%	No.	%	No.	%	No.	%	No.	%	Total	%
D	9	42.9	6	20.7	6	20.0	10	35.7	13	48.1	44	32.6
E	3	14.3	8	27.6	11	36.7	8	28.6	0	0.0	30	22.2
F	9	42.9	15	51.7	13	43.3	10	35.7	14	51.9	61	45.2
TOTAL	21	100	29	100	30	100	28	100	27	100	135	100
E + F	12	57.1	23	79.3	24	80.0	18	64.3	14	51.9	91	67.4
Worst-case	9	42.9	12	41.4	6	20.0	7	25.0	6	22.2	40	29.6

B. Statistical treatment of acoustic data:

Visual inspection of the $L_{90A,5\text{-min}}$ sound level data from the two mobile surveys suggested a skewed, non-normal distribution. I calculated Shapiro-Wilk test statistics for A-weighted and C-weighted L_{90}, L_{EQ} and L_{10} SPLs and found that L_{90A}, L_{EQA} and L_{90C} distributions were significantly different from normal ($P \leq 0.05$). Consequently, I used medians instead of means to describe central tendency and Kruskal-Wallis non-parametric ANOVA to test differences in the distributions of the sound pressure levels.

C. Fixed surveys for baseline background noise:

$L_{90A,9\text{-hr}}$ sound pressure levels are plotted for 10-minute intervals at five baseline monitoring locations in Figure 3. At locations A, B and D sound pressure levels were consistently low, ~25 dBA, from 9:00 PM throughout the night, then increased around 4:30 AM due to bird vocalizations. Monitoring location C was similar except for elevated levels from 9:00-11:00 PM, which were attributable to barn noises in early evening and frog choruses later. The $L_{90A,9\text{-hr}}$ for location E was 6.2 dBA higher than the other four sites. This site was 200 m from the lakeshore, and in spite of an average wind speed of 1.3 m/s, there was additional background noise associated with wave action on the shoreline.

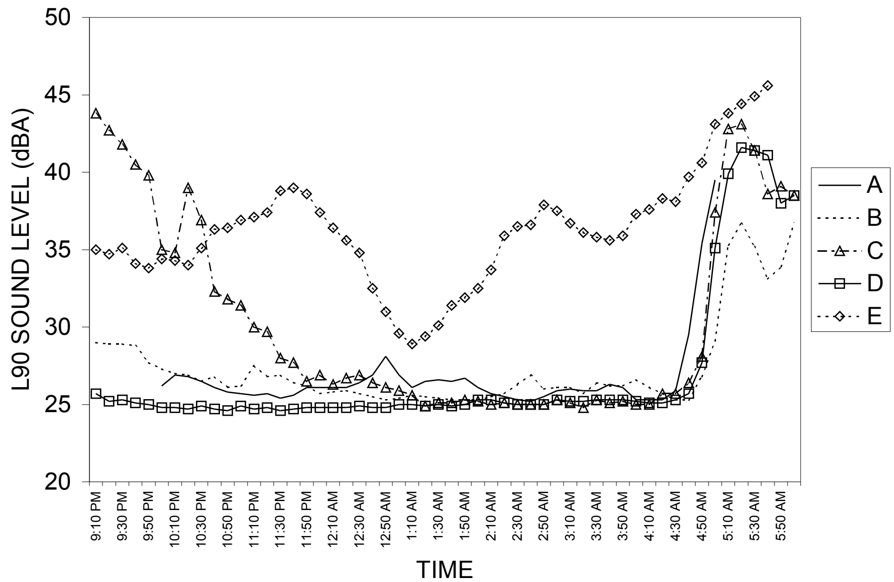

Figure 3: Night-time sound pressure levels (SPL) at five fixed monitoring stations A-E in Cape Vincent, NY

Collecting unattended, background sound pressure levels (SPL) in 10-min intervals is how consultants in New York normally acquire and report background noise, although they more typically collect data for a week or two. I used fixed survey data as a baseline to help gauge the accuracy of the mobile survey. At the five fixed survey sites, SPL was consistently low: the median $L_{90A,9\text{-}hr}$ level for the five monitoring locations was 25.7 dBA (Table 3). The median SPL based on two alternate methods were comparable: 25.2 dBA for the lowest 1-hr arithmetic average of 10-min SPL[14] and 25.0 dBA for the lowest 10-min SPL[15]. The night-time sound levels at these fixed stations were also typified by a floor in the meter response at 25-26 dBA (Figure 3).

Table 3: Summary of fixed survey, A-weighted sound pressure levels comparing three reporting time frames: 1) 9-hr period, 2) the lowest 1-hr arithmetic mean for the 9-hr period[14], and 3) the lowest 10-min interval within the 9-hr period[15].

	Monitor	Wind	9-hr Period			Lowest 1-hr Average			Lowest 10-min		
Date	Location	Speed	L90	LEQ	L10	L90	LEQ	L10	L90	LEQ	L10
11-12MAY08	A	0.1	25.7	36.8	33.0	25.6	26.1	26.5	25.2	25.7	26.1
13-14MAY08	B	0.0	25.7	36.2	37.8	25.4	25.8	26.2	25.3	25.6	25.8
15-16MAY08	C	0.0	25.7	44.1	49.0	25.0	36.8	39.3	24.8	30.2	31.9
16-17MAY08	D	0.0	24.9	45.7	41.6	24.8	28.1	26.8	24.6	24.8	25.0
25-26MAY08	E	0.6	31.9	41.3	43.7	30.2	30.8	31.4	28.9	29.3	29.6
Median			**25.7**	41.3	41.6	**25.2**	27.1	26.7	**25.0**	25.7	26.0

D. Cape Vincent mobile, background noise surveys:

For the 10 survey stations along Burnt Rock Road, the median $L_{90A,5\text{-}min}$ SPL was 25.5 dBA (Table 4). Both the L_{EQA} and L_{10A} median background noise levels were 1.7 and 2.3 dBA greater than L_{90} levels, respectively. Median C-weighted background $L_{90C,5\text{-}min}$ was 40.0 dBC. All three C-weighted sound metrics were 14-17 dB greater than their A-weighted equivalents.

Table 4: Summary for Mobile-Background Noise Survey, May 29-30, 2008, Burnt Rock Rd., Cape Vincent, NY

Monitor	Wind	A-weighted			C-weighted		
Location	Speed (m/s)	L90	LEQ	L10	L90	LEQ	L10
1	0	26.9	27.8	28.5	41.6	42.9	43.4
2	0.1	30.6	32.7	34.1	41.6	48.6	52.1
3	0	24.8	25.8	26.8	39.6	45.6	42.7
4	0	24.8	25.1	25.3	39.1	45.5	45.1
5	0	24.8	25.3	25.8	38.8	43.7	41.7
6	0.1	24.9	26.0	27.1	38.7	44.5	44.0
7	0	28.3	31.4	32.9	38.7	40.1	40.8
8	0	25.2	26.6	26.2	42.4	45.5	46.1
9	0	25.7	27.9	29.5	41.3	43.1	44.2
10	0	26.5	28.3	29.6	40.3	42.3	43.4
Median		**25.5**	27.2	27.8	**40.0**	44.1	43.7

The summary for the second part of the mobile survey, along NYS Rte 12E, is presented in Table 5. Median background noise $L_{90A,5\text{-min}}$ SPL level was 26.7 dBA. The $L_{EQA,5\text{-min}}$. and $L_{10A,5\text{-min}}$ medians were 1.9 and 3.0 dB greater than $L_{90A,5\text{-min}}$ levels, respectively. C-weighted noise levels along NYS Rte 12E were 43.9, 46.2 and 47.5 dBC for $L_{90C,5\text{-min}}$, $L_{EQC,5\text{-min}}$ and $L_{10C,5\text{-min}}$, respectively (Table 5). All three metrics were about 4 dBC higher than their C-weighted counterparts from the Burnt Rock Road survey. Moreover, the median C-weighted L_{90C} was 17.2 dB greater than the A-weighted L_{90A}, compared to a 14.5 dB differential at Burnt Rock Road.

Table 5: Summary for Mobile-Background Noise Survey, June 13, 2008, NYS Rte 12E, Cape Vincent, NY

Monitor	Wind	A-weighted			C-weighted		
Location	Speed (m/s)	L90	LEQ	L10	L90	LEQ	L10
11	0	27.3	28.2	28.4	42.6	43.7	44.4
12	0.1	30.5	30.4	30.9	44.6	46.2	48.0
13	0	25.1	27.4	28.3	40.2	41.7	42.7
14	0	32.2	32.6	32.9	45.3	47.0	48.3
15	0	26.5	28.6	29	42.9	44.5	45.6
16	0.1	26.7	29.3	31.3	43.9	47.2	49.9
17	0	26.5	27.3	28.2	43.9	46.3	47.9
18	0	25.7	26.1	26.3	44.5	45.8	46.5
19	0	36.0	36.3	36.6	52.4	53.1	53.4
20	0	29.2	30.8	32	45.1	46.9	47.5
21	0	26.7	28.2	29.7	42.2	43.8	44.5
Median		**26.7**	28.6	29.7	**43.9**	46.2	47.5

A single site for each of the mobile survey's L_{90} SPL is plotted in Figure 4. The sites selected for the plot were those that best conformed to the medians for each survey. At the start of each A-weighted sample and the crossover to C-weighted measurements, there were 5-10 dB increases in noise associated with my walking to and from the meter. Passing vehicles were noisy (e.g., 60-70 dB), but were infrequent occurrences, less so along Burnt Rock Road. Passing vehicles occurred at one site on Burnt Rock Road (site 2) and at five sites along NYS Rte 12E (sites 12, 13, 16, 19 and 21). Other sources of anthropogenic noise were a plane (site 1), dairy farm barn cleaner (site 12), and refrigeration fans (sites 14 and 19). Elevated noise was also attributable to natural causes, too: birds and frogs (sites 7 and 10), barking dogs and coyotes (sites 9 and 16), and waves on a nearby beach along the St. Lawrence River (site 20). Most of these short-duration noises, however, had little effect on the $L_{90A,5\text{-min}}$ SPL. As noted in the fixed survey, the L_{90A} measurements at a number of sites went down to 25 dBA and no lower, again indicating a “floor” in meter readings.

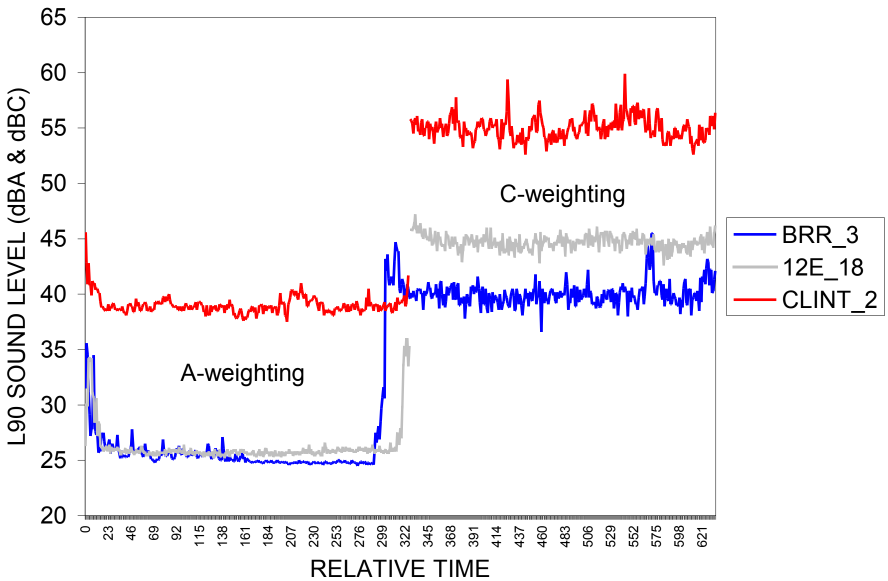

Figure 4: L_{90} sound pressure levels (SPL) for three mobile surveys: BRR_3 =Burnt Rock Rd. survey, site #3; 12E_18 =NYS Rte 12E survey, site #18 and CLINT_2 =Clinton Wind Park survey, site #2. Sites selected to best conform to medians listed in Tables 4, 5 and 6.

Statistical tests showed that L_{90A} noise levels for the fixed survey and two mobile surveys were the same, but the low frequency L_{90C} levels were different. The L_{90A} medians were 25.7, 26.7 and 25.5 dBA for the fixed, NYS Rte 12E and Burnt Rock Road surveys, respectively. The Kruskal-Wallis test indicated that all three surveys had the same distribution ($H = 4.8082, df=2, P= 0.0903$). However, for the low frequency L_{90C} noise levels the Kruskal-Wallis statistic showed a highly significant difference between the two Cape Vincent mobile surveys[d]. The C-weighted $L_{90C,5\text{-min}}$ medians were 43.9 and 40.0 dBC for NYS Rte 12E and Burnt Rock Road, respectively, and were significantly different ($U= 104.00, P=0.001$).

E. Clinton Wind Park background noise survey:

For the ten monitoring locations within the Clinton Wind Park, A-weighted $L_{90A,5\text{-min}}$ SPL ranged from 35-43 dBA with a median of 38.0 dBA. C-weighted $L_{90C,5\text{-min}}$ SPL ranged from 49-58 dBC with a median of 52.6 dBC (Table 6). Aside from two cars that passed during the C-weighting data collection at site 3, there was no other noise intrusion, other than wind turbine sounds. A typical site plot of A and C-weighted SPL is shown in Figure 4 in comparison with the Cape Vincent mobile surveys.

[d] No C-weighted data was collected for the fixed survey. Hence, the Mann-Whitney two-sample test in lieu of Kruskal-Wallis for three or more samples.

Table 6: Summary for Mobile-Background Noise Survey, June 24-25, 2008, Clinton Wind Park, Clinton, NY

Monitor Location	Wind Speed (m/s)	A-WEIGHTED L90	A-WEIGHTED LEQ	A-WEIGHTED L10	C-WEIGHTED L90	C-WEIGHTED LEQ	C-WEIGHTED L10
1	0.4	36.0	44.8	38.6	51.9	54.7	54.3
2	0.8	38.6	39.8	40.0	54.4	57.0	57.7
3	0.1	40.3	41.7	42.4	53.3	57.8	55.5
4	0.1	35.0	37.0	37.2	48.8	52.3	52.2
5	0.2	36.3	37.8	37.4	51.0	54.3	53.3
6	0.1	37.3	39.8	39.2	51.7	55.3	54.7
7	0.1	41.0	42.7	43.2	55.9	57.9	58.4
8	0.6	41.5	42.9	43.3	55.8	58.5	59.0
9	0.3	34.4	36.0	35.7	49.6	53.9	53.5
10	0.1	43.3	45.0	43.3	57.6	59.4	60.0
Median		**38.0**	40.8	39.6	**52.6**	56.2	55.1

The $L_{90A,5\text{-min}}$ SPL for Clinton were compared with the samples from the two mobile surveys in Cape Vincent. The higher levels at Clinton were significantly different from the sample distributions observed in Cape Vincent (Kruskal-Wallis $H= 20.7080$, $P< 0.001$); the mean ranks for the two Cape surveys were similar while Clinton was significantly greater. Comparisons of C-weighted SPL were significantly different for each of the distributions and mean ranks ($H= 23.9684$, $P< 0.001$); again the samples at Cape Vincent and Clinton were all significantly different.

4. DISCUSSION - CONCLUSIONS

Night-time, stable atmospheric conditions were very common in Cape Vincent between June and October, 2008. The prevalence of Pasquill stability classes E and F were 22% and 45% of nights, respectively. Putting aside any differences in meteorological equipment, prevalence of stability at Cape Vincent is similar to 34% (E) and 32% (F) reported by van den Berg[11] for the northern part of the Netherlands. He also noted that high wind shears at night are a very common feature of the night atmosphere in temperate zones. Furthermore, the frequent occurrence of stability in Cape Vincent, along with the operation of the Clinton Wind Park during a calm night, contradict the observation that wind turbines “do not operate during calm, still or tranquil conditions.”[16]

Having demonstrated that atmospheric stability is a common occurrence in Cape Vincent, the graphic in Figure 5, taken from the Flat Rock Wind Farm sound report[17], illustrates why stable, night-time atmospheric conditions represent a worst-case wind turbine noise state. At night, predicted wind turbine noise (upper blue lines) will be most noticeable, e.g., 17 dBA louder than ambient background (lower red lines), at the lowest wind speeds. At higher wind speeds, however, wind turbine noise will be masked (e.g., no difference) by background noise (Figure 5). During daytime, the difference between predicted wind turbine and background noises at low wind speeds would be one-half as great as at night. Therefore, worst-case wind turbine noise impacts will occur at night with stable atmospheric conditions, and consequently, environmental assessments should focus on these worst-case conditions.

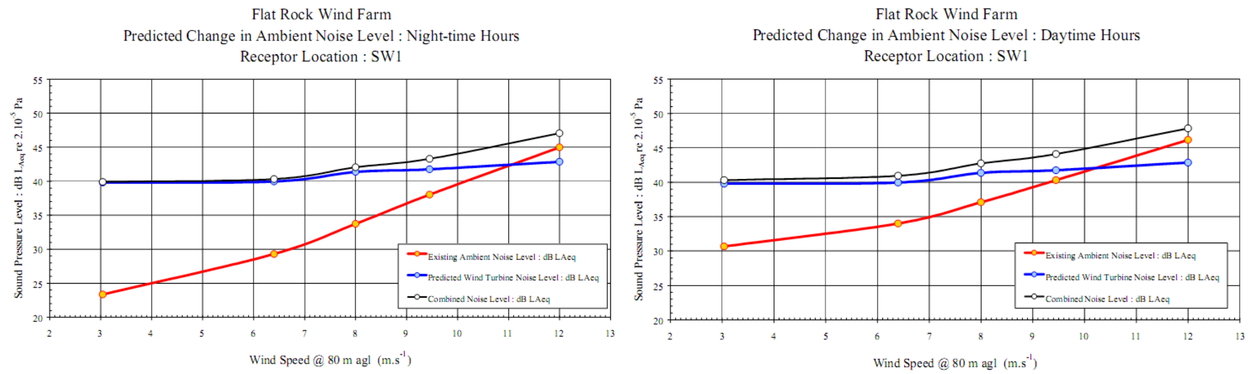

Figure 5: Night-time (left pane) and daytime (right pane) background A-weighted SPL in relation to wind speed at monitoring site SW1 from Hayes McKenzie Partnership's Flat Rock Wind Farm Noise Assessment[17], Lowville, NY. Upper, blue lines represent predicted wind turbine noise and lower, red lines the existing ambient background noise.

Background sound pressure levels measured in this study were far lower than the levels reported by wind power developers in their sound level studies. For the fixed surveys the L_{90A} medians were 25.7, 25.2, and 25.0 dBA for the 9-hr, lowest 1-hr arithmetic average, and lowest 10-min interval summary approaches, respectively. All three methods provided similar estimates of background noise, suggesting any of the three methods will provide adequate estimates of the "quietest periods." For two mobile surveys, the L_{90A} medians were 25.5 dBA and 26.7 dBA for Burnt Rock Road and NYS Rt. 12E surveys, respectively, and they were consistent with those levels measured for the fixed surveys. At the same time, the 25 dBA "floor"observed in both the fixed and mobile surveys indicate that a more sensitive meter and microphone combination would probably exhibit even lower A-weighted background noise levels. Any future study should include the use of the most sensitive instrumentation available.

A-weighted sound pressure levels from the mobile surveys in Cape Vincent were the same as levels observed at fixed, unattended monitoring locations. The fact the SPL distributions were not statistically different seems to suggest arbitrarily selected monitoring locations are just as efficient and accurate as a systematic survey with a random start. Yes, a few fixed sites can be accurate and efficient if care is taken to find appropriate sites and operating conditions. However, I could have increased the measured SPL if I had located equipment closer to homes, barns and roads, and if I had picked nights with moderate winds.

A systematic mobile survey removes the subjective selection of sites, and thus, it can help minimize potential abuse. There are other advantages as well: no landowner permission is required, no extensive hiking off-road at night, no security problems with unattended metering far from landowner premises, little time needed to prepare a survey, and no requirement for big battery packs and waterproof environmental housings. There are also the advantages of attended metering, such as being able to document various noise intrusions. A mobile survey could also be used to help verify and supplement fixed station SPLs in cases where a few fixed sites were used to characterize background noise over a large geographic area.

AES-Acciona and BP Alternative Energy reported background noise levels in Cape Vincent as 45 dBA and 47 dBA, respectively, more than 20 dBA greater than this study.[1,2] Neither developer, however, focused their studies on the night-time period, even though night noise levels are far quieter than daytime and represent worst-case conditions. Rather, they chose to include daytime, windy conditions where background noise is greater and wind turbine noise impacts the least. The median A-weighted and C-weighted levels measured within the Clinton Wind Park were 13-16 dB greater than Cape Vincent. These increases in background noise are undoubtedly due to wind turbine operation. It also suggests that the quiet, night-time, rural soundscape, which residents value most[18], could be transformed into one where night-time sound levels more closely resemble suburban and urban environments[19].

The low background sound levels reported in this study result in very different wind turbine noise impacts than those predicted by AES-Acciona. Columns A-C in Table 7 are taken from AES-Acciona's sound level report's predicted impacts from the St. Lawrence Wind Farm, assuming 45 dBA background noise.[1] With no impacts more than 5 dBA above background levels (col. C) they concluded, *"As a result, noise levels from the proposed St. Lawrence Wind Energy Project are in compliance with State guidelines, local draft zoning ordinance criteria for noise associated with commercial wind turbine operation, and will not produce noise impacts above New York policy."* However, recalculating worst-case impacts using 25.6 dBA, background SPL (col. D) show that most receptors will have night levels exceeding the local ordinance and State guidelines (e.g., ≤6 dBA above background). Moreover, applying probable human responses from New York State policy[13], shows that 34.4% of residences within range will consider turbine noise "Objectionable" and 19.4% "Very objectionable to intolerable." In total, more than half of the residents may find night-time wind turbine noise "objectionable" to "intolerable".

Table: 7. Predicted sound levels at nearest receptors to turbines. Columns A-C from Table 4 of the St. Lawrence Wind Farm sound level report.[1] Column D is the predicted sound level to nearest receptors using 25.6 dBA worst-case background levels from this study. Column E is expected human reactions to new predicted noise levels in column D, according to NYSDEC Assessing and Mitigating Noise Impacts.[13]

A Predicted Sound Level Range (dBA)	B Number of Residences Within Range	C Predicted Increase in 45 dBA Ambient (dBA)	D Predicted Increase in 25.6 dBA Ambient (dBA)	E Human Reaction NYSDEC Policy[13]
22.9 – 24.9	7	0	0	Unnoticed to tolerable
25 – 29.9	3	0-0.1	0-4.3	Unnoticed to tolerable
30 – 34.9	38	0.1-0.4	4.4-9.3	Intrusive
35 – 39.9	67	0.4-1.2	9.4-14.3	Very noticeable
40 – 44.9	84	1.2-3.0	14.4-19.3	Objectionable
45 – 48.3	48	3.0-5.0	19.4-24.7	Very objectionable to intolerable

In its most recent wind turbine noise impact assessment for the St. Lawrence Wind Farm[20], AES-Acciona assumed a background noise level of 37 dBA, used the NYSDEC noise increase guideline of 6 dBA above background, and adopted a Project-only sound level of 42 dBA to assess potential adverse impacts. They concluded *"..the numerous houses along the St. Lawrence River shoreline, are well outside of the area of adverse Project noise impacts."* Again, if AES-Acciona had assumed a worst-case background level of 25.6 dBA from this study, they would have to conclude that nearly all the houses along the river will be within the area of adverse noise impacts from the St. Lawrence Wind Farm.

The difference between C- and A-weighted SPL is used as a simple screening method for assessing potential low frequency noise problems.[15,21] If this difference exceeds 20 dB, then a low frequency problem may exist. For the mobile surveys in Cape Vincent, the differentials in median L_{EQC}–L_{EQA} were below this threshold.

5. ACKNOWLEDGEMENTS

I wish to thank Chuck Ebbing for his encouragement and advice. I also want to thank Rick Bolton, George Kamperman and Rick James for their reviews of my manuscript.

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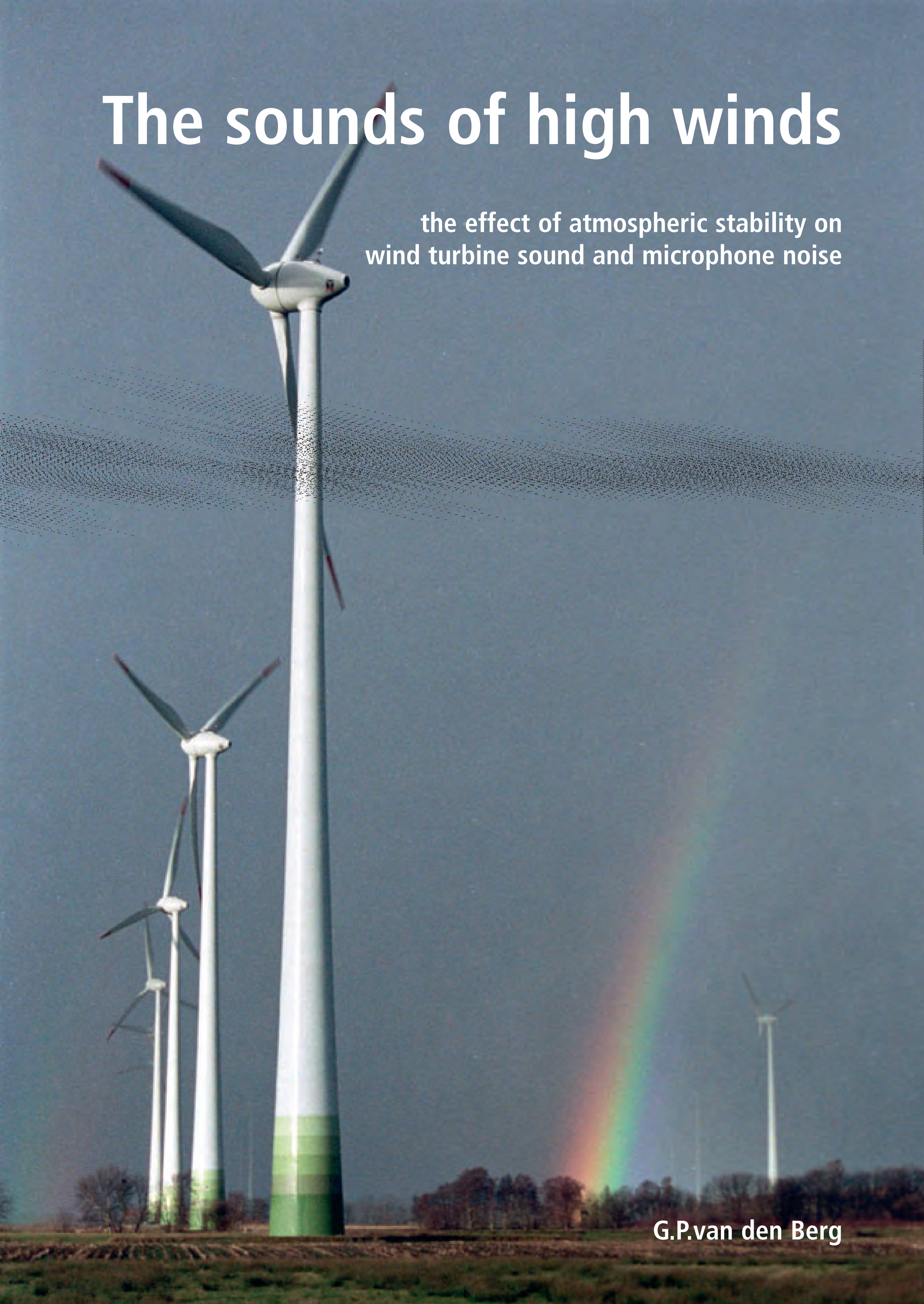
EXHIBIT D

The sounds of high winds

the effect of atmospheric stability on wind turbine sound and microphone noise



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RIJKSUNIVERSITEIT GRONINGEN

The sound of high winds: the effect of atmospheric stability on wind turbine sound and microphone noise

Proefschrift

ter verkrijging van het doctoraat in de
Wiskunde en Natuurwetenschappen
aan de Rijksuniversiteit Groningen
op gezag van de
Rector Magnificus, dr. F. Zwarts,
in het openbaar te verdedigen op
vrijdag 12 mei 2006
om 16:15 uur

door

Godefridus Petrus van den Berg
geboren op 7 januari 1952
te Rotterdam

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The sound of high winds:

the effect of atmospheric stability on wind turbine sound and microphone noise

G.P. van den Berg

Cover photograph by Richard de Graaf

Contents

I WIND POWER, SOCIETY, THIS BOOK: an introduction

Bobby asks: 'Do you ever hear the windmills?'
'What sound do they make?'
'It's a clanking metal noise, but when the wind is really strong
the blades blur and the air starts screaming in pain.' He shudders.
'What are the windmills for ?'
'They keep everything running.
If you put your ear to the ground you can hear them.'
'What do you mean by everything?'
'The lights, the factories, the railways. Without the windmills it all stops.' [1]

This is the story of the discovery of a new phenomenon: why wind turbines sound different at night time. This discovery was related to a problem in society, namely that of perceived noise by residents living close to such turbines..
This introduction sketches the context in which my work proceeded: how the questions came up, why noise is an inseparable part of wind power development, and that being critical does not need to imply a negative attitude towards wind power. Let's start at the beginning.

I.1 A 'new' phenomenon

The discovery was modest: I have not found a new law of nature or a new way to make money. It was rather the idea to apply existing knowledge in a new context: the application of atmospheric physics to solve the mystery why people complained about noise from wind turbines that according to wind developers and acoustic consultants they should not even be able to hear. In principle it was not very difficult to find out why. When Walter Flight (a very Dutch citizen despite his name) told me he could see the wind turbines near his house rotating at high speed while at the same time his garden was completely calm, I thought: oh yes, I know that, that's

[1] 'The suspect', by Michael Robotham, Time Warner Paperbacks, 2003 (p. 151)

because at night, especially on nice summer evenings, the atmosphere becomes stable. I teach this in a course, Environmental Techniques. The phenomenon is treated extensively in this book, but for now it is sufficient to know that, due to strong winds at greater heights coupled with very light winds at ground level, wind turbines can be a lot noisier in a night time atmosphere than they are in daytime. This was why Walter and his neighbours complained. Also the nature of the sound changes: a thumping character can become very pronounced at night.

In this book I will often use the terms ‘day’ and ’night’, though the distinction is more accurately stated as the atmosphere being unstable (which is usually in daytime, that is: sun up) or stable (night time, sun down). The heat coming in from the sun or radiated out at night is the real cause of the difference in stability. In between is another state, namely neutral, where heating or cooling are unimportant beacause of heavy clouding and/or strong wind and which can occur in day as well as night time, though not very often in a temperate climate and over land. Atmospheric stability means that vertical movements in the air are damped and as a consequence horizontal layers of air can have a greater difference in velocity: close to the ground the wind can be weak while higher up there is a strong wind.

Though in principle the explanation is simple and easily understood, it of course had to be shown from solid theory and with sufficient data that the explanation was correct. The first steps were extensive measurements in Bellingwolde, where severe complaints had arisen about noise from the nearby Rhede wind farm. This I did together with Richard de Graaf, then a physics student.

After this simple discovery, a new mystery (to me) was why this did not play a role in the assessment of wind turbine noise? Every meteorologist knows about atmospheric stability, so why had none of the experts dealing with wind turbine sound ever come across it? Wind turbines have been built for several decades and since the 1980’s in ever larger numbers, so there should be a lot of accumulated experience. Had no one (except some

residents) noticed the discrepancy between predicted and real noise exposure?
There are probably several reasons. One of them is that for a long time wind turbines were not big enough for the effects of atmospheric stability to be clearly noticeable. Since wind turbines have grown taller the effect manifests itself more clearly. Secondly, as the more distant locations have become scarce, more and more turbines are being built closer to where people live, so more people now experience the sound of wind turbines. Thirdly, atmospheric stability over flat land is easier to understand and quantify than in a mountainous or coastal area where the atmosphere is more complex so the effect on wind turbines may be less easily recognizable.
Wind turbines as such have not become that much noisier, despite their increase in height and blade span (the sound power depends more on speed than on physical dimensions of the towers). Earlier machines could be quite noisy due to whining or severe thumping, and modern designs are certainly better. The point is they now reach into less familiar parts of the atmosphere.

Finally, an important reason to not recognize the unexpected high sound levels certainly is the fact that it impedes commercial interests and national policy. The positive ring of the term 'sustainability' helps investors in wind energy and local authorities (applying national policy) to counterbalance objections concerning possible disadvantages of new projects. As these objections are sometimes strong enough to torpedo projects, investors and authorities don't welcome more negative news. Though the population widely supports sustainable energy, reactions are less positive when a new project adversely affects their lives. This 'contradictory behaviour' is in fact quite understandable: when a new project is planned in an area, residents for the first time have to balance the positive social consequences to the negative local impact: visual impact, flickering shadows, noise and possibly ice throw from turbine blades.

The first reaction of wind energy proponents, represented by the Windkoepel (‘Wind dome’), to our research results was to pay a consultant to comment on our report [Van den Berg *et al* 2002]. This consultant boasted of having advised a large number of wind farm projects, so he clearly understood the position of the wind power industry. In the resulting 'second opinion' [Kerkers 2003] no material critique was presented, only procedural arguments were used to declare our results inaccurate and thus irrelevant. The Windkoepel issued a press statement concluding that we had made a lot of fuss, but had not contributed any new insights.[1] They could get back to business.

I.2 Digging deeper

I too went back to my business, which can be summarized as helping citizen groups to defend their position by objective arguments using known principles of physics. In 2004 an article about my research was published in a scientific journal [Van den Berg 2004a] lending my results the respectability of peer review and triggering an international e-mail influx from interested consultants as well as worried residents, as our first report had done earlier on a national scale.

What still puzzled me at that time was how a single turbine could start thumping at night. I thought I understood how the modest blade swish of a single turbine could evolve into louder thumping: the small sound variations due to blade swish from several turbines could add up to louder pulses. But with a single turbine there is nothing to add! Apart from this, in news media in the UK there were complaints that low frequency wind turbine noise had been underestimated and had been making people sick.[2]

Some thoughts about this were presented at a conference in Maastricht [Van den Berg 2004b]. I agreed with delegate Jørgen Jakobsen, who presented a paper on low frequency wind turbine noise [Jakobsen 2004],

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[1] Press statement February 2, 2003 "Onlangs is opschudding ontstaan …..," ("Recently an upheaval was caused…"), De Windkoepel, Arnhem

[2] Catherine Milner: "Wind farms make people sick who live up to a mile away", online Telegraph, filed January 25, 2004 (http://news.telegraph.co.uk/news/ main.jhtml?xml=/ news/2004/01/25/ nwind25.xml, consulted December 10, 2005)

that even though wind turbines did produce an appreciable amount of infrasound, the level was so far below the average human hearing threshold that it could not be a large scale problem. But it was possible that complaints had been expressed in a way not understood by experts. Perhaps people bothered by the endless thumping of a relatively low pitched sound (such as I had heard myself on several occasions), thought that 'low frequency sound' was a term to use, as official sounding jargon. They might not be aware that the term 'low frequency sound' makes acousticians think of frequencies below 100 to 200 hertz, and in that range the sound level was not considered to be problematic. A classical misunderstanding perhaps, that could be clarified. After the Maastricht conference I wanted to quantify my ideas on the origin of the night time thumping of wind turbines and the relevance of low frequencies. This resulted in a second scientific article [Van den Berg 2005a] in which I tried to put these ideas together.

What had surprised me from early on was that people in the wind power business seemed to know so little about their raw material, the wind. In the Windkoepel press statement (see footnote previous page) a wind turbine manufacturer's spokesman argued that if the hub height wind velocity indeed was structurally higher at night, this must be visible in production statistics. This indeed seems plausible, so why not investigate that? If the wind industry had done so, they might have come up with results I found from measured wind profiles at Cabauw over an entire year [Van den Berg 2005b]. Indeed for an 80 m high turbine the night time yield is significantly higher than expected, whereas the daytime yield is lower. The net result was that in the real atmosphere at Cabauw annual production was 14% to 20% (depending on wind turbine power settings) higher than in an atmosphere extrapolated from 10-m wind velocities with a perpetual neutral wind profile. For wind power production forecasting there is a method that incorporates a correction for atmospheric stability [Troen *et al* 1989], but such knowledge has never been used for sound exposure forecasting.

I.3 Commercial and policy implications

So from an energy point of view a stable atmosphere is very attractive. The challenge is to use that potential, but not put the burden on those living nearby. One solution is to build wind farms offshore where no people are affected if enough distance is kept (and calculation models are used that accurately model long range sound propagation over water). Over large bodies of water seasonal, not diurnal atmospheric stability will boost production in part of the year but lower it when the water has warmed. Another solution is to improve turbine design from two perspectives: decreasing sound power without substantially decreasing electric power, and reducing annoyance by minimizing fluctuations in the sound. Part of any solution is to respect complainants and try to achieve a better balance between national benefits and local costs.

Oblivious of any research, residents had already noticed a discrepancy between predicted and real noise exposure. Opponents of wind farms have organized themselves in recent years in the Netherlands and elsewhere, and word had spread that noise exposure in some cases was worse than predicted. Though atmospheric stability and sometimes a malfunctioning turbine could explain this, most wind farm developers and their consultants relied on the old prediction methods. An energy firm's spokesman complained that each and every new project attracted complaints (from local groups) and called this "a new Dutch disease".[1] This is a very narrow view on the problem, denying the detrimental effects for residents. If their real concerns are denied it is not unreasonable for residents to oppose a new project, because practical experience shows that once the wind farm is there (or any other noise producer) and problems do arise, complaints will very probably not alter the situation for at least several years. Social scientists are familiar with such situations and suggest better strategies such as being honest and respectful, treating residents as equal partners, and not being arrogant: already in 1990 Wolsink mentioned this in a study on acceptance of wind energy and warned that it was wrong to label opposition as NIMBY (Not In My Back Yard) and refuse to recognize

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[1] NRC Handelsblad, August 26 2005: "Verzet tegen windmolens succesvol" ("Opposition to wind mills succesful")

legitimate problems [Wolsink 1990]. It is sad that most of the proponents still emanate a WARYDU attitude (We Are Right but You Don't Understand).

When real complaints are not addressed seriously, the "new Dutch disease" may well become an Australian, British, Chinese or any nation's disease. In the Netherlands assessment of wind turbine noise still is according to the old standard procedure (with one exception, see chapter VII), assuming a neutral atmosphere at all times, even though this has been admitted to be wrong for more than a year now.[1] Consultants apparently are afraid to be critical, perhaps because they don't want to jeopardize new assignments or because a change in assessment implies they were not correct before (they were not correct, but we were wrong collectively). Though most consultants claim to be impartial, the problem of 'not biting the hand that feeds' is more subtle, as I concluded in an earlier desk study on the quality of acoustic reports [Van den Berg 2000]. *E.g.*, it involves authorities who do not question the position of paid experts, and a society hiding political decisions behind the demand for more research.

I hope other countries do not to follow the Dutch way: first denying the consistency and legitimacy of the complaints, then being late in addressing them and in the end finding this has created more opposition. It is evident that also in the UK there are (a few?) serious complaints from honest people that are not dealt with adequately. In at least some cases atmospheric stability again seems to offer an explanation for observations of unpleasant wind turbine noise by residents (see example in box on next page), but the matter has not been investigated correctly.

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[1] In March 2004 I showed in an article in 'Geluid', a Dutch professional journal, how to deal with non-neutral atmospheric conditions within the existing legal procedures [Van den Berg 2004c]; in July 2004 the Ministry of Housing, Environment and Spatial Planning advised to investigate the 'wind climate' at new wind farm locations (letter on "Beoordeling geluidmetingen Natuurkundewinkel RUG bij De Lethe, gem. Bellingwedde" to Parliament by State Secretary van Geel, June 21, 2004); in the 2005 Annual report of BLOW, a union of local, provincial and national authorities to promote wind energy development, it is recognized that the effect of wind shear still should be addressed, but no action is announced (Annual report BLOW 2005, January 2006).

NOISE FROM WINDFARM MAKING LIFE A MISERY

A recent settler in Caithness claimed yesterday his life is being blighted by ghostly noises from his new neighbours, the county's first large-scale windfarm. (…..) Mr Bellamy said: "The problem is particularly bad at night when I try to get to sleep and there's a strong wind coming from the direction of the turbines. "They just keep on droning on. It's a wooh wooh type of sound, a ghostly sort of noise. It's like torture and would drive anyone mad."

Mr Bellamy believes the noise is being transmitted through the ground since it seems to intensify when he lies down. He said he has got nowhere with complaints to the wind company and environmental health officers. "I feel I'm just getting fobbed off and can't get anyone to treat me seriously," he said. Mr Bellamy has been asked to take noise readings every 10 minutes during problem times, something he claims is unrealistic to expect him to do. He said the company's project manager Stuart Quinton-Tulloch said they could not act until it had proof of unacceptable noise levels. Mr Bellamy said: "I'm not the moaning type and I have no problem with the look of the windmills. I'm not anti-windfarm. It's just the noise which is obviously not going to go away." (…..)

Highland Council's principal environment officer Tom Foy who has been dealing with Mr Bellamy's complaint was unavailable for comment. His colleague David Proudfoot said he was aware of noise complaints about the Causewaymire turbines being lodged by two other residents, but said he had gone out several times and found no evidence to support the concerns.

Part of an article in *Press and Journal* of Aberdeen, 25 May 2005

Thinking that this could perhaps be solved by the Sustainable Development Commission (SDC), the UK government's 'independent advisory body on sustainable development'. I wrote to the SDC about remarks on wind turbine noise in their report "Wind power in the UK" [SDC 2005], which was in my opinion too positive and somewhat overly optimistic regarding wind turbine noise. The SDC replied, on authority of its (unknown) consultants, that they had no detailed knowledge of atmospheric conditions in the UK but still thought an impulsive character of the noise 'likely to be very rare'. After I presented some examples the SDC preferred to close the discussion.

The situation in the Netherlands is not very different. In the latest annual report of the body of national, provincial and local authorities responsible for wind energy development it is acknowledged that the problem of underrated noise has justly been brought to the policy agenda.[1] Nevertheless, no activity is undertaken to remedy this.

I.4 Large scale benefits and small scale impact

Though wind turbine noise is the main topic of this book, it is not the main problem in wind power development. Visual impact is usually considered the most important and most discussed local or regional effect. It is often presented as a matter of individual taste, though there are some common factors in 'public taste'. One such factor is the perceived contrast of a wind turbine (farm) and its environment: a higher contrast will have more impact, either in a positive or negative way. A peculiarity of turbines is that the rotational movement makes them more conspicuous and thus enhances visual impact. This common notion suggests that wind turbines in a built up area will have less impact relative to a remote natural area (though this may be overruled by the number of people perceiving the impact).

A second factor is attitude: *e.g.* farmers usually have a different attitude to the countryside than 'city folk' have, and hence they differ in judgments on the appropriateness of a building, construction or activity in the

[1] Jaarverslag BLOW (Bestuursovereenkomst Landelijke Ontwikkeling Windenergie). 2005 (Aanual report BLOW 2005; in Dutch), January 2006

countryside. It is predictable that when residents have a positive association with a neighbouring wind farm they will experience less annoyance from the visual impact. For a wind turbine owner the sound of each blade passing means another half kWh is generated[1] and is perhaps associated with the sound of coins falling into his lap, a lullaby. The very same rhythm, like the proverbial leaking faucet tap, might prevent his neighbour from falling asleep.

Other issues have gained attention in the public discussion, such as the modest contribution of wind energy to total energy consumption and the problematic variability of wind power. This is not the place to discuss these issues, except that they partially depend on a person's world view and expectations of the future. But I would like to show my personal position here. I find it astounding to realize that *all* wind turbine energy generated in the Netherlands in one year (2004) is equal to two months' *growth* of the total Dutch energy consumption. And even though wind turbine energy now provides about 2% of the total Dutch electricity consumption, this is only 0.2% of our total energy consumption.[2] This is also true on a global scale as is clear from figure I.1: wind power is now negligible and expected to supply 0.5% in 2030.

Despite the disappointingly low percentages I still think that wind energy need not be insignificant. In my view the problem is rather that we use such vast amounts of energy and keep on using ever more, which is a problem that no source, including wind power, can solve. Society will need to find a stand in the variety of opinions that have been brought forward since the 1970's. In a recent newspaper discussion about the liberalization of the energy market an opinion maker stated: "It is now generally appreciated that the end of the rich era of energy approaches rapidly, and the competition has begun for the last stocks", whilst his opponent the Minister or Economic Affairs wrote: "The lights must be kept burning, the

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[1] when the turbine generates 2 MW at 20 rpm

[2]: the percentages are based on data from Statistics Netherlands (Centraal Bureau voor Statistiek) for the Netherlands for the year 2004: wind energy production: 1.9 TWh; total electricity consumption: 108.5 TWh; total energy consumption: 919 TWh. Growth in total energy consumption in period 1995 – 2004: + 100 TWh or 1.7 TWh per two months. Growth in total electricity consumption 1995 - 2004: +23 TWh or 2.3 TWh per year.

gas must keep flowing" .[1] I do not agree with the Minister: I think that a limited resource should require limited consumption, even at the cost of some discomfort to our spoiled society. If we can curb our Joule addiction, wind power may help us to produce part of the sustainable energy we need to satisfy basic needs.

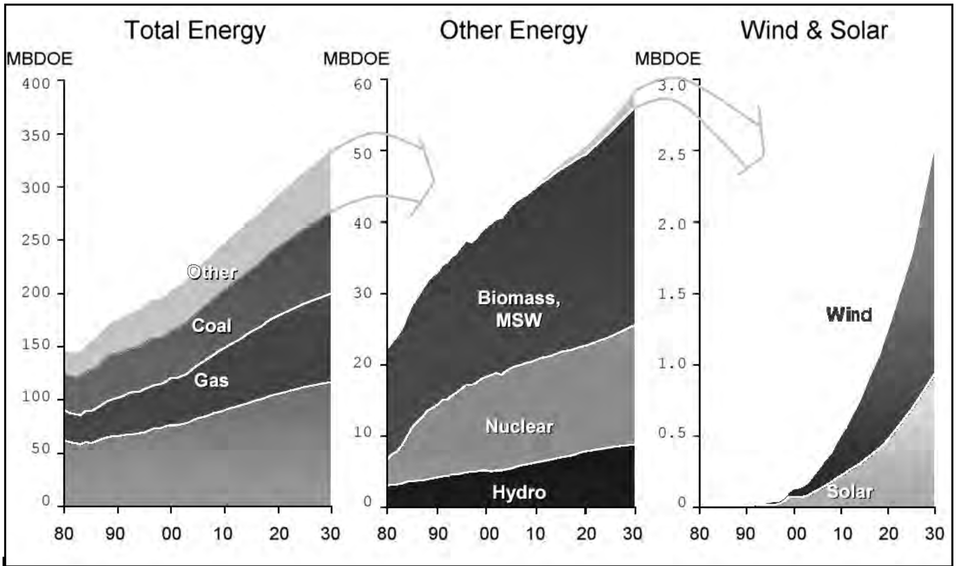

Figure I.1: history since 1980 and forecast until 2030 of global energy production (adapted from the ExxonMobil 2004 Energy Outlook); MBDOE = million barrels per day oil-equivalent = 620 TWh per year

Wind turbine noise is a problem that may grow due to neglect by wind energy proponents and thus it may be another reason for part of the public, with politicians following, to turn away from wind power. This problem can be solved when it is also addressed at the level of local impact: sustainability must also apply at the local level. Some technical possibilities for noise reduction are given in this book and more competent, hardware oriented people may come up with better solutions. In addition to this, the social side of the problems must not be neglected. In a recent study [Van As *et al* 2005] it was concluded that "growing public resistance

[1] NRC Handelsblad 8-11-2005, articles "Bezinning nodig over energiebeleid" ("Energy policy needs reflection" by W. van Dieren) and "Nieuw debat schept slechts onzekerheid" ("New debate only creates uncertainty" by Laurens Jan Brinkhorst); my translations

to onshore wind turbines” obstructs wind energy development in the Netherlands. According to the report this opposition is now the main bottle-neck: local communities and residents are faced with the disadvantages whilst others (proponents, society at large) reap the benefits. The report recommends that the former share in the benefits too.

I.5 Microphone wind noise

In contrast to the impact my wind turbine research has had in society, the same knowledge of atmospheric physics helped me solve a non-controversial problem of interest to only a few: what is the nature of the noise that wind creates in a microphone? It occurred to me that if atmospheric turbulence was the cause, then one must be able to calculate the level of this noise. I was delighted when I found out how well theoretical considerations fitted hitherto only vaguely understood measurement results. Eureka!, such is the joy of work in science.

Somewhat unexpectedly this second discovery turns out to be related to wind turbine sound, which is why it is in this book. Originally it was considered difficult to measure wind turbine sound, because the strong winds that were supposed to cause high wind turbine sound levels, also were believed to be responsible for a lot of microphone wind noise. Solutions to this problem were either to put the microphone out of the wind on the ground or use several microphones and decrease microphone noise by averaging over all microphone signals. A new solution offered in this book is to take measurements in a stable atmosphere where near-ground wind velocity is so low that microphone noise is far less of a problem. One can measure sound at distances from a wind farm most researchers would not now believe to be possible.

The relationship is even stronger. In some countries the level of ambient background sound determines (part of) the limit imposed on sound exposure. To measure the level of this background sound the microphone must be put up in a place where residents stay outdoors, also in stronger winds. In this case it is important to discriminate between real ambient sound and the noise that wind produces in the microphone. With the calculation methods in this book it is now possible to do so.

I.6 Research aims

The issues raised above concerning wind turbine noise and its relationship to altitude dependent wind velocity led to the following issues to be investigated:

- what is the influence of atmospheric stability on the speed and sound power of a wind turbine?
- what is the influence of atmospheric stability on the character of wind turbine sound?
- how widespread is the impact of atmospheric stability on wind turbine performance: is it relevant for new wind turbine projects?; how can noise prediction take this stability into account?
- what can be done to deal with the resultant higher impact of wind turbine sound?

Apart from these directly wind turbine related issues, a final aim was to address a measurement problem:

- how does wind on a microphone affect the measurement of the ambient sound level?

I.7 Text outline and original work

This book gives an overview of results of the wind turbine noise research that has been presented in the international arena in the last few years, as well as some opinions on this topic in the Introduction and Epilogue. Most of the text in this book has been published in scientific journals or presented at conferences. However, the texts have been adapted somewhat so as to form a continuous story without too much overlap. Other changes have been listed below.

- *Chapter II* is a reflection on some problems I encountered in doing research and presenting the results, most of it concerning wind turbine noise, but set against a more general background. It corresponds to a paper presented at Euronoise 2003 [Van den Berg 2003], but some overlap with later chapters is taken out and some new information concerning the variation of wind turbine sound has been added (last paragraph in II.2). The remaining text has been edited slightly.

- *Chapter III* gives some numbers on wind energy development in the European Union, as well as an introduction on atmospheric wind gradients and the origins of aerodynamic wind turbine sound. It corresponds to sections of two published papers [Van den Berg 2004a and 2005a] to which remarks on the local wind speed at the turbine blade (section III.3) and on the spectrum of thickness sound (footnote in III.4) has been added. Also a description of sound and effects as given by a residential group with practical experience is added (box at end of chapter) and a remark on constant speed and variable speed wind turbines (in III.4).
- *Chapter IV* corresponds to my first paper on this topic [Van den Berg 2004a] on measurements at the Rhede wind farm. The section on Impulsive Sound has been taken out here and transferred to the next chapter. A new section (IV.10) has been added describing previously unpublished measurements at the Rhede wind farm as well as a comparison with calculated sound levels. Chapter IV demonstrates the fact that sound levels due to wind turbines have been systematically underestimated because hub height wind velocities were not correctly predicted. This effect is becoming more important for modern, tall wind turbines particularly when the atmosphere is 'non standard' (*i.e.* diverging from neutrality).
- In *chapter V* a second effect of atmospheric stability is investigated. Not only has the sound level been underestimated, but also the effect on the sound character: when the atmosphere turns stable, a more pronounced beating sound evolves. Most of the data are from the Rhede wind farm, complemented by data from a smaller single turbine elsewhere and theoretical calculations. In a section on the perception of fluctuating sound, it is explained how an apparently weak sound level variation can indeed turn into audibly pronounced beating. This chapter corresponds to a published paper [Van den Berg 2005a], but the section on interaction of several turbines (V.2.4) has been

combined with the corresponding section of the first paper [Van den Berg 2004a]. In this chapter the fact that wind velocity in the rotor is not equal to the free wind velocity, which was neglected in the paper, has been taken into account.

- In *chapter VI* data on atmospheric stability and wind statistics are presented. The raw data are from a location in the mid west of the Netherlands and have been provided by the KNMI. The analysis and application to a reference wind turbine help us to understand the behaviour of wind turbines and, together with research results from other countries, show that the atmospheric conditions found at the Rhede wind farm certainly were no exception. This chapter is the text of a paper presented at the WindTurbineNoise2005 conference [Van den Berg 2005b], with some results from other presentations at that conference added (in section VI.6).
- In *chapter VII* some possibilities are discussed to cope with the effects of atmospheric stability on wind turbine noise, either by controlling wind turbine performance or by new designs. In part this is derived from a project in the town of Houten where the town council wants to permit a wind farm, taking into account the effect on residents, especially at night. This chapter is a somewhat expanded version (a concluding section has been added) of a second paper presented at the WindTurbineNoise2005 conference [Van den Berg 2005c].
- In *chapter VIII* a new topic is introduced: how does wind affect sound from a microphone? It shows that atmospheric turbulence, closely related to -again- atmospheric stability, is the main cause of wind induced microphone noise. The chapter corresponds to a published article [Van den Berg 2006].
- In *Chapter IX* all results are summarized. Based on these general conclusions recommendations are given for a fresh look at wind turbine noise.
- Finally, in *chapter X*, some thoughts are given to conclude the text. After that the appendices give additional information.

II ACOUSTICAL PRACTICE AND SOUND RESEARCH

II.1. Different points of view

In 2001 the German wind farm Rhede was put into operation close to the Dutch border. Local authorities as well as residents at the Dutch side had opposed the construction of the 17 wind turbines because of the effects on landscape and environment: with 98 m hub height the 1.8 MW turbines would dominate the skyline of the early 20th century village of Bellingwolde and introduce noise in the quiet area.
With the turbines in operation, residents at 500 m and more from the wind farm found the noise (and intermittent or flicker shadow, which will not be dealt with here) worse than they had expected. The wind farm operator declined to take measures as acoustic reports showed that German as well as Dutch noise limits were not exceeded. When the residents brought the case to a German court, they failed on procedural grounds. For a Dutch court they had to produce arguments that could only be provided by experts.

Science Shops are specifically intended to help non-profit groups by doing research on their behalf. For the Science Shop for Physics in Groningen noise problems constitute the majority of problems that citizens, as a group or individually, come up with. Although the aim of our research is the same as for acoustic consultants to quantify sound levels relevant for annoyance- the customers are different: consultants mostly work for the party responsible for the sound production, whereas the Science Shop mostly works for the party that is affected by the sound. This may lead to different research questions. In the case of wind farm Rhede a consultancy will check the sound production of the turbines and check compliance of the calculated sound immission level with relevant limits. However, the Science Shop, taking the strong reaction from the residents as a starting point, wanted to check whether the real sound immission agrees with the calculated one and whether sound character could explain extra annoyance.

In the Dutch professional journal ‘Geluid’ it was shown, on the basis of 30 acoustic reports, that acoustic consultants tend to rely too much on information from their customers, even when they had reason to be critical about it [Van den Berg 2000]. As consultants’ customers are usually noise producers and authorities, the point of view of those that are affected by noise is not usually very prominent. This book shows that for wind turbines a similar case can be made.

II.2 Results from our wind turbine research

The results of the investigation of the sound from the wind farm Rhede are given in the next chapters. Here the results will be dealt with briefly. The main cause for the high sound level perceived by residents is the fact that wind velocities at night can, at 100 m height, be substantially higher than expected. As a consequence a wind turbine produces more sound. As measured immission levels near the wind farm Rhede show, the discrepancy may be very large: sound levels are up to 15 dB higher than expected at 400 m from the wind farm. The important point is not so much that the maximum measured sound level is higher than the maximum expected sound level (it was, around +2 dB, but this was not an effect of the wind velocity profile). The point is that this maximum does not only occur at high wind velocities as expected, accompanied by high wind induced ambient sound levels, but already at relatively low wind velocities (4 m/s at 10 m height) when there is little wind at the surface and therefore little wind induced background sound. Thus, the discrepancy of 15 dB occurs at quiet nights, but yet with wind turbines at almost maximum power. This situation occurs quite frequently.

A second effect that adds to the sound annoyance is that the sound has an impulsive character. The primary factor for this appeared to be the well known swishing sound one hears close to a turbine. For a single turbine these 1 2 dB broad band sound pressure fluctuations would not classify as impulsive, but at night this swish seems to evolve into a less gentle thumping. Also, when several turbines operate nearly synchronously the

pulses may occur in phase increasing pulse strength further. At some distance from the wind farm this sound characteristic, described as thumping or beating, can be very pronounced though in the wind farm, close to a turbine, we never heard this impulsiveness.
Indeed, close to a turbine it seems that most sound is coming from the downgoing blade, not when it passes the tower. One has to be careful in estimating blade position, as an observer at, say, 100 m from the foot of the tower is 140 m from a 100 m hub and therefore hears the sound from a blade approximately half a second after it was produced, in which time a blade may have rotated over some 30°. At the Berlin WindTurbineNoise conference Oerlemans [2005] explained this phenomenon: when the blade comes down and heads towards the observer, the observer is at an angle to the blade where most sound is radiated (see remark on directivity just below equation B.5 in Appendix B). On top of that the high tip velocity (70 m/s) causes a Doppler amplification. Both effects increase the sound level for our observer. However, this observation cannot be used for a distant turbine as in that case the observer sees the rotor sideways. Then the change due to the directivity of the sound is small, and also the Doppler effect is nil as the change in the velocity component towards the observer is negligible.

II.3 Early warnings of noisy wind turbines?

One may wonder why the strong effect of the nightly wind profile or the thumping was not noticed before. In the 1998 publication IEC 16400 only the neutral logarithmic wind profile is used [IEC, 1998]. As recent as 2002 it was stated that wind turbine sound is not impulsive [Kerkers *et al* 2002], which was concluded from assumed, not from measured sound level variations.

There have been some warnings, though. In 1998 Rudolphi concluded from measurements that wind velocity at 10 m height is not a good measure for the sound level: at night the (58 m hub height) turbine sound level was 5 dB higher than expected [Rudolphi 1998]. This conclusion was not followed by more thorough investigation. Since several years residential groups in the Netherlands and abroad complained about

annoying turbine sound at distances where they are not even expected to be able to hear the sound. Recently Pedersen *et al* [2003, 2004] found that annoyance was relatively high at calculated maximum sound immission levels below 40 dB(A) where one would not expect strong annoyance.
As wind turbines become taller, the discrepancy between real and expected levels grows and as more tall wind turbines are constructed complaints may become more widespread. In the Netherlands residents near the German border were the first Dutch to be acquainted with turbines of 100 m hub heights.

It may be that earlier discrepancies between real and projected sound immission were not sufficient to evoke strong community reactions and that only recently turbines have become so tall that the discrepancy now is intolerable.
There are other reasons that early warnings perhaps did not make much impression. One is that sound emission measurements are usually done in daytime. It is hard to imagine the sound would be very different at night time, so (almost) no one did. Until some years ago, I myself could not imagine how people could hear wind turbines 2 km away when at 300 to 400 m distance the (calculated) immission level was, for a given wind velocity, already equal to the ambient background sound level (L_{95}). But it proved I had not listened in a relevant period: an atmospherically stable night.
What is probably also a reason is the rather common attitude that ‘there are always people complaining’. Complaints are a normal feature, not as such a reason to re-investigate. Indeed Dutch noise policy is not to prevent any noise annoyance, but to limit it to acceptable proportions. Added to this is a rather general conviction of Dutch authorities and consultants that routine noise assessment in compliance with legal standards must yield correct results. If measurements are performed it is to check actual emission levels usually in normal working hours, so in daytime. It is quite unusual to compare the calculated sound immission from a wind turbine (farm) with measured immission levels (so unusual that it is likely that we were the first to do so).

A third reason may be partiality to the outcome of the results. Wind turbine operators are not keen on spending money that may show that sound levels do not comply with legal standards. And if, as expected, they do comply, the money is effectively wasted. Apart from this, we have the experience that at least some organisations that advocate wind energy are not interested in finding out why residents oppose wind farms.

II.4 The use of standard procedures

Although our objective was to measure immission sound levels, we also wanted to understand what was going on: if levels were higher than expected, was that because emission was higher or attenuation less? Could there be focussing or interference? We therefore also measured sound emission as a function of rotational speed of the variable speed turbines. An interesting point that came up with the emission measurement was that compliance with the recommended standard [Ljunggren 1997 or IEC 1998] was impossible. As the farm operator withdrew the co-operation that was previously agreed upon, we had to measure emission levels with the full wind farm in operation, as we obviously did not have the means to stop all turbines except the one to be measured, as the standard prescribes. To measure ambient background sound level, even the last turbine should be stopped.

According to the recommended standard the sound emission should be measured within 20% of the distance to the turbine equal to hub height + blade length. However, to prevent interference from the sound from other turbines the measurement location had to be chosen closer to the turbine.

The primary check on the correctness of the distance (i.e. not too close to other turbines) was by listening: the closest turbine should be the dominant source. If not, no measurement was done, and usually a measurement near another turbine was possible. Afterwards we were able to perform a second check by comparing the measured sound immission of the wind farm at a distance of 400 m with the level calculated with a sound propagation model with the measured emission level of all (identical) turbines as input. The calculated difference between a single turbine sound power level and the immission level was 58.0 dB (assuming a constant spectrum this is independent from the power level itself). The measured average difference

was 57.9 dB, with a maximum deviation of individual measurement points of 1.0 dB. So our measurements proved to be quite accurate, deviating only 0.1 ± 1.0 dB from the expected value! In fact, from our measurements one may conclude that, to determine turbine sound power level, it is easier and cheaper to determine total sound emission by measurements at some distance from a wind farm than measuring separate turbines. The wind induced ambient sound, that easily spoils daytime measurements, is not an important disturbance in many nights!
Using a 1 m diameter round hard board, again to comply with the standard, was quite impractical and sometimes impossible. *E.g.* at one place potato plants would have to be cleared away, at another place one would have to create a flat area in clumps of grass in a nature reserve, both unnecessarily. Instead of the large board we used the side (30·44 cm^2) of a plastic sound meter case. We convinced ourselves that (in this case) this was still a good procedure by comparing at one location sound levels measured on the case on soft ground with sound levels measured on a smooth tarmac road surface a few meters away, both at the same distance to the turbine as in the other measurements: there was no difference.

Whether a turbine produces impulsive sound is usually determined by listening to and measuring the sound near a single turbine (along with measurements to determine sound power and spectral distribution). In the Netherlands impulsivity is judged subjectively (by ear), not by a technical procedure as in Germany, though judgement can be supported with a sound registration showing the pulses. Interestingly, in Dutch practice only an acoustician's ear seems reliable, though even their opinions may disagree. From our measurements the impulsive character can be explained by the wind profile and the interaction of the sound of several turbines. Even at a time the impulsive character can be heard near residents' dwellings, it cannot clearly be heard close to the turbines in the wind farm (as explained in section II.2). So here also there was need to do measurements where people are actually annoyed, and not to rely on source measurements only, certainly not from a single turbine.

When noise disputes are brought to court, it is clearly advantageous to have objective procedures and standards to assure that the technical quality, which can hardly be judged by non experts, is sufficient and therefore the results are reliable. In the case made here however, a standard may be non-applicable for valid reasons. Nonetheless, the emission measurements have been contested on procedural grounds (*viz.* we have not complied to the standard [Kerkers 2003]), even though the immission sound levels were the primary research targets and we did not really need the sound emission measurement results (which, however, proved very accurate).
The tendency to put all noise assessment into technical standard procedures has the disadvantage that when there is a flaw in a legally enforced standard, still the standard is followed, not reality. It is hardly possible for non experts, such as residents, to bring other arguments to court. They, the annoyed, will have to hire an expert to objectify their annoyance. This is not something every citizen can afford.

II.5 Modelling versus measurements

Being able to calculate sound levels from physical models is a huge advantage over having to do measurements (if that, indeed, is possible) especially as in practical situations conditions keep changing and other sounds disturb the measurements. Because of its obvious advantages models have become far more important for noise assessment than measurements. In the Netherlands usually sound emission measurements are carried out close to a source to determine sound power levels. Then, with the sound power level, the immission level is calculated, usually on façades of residences close to the sound source. It is not common to measure immission levels in the Netherlands; in some cases (e.g. railway, aircraft noise) there is not even a measurement method (legally) available to check calculated levels.

However, a physical model is never the same as reality. As will be shown in this book, the widely used standard to quantify sound emission from wind turbines is implicitly based on a specific wind profile. This profile is

not correct at night, although the night is the critical period for wind turbine noise assessment.
Even a perfect physical model will not reproduce reality if input values are not according to reality. An example is to apply sound power levels from new sources (cars, road surfaces, aeroplanes, mopeds, vacuum cleaners, etc.), maybe acquired in a specific test environment, to real life situations and conditions. Another example is a wind farm south of the Rhede wind farm where a turbine produced a clearly audible and measurable tonal sound, probably caused by damage on a blade. It is very hard for residents to convince the operator and authorities of this annoying fact, partly because most experts say that modern wind turbines do not produce tonal sound.
Incorrect models and incorrect input may well occur together and be difficult to separate. It is important that calculation models are checked for correctness when they are used in new applications. Situations where (strong) complaints arise may indicate just those cases where models do not cover reality.

II.6 Conclusion

In modelling wind turbine sound very relevant atmospheric behaviour has been ‘overlooked’. As a consequence, at low surface wind velocities such as often occur at night, wind turbine noise immission levels may be much higher than expected. The discrepancy between real and modelled noise levels is greater for tall wind turbines. International models used to assess wind turbine noise on dwellings should be revised for this atmospheric effect, at least by giving less attention to the 'standard' neutral atmosphere.

A discrepancy between noise forecasts and real noise perception, as a result of limited or even defective models, cannot always be avoided, even not in principle. However, its consequences can be minimised if immission levels are measured at relevant times and places. This relevancy is also determined by observations of those affected. It should always be possible to check noise forecasts by measurement.

For wind turbine noise (and other noise sources) standard measurement procedures require co-operation of the operator to be able to check emission sound levels. This introduces an element of partiality to the advantage of the noise producer. This is also generally a weak point in noise assessment: the source of information is usually the noise producer. Hence there should always be a procedure to determine noise exposure independently of the noise producer.

Standard technical procedures have the benefit of providing quality assurance: when research has been conducted in compliance with a standard procedure lay persons should be able to rely on the results. It may however also have a distinct disadvantage for lay people opposing a noise source: when an assessment does not comply with a standard procedure it is not accepted in court, regardless of the content of the claim. A consequence is they have to depend on legal as well as acoustical expertise. If citizens are forced to use expert knowledge, one may argue that they should be given access to that knowledge. An important obstacle is the cost of that access.

III BASIC FACTS: wind power and the origins of modern wind turbine sound

III.1 Wind energy in the EU

Modern onshore wind turbines have peak electric power outputs up to 3 MW and tower heights of 80 to 100 meters. In 2003, 75% of the global wind power peak electric output of 40 GW was installed in the European Union. The original European target for 2010 was 40 GW, but the European Wind Energy Association have already set a new target for 2010 of 75 GW, of which 10 GW is projected off-shore, while others have forecasted a peak output of 120 GW for that year [EWEA 2004]. Whether this growth will actually occur is uncertain; with the proportional increase of wind energy in total electric power the difficulties and costs of integrating large scale windpower with respect to grid capacity and stability, reserve capacity and CO_2 emission reductions are becoming more prominent [see, *e.g.*, E.On 2004, ESB 2004]). However, further expansion of wind energy is to be expected, and as a result of this (predominantly on-shore) growth an increasing number of people may face the prospect of living near wind farms, and have reason to inquire and perhaps be worried about their environmental impact. Visual intrusion, intermittent reflections on the turbine blades, as well as intermittent shadows (caused when the rotating blades pass between the viewer and the sun), and sound, are usually considered potentially negative impacts.

III.2 Wind profiles and atmospheric stability

Atmospheric stability has a profound effect on the vertical wind profile and on atmospherical turbulence strength. Stability is determined by the net heat flux to the ground, which is a sum of incoming solar and outgoing thermal radiation, and of latent and sensible heat exchanged with the air and the subsoil. When incoming radiation dominates (clear summer days) air is heated from below and rises: the atmosphere is unstable. Thus, thermal turbulence implies vertical air movements, preventing large variations in the vertical wind velocity gradient (*i.e.* the change in time averaged wind velocity with height). When outgoing radiation dominates (clear nights) air is cooled from below; air density will increase closer to the ground, leading to a stable configuration where vertical movements are damped. The 'decoupling' of horizontal layers of air allows a higher vertical wind velocity gradient. A neutral state occurs when thermal effects are less significant, which is under heavy clouding and/or in strong winds.

Wind velocity at altitude h_2 can be deduced from wind velocity at altitude h_1 with a simple power law function:

$$V_{h2}/V_{h1} \quad (h_2/h_1)^m \tag{III.1}$$

Equation III.1 is an engineering formula used to express the degree of stability in a single number (the shear exponent *m*), but has no physical basis. The relation is suitable where h is at least several times the roughness height (a height related to the height of vegetation or obstacles on the ground). Also, at high altitudes the wind profile will not follow (III.1), as eventually a more or less constant wind velocity (the geostrophic wind) will be attained. At higher altitudes in a stable atmosphere there may be a *de*crease in wind velocity when a nocturnal 'jet' develops. The maximum in this jet is caused by a transfer of kinetic energy from the near-ground air that decouples from higher air masses as large, thermally induced eddies vanish because of ground cooling. In fact, reversal of the usual near-ground diurnal pattern of low wind velocities at night and higher wind velocities in daytime is a common phenomenon at higher altitudes over land in clear nights as will be shown further below (Chapter VI). Over large bodies of water the phenomenon may be seasonal as atmospheric stability occurs more often when the water is relatively cold (winter, spring). This may also be accompanied by a maximum in wind velocity at a higher altitude [Smedman *et al* 1996].

In flat terrain the shear exponent *m* has a value of 0.1 and more. For a neutral atmosphere *m* has a value of approximately 1/7. In an unstable atmosphere -occurring in daytime- thermal effects caused by ground heating are dominant. Then *m* has a lower value, down to approximately

0.1. In a stable atmosphere vertical movements are damped because of ground cooling and *m* has a higher value. One would eventually expect a parabolic wind profile, as is found in laminar flow, corresponding to a value of *m* of 0.7   √½. Our measurements near the Rhede wind farm yielded values of *m* up to 0.6. A sample (averages over 0:00 0:30 GMT of each first night of the month in 1973) from data from a 200 m high tower in flat, agricultural land [Van Ulden *et al* 1976] shows that the theoretical value is indeed reached: in ten out of the twelve samples there was a temperature inversion in the lower 120 m, indicating atmospheric stability. In six samples the temperature increased with more than 1 °C from 10 to 120 m height and the exponent *m* (calculated from (III.1): *m* $\log(V_{80}/V_{10})/\log(8)$) was 0.43, 0.44, 0.55, 0.58, 0.67 and 0.72. More data from this site (Cabauw) and other areas will be presented in chapter VI.

A physical model to calculate wind velocity V_h at height h is ([Garrat 1992], p. 53):

$$V_h \quad (u_*/\kappa)\cdot[\ln(h/z_o) \quad \Psi] \tag{III.2}$$

where κ 0.4 is von Karman's constant, z_o is roughness height and u_* is friction velocity, defined by $u_*^2 \quad \sqrt{(<uw>^2 + <vw>^2)} \quad \tau/\rho$, where τ equals the momentum flux due to turbulent friction across a horizontal plane, ρ is air density and u, v and w are the time-varying components of in-wind, cross-wind and vertical wind velocity, with $<x>$ the time average of x. The stability function $\Psi \quad \Psi(\zeta)$ (with $\zeta \quad h/L$) corrects for atmospheric stability. Here Monin-Obukhov length L is an important length scale for stability and can be thought of as the height above which thermal turbulence dominates over friction turbulence; the atmosphere at heights $0 < h < L$ (if L is positive and not very large) is the stable boundary layer. The following approximations for Ψ, mentioned in many text books on atmospheric physics (*e.g.* [Garrat 1992]), are used:

- in a stable atmosphere ($L > 0$) $\Psi(\zeta) \quad -5\zeta < 0$.
- in a neutral atmosphere ($|L|$ large $\rightarrow 1/L \approx 0$) $\Psi(0) \quad 0$.
- in an unstable atmosphere ($L < 0$) $\Psi(\zeta) \quad 2\cdot\ln[(1+x)/2] + \ln[(1+x^2)/2]$ $2/\tan(x) + \pi/2 > 0$, where $x \quad (1-16\cdot\zeta)^{1/4}$.

For Ψ 0 equation (III.2) reduces to $V_{h,log}$ $(u_*/\kappa)\cdot\ln(h/z_o)$, the widely used logarithmic wind profile. With this profile the ratio of wind velocities at two heights can be written as:

$$V_{h2,log}/V_{h1} \quad \log(h_2/z_o)/\log(h_1/z_o) \tag{III.3}$$

For a roughness length of z_o 2 cm (pasture) and m 0,14, the wind profiles according to equations III.1 and III.3 coincide within 2% for h < 100 m. In figure III.1 wind profiles are given as measured by Holtslag [1984], as well as wind profiles according to formulae (III.1) and (III.3).

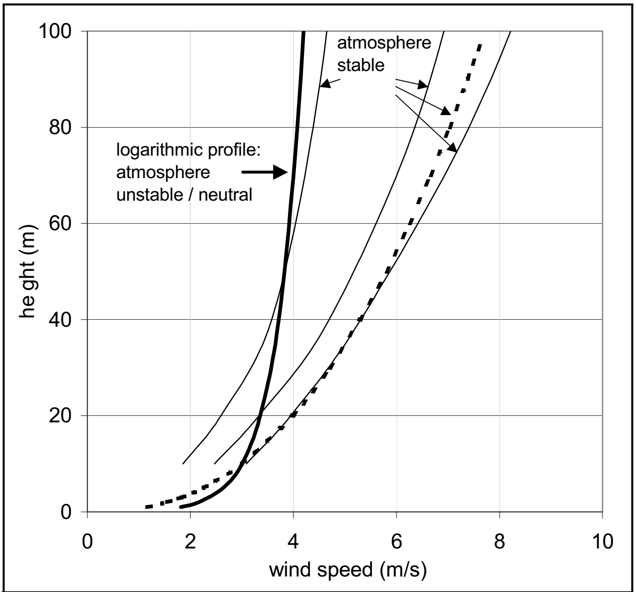

Figure III.1: wind profiles

Formula III.3 is an approximation of the wind profile in the turbulent boundary layer of a neutral atmosphere, when the air is mixed by turbulence resulting from friction with the surface of the earth. In daytime thermal turbulence is added, especially when there is strong insolation. At night time a neutral atmosphere, characterized by the adiabatic temperature gradient of -1 ºC per 100 m, occurs under heavy clouding and/or at relatively high wind velocities. When there is some clear sky and in the absence of strong winds the atmosphere becomes stable because of radiative cooling of the surface: the wind profile changes and can no longer be adequately described by (III.3). The effect of the change to a stable atmosphere is that, relative to a given wind velocity at 10 m height in daytime, at night there is a higher wind velocity at hub height and thus a higher turbine sound power level; also there is a lower wind velocity below 10 m and thus less wind-induced sound in vegetation.

With regard to wind *power* some attention is being paid to stability effects and thus to other wind profile models such as the diabatic wind velocity model (III.2) [see, *e.g.*, Archer *et al* 2003, Baidya Roy *et al* 2004, Pérez *et al* 2004, Smedman *et al* 1996, Smith *et al* 2002]. In relation to wind turbine *sound*, much less attention has been given to atmospheric stability (see section II.3).

Stability can also be categorized in Pasquill classes that depend on observations of wind velocity and cloud cover (see, *e.g.*, [LLNL 2004]). They are usually referred to as classes A (very unstable) through F (very stable). In a German guideline [TA-Luft 1986] a closely related classification is given (again closely related to the international Turner classification [Kühner 1998]). An overview of stability classes with the appropriate value of m is given in table III.1.

Table III.1: stability classes and shear exponent *m*

Pasquill class	name	comparable stability class [TA-Luft 1986]	*m*
A	very unstable	V	0.09
B	moderately unstable	IV	0.20
C	neutral	IV2	0.22
D	slightly stable	IV1	0.28
E	moderately stable	II	0.37
F	(very) stable	I	0.41

According to long-term data from Eelde and Leeuwarden [KNMI 1972], two meteorological measurement sites of the KNMI (Royal Netherlands Meteorological Institute) in the northern part of the Netherlands, a stable atmosphere (Pasquill classes E and F) at night occurs for a considerable proportion of night time: 34% and 32% respectively.

From formula (III.3) the ratio of wind velocities at hub height (98 m) and reference height, over land with low vegetation (z_o 3 cm), is f_{log} V_{98}/V_{10} 1.4. According to formula (III.1) and table III.1 this ratio would be $f_{unstable}$ 1.2 $0.85 \cdot f_{log}$ in a very unstable atmosphere and f_{stable} 2.5 $1.8 \cdot f_{log}$ in a (very) stable atmosphere.

The shear exponent *m* can be determined from the measured ratio of wind velocities at two heights (V_{h2}/V_{h1}) using equation III.1:

$$m_{h1,h2} \quad \ln(V_{h2}/V_{h1})/\ln(h_2/h_1) \qquad \text{(III.4)}$$

III.3 Air flow on the blade

As is the case for aircraft wings, the air flow around a wind turbine blade generates lift. An air foil performs best when lift is maximised and drag (flow resistance) is minimised. Both are determined by the angle of attack: the angle (α) between the incoming flow and the blade chord (line between front and rear edge; see figure III.2). The optimum angle of attack for turbine blades is usually between 0 and 4º, depending on the blade profile.

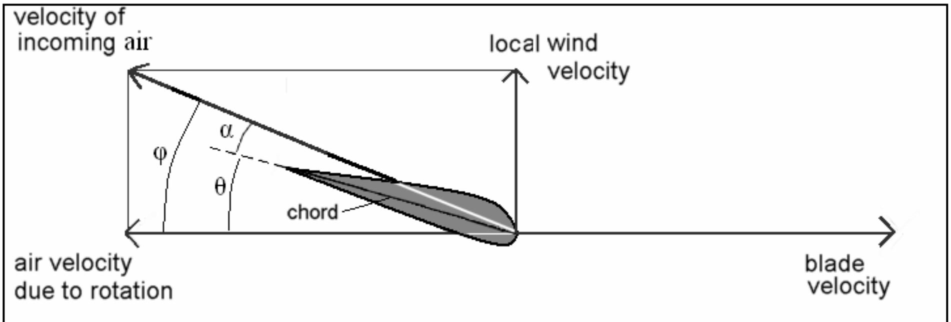

Figure III.2: flow impinging on a turbine blade with flow angle φ, blade pitch angle θ and angle of attack on blade $\alpha = \varphi - \theta$

The local wind at the blade is not the unobstructed wind velocity. The rotor extracts energy from the air at the cost of the kinetic energy of the wind. The velocity of the air passing through the rotor is thus reduced to V_b (1 a)V_h, where a is the induction factor. The highest efficiency of a wind turbine is reached at the Betz limit: at this theoretical limit the induction factor is 1/3 and the efficiency is 16/27 (≈ 60%) [Hansen 2000]. The wind velocity at the blade is thus:

$$V_b \quad V_h \cdot 2/3 \qquad \text{(III.5)}$$

III.4 Main sources of wind turbine sound

There are many publications on the nature and power of turbine sound: original studies [*e.g.* Lowson 1985, Grosveld 1985] and reviews [*e.g.* Hubbard *et al* 2004, Wagner *et al* 1996]. A short introduction on wind aeroacoustics will be given to elucidate the most important sound producing mechanisms.

If an air flow is smooth around a (streamlined) body, it will generate very little sound. For high velocities and/or over longer lengths the flow in the boundary layer between the body and the main flow becomes turbulent. The rapid turbulent velocity changes at the surface cause sound with frequencies related to the rate of the velocity changes. The turbulent boundary layer at the downstream end of an airfoil produces *trailing edge sound*, which is the dominant audible sound from modern turbines. When the angle of attack increases from its optimal value the turbulent boundary layer on the suction (low pressure) side grows in thickness, thereby decreasing power performance and increasing sound level. For high angles of attack this eventually leads to stall, that is: a dramatic increase of drag on the blades. Apart from this turbulence inherent to an airfoil, the atmosphere itself is turbulent over a wide range of frequencies and sizes.

Figure III.3: 15 m blades for Altamont Pass, Ca (photo: Alex Haag)

Turbulence can be defined as changes over time and space in wind velocity and direction, resulting in velocity components normal to the airfoil varying with the turbulence frequency causing *in-flow turbulent sound*. Atmospheric turbulence energy has a maximum at a frequency that depends on altitude and on atmospheric stability. For wind turbine altitudes this peak frequency is of an order of magnitude of once per minute (0.017 Hz). The associated eddy (whirl) scale is of the order of magnitude of several hundreds of meters [Petersen *et al* 1998] in an unstable atmosphere, less in a stable atmosphere. Eddy size and turbulence strength decrease at higher frequency, and vanish due to viscous friction when the eddies have reached a size of approximately one millimetre.[1]

A third sound producing mechanism is the response of the blade to the change in lift when it passes the tower. The wind is slowed down by the tower which changes the angle of attack on the blade; as a result the lift and drag forces on the blade suddenly change. The resulting sideways movement of the blade causes *thickness sound* at the blade passing frequency and its harmonics.[2] Thickness sound is also mentioned as sound originating from the (free) rotating blade pushing the air sideways. However, the associated air movement is relatively smooth and is not a relevant source of sound.

A more thorough review of these three sound production mechanisms is given in appendix B, where frequency ranges and sound levels are quantified in so far as relevant for this book.

Sound originating from the generator or the transmission gear has decreased in level in the past decades and has become all but irrelevant if considering annoyance for residents.

To summarize, a modern wind turbine sound spectrum can be divided in (overlapping) regions corresponding to the three mechanisms mentioned:

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[1] for more information on atmospheric turbulence: see chapter VIII

[2] a thickness sound pulse has a length t_{pulse} with an order of magnitude of (tower diameter/tip speed ≈) 0,1 s, so its spectrum has a maximum at $1/t_{pulse} \approx 10$ Hz. The spectrum of a periodic series of Dirac pulses (unit energy 'spikes' with, here, a period of T_{blade}) is a series of spikes at frequencies n/T_{blade} (n = 1, 2, 3, 4, ...). When periodic thickness sound is considered as a convolution of the single sound pulse with a series of Dirac pulses, the Fourier transform is the product of the transforms of both, that is: the product of the sound pulse spectrum centered at $1/t_{pulse}$ and spikes at n/T_{blade}. The result is a series of spikes with the single sound pulse spectrum as an envelope, determining each spike level. In practice $1/T_{pulse}$ usually has a value of 4 to 8 Hz (see *e.g.* [Wagner 1996]) and the harmonic closest to this frequency carries most energy.

- High frequency: *trailing edge (TE) sound* is noise with a maximum level at 500 1000 Hz for the central octave band, decreasing with 11 dB for neighbouring octave bands and more for further octave bands.
- Low frequency: *in-flow turbulent sound* is broad band noise with a maximum level of approximately 10 Hz and a slope of 3 6 dB per octave.
- Infrasound frequency (f < 30 Hz): the *thickness sound* is tonal, the spectrum containing peaks at the blade passing frequency f_B and its harmonics.

As thickness sound is not relevant for direct perception, turbulent flow is the dominant cause of (audible) sound for modern wind turbines. It is broad band noise with no tonal components and only a little variation, known as blade swish. Trailing edge sound level is proportional to 50·logM (see equation B.4 in appendix B), where M is the Mach number of the air impinging on the blade. TE sound level, the dominant audible sound source in a modern turbine, therefore increases steeply with blade speed and is highest at the high velocity blade tips. Writing Mach number at the blade tip as M V_{tip}/c, wind turbine sound level strongly depends on blade tip speed V_{tip}:

$$L_{TE} \sim 50 \cdot \log(V_{tip}/c) \qquad \text{(III.6)}$$

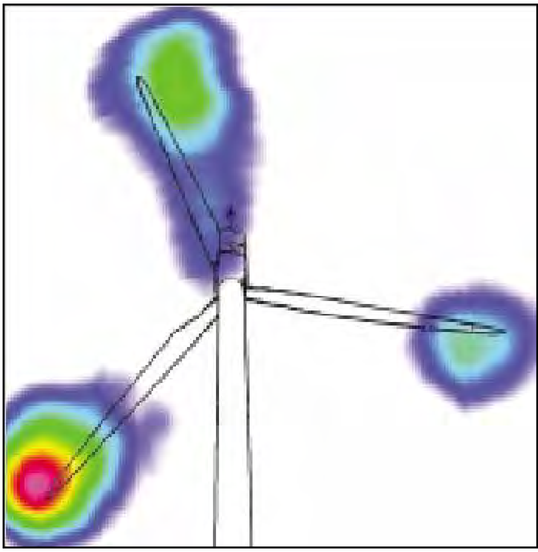

Figure III.1: an 'acoustic photograph' showing the high speed tips of a wind turbine radiate most sound; colors from centre to outside contour indicate an decreasing sound level (photo: Acoustic Camera, GFaI, Berlin)

Swish, which is the variation in TE sound, thus also originates predominantly at the tips.

This book deals with modern variable speed turbines where the angle of attack is constant over a wide range of wind speeds. Keeping blade pitch (the angle between the blade chord and the rotor plane) constant, the rotational speed increases with wind speed usually up to a rated wind speed of some 14 m/s. At higher wind speeds the pitch angle is decreased at constant rotational speed to keep a constant angle of attack until for safety reasons the rotor is stopped. The effect on sound production is that first the sound power level increases up to the rated wind speed, then remains almost constant at higher wind speeds.
In a constant speed turbine the rotational speed has a fixed value, though usually a turbine then has two speeds to accommodate for low and high wind speeds. Here the blade pitch is set to optimize the angle of attack up to the rated power. Above rated power, a situation that will not occur very often, the pitch angle is kept constant, so the angle of attack increases with wind speed and the turbine becomes less efficient. The result is that the sound power at low speed is almost constant, then increases sharply at the change to the higher speed. After that it is again almost constant, increasing again above the rated power when the angle of attack drifts away from the optimum value.

Sound from downwind rotors, *i.e.* with the rotor downwind from the tower, was considered problematic as it was perceived as a pulsating sound (see appendix B). For modern upwind rotors this variation in sound level is weaker. It is not thought to be relevant for annoyance and considered to become less pronounced with increasing distance due to loss of the effect of directivity, due to relatively high absorption at swish frequencies, and because of the increased masking effect of background noise [ETSU 1996]. However, an increase in the level of the swishing sound related to increasing atmospheric stability has not been taken into account as yet. In this context the periodic change in angle of attack near the tower proves to be important, not in relation to thickness sound but as a modulation period.

So, what's the sound like...?

(.....) Our experience is that mechanical noise is insignificant compared to the aerodynamic noise, or 'blade thump' as we call it. At "our" windfarm the mechanical noise is usually only audible when within about 100 metres of the turbine, but the blade thump can be heard at distances of up to 1.5 Km away.
(.....)
Some residents describe this noise as an old boot in a tumble dryer, others as a Whumph! Whumph! Whumph! Either way its not particularly loud at 1.5 km distance but closer than that and it can be extremely irritating when exposed to it for any period of time. Some residents have even resorted to stuffing chimney stacks with newspaper as the sound reverberates down the stack.
Because it is generally rhythmic, it's not the kind of noise that you can shut out of your mind, like, say, distant road noise - this is why we think the noise level stipulation on the planning conditions of such a windfarm development is woefully inadequate for protecting local residents from the noise effects of a windfarm.
All of us agree that the most disturbing aspect of the noise is the beat that we think is caused by the blades passing the tower of the turbine. As the rotational speed of the 3 bladed turbines is about 28 rpm "on full song" this results in a sound of about 84 beats per minute from each turbine.
The sound rises and falls in volume due to slight changes in wind direction but the end result for those in the affected area is a feeling of anxiety, and sometimes nausea, as the rate continually speeds and slows - we think that is maybe because this frequency of the pulses is close to the human heart rate and some residents feel that their own pulse rate is trying to match that of the turbines. (.....)

When does it strike?
The windfarm makes a noise all the time it is operating, however there are times when it becomes less of a nuisance.
When the wind is very strong, the background noise created by the wind whistling around trees etc. drowns out the noise of the turbines and the problem is reduced. (.....)
In this area we all agree that the worst conditions are when the wind is blowing lightly and the background noise is minimal. Under these conditions residents up to 1 kilometre have complained to the Environmental Health department about the drone from the turbines. Unfortunately these are just the sort of weather conditions that you would wish to be outside enjoying your garden. (.....)
During the summer nights it is not possible for some residents, even as far away as 1000 metres, to sleep with the window open due to the blade thump. (......)

Excerpts describing wind turbine sound and its effects, from a page of the website of MAIWAG (consulted December 3, 2005), a group of residents in three villages in the south of Cumbria (UK)

IV LOUD SOUNDS IN WEAK WINDS: effect of the wind profile on turbine sound level

IV.1 The Rhede wind farm

In Germany several wind turbine farms have been and are being established in sparsely populated areas near the Dutch border. One of these is the Rhede wind farm in nortwestern Germany (53° 6.2′ latitude, 7° 12.6′ longitude) with seventeen Enercon E-66 1.8 MW turbines of 98 m hub height and with 3-blade propellers of 35 m blade length. The turbines have a variable speed increasing with wind velocity, starting with 10 rpm (revolutions per minute) at a wind velocity of 2.5 m/s at hub height up to 22 rpm at wind velocities of 12 m/s and over.

At the Dutch side of the border is a residential area along the Oude Laan and Veendijk in De Lethe (see figure IV.2): countryside dwellings surrounded by trees and agricultural fields. The dwelling nearest to the wind farm is some 500 m west of the nearest wind turbine (nr. 16). According to a German noise assessment study a maximum immission level of 43 dB(A) was expected, 2 dB below the relevant German noise limit. According to a Dutch consultancy immission levels would comply with Dutch (wind velocity dependent) noise limits.

After the farm was put into operation residents made complaints about the noise, especially at (late) evening and night. The residents, united in a neighbourhood group, could not persuade the German operator into mitigation measures or an investigation of the noise problem and brought the case to court. The Science Shop for Physics had just released a report explaining a possible discrepancy between calculated and real sound immission levels of wind turbines because of changes in wind profile, and was asked to investigate the consequences of this discrepancy by sound measurements. Although at first the operator agreed to supply measurement data from the wind turbines (such as power output, rotation speed, axle direction), this was withdrawn after the measurements had started. All relevant data therefore had to be supplied or deduced from our own measurements.

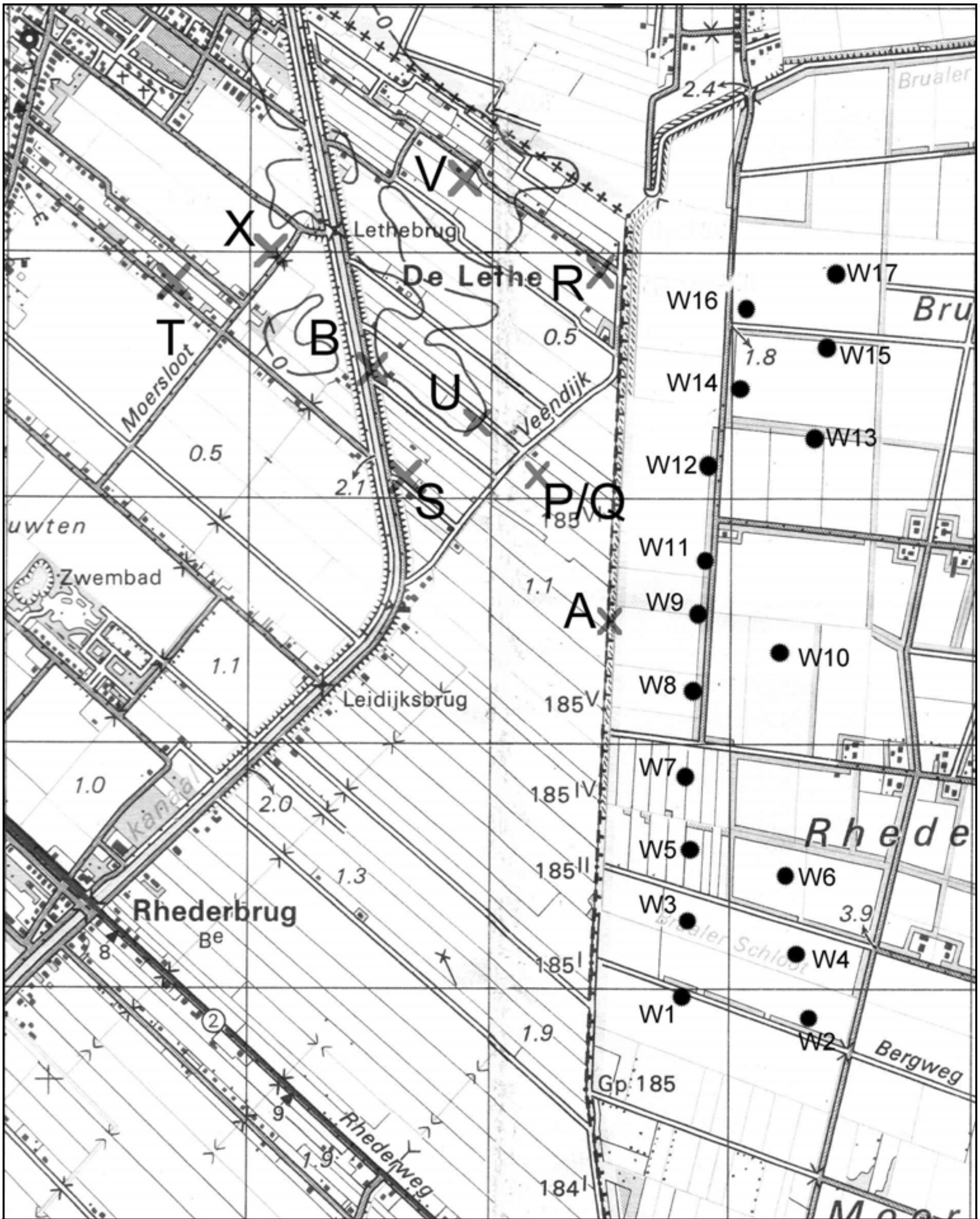

Figure IV.2: turbines (dots W1….W17) in and measurement locations (crosses A….X) near the Rhede wind farm; Duch – German border indicated by line of +++ (through A); grid lines are 1 km apart, north is at top

Figure IV.1: the Rhede wind farm, view from the north-northwest

IV.2 Noise impact assessment

In the Netherlands and Germany noise impact on dwellings near a wind turbine or wind farm is calculated with a sound propagation model. Wind turbine sound power levels L_W are used as input for the model, based on measured or estimated data. In Germany a single ‘maximum’ sound power level (at 95% of maximum electric power) is used to assess sound impact. In the Netherlands sound power levels related to wind velocities at 10 m height are used; the resulting sound immission levels are compared to wind velocity dependent noise limits (see figure VII.1). Implicitly this assessment is based on measurements in daytime and does not take into account atmospheric conditions affecting the wind profile, especially at night.

In the Netherlands a national calculation model is used [VROM 1999] to assess noise impact, as is the case in Germany [TA-Lärm 1998]. According to Kerkers [Kerkers 1999] there are, at least in the case of these wind turbines, no significant differences between both models.
In both sound propagation models the sound immission level L_{imm} at a specific observation point is a summation over j sound power octave band levels L_{Wj} of k sources (turbines), reduced with attenuation factors $D_{j,k}$:

$$L_{imm} = 10\cdot\log\left[\Sigma_j\,\Sigma_k\,10^{0.1\cdot(L_{Wj} - D_{j,k})}\right] \tag{IV.1}$$

L_{Wj}, assumed identical for all k turbines, is a function of rotational speed. D_j is the attenuation due to geometrical spreading (D_{geo}), air absorption ($D_{j\ air}$) and ground absorption ($D_{j\ ground}$): $D_{j,k}$ $D_{geo,k} + D_{j\ air,k} + D_{j\ ground,k}$.
Formula (IV.1) is valid for a downwind situation. For long term assessment purposes a meteorological correction factor is applied to (IV.1) to account for 'average atmospheric conditions'. When comparing calculated and measured sound immission levels in this study no such meteo-correction is applied because measurements were always downwind of a turbine or the wind farm.

IV.3 Wind turbine noise perception

There is a distinct audible difference between the night and daytime wind turbine sound at some distance from the turbines. On a summer's day in a moderate or even strong wind the turbines may only be heard within a few hundred meters and one might wonder why residents should complain of the sound produced by the wind farm. However, in quiet nights the wind farm can be heard at distances of up to several kilometers when the turbines rotate at high speed. In these nights, certainly at distances from 500 to 1000 m from the wind farm, one can hear a low pitched thumping sound with a repetition rate of about once a second (coinciding with the frequency of blades passing a turbine mast), not unlike distant pile driving, superimposed on a constant broad band 'noisy' sound. A resident living at 1 km from the nearest turbine says it is the rhythmic character of the sound that attracks attention: beats are clearly audible for some time, then fade away to come back again a little later. A resident living at 2.3 km from the wind farm describes the sound as ‘an endless train’. In daytime these pulses are usually not audible and the sound from the wind farm is less intrusive or even inaudible (especially in strong winds because of the then high ambient sound level).
In the wind farm the turbines are audible for most of the (day and night) time, but the thumping is not evident, although a ‘swishing’ sound a regular variation in sound level- is readily discernible. Sometimes a rumbling sound can be heard, but it is difficult to assign it, by ear, to a specific turbine or to assess it’s direction.

IV.5 Measurement instruments and method

Sound immission measurements were made over 1435 hours, of which 417 hours at night, within four months on two consecutive locations with an unmanned Sound and Weather Measurement System (SWMS) consisting of a sound level meter (type 1 accuracy) with a microphone at 4.5 m height fitted with a 9 cm diameter foam wind shield, and a wind meter at 10 m as well as at 2 m height. Every second wind velocity and wind direction (at 10 m and at 2 m height) and the A-weighted sound level were measured; the measured data were stored as statistical distributions over 5 minute intervals. From these distributions all necessary wind data and sound levels can be calculated, such as average wind velocity, median wind direction or equivalent sound level and any percentile (steps of 5%) wind velocity, wind direction or sound level, in intervals of 5 minutes or multiples thereof.

Also complementary measurements were done with logging sound level meters (type 1 and 2 accuracy) and a spectrum analyser (type 1) to measure immission sound levels in the residential area over limited periods, and emission levels near wind turbines. Emission levels were measured according to international standards [IEC 1998, Ljunggren 1997], but for practical purposes they could not be adhered to in detail: with respect to the recommended values a smaller reflecting board was used for the microphone (30·44 cm2 instead of a 1 m diameter circular board) and a smaller distance to the turbine (equal to tower height instead of tower height + blade length); reasons for this were given in Chapter II. Also it was not possible to do emission measurements with only one turbine in operation.

IV.6 Results: sound emission

Emission levels L_{eq} measured very close to the centre of a horizontal, flat board at a distance R from a turbine hub can be converted to a turbine sound power level L_W [IEC 1998, Ljunggren 1997]:

$$L_W \quad L_{eq} \quad 6 + 10\cdot\log(4\pi\cdot R^2/A_o) \qquad \text{(IV.2)}$$

where A_o is a unit surface (1 m^2). From earlier measurements [Kerkers 1999] a wind velocity dependence of L_W was established as given in table

IV.1. As explained above, the wind velocity at 10 m height was not considered a reliable single measure for the turbine sound power, but rotational speed was a better measure.

Emission levels have been measured, typically for 5 minutes per measurement, at nine turbines on seven different days with different wind conditions. The results are plotted in figure IV.3; the sound power level is plotted as a function of rotational speed N. N is proportional to wind velocity at hub height and could be determined by counting, typically during one minute, blades passing the turbine mast. This counting procedure is not very accurate (accuracy per measurement is ≤ 2 counts, corresponding to 2/3 rpm) and is probably the dominant reason for the spread in figure IV.3. The best logarithmic least squares fit to the data points in figure IV.3 is:

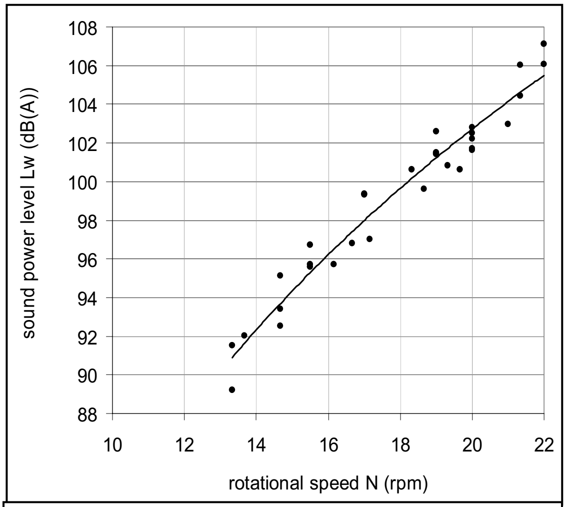

Figure IV.3: measured wind turbine sound power level L_W as a function of turbine rotational speed N

$$L_W \quad 67.1 \cdot \log(N) + 15.4 \ \text{dB(A)} \qquad \text{(IV.3)}$$

with a correlation coefficient of 0.98. The standard deviation of measurement values with respect to this fit is 1.0 dB.

Table IV.1: sound power level of wind turbines [Kerkers 1999]

wind velocity V_{10}	m/s	5	6	7	8	9	10
sound power level L_W	dB(A)	94	96	98	101	102	103

Table IV.2: octave band spectra of wind turbines at L_W = 103 dB(A)

frequency	Hz	63	125	250	500	1000	2000	4000	L_W
this report	dB(A)	82	92	94	98	98	93	88	103
[Kerkers 1999]	dB(A)	85	91	95	98	98	92	83	103

At the specification extremes of 10 rpm and 22 rpm the (individual) wind turbine sound power level L_W is 82.8 dB(A) and 105.7 dB(A), respectively. In table IV.2 earlier measurement results [Kerkers 1999] are given for the octave band sound power spectrum. Also in table IV.2 the results of this study are given: the logarithmic average of four different spectra at different rotational speeds. In all cases spectra are scaled, with formula IV.3, to the same sound power level of 103 dB(A).
To calculate sound immission levels at a specific rotational speed (or vice versa) the sound power level given in formula (IV.3), and the spectral form in table IV.2 (‘this report’) have been used.

IV.7 Results: sound immission

The sound immission level has been measured with the unmanned SWMS on two locations. From May 13 until June 22, 2002 it was placed amidst open fields with barren earth and later low vegetation at 400 meters west of the westernmost row of wind turbines (location A, see figure IV.2). This site was a few meters west of the Dutch-German border, visible as a ditch and a 1.5 to 2 m high dike. From June 22 until September 13, 2002 the SWMS was placed on a lawn near a dwelling at 1500 m west of the westernmost row (location B), with low as well as tall trees in the vicinity. On both locations there were no reflections of turbine sound towards the microphone, except via the ground, and no objects (such as trees) in the line of sight between the turbines and the microphone. Apart from possible wind induced sound in vegetation relevant sound sources are traffic on rather quiet roads, agricultural activities, and birds. As, because of the trees, the correct (potential) wind velocity and direction could not be measured on location B, wind measurement data provided by the KNMI were used from their Nieuw Beerta site 10 km to the north. These data fitted well with the measurements on location A.

At times when the wind turbine sound is dominant, the sound level is relatively constant within 5 minute intervals. In figure IV.4 this is demonstrated for two nights. Thus measurement intervals with dominant turbine sound could be selected with a criterion based on a low variation in sound level: L_5 $L_{95} \leq 4$ dB, where L_5 and L_{95} are the 5 and 95 percentile sound level in the measurement interval. In a normal (Gaussian) distribution this would equal $\sigma \leq 1.2$ dB, with σ the standard deviation.

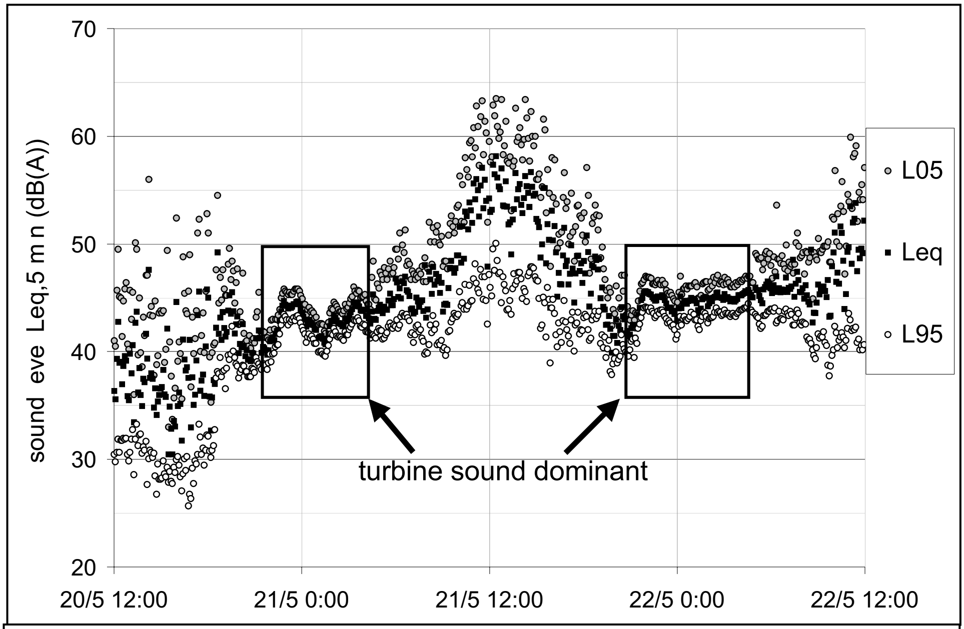

Figure IV.4: 48 hour registration of immission level (L_5, L_{eq} and L_{95}) per 5 minutes at location A; turbines are considered the dominant sound source if L_5-$L_{95} \leq 4$ dB

On location A, 400 m from the nearest turbine, the total measurement time was 371 hours. In 25% of this time the wind turbine sound was dominant, predominantly at night (23:00 6:00 hours: 72% of all 105 nightly hours) and hardly in daytime (6:00 19:00 hours: 4% of 191 hours). See table IV.3.

On location B, 1500 m from the nearest turbine, these percentages are almost halved, but still the turbine sound is dominant for over one third of the time at night (38% of 312 hours). The trend in percentages agree with complaints concerning mostly noise in the (late) evening and at night and their being more strongly expressed by residents closer to the wind farm.

Table IV.3: total measurement time in hours and selected time with dominant wind turbine sound

Location	total time (hours and % of total measurement time at location)	Night 23:00-6:00	Evening 19:00-23:00	Day 6:00-19:00
A: total	371 h	105	75	191
A: selected	92 h 25%	76 72%	9 12%	7 4%
B: total	1064 h	312	183	569
B: selected	136 h 13%	119 38%	13 7%	4 0,7%

In figure IV.5 the selected (L_5-$L_{95} \leq 4$ dB) 5 minute equivalent immission sound levels $L_{eq,5min}$ are plotted as a function of wind direction (left) and of wind velocity (right) at 10 m height, for both location A (above) and B (below). The KNMI wind velocity data (used for location B) were given as integer values of the wind velocity.
Also the wind velocity at 10 m and 2 m height on location A are plotted (in IV.5A and IV.5B, respectively), and the local wind velocity (influenced by trees) at 10 m on location B (IV.5C). The immission level data points are separated in two classes where the atmosphere was stable or neutral, according to observations of wind velocity and cloud cover at Eelde. Eelde is the nearest KNMI site for these observations, but it is 40 km to the west, so not all observations will be valid for our area.

In figure IV.5B a grey line is plotted connecting calculated sound levels with sound power levels according to table IV.1 (the lowest value at 2.5 m/s is extrapolated [Van den Berg *et al* 2002]), implicitly assuming a fixed logarithmic wind profile according to formula (III.2). If this line is compressed in the direction of the abscissa with a factor 2.6, the result is a (black) line coinciding with the maximum one hour values ($L_{eq,1h}$). Apparently for data points on this line the sound emission corresponds to a wind velocity at hub height that is 2.6 times higher than expected. In figure IV.6 this is given for one hour periods: all 5 minute measurement periods

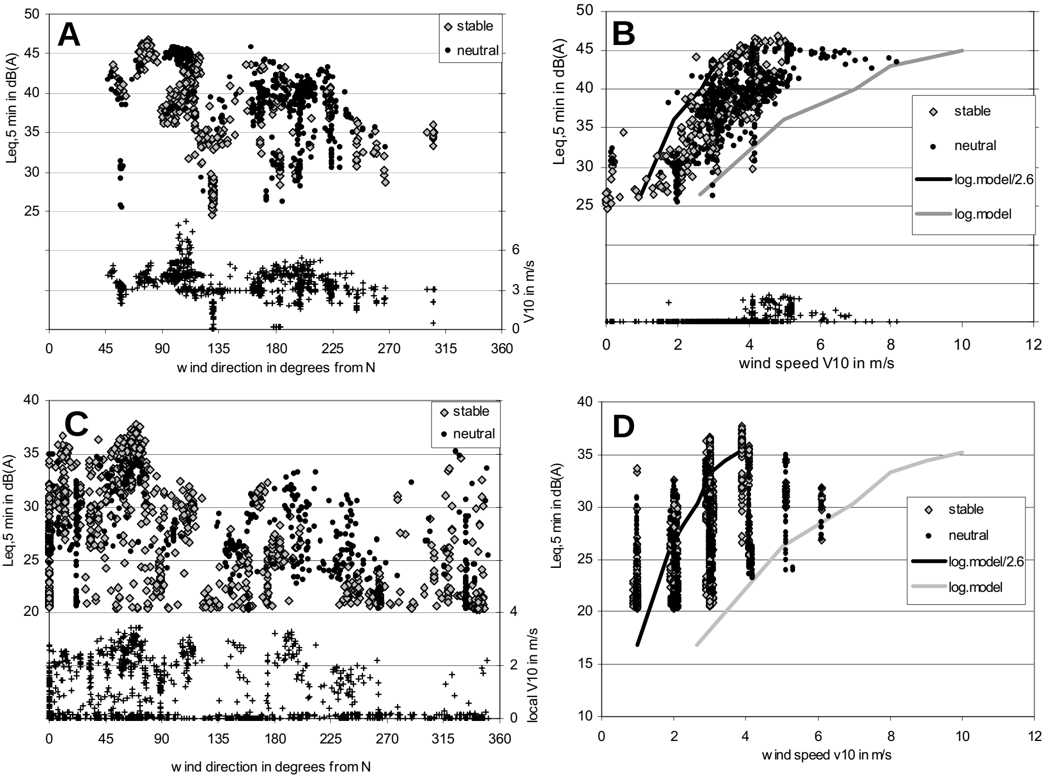

Figure IV. 5: measured sound levels $L_{eq,5\,min}$ at locations A (above) and B (below) as a function of median wind direction (left) and average wind speed (right) at reference height (10 m), separated in classes where the atmosphere at Eelde was observed as stable (open diamonds) or neutral (black dots). Also plotted are expected sound levels according to logarithmic wind profile and wind speed at reference height (grey lines in B and D), and at a 2.6 times higher wind speed (black lines in B and D). Figures A, B and C also contain the wind speed v_{10}(A), v_2 (B), and the local v_{10} (C) disturbed by trees, respectively.

that satisfied the L_5-L_{95}-criterion, with at least 4 periods per hour, were taken together in consecutive hourly periods and the resulting $L_{eq,T}$ (T 20 to 60 minutes) was calculated. The resulting 83 $L_{eq,T}$-values are plotted against the average wind velocity V_{10}. Also plotted in figure IV.6 are the expected immission levels assuming a logarithmic wind profile calculated from (III.4), with f_{log} $(V_{98}/V_{10})_{log}$ 1.4 (for f_{xx}: see text above equation III.4); the immission levels assuming a stable wind profile with *m* 0.41, so f_{stable} 2.5 $1.8 \cdot f_{log}$; the maximum immission levels assuming f_{max} 3.7

$2.6 \cdot f_{log}$, in agreement with a wind profile (III.2) with m 0.57. The best fit of all data points ($L_{eq,T}$) in figure IV.6 is L_{eq} $32 \cdot \log(V_{10}) + 22$ dB (correlation coefficient 0.80) with $1 < V_{10} < 5.5$ m/s. This agrees within 0.5 dB with the expected level according to the stable wind profile. The best fit of all 5 minute data-points in figure IV.5B yields the same result.

Thus on location A the highest one hour averaged hub height wind velocities at night are 2.6 times the expected values according to the logarithmic wind profile in formula (III.4). As a consequence, sound levels at (in night-time) frequently occurring wind velocities of 3 and 4 m/s are 15 dB higher than expected, 15 dB being the vertical distance between the expected and highest one-hour immission levels at 3- 4 m/s (upper and lower lines in figures 5B and 6).

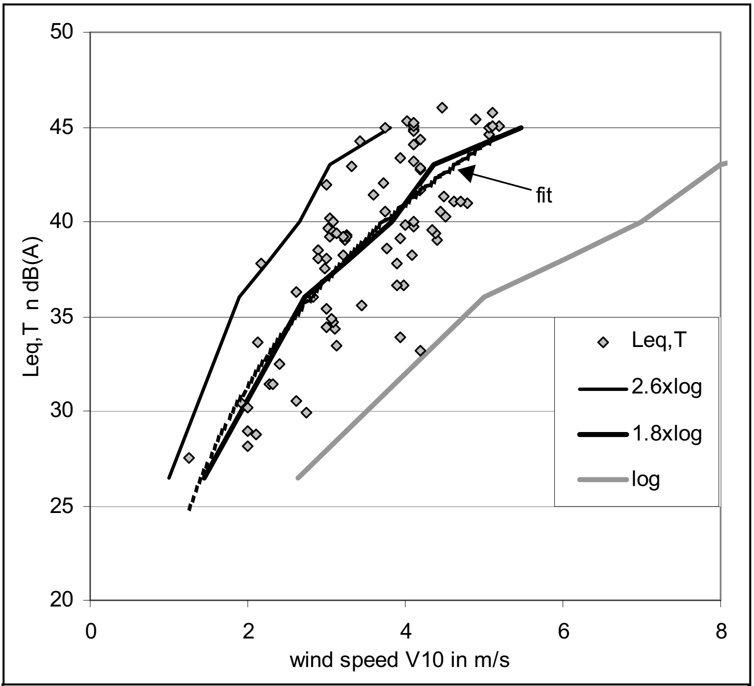

Figure IV.6: selected measured sound levels $L_{eq,T}$ (T = 20 – 60 min) at location A with best fit; and expected sound levels according to a logarithmic wind profile ($v_{98}/v_{10} = f_{log} = 1.4$), a stable wind profile ($v_{98}/v_{10} = 1.8 \cdot f_{log}$) and with the maximum wind speed ratio ($v_{98}/v_{10} = 2.6 \cdot f_{log}$)

The same lines as in figure IV.5B, but valid for location B, are plotted in figure IV.5D; immission levels here exceed the calculated levels, even if calculated on the basis of a 2.6 higher wind velocity at hub height. An explanation may be that a lower ambient sound level is necessary compared to location A to allow wind turbine sound to be dominant at location B (as selected with the L_5 L_{95} -criterion), implying a lower near ground wind velocity and thus a higher stability. It may also be caused by an underestimate of actual sound level in the calculation model for long distances, at least for night conditions (this issue will be addressed in section IV.10).

As is clear from the wind velocity at 2 m height plotted in figure IV.5B, there is only a very light wind near the ground even when the turbines rotate at high power. This implies that in a quiet area with low vegetation the ambient sound level may be very low. The contrast between the turbine sound and the ambient sound is therefore at night higher than in daytime.

Although at most times the wind turbine sound dominates the sound levels in figure IV.5, it is possible that at low sound levels, *i.e.* at low rotational speeds and low wind velocities, the L_5-L_{95}-criterion is met while the sound level is not entirely determined by the wind turbines. This is certainly the case at levels close to 20 dB(A), the sound level meter noise floor. The long term night-time ambient background level, expressed as the 95-percentile (L_{95}) of all measured night-time sound levels on location B, was 23 dB(A) at 3 m/s (V_{10}) and increasing with 3.3 dB/m·s ^{1} up to V_{10} 8 m/s [Van den Berg *et al* 2002]. Comparing this predominantly non-turbine background level with the sound levels in figure IV.5B and 5D, it is clear that the lowest sound levels may not be determined by the wind turbines, but by other ambient sounds (and instrument noise). This wind velocity dependent, non-turbine background sound level L_{95} is, however, insignificant with respect to the highest measured levels. Thus, the high sound levels do not include a significant amount of ambient sound not coming from the wind turbines. This has also been verified in a number of evenings and nights by personal observation.

IV.8 Comparison of emission and immission sound levels

From the 30 measurements of the equivalent sound level $L_{eq,T}$ (with T typically 5 minutes) measured at distance R from the turbine hub (R typically 100√2 m), a relation between sound power level L_W and rotational speed N of a turbine could be determined: see formula (IV.3).
This relation can be compared with the measured immission sound level $L_{imm,T}$ (T   5 minutes) at location A, 400 m from the wind farm (closest turbine), in 22 cases where the rotational speed was known. The best logarithmic fit for the data points of the immission sound level L_{imm} as a function of rotational speed N is:

$$L_{imm} \quad 57.6\cdot\log(N) \quad 30.6 \text{ dB(A)} \qquad \text{(IV.4)}$$

with a correlation coefficient of 0.92 and a standard deviation of 1.5 dB with respect to the fit. Both relations from formulae (IV.3) and (IV.4) and the datapoints are given in figure IV.7. The difference between both relations is L_W - L_{imm} 9.5·log(N) + 46.0 dB. For the range 14   20 rpm, where both series have data points, the average difference is 57.9 dB, the maximum deviation from this average is 0.8 dB (14 rpm: 57.1 dB(A); 20 rpm: 58.6 dB(A); see lower part of figure IV.7). It can be shown by calculation that about half of this deviation can be explained by the variation of sound power spectrum with increasing speed N.

The sound immission level can be calculated with formula (IV.1). For location A, assuming all turbines have the same sound power L_W, this leads to L_W L_{imm} 58.0 dB. This is independent of sound power level or rotational speed, as it is calculated with a constant spectrum averaged over several turbine conditions, *i.e* turbine speeds. The measured difference (57.9 dB) matches very closely the calculated difference (58.0 dB).

The variation in sound immission level at a specific wind velocity V_{10} in figures IV.5B and IV.5D is thus seen to correspond to a variation in rotational speed N, which in turn is related to a variation in wind velocity at hub height, not to a variation in V_{10}. At location A, N can be calculated from the measured immission level with the help of formula (IV.4) or its inverse form: N $\quad 3.4 \cdot 10^{\mathrm{Limm}/57.6}$.

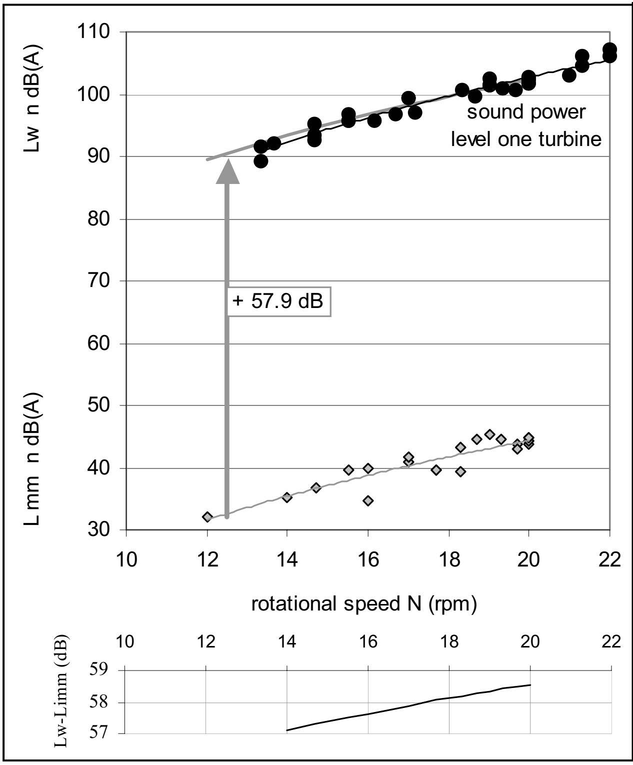

Figure IV.7: turbine sound power levels L_W measured near wind turbines and immission levels L_{imm} measured at 400 m from wind farm: averages differ 57.9 dB; (below) increase of difference $L_W - L_{imm}$ with rotational speed

(L_W data points taken from figure IV.3)

IV.9 Atmospheric stability and Pasquill class

In figure IV.5 measurement data have been separated in two sets according to atmospheric stability in Pasquill classes, supplied by KNMI from their measurement site Eelde, 40 km to the west of our measurement site. Although the degree of stability will not always be the same for Eelde and our measurement location, the locations will correlate to a high degree in view of the relatively small distance between them. For night-time conditions ‘stable’ refers to Pasquill classes E and F (lightly to very stable) and corresponds to $V_{10} \leq 5$ m/s and cloud coverage $C \leq 50\%$ or $V_{10} \leq 3.5$ m/s and $C \leq 75\%$, ‘neutral’ (class D) corresponding to all other situations. Although from figure IV.5 it is clear that the very highest sound levels at an easterly wind (≈ 80°) do indeed occur in stable conditions, it is also clear that in neutral conditions too the sound level is higher than expected for most of the time, the expected values corresponding to the grey lines in figures IV.5B and D, derived from daytime conditions. According to this study the sound production, and thus wind velocity at 100 m height is at night often higher than expected, in a stable, but also in a neutral atmosphere. On the other hand, even in stable conditions sound levels may be lower than expected (i.e. below the grey lines), although this occurs rarely. It may be concluded from these measurements that a logarithmic wind profile based only on surface roughness does not apply to the night-time atmosphere in our measurements, not in a stable atmosphere and not always in a neutral atmosphere when determined from Pasquill classes.

IV.10 Additional measurements

In several nights in the period that the SMWS was measuring at location A, manual measurements were performed at a number of locations in the area between 0.6 and 2.3 km west of the wind farm. The locations are plotted in figure IV.2. Most locations were close to dwellings, but two (locations U and X) were in open fields. Locations P and Q are close and at the same distance from the western row of turbines and can be considered equal with respect to the turbines (Q was chosen instead of P as P was at the verge of a garden with a loud bird chorus in the early morning). The surface of most of the area is covered with grass and low crops, with trees at some places.

For these measurements one or more logging sound level meters (accuracy type 1 or 2) were used simultaneously, storing a broad band A-weighted sound pressure level every second. Before and after measurement the meters were calibrated with a 94.0 dB, 1000 Hz calibration source, and as a result measurement accuracy due to the instruments is within 0.2 dB. On every location the microphone was in a 10 cm spherical foam wind screen approximately 1.2 m above the surface. There were no reflections of the wind turbine sound to the microphone, except via the ground.

IV.10.1 Measured and calculated immission sound levels

Figure IV.8 gives a simultaneous registration from just before midnight on May 17, 2002, till noon on May 18, of the equivalent sound pressure levels per 5 minutes at locations A (from the SWMS), P/Q and U (from the manual meters) at distances to the westernmost row of turbines of 400, 750 and 1050 m, respectively. In the night hours the sound of the turbines was dominant at each of these locations, apart from an occasional bird or car. Also plotted in figure IV.8 are the wind velocity at 2 and 10 m heights at location A.

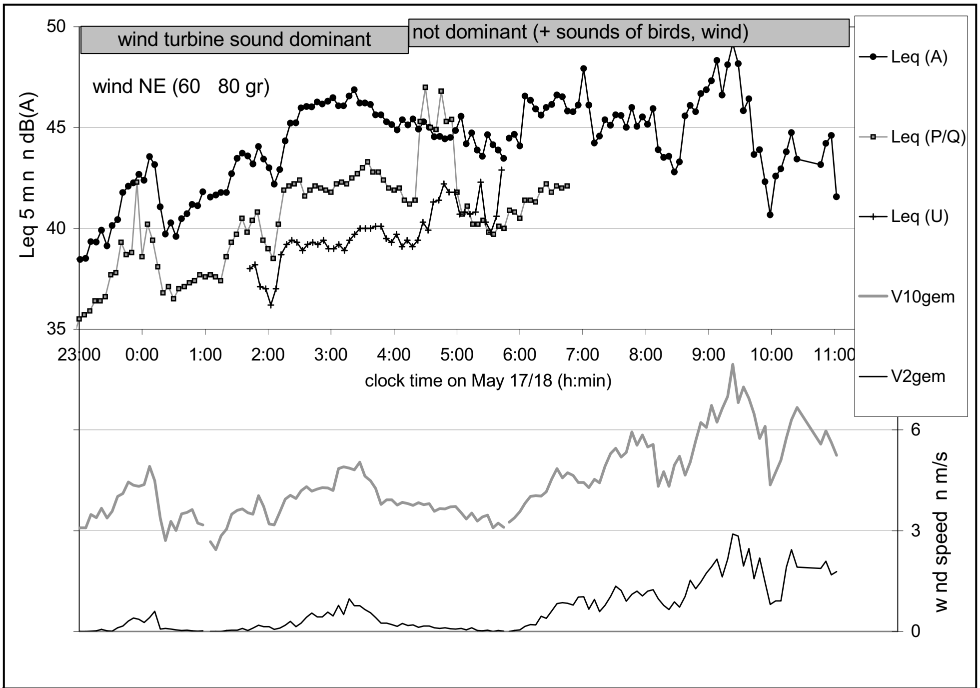

Figure IV.8: measured sound immission level ($L_{eq,5mn}$) at locations A, P/Q, and U, and wind velocities at A with an eastnortheasterly wind

A short decrease in wind velocity at around 2:00 is apparently accompanied by a similar decrease in wind velocity at hub height, as the sound level varies much in the same way. However, the registrations show that the sound level increases from 0:30 until 6:00 while the 10-m wind velocity does not show a net increase in this period. In fact the sound level at location A at 3:00 implies a rotational speed of 21 rpm, which is just below maximum (22 rpm), even though the wind velocity at 10 m height is only 4.5 m/s and at 2 m height is less than 1 m/s. Only occasionally there are other sounds until the dawn chorus of birds just after 4:00 and after that the near-ground wind picks up.

In figure IV.9 the 5-minute equivalent sound levels at P/Q and U relative to the sound level at A are plotted. The advantage of taking the sound level at A as a reference value is that it is not necessary to know the exact sound power level of the turbines themselves. The level differences are 3.5 and 6.5 dB, respectively, with a variation of ± 1 dB. The variations must be due to differences in sound propagation mostly, because other disturbances (such as one at 23:55 at P) are rare.

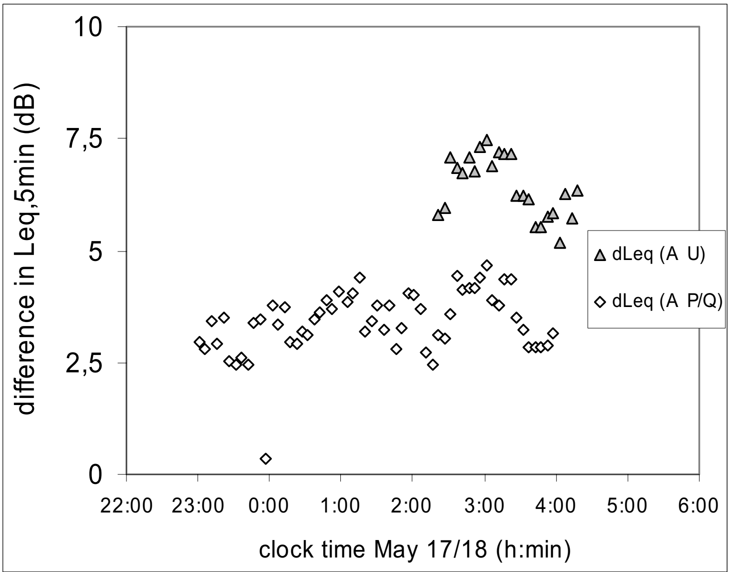

Figure IV.9: difference between simultaneously measured broad band A-weighted immission levels at locations U and P/Q and at location A

Comparable simultaneous measurements have been made in the night of June 2 - 3 and of June 17 18, 2002. In Appendix C the registrations are given, as well as the level differences between the distant locations P through T, V and X and the reference location A. The measured and calculated decrease in sound level with distance, relative to location A, as well as the discrepancy between both, are given in table IV.4 and figure IV.10. In all cases the wind was easterly (60° 100°), that is: from the

wind farm to the measurement location. Also there was little near-ground wind and low background sound levels from other sources.
The calculated differences have been determined with equation IV.1 and the Dutch national model [VROM 1999]. The measured differences in table IV.4 are the difference in the equivalent sound level at a location minus the same at location A over the given measurement time T; only very few of the $L_{eq,5min}$ values were omitted from this Leq,T because they were apparently disturbed by another sound. To minimize influence of possible disturbing sounds the median of all $L_{eq,5min}$ values can be used, as this value gives the prevailing difference and is thus less sensitive to the influence of disturbances; this, however, yields the same results within 0.5 dB.
The discrepancies between measured and calculated levels are small, especially considering the large distances involved: -0.2 to 1.5 dB. One may conclude that the calculation model is quite satisfactory in this relatively simple situation (a high sound source above flat ground).

Table IV.4: measured and calculated differences in sound level $L_{eq,T}$ at locations R - T and at location A, when wind blows from the wind farm

location	R	P/Q	U	V	S	X	T
distance to western row wind farm (m)	600	750	1000	1100	1250	1900	2250
date of measurement (in 2002)	June 2/3	May 17/18, June 2/3 +18	May 17/18	June 18	June 2/3	June 18	June 2/3
measurement time T (min.)	200	295+200+115	120	140	190	85	195
measured difference	-3.5	-3.8 *	-6.4	-9.1	-8.5	-12.1	-1.3
calculated difference	-4.5	-4.1	-6.6	-10.6	-8.3	-13.1	-14.2
discrepancy calculation - meaurement	-1.0	-0.3	-0.2	-1.5	0.2	-1.0	-12.9

*: measurement time weighted logarithmic average of resp. 3.5, 3.6 and 4.6 dB

In figure IV.10 a line is plotted corresponding to -20·log(R/R_a) , where R_a is the distance from A to the western turbine row. This decrease corresponds to spherical divergence from a point source only, with no attenuation due to absorption. It is clear that, with the exception of location T (see next section), the measured decrease is close to this spherical divergence: the measured values at the locations P/Q, U, S and X are 1.4 to 1.7 dB above the plotted line, at the more northern locations R and V they are 0 to 0.3 dB below the line. Approximately the same is true for the calculated levels: the calculated values at the locations P/Q, U, S and X are 0.4 to 1.6 dB above the plotted line, at the more northern locations R and V they are 1.0 to 1.8 dB below the line.

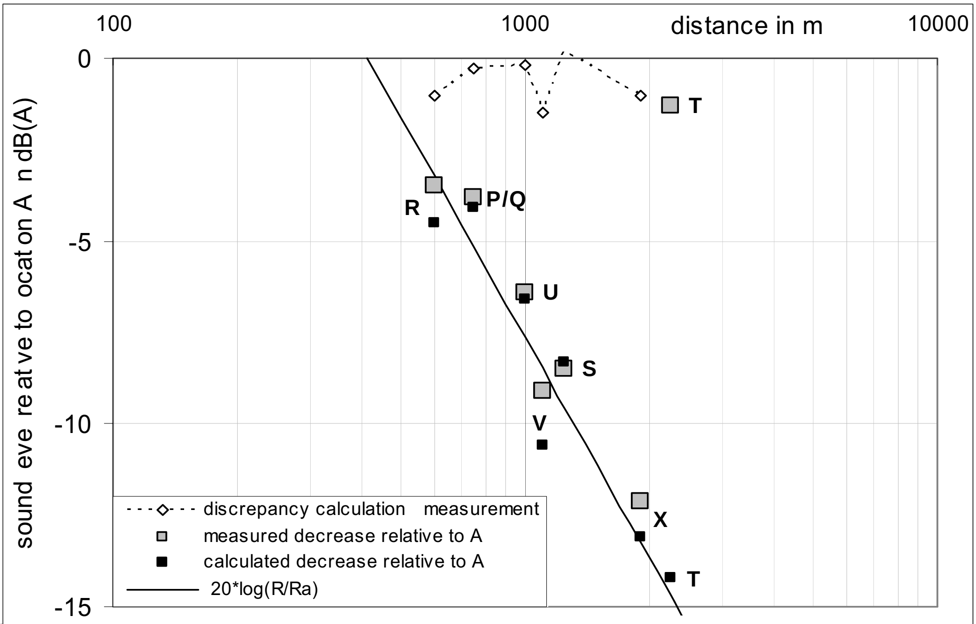

Figure IV.10: measured and calculated decrease in immission sound level due toi the wind farm at locations P through X relative to location A, and the discrepancy between both; the straight line corresponds to -20·log(R/R_a)

There are two counteracting causes explaining this apparently 'almost spherical' attenuation. The first is that the wind farm cannot be considered a point source. Due to its large dimension (3 km from south to north, see figure IV.2) normal to the shortest distance from location A and locations further west, the geometrical divergence should be between cylindrical and spherical divergence, that is: proportional to $-X \cdot \log(R/R_A)$, with $10 < X < 20$. Secondly one expects a decrease due to absorption ('excess attenuation') above the decrease due to geometrical divergence: for the Rhede turbines calculation shows that this excess attenuation is expected to be 1.7 dB per km.

IV.10.2 Immission level increase due to inversion layer?

In the night of June 2 to 3, 2002, high sound levels were measured at the most distant measurement location T, 2250 m from the wind farm. The immission sound level varied between approximately 40 and 45 dB(A) and was more variable than at the other locations (see Appendix C). The resident close to this measurement location could hear the wind farm well, at 22:30 hours describing it as: “The sound changes from ‘an endless train’ to a more pulsating sound; the sound grows louder en sharper. At the background is a kind of humming, comparable to the sound of a welding transformer”. The sound was audible indoors.

In our research we have not met this phenomenon again. However, mr. Flight living near another wind farm south of the Rhede wind farm observed the same phenomenon: on a location appr. 750 m from the closest turbine, where at night he usually measured an immission level of 42 to 44 dB(A), he measured a level of 50 to 52 dB(A) in the night of September 24, 2002. It was clear that the sound came from the nearest wind farm, but also from a second, more distant wind farm that usually was not audible here. Again, the atmosphere was stable and there was a weak near-ground easterly wind, blowing from the wind farm to the observer.

This may be a result of strong refraction of sound below an inversion layer. This inversion layer must be at or above the rotor to have the highest effect, so at or above 130 m (hub height + blade length).
Suppose the turbines in the Rhede wind farm each have a sound power level L_W at a certain wind velocity. If we substitute the entire farm by one single turbine at the site of the turbine closest to location T (nr. 12), it can be calculated that the sound level of that single turbine must be $L_W + 9.4$ to produce the same immission level at T as the entire wind farm.

Considering only spherical spreading, this immission level is L_{imm} L_W + 9.4 $10 \cdot \log(4\pi \cdot 2250^2)$ L_W 68.6. Now the sound waves will be refracted downwards at the inversion layer and we assume that all sound propagates below the inversion layer. At large distances (>> height inversion layer) this is equivalent to sound spreading cylindrically from a vertical line source. To simulate this we replace the substitute single turbine, which was modelled as a point source at hub height, by a vertical line source from the ground up to the inversion layer height (130 m). If the sound power levels of both point and line source are equal, the line source must have a sound power level of L_W' L_W + 9.4 -10·log(130) L_W 11.7 dB/m. If again the sound level decreases by geometrical (now: cylindrical) spreading only, the sound immisson level at 2250 m from this line source is L_{imm}' L_W 11.7 - $10 \cdot \log(2\pi \cdot 2250)$ L_W 54.6 dB. Comparison of the immission level due to a point source (L_W 68.6) and a line source (L_W 54.6) shows that the line source causes a 14 dB higher immission level. This simple calculation shows that the rise in level caused by a simplified high inversion layer is close to the observed increase (13 dB): the higher level is a result of the sound being 'trapped' below the inversion layer. However, more observations and data are needed to verify this hypothesis.

IV.11 Conclusion

Sound immission measurements have been made at 400 m (location A) and 1500 m (location B) from the wind farm Rhede with 17 tall (98 m hub height), variable speed wind turbines. It is customary in wind turbine noise assessment to calculate immission sound levels assuming wind velocities based on wind velocities V_{10} at reference height (10 m) and a logarithmic wind profile. Our study shows that the immission sound level may, at the same wind velocity V_{10} at 10 m height, be significantly higher in night-time than in daytime. A 'stable' wind profile predicts a wind velocity V_h at hub height 1.8 times higher than expected and agrees excellently with the average measured night-time sound immission levels. Wind velocity at hub height may still be higher: at low wind velocities V_{10} up to 4 m/s, the wind velocity v_h is at night up to 2.6 times higher than expected.

Thus, the logarithmic wind profile, depending only on surface roughness and not on atmospheric stability, is not a good predictor for wind profiles at night. Especially for tall wind turbines, estimates of the wind regime at hub height based on the wind velocity distribution at 10 m, will lead to an underestimate of the immission sound level at night: at low wind velocities (V_{10} < 5 m/s) the actual sound level will be higher than expected for a significant proportion of time. This is not only the case for a stable atmosphere, but also -to a lesser degree- for a neutral atmosphere.

The change in wind profile at night also results in lower ambient background levels then expected: at night the wind velocity near the ground may be lower than expected from the velocity at 10 m and a logarithmic wind profile, resulting in low levels of wind induced sound from vegetation. The contrast between wind turbine and ambient sound levels is therefore at night more pronounced.

Measured immission sound levels at 400 m from the nearest wind turbine almost perfectly match (average difference: 0,1 dB) sound levels calculated from measured emission levels near the turbines. From this it may be concluded that both the emission and immission sound levels could be determined accurately, even though the emission measurements were not fully in agreement with the standard method. As both levels can be related through a propagation model, it may not be necessary to measure both: the immission measurements can be used to assess immission as well as emission sound levels.
At greater distances the calculated level may underestimate the measured level, but considering the distances involved (up to 2 km) the discrepancy is small: 1.5 dB or less.

In one night the sound level at a distant location (over 2 km from the wind farm) was much higher than expected, perhaps because of an inversion layer adding more downward refracted sound. It apparently is a rare occurrence at the Rhede wind farm, and could be more significant where high inversion layers occur more often.

V THE BEAT IS GETTING STRONGER: low frequency modulated wind turbine sound

V.1 Effects of atmospheric stability

Atmospheric stability is not only relevant for wind turbine sound *levels*, as we saw in the preceding chapter, but also for the *character* of the sound. In conditions where the atmosphere is stable, distant wind turbines can produce a beating or thumping sound that is not apparent in daytime.

The magnitude of the effects of increasing stability depends on wind turbine properties such as speed, diameter and height. We will use the dimensions of the wind turbines in the Rhede wind farm, that are typical for a modern variable speed 2 MW wind turbine: hub height 100 m, blade length 35 m and blade tip speed increasing with wind velocity up to a maximum value of $\Omega \cdot R$ 81 m/s (at 22 rpm). Here a speed of 20 rpm (70 m/s) will be used as this was typical for situations where at the Rhede wind farm a clear beating sound was heard.

We will assume the optimum angle of attack α is 4º. The change in trailing edge (TE) sound pressure level SPL_{TE} with the angle of attack from this optimum up to 10º can be approximated by $\Delta SPL_{TE}(\alpha)$ $1.5 \cdot \alpha - 1.2$ dB or $d(\Delta SPL_{TE})/d\alpha$ 1.5 (see appendix B, equation B.8). When the pitch angle is constant, the change in angle of attack due to a variation dV in wind velocity is $d\alpha$ $0.84 \cdot dV$ (see appendix B, equation B.9).

To calculate vertical wind velocity gradients the simple engineering formula (III.1) will be used: V_h $V_{ref} \cdot (h/h_{ref})^m$ (see section III.2). In the text below we will use a value m 0.15 for a daytime atmosphere (unstable   neutral), m 0.4 for a stable, and m 0.65 for a very stable atmosphere (see table III.1).[1] These values will be used for altitudes between 10 and 120 m.

[1] A value $m = 0.65$ is not obvious from table III.1, but is chosen as a relatively high value that is exceeded for a small part of the time (see figures VI.6 and VI.16, and section VI.6)

There are now three factors influencing blade swish level when the atmosphere becomes more stable: a) the higher wind velocity gradient, b) the higher wind direction gradient, and c) the relative absence of large scale turbulence.

a. Wind velocity gradient. Rotational speed is determined by a rotor averaged wind velocity, which here is assumed to be the induced wind velocity at hub height (equation III.5). The free, unobstructed wind at height h is denoted by V_h, the induced wind speed at the blade by $V_{h,b}$. With increasing atmospheric stability the difference in wind velocity between the upper and lower part of the rotor increases. As in a complete rotation the pitch angle is constant the change in angle of attack due to a change in induced wind velocity is $d\alpha \quad 0.82 \cdot dV_{h,b}$ which can be expressed in a change of the free wind velocity by $d\alpha \quad 0.82 \cdot (2/3) \cdot dV_h \quad 0.55 \cdot dV_h$ (see equation III.5).

Suppose that the free wind velocity at hub height is $V_{100} \quad 14$ m/s, corresponding to $V_{10} \quad 9.8$ m/s in a neutral atmosphere in flat open grass land (roughness length 5 cm). Then in daytime ($m \quad 0.15$) the free wind velocity at the height of the lowest point of the rotor would be $V_{65} \quad 13.1$ m/s, at the height of the highest point $V_{135} \quad 14.6$ m/s (corresponding to velocities at the blade of $V_{65,b} \quad 8.7$ m/s and $V_{135,b} \quad 9.7$ m/s, respectively). The difference of 1.0 m/s between the low tip and hub height wind velocities causes a change in angle of attack on the blade of $\Delta\alpha \quad 0.55°$. Between the high tip and hub height the change is smaller and of opposite sign: -0.3°. In a stable atmosphere ($m \quad 0.4$), at the same wind velocity at hub height, V_{65} is 11.8 m/s causing a change in angle of attack at the lower tip relative to hub height of 1.2° (at the high tip: $V_{135} \quad 15.8$ m/s, $\Delta\alpha \quad -1.0°$). When the atmosphere is very stable ($m \quad 0.65$), wind velocity $V_{65} \quad 10.5$ m/s and the angle of attack on the low altitude tip deviates 1.9° from the angle at hub height (at the high tip: $V_{135} \quad 17.0$ m/s, $\Delta\alpha \quad -1.7°$).
In fact when the lower tip passes the tower there is a greater mismatch between optimum and actual angle of attack α because there was already a change in angle of attack related to the wind velocity deficit in front of the tower. For a daytime atmosphere and with respect to the situation at hub

height, the change in α associated to a blade swish level of 2 ± 1 dB is estimated as 1.8 ± 1.1° (see appendix B.3), part of which (0.55 °) is due to the wind profile and the rest to the tower. The increase in α due to the stability related wind profile change must be added to this daytime change in α. Thus, the change in angle of attack when the lower tip passes the mast is 1.8 ± 1.1° in daytime (unstable to neutral atmosphere), increasing to 2.5 ± 1.1° in a stable atmosphere and to 3.2 ± 1.1° in a very stable atmosphere. The associated change in TE sound level is 3.8 ± 1.7 dB for a stable and 4.8 ± 1.7 dB for a very stable atmosphere (compared to 2 ± 1 dB in daytime), which is the increase when the blade passes the tower. The corresponding total A-weighted sound level will be somewhat less as trailing edge sound is not the only sound source (but it is the dominant source; see section V.2.3).
At the high tip the change in angle of attack is smaller and of opposite sign with respect to the low tip, and also there is no (sudden) tower induced change to add to the wind gradient dependent change. The change in angle of attack at the high tip in a very stable atmosphere (-1.7°) is comparable to the change at the low tip in daytime, and this change is more gradual than for the low tip. This in fact lowers the sound emission from the high tip (with approximately 2 dB), most so when the high blade is vertical so just before and just after the low blade passes the tower, thereby in fact increasing the variation in swish sound level even more.

Thus we find that, for v_{100} 14 m/s, the 1-2 dB daytime blade swish level increases to approximately 5 dB in a very stable atmosphere. The effect is stronger when wind velocity increases, up to the point where friction turbulence overrides stability and the atmosphere becomes neutral. The increase in trailing edge sound level will be accompanied by a lower peak frequency (see appendix B, equation B.2). For Δα 5° the shift is one octave.

b. Wind direction gradient. In a stable atmosphere air masses at different altitudes are only coupled by small scale turbulence and are therefore relatively independent. Apart from a higher velocity gradient a higher wind direction gradient is also possible, and with increasing height the wind direction may change significantly. This wind direction shear will change the angle of attack with height. Assuming the wind at hub height to be normal to the rotor, the angle of attack will decrease below and increase above hub height (or vice versa). This effect, however, is small: if we suppose a change in wind direction of 20° over the rotor height at an induced wind velocity of 10 m/s, the change in angle of attack between extreme tip positions at 20 rpm is only 0.25°, which is negligible relative to the wind velocity shear.

c. Less turbulence. In a stable atmosphere turbines in a wind farm can run almost synchronously because the absence of large scale turbulence leads to less variation superimposed on the constant (average) wind velocity at each turbine. In unstable conditions the average wind velocity at the turbines will be equal, but instantaneous local wind velocities will differ because of the presence of large, turbulent eddies at the scale of the inter-turbine distance. In a stable atmosphere the turbulence scale decreases with a factor up to 10, relative to the neutral atmosphere and even more relative to an unstable atmosphere [Garratt 1992]. In stable conditions turbines in a wind farm therefore experience a more similar wind and as a consequence their instantaneous speeds are more nearly equal. This is confirmed by long term measurements by Nanahara *et al*. [2004] who analysed coherence of wind velocities between different locations in two coastal areas. At night wind velocities at different locations were found to change more coherently than they did at daytime [Nanahara 2004]. The difference between night and day was not very strong, probably because time of day on its own is not a sufficient indicator for stability.[1] The decay of coherence was strongly correlated with turbulence intensity, which in turn is closely correlated to stability.

Thus several turbines can be *nearly* synchronous: sometimes two or more turbines are in phase and the blade passing pulses coincide, then they go out of phase again. Synchronicity here refers to the sound pulses from the

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[1] In a coastal location atmospheric stability also depends on wind direction as landwards stability is a diurnal, but seawards a seasonal phenomenon. Also, a fixed duration for all nights in a year does not coincide with the time that the surface cools (between sundown and sunrise), which is a prerequisite for stability.

different turbines as observed at the location of the observer: pulses synchronise when they arrive simultaneously. This is determined by differences in phase (rotor position) between turbines and in propagation distances of the sound from the turbines. Phase differences between turbine rotors occur because turbines are not connected and because of differences in actual performance. The place where synchronicity is observed will change when the phase difference between turbines changes. With exact synchronicity there would be a fixed interference pattern, with synchronicity at fixed spots. However, because of *near*-synchronicity, synchronous arrival of pulses will change over time and place and an observer will hear coinciding pulses for part of the time only.
Near a wind farm the variation in sound level will depend on the distances of the wind turbines relative to the observer: the level increase due to several turbines will reach higher levels when more turbines are at approximately equal distances and thus contribute equal immission levels. The increase in level variation, or beating, is thus at well-audible frequencies and has a repetition rate equal to the blade passing frequency.

A second effect of the decrease in turbulence strength is that in-flow turbulent sound level also decreases. The resulting decrease in sound level at frequencies below that of TE noise lowers the minimum in the temporal variations, thereby increasing modulation depth. The higher infrasound level due to extra blade loading is not perceptible because of the high hearing threshold at the very low blade passing frequency and its harmonics.
Thus, theoretically it can be concluded that in stable conditions (low ambient sound level, high turbine sound power and higher modulation or swish level) wind turbine sound can be heard at greater distances where it is of lower frequency due to absorption and the frequency shift of swish sound. It will thus be a louder and more low frequency ‘thumping’ sound and less the swishing sound that is observed close to a daytime wind turbine.

V.2 Measurement results

V.2.1 Locations

In the summer of 2002 and of 2004 wind turbine sound has been recorded in and near the Rhede wind farm (see section IV.1 for a specification of the turbines and a map of the area). In this chapter measurement results will be used from two locations: R and P (see figure IV.2). Location R is close to a dwelling west of the turbines, 625 m from the nearest turbine. The microphone position was at 4 m height and close to the house, but with no reflections except from the ground. Location P, 870 m south of R, was 1.5 m above a paved terrace in front of the façade of a dwelling at 750 m distance from the nearest turbine (in fact this is a short distance from the location P in chapter IV, which was not in front of the façade). The entire area is quiet, flat, agricultural land with some trees close to the dwellings. There is little traffic and there are no significant permanent human sound sources.

A third dwelling Z is in Boazum in the northern part of the Netherlands, 280 m west of a single, two-speed turbine (45 m hub height, 23 m blade length, 20/26 rpm). The area is again quiet, flat and agricultural, with some trees close to the dwelling. The immission measurement point is at 1.5 m height above gravel near dwelling Z. This measurement site is included here to show that the influence of stability on blade swish levels occurs also with smaller and single turbines. At all locations near dwellings the microphone was fitted in a 9 cm diameter foam wind screen.

Table V.1 gives an overview of measurement (start) time and date, of observed turbine speed and of wind velocity and direction, for situations of which results will be given below. The wind velocity at hub height V_{hub} has been determined from turbine rotation speed N or sound power level L_W (figure III.3, the relation V_{hub} N follows from [Kerkers 1999] and [Van den Berg 2002]). The wind velocity V_{10} was continuously measured at or near location A, except for location Z, where data from several meteorological stations were used showing that the wind was similar and nearly constant throughout the night of the measurement in the entire nothern part of the Netherlands. In all cases there were no significant variations in wind velocity at the time of measurement. Wind velocity at

the microphone was lower than V_{10} because of the low microphone height and shelter provided by trees nearby. Wind direction is given in degrees relative to north and clockwise (90° is east).
The spectra near a turbine were measured with the microphone just above a hard surface at ground level 100 m downwind of a turbine in compliance with IEC 61400 [IEC 1998] as much as possible (non-compliance did not lead to differences in result; for reasons of non-compliance, see section II.4). The levels presented here are broad band immission levels: measured L_{eq} minus 6 dB correction for coherent reflection against the hard surface [IEC 1998]. The presented levels near the dwellings are also broad band immission levels: measured L_{eq} minus 3 dB correction for incoherent reflection at the façade for dwelling P, or measured L_{eq} without any correction for dwellings R and Z.

Table V.1: overview of measurement locations and times and of turbine speed and wind

Location	measurement date	time	turbine speed (rpm)	wind velocity (m/s) V_{10}	V_{hub}	wind direction (° north)
Dwelling P	June 3, 2002	00:45	20	5	14	100
Turbine 7	June 3, 2002	06:30	19	5	15	100
Turbine 1	June 3, 2002	06:45	19	5	15	100
Dwelling R Turbine 16	Sep.9, 2004	23:07	18	4	14	80
Dwelling Z	Oct.18, 2003	01:43	26	3	6	60

At dwelling P at the time of measurement the beat in the turbine sound was very pronounced. In the other measurements (dwellings R and Z) the beating was not as loud. The measurements near turbine 16 and dwelling R at 23:07 on September 9 were performed simultaneously.

V.2.2 Frequency response of instruments

For the Rhede measurements in this chapter sound was recorded on a TASCAM DA-1 DAT-recorder with a precision 1" Sennheiser MKH 20

P48 microphone. The sound was then sampled in 1-second intervals on a Larson Davis 2800 frequency analyser. From 1 to 10 000 Hz the frequency response of the DAT-recorder and LD2800 analyser have been determined with a pure tone electrical signal as input. The LD2800 response is flat (±1 dB) for all frequencies. The DAT-recorder is a first order high pass filter with a corner frequency of 2 Hz. The frequency response of the microphone was of most influence and has been determined relative to a B&K ½" microphone type 4189 with a known frequency response [B&K 1995]. Equivalent spectral sound levels with both microphones in the same sound field (10 cm mutual distance) were compared. For frequencies of 2 Hz and above the entire measurement chain is within 3 dB equivalent to a series of two high pass filters with corner frequencies of f_1 4 Hz and f_2 9 Hz, or a transfer function equal to $-10 \cdot \log[1+(f_1/f)^2]$ $-10 \cdot \log[1+(f_2/f)^2]$. For frequencies below 2 Hz this leads to high signal reductions (< -40 dB) and consequentially low signal to (system) noise ratios. Therefore values at frequencies < 2 Hz are not presented.

For the Boazum measurements sound was recorded on a Sharp MD-MT99 minidisc recorder with a 1" Sennheiser ME62 microphone. The frequency response of this measurement chain is not known, but is assumed to be flat in the usual audio frequency range. Simultaneous measurement of the broad band A-weighted sound level were done with a precision (type 1) 01dB sound level meter. Absolute precision is not required here as the minidisc recorded spectra are only used to demonstrate relative spectral levels. Because of the ATRAC time coding of a signal, a minidisc recording does not accurately follow a level change in a time interval < 11.6 ms. This is insignificant in the present case as the ‘fast’ response time of a sound level meter is much slower (125 ms).

V.2.3 Measured emission and immission spectra

Recordings were made at evening, night or early morning. On June 3, 2002, sound was recorded at dwelling P at around midnight and early in the morning near two turbines (numbers 1 and 7 in figure IV.1). At P at these times a distinct beat was audible in the wind turbine sound. In figure V.1, 1/3 octave band spectra of the recorded sound at P and at both turbines have been plotted. In each figure A, B and C, 200 sound pressure spectra sampled in one-second intervals, as well as the energy averaged spectrum of the 200 samples have been plotted. The standard deviation of 1/3 octave band levels is typically 7 dB at very low frequencies, decreasing to approx. 1 dB at 1 kHz. The correlation coefficient ρ between all 200 unweighted 1/3 octave band levels and the overall A-weighted sound level has also been plotted for each 1/3 octave band frequency.

For frequencies below approximately 10 Hz the sound is dominated by the thickness sound associated with the blade passing frequency and harmonics. In the rest of the infrasound region and upwards, in-flow turbulence is the dominant sound producing mechanism. Gradually, at frequencies above 100 Hz, trailing edge sound becomes the most dominant source, declining at high frequencies of one to several kHz. Trailing edge sound is more pronounced at turbine 1 (T1) compared to turbine 7 (T7), causing a hump near 1000 Hz in the T1 spectra. At very high frequencies (> 2 kHz) sometimes spectral levels are influenced by birds'sounds.

It is clear from the spectra that most energy is found at lower frequencies. However, most of this sound is not perceptible. To assess the infrasound level relevant to human perception it can be expressed as a G-weighted level [ISO 1995], With G-weighting sound above the infrasound range is suppressed. The average infrasound perception threshold is 95 dB(G) [Jakobsen 2004]. The measured G-weighted levels are 15-20 dB below this threshold: 80.5 and 81.1 dB(G) near turbines 1 and 7 respectively, and 76.4 dB(G) at the façade.

The correlations show that variations in total A-weighted level near the turbines are correlated with the 1/3 octave band levels with frequencies from 400 through 3150 Hz (where ρ > 0.4), which is trailing edge sound. This is one octave lower (200 - 1600 Hz) for the sound at the façade: the higher frequencies were better absorbed during propagation through the atmosphere.

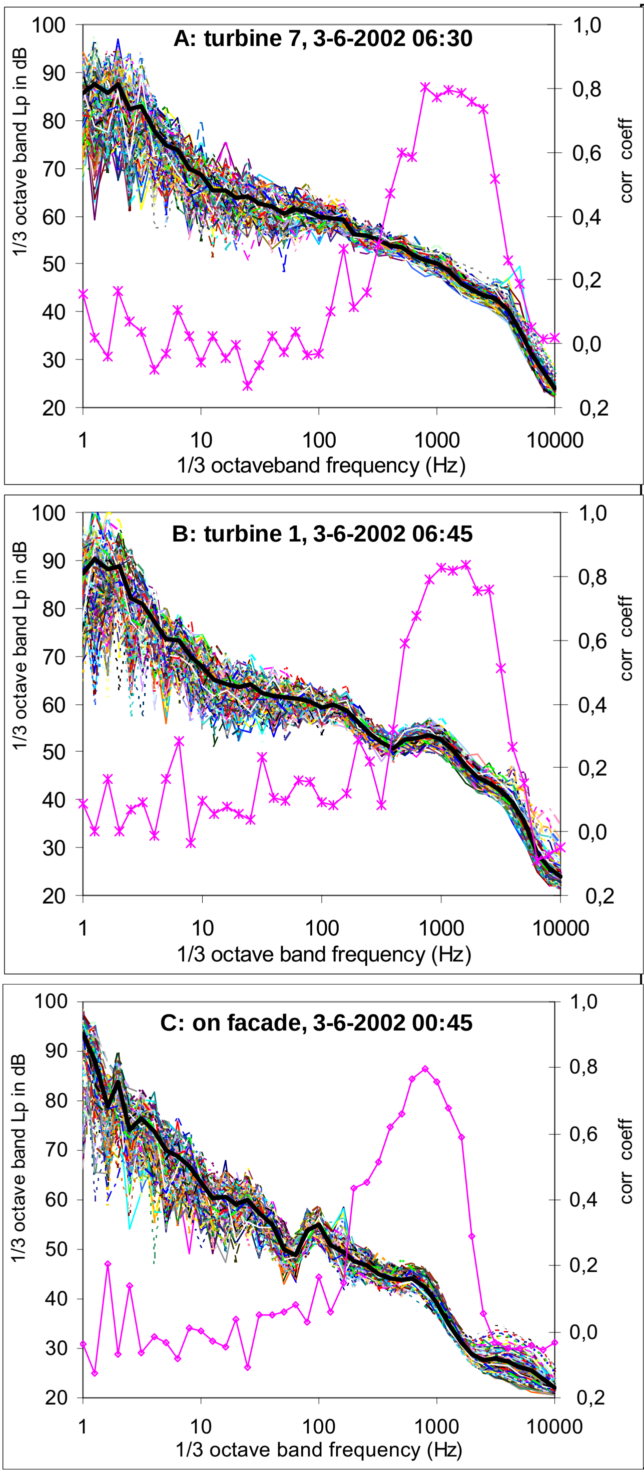

Figure V.1: left axis: 200 consecutive, unweighted and 1 second spaced 1/3 octave band spectra (thin lines), and averaged spectrum (thick line) of sound pressure level L_p near turbines 1 (A) and 7 (B) and near dwelling P (C);

right axis: coefficient of correlation (line with markers) at each 1/3 octave band frequency between all 200 1/3 octave band levels and overall A-weighted level

The façade spectra in figure V.1C show a local minimum at 50-63 Hz, followed by a local maximum at 80-100 Hz.[1] This is caused by interference between the direct sound wave and the wave reflected by the façade at 1.5 m from the microphone: for wave lengths of approximately 6 m (55 Hz) this leads to destructive interference, for wave lengths of 3 m (110 Hz) to constructive interference.

In figure V.2A the three average spectra at the same locations as in figure V.1A-C have been plotted, but now for a total measurement time of 9.5 (façade), 5 (T7) and 6 (T1) minutes. For each of these measurement periods the average of the 5% of samples with the highest broad band A-weighted sound level (*i.e.* the equivalent spectral level of the L_{A5} percentile) has also been plotted, as well as the 5% of samples with the lowest broad band level (L_{A95}). The range in A-weighted broad band level can be defined as the difference between the highest and lowest value: R_{bb} L_{Amax} - L_{Amin} . Similarly the range per 1/3 octave or octave band R_f can be defined by the difference in spectral levels corresponding to L_{Amax} and L_{Amin}. The difference between L_{A5} and L_{A95} is a more stable value, avoiding possibly incidental extreme values, especially when spectral data are used. $R_{bb,90}$ is defined as the difference in level between the 5% highest and the 5% lowest broad band sound levels: $R_{bb,90}$ L_{A5} - L_{A95}. For spectral data, $R_{f,90}$ is the difference between spectral levels associated with L_{A5} and L_{A95}. Values of $R_{f,90}$ are plotted in the lower part of figure V.2A (here octave bandlevels have been used to avoid the somewhat 'jumpy' behaviour of the 1/3 octave band levels). Close to turbines 1 and 7 R_{bb} is 4.8 and 4.1 dB, respectively. $R_{bb,90}$ is 3.2 and 2.6 dB, which is almost the same as $R_{f,90}$ (3.2 and 3.0 dB) at 1000 4000 Hz. Further away, at the façade, R_{bb} is comparable to the near turbine values: 4.9 dB. $R_{bb,90}$ at the façade is 3.3 dB and again almost the same as maximum $R_{f,90}$ (3.5 dB) at 1000 Hz.
Also, close to the turbine there is a low frequency maximum in $R_{f,90}$ at 2 (or 8) Hz that is also present at the façade, indicating that the modulation of trailing edge sound is correlated in time with the infrasound caused by the blade movement.

[1] In an FFT spectrum minima are at 57 and 170 Hz, maxima at 110 and 220 Hz

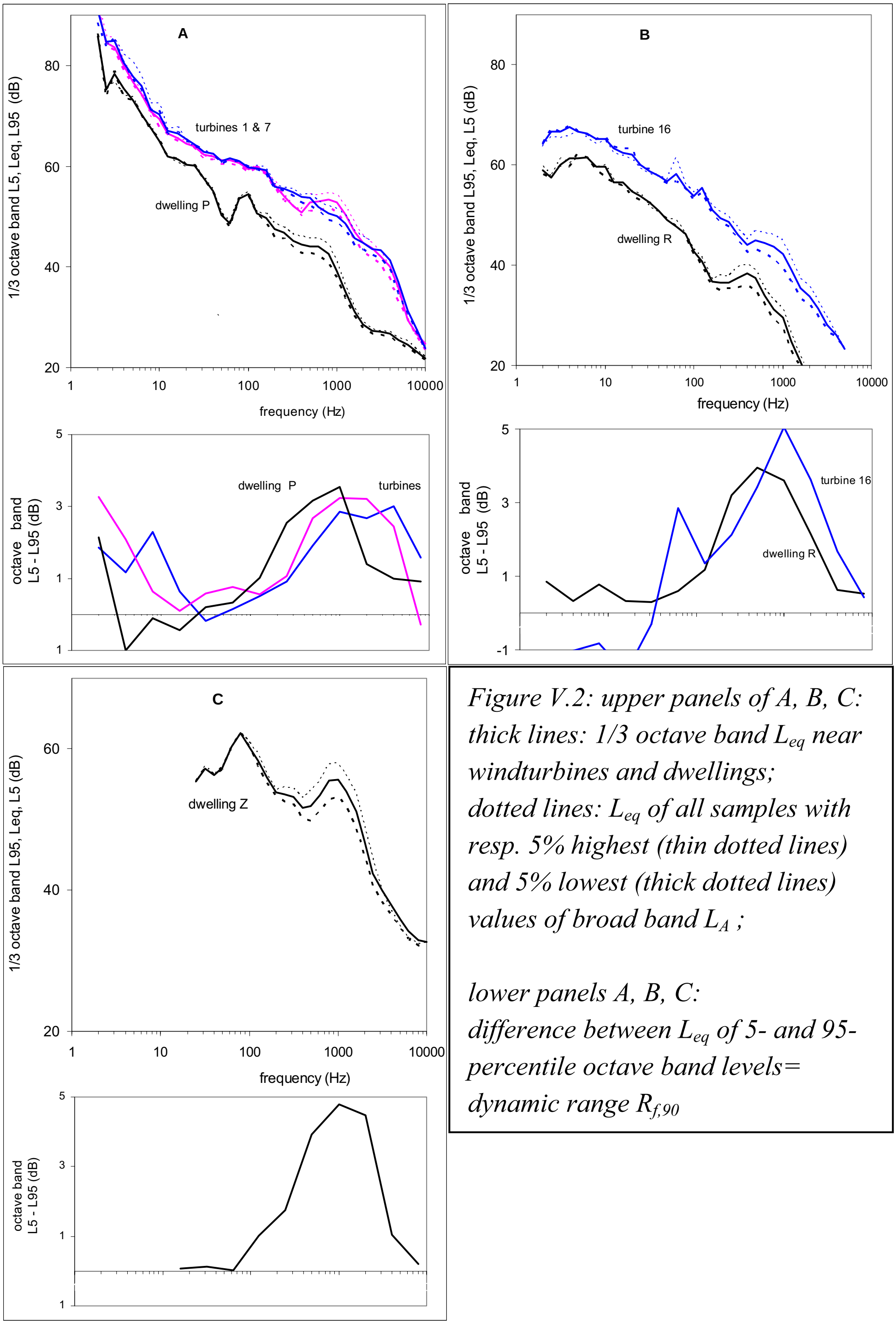

Figure V.2: upper panels of A, B, C: thick lines: 1/3 octave band L_{eq} near windturbines and dwellings; dotted lines: L_{eq} of all samples with resp. 5% highest (thin dotted lines) and 5% lowest (thick dotted lines) values of broad band L_A ;

lower panels A, B, C: difference between L_{eq} of 5- and 95-percentile octave band levels= dynamic range $R_{f,90}$

Figure V.2B presents similar plots for the average spectra and the L_{A5} and L_{A95} spectra at dwelling R and near turbine T16, simultaneously over a period of 16 minutes. Close to the turbine the broadband R_{bb} is 6.2 dB and $R_{bb,90}$ is 3.7 dB; octave band $R_{f,90}$ is highest (5.1 dB) at 1000 Hz. Near R broad band $R_{bb,90}$ is also 3.7 dB, and octave band $R_{f,90}$ is highest (4.0 dB) at 500 Hz. The R_{bb} ranges are 2.3 2.5 dB higher than the 90% ranges $R_{bb,90}$.
In the measurements at this time and place (dwelling R) the infrasound level was lower than in the previous measurements at dwelling P where beating was more pronounced. G-weighted sound level during the 16 minutes at R was 70.4 dB(G), and at T16 77.1 dB(G).

Finally figure V.2C gives average spectra over a period of 16 minutes at dwelling Z. $R_{f,90}$ is now highest (4.8 dB) at 1 kHz, and broadband $R_{bb,90}$ is 4.3 dB (R_{bb} 5.9 dB). The turbine near Z is smaller and lower, but rotates faster than the Rhede turbines; for a hub height wind velocity of 6 m/s the expected calculated increase in trailing edge sound for the lower tip relative to the day time situation is 2.0 ± 0.8 dB for a stable, and 2.9 ± 0.8 dB for a very stable atmosphere. For this turbine a peak trailing edge sound level is expected (according to equation B.2 in appendix B) at a frequency of 1550/b Hz $\approx$ 400   800 Hz.

In all cases above the measured sound includes ambient background sound. Ambient background sound level could not be determined separately at the same locations because the wind turbine(s) could not be stopped (see section II.4). However, at audible frequencies it could be ascertained by ear that wind turbine sound was dominant. At infrasound frequencies this could not be ascertained. But if significant ambient sound were present, subtracting it from the measured levels would lead to lower (infrasound) sound levels, which would not change the conclusion, based on the G-weighted level, that measured infrasound must be considered inaudible.

A 25 second part of the 16 min period that corresponds with the spectra in figure V.2B is shown in figure V.3. The broad band level L_A changes with time at T16 and R, showing a more or less regular variation with a period of approximately 1 s ($1/f_B$). Note that the level differences at R are of the same magnitude as close to the turbine, but the fluctuations at R consist of narrow peaks in comparison to the broader near-turbine fluctuations.

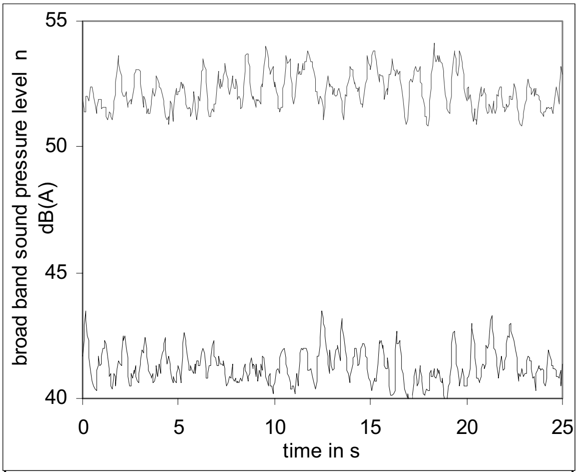

Figure V.3: broad band A-weighted immission sound level near turbine 16 (upper plot) and close to dwelling R (lower plot)

V.2.4 Beats caused by interaction of several wind turbines

In the previous section we saw that measured variations in broad band sound level (R_{bb}) were 4 to 6 dB. In figure V.4 a registration is given of the sound pressure level every 50 msec over a 180 seconds period, taken from a DAT-recording on a summer night (June 3rd, 0:40 h) on a terrace of dwelling P at 750 m west of the westernmost row of wind turbines (this sound includes the reflection on the façade). In this night stable conditions prevailed (*m* 0.45 from the wind velocities in table V.1). Turbines 12 and 11 are closest at 710 and 750 m, followed by turbines 9 and 14 at 880 and 910 m. Other turbines are more than 1 km distant and have an at least 4 dB lower immission level than the closest turbine has.

In figure V.4 there is a slow variation of the 'base line' (minimum levels) probably caused by variations in wind velocity and atmospheric sound transmission. There is furthermore a variation in dynamic range: a small difference between subsequent maximum and minimum levels of less than 2 dB is alternated by larger differences.

The expanded part of the sequence in figure V.4 (lower panel) begins when the turbine sound is noisy and constant within 2 dB. After some time (at t 155 s) regular pulses[1] appear with a maximum height of 3 dB, followed by a short period with louder (5 dB) and steeper (rise time up to 23 dB/s)

[1] the term ‘pulse’ is used to indicate a short, upward variation in sound level

pulses. The pulse frequency is equal to the blade passing frequency. Then (t > 175 s) the pulses become weaker and there is a light increase in wind velocity.
This was one of the nights where a distinct beat was audible: a period with a distinct beat alternating with a period with a weaker or no beat, repeated more or less during the entire night. This pattern is compatible with a complex of three pulse trains with slightly different repetition frequencies of ca. 1 Hz. When the pulses are out of phase (around 150 s in figure V.4), the variations are 1 dB or less. When 2 of them are in phase (around 160 s) pulse height is doubled (+3 dB), and tripled (+5 dB, 170 s) when all three are in phase. The rotational speed of the turbines at the time was 20 rpm, so the repetition rate of blades passing a mast was 1 Hz.
The low number of pulse trains, compared to 17 turbines, is compatible with the fact that only a few turbines dominate the sound immission at this location. The calculated immission level is predominantly caused by two wind turbines (numbers 11 and 12: see figure IV.2, contributing 35% of the A-weighted sound energy), less by two others (9 and 14; 21%), so only 4 turbines contribute more than half of the sound immission energy.

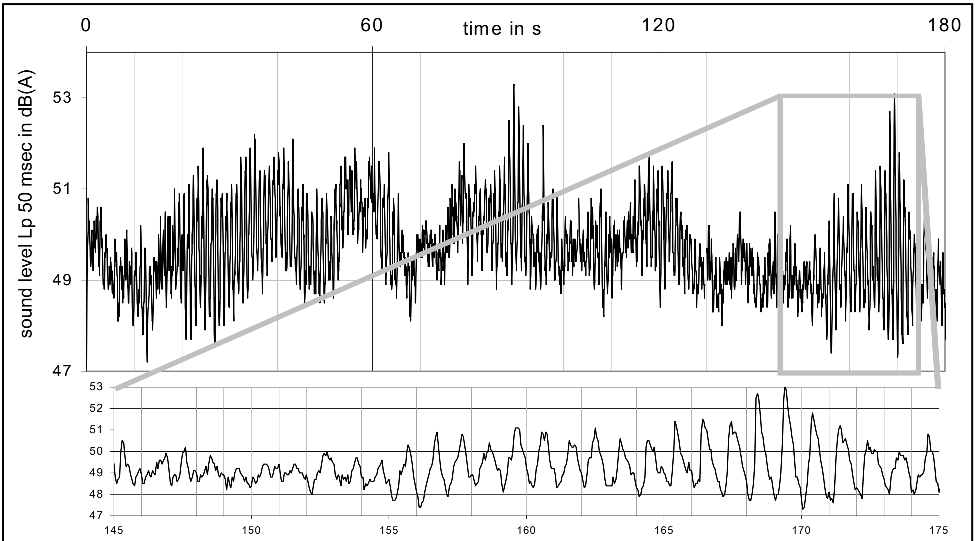

Figure V.4: fluctuations in broad band A-weighted sound immission level at façade of dwelling P; the lower panel is an expansion of the part within the grey rectangle

In figure V.5 the equivalent 1/3 octave band spectrum at the façade of P has been plotted for the period of the beat (165 < t < 175 s in figure 6, spectra sampled at a rate of 20 s^{1}), as well as the equivalent spectrum associated with the 5% highest (L_{A5} 52.3 dB(A)) and the 5% lowest (L_{A95} 47.7 dB(A)) broad band levels within this 10 s period, and the difference between both. As in the similar spectra in figure 4 we see that the beat corresponds to an increase at frequencies where trailing edge sound dominates: the sound pulses correspond to variations in 1/3 octave band levels at frequencies between 200 and 1250 Hz and are highest at 800 Hz. In figure V.5 also the equivalent 1/3 octave band levels are plotted for the period after beating where the wind was picking up slightly (t > 175 s in figure 6). Here spectral levels above 400 Hz are the same or slightly lower as on average at the time of beating, but at lower frequencies down to 80 Hz (related to in-flow turbulence) levels now are 1 to 2 dB higher. The increase in the 'more wind' spectrum at high frequencies (> 2000 Hz) is probably from rustling tree leaves.

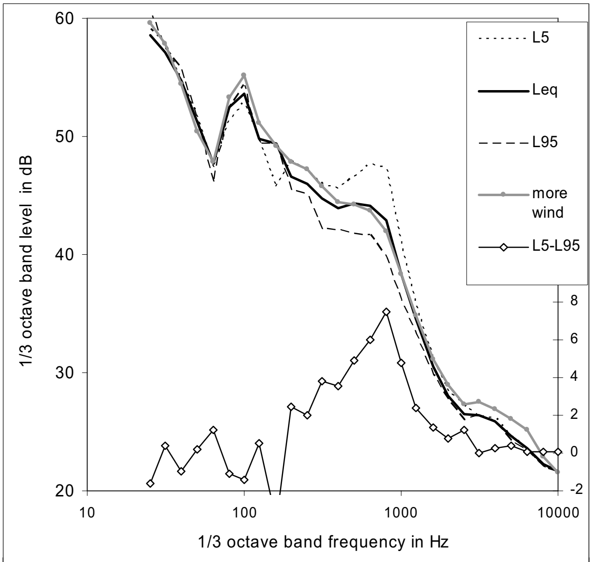

Figure V.5: 1/3 octave band levels at façade of dwelling P during beating (L_{eq}, L_5 and L_{95}) and when wind speed is picking up (L_{eq}); lower line: dynamic range ($R_{f,90}$) of 1/3 octave band

Figure V.6 shows sound power spectra for a period with a distinct beat (150 < t < 175 s in figure 6), and a period with a weak or no beat (130 < t < 150 s). Each spectrum is an FFT of 0.2 Hz line width from broad band A-weighted immission sound pressure level values. The frequencies are therefore *modulation*, not sound frequencies. The spectra show that distinct beating is associated with higher total A-weighted levels at the blade passing frequency and its harmonics ($k \cdot f_B$ with k 1, 2, 3, …). As has been shown above, the higher level is related to the frequency range of trailing edge sound. Infrasound frequencies linked to thickness sound are negligible in total A-weighted sound levels. When beating is weaker but there is more wind ($t > 175$ s), the level of the odd harmonics (base frequency k 1, and k 3) is lower than during ‘beat’, whereas the first two even harmonics (k 2, 4) are equally loud, indicating more distorted (less sinusoidal) and lower level pulses. It is important to realize that the periodic variation as represented in figure V.6 is the result from a wind farm, not from a single turbine.

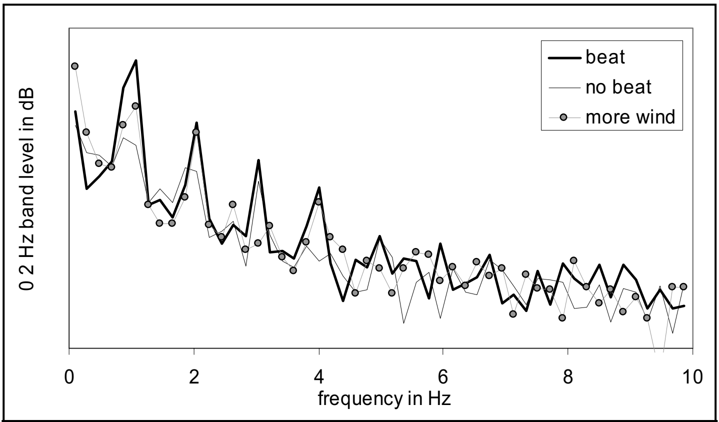

Figure V.6: sound power spectrum of A-weighted broad band immission sound level at façade of dwelling P when beating is distinctly or not audible and with slightly increased wind speed. The ordinate spans 20 dB.

In the long term measurements near the Rhede wind farm (see Chapter IV) average and percentile sound levels were determined over 5 minute periods. Periods where wind turbine sound was dominant could be selected with a criterion ($R_{bb,90} \leq 4$ dB) implying a fairly constant source with less than 4 dB variation for 90% of the time. The statistical distribution of the values of $R_{bb,90}$ L_{A5} - L_{A95} (≤ 4 dB) has been plotted in 1 dB intervals in figure V.7 for the two long term measurement locations A and B (see map in figure IV.1). Relative to dwellings P and R, location A (400 m from nearest turbine) is closer to the turbines, while location B (1500 m) is further away. Total measurement times with levels in compliance with the criterion- were 110 and 135 hours, respectively. Figure V.7 shows that the criterion value $R_{bb,90}$ (cut off at 4 dB) at both locations peaks at 2.5 dB.

Also plotted in figure V.7 is the value of L_{Amax} - L_{Aeq} within 5 minute periods (while $R_{bb,90} \leq 4$ dB), peaking at 3.5 dB at both locations. Finally, the difference between maximum and minimum level within 5 minute periods, R_{bb} L_{Amax} - L_{Amin}, peaks at 4.5 dB (location A) and 5.5 dB (B).

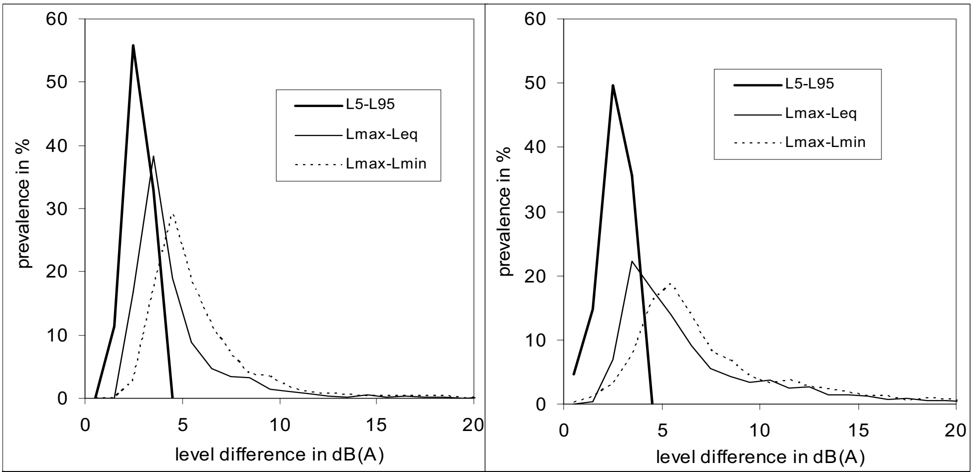

Figure V.7: statistical distribution of level differences (in 1 dB-classes) between high and low sound levels within 5 minute periods at 400 m (left) and 1500 m (right) from the nearest wind turbine

Where $R_{bb} > 7$ dB, the distributions are influenced by louder (non-turbine) sounds, such as from birds, causing a tail in the distributions at high levels. If we assume approximately symmetrical distributions without high level tails, the maximum range L_{Amax} - L_{Amin} R_{bb} due to the wind farm is 8.5 dB (location A) to 9.5 dB (B). This is 4 dB more than the prevailing difference at both locations.

V.2.5 Summary of results

In table V.2 the level variations due to blade swish as determined in the previous sections have been summarised. Some values not presented in the text have been added.[1] The ranges are presented as R_{bb} and $R_{bb,90}$. The

[1] in table in [Van den Berg 2005a] level variations close to the turbines were also given (as shown in figures V.2A-B); these values (R_{bb} = 4.8 dB close to turbine T1, 4.1 dB at T7 and 6.0 dB at T16) are not presented here as in fact these variations are not caused by the mechanism given in section V.1, but by other phenomena (see section II.2)

latter is of course a lower value as it leaves out high and low excursions occurring less than 10% of the time. The time interval over which these level differences occur differ: from several up to 16 minutes for the short term measurements, where wind conditions can be presumed constant, up to over 100 hours at locations A and B.

Table V.2: level variation in wind turbine [1)] sound due to blade swish, in dB

	location	Reference	atmospheric condition	R_{bb} L_{Amax}-L_{Amin}	$R_{bb,90}$ L_{A5}-L_{A95}
Calculated results					
Single turbine		Section V.1*a*	neutral	2 ± 1	
		Section V.1*a*	stable	3.8 ± 1.7	
		Section V.1*a*	very stable	4.8 ± 1.7	
N equidistant turbines			(very) stable	single + 10·logN	
Measured results					
Single turbine		[ETSU 1996]	unspecified [2)]	< 3	
	dwelling Z	Fig. V.2C	stable	5.9 [3)]	4.3
Multiple turbines	dwelling R	Fig. V.2B	stable	6.2	3.7
	façade dwelling P	Fig. V.2A	stable	4.9	3.3
	façade P + beat	Fig. V.5	stable	5.4	
	location A	fig. V.7left	long term, stable	4.5 (most frequent) 8.5 (maximum)	
	location B	fig. V.7right	long term, stable	5.5 (most frequent) 9.5 (maximum)	

notes: 1) hub height 100 m, rotor diameter 70 m, 20 rpm; 2) probably neutral; 3) for this turbine (H = 45 m, D =46 m, 26 rpm, V_h = 12 m/s) $R_{bb} \leq 3.3$ dB was calculated

V.3 Perception of wind turbine sound

In a review of literature on wind turbine sound Pedersen concluded that wind turbine noise was not studied in sufficient detail to be able to draw general conclusions, but that the available studies indicated that at relatively low levels wind turbine sound was more annoying than other sources of community noise such as traffic [Pedersen 2003]. In a field study by Pedersen and Persson Waye [2004] 8 of 40 respondents living in dwellings with (calculated) maximum outdoor immission levels of 37.5 - 40.0 dB(A) were very annoyed by the sound, and at levels above 40 dB(A) 9 of 25 respondents were very annoyed. The correlation between sound level (in 2.5 dB classes) and annoyance was significant ($p < 0.001$). In this field study annoyance was correlated to descriptions of the sound characteristics, most strongly to swishing with a correlation coefficient of 0.72 [Pedersen *et al* 2004]. A high degree of annoyance is not expected at levels below 40 dB(A), unless the sound has special features such as a low-frequency components or an intermittent character [WHO 2000]. Psychoacoustic characteristics of wind turbine sound have been investigated by Persson-Waye and Öhrström in a laboratory setting with naive listeners (students not used to wind turbine sound): the most annoying sound recorded from five different turbines were described as ‘swishing’, ‘lapping’ and ‘whistling’, the least annoying as ‘grinding’ and ‘low frequency’ [Persson Waye *et al* 2002]. People living close to wind turbines, interviewed by Pedersen *et al.* [2004], felt irritated because of the intrusion of the wind turbines in their homes and gardens, especially the swishing sound, the blinking shadows and constant rotation.

Our experience at distances of approx. 700 to 1500 m from the Rhede wind farm, with the turbines rotating at high speed in a clear night and pronounced beating audible, is that the sound resembles distant pile driving. When asked to describe the sound of the turbines in this wind farm, a resident compares it to the surf on a rocky coast. A resident living further away from the wind farm (1200 m) likens the sound to an ‘endless train’. Another resident near a set of smaller wind turbines, described the sound as that of a racing rowing boat (where rowers simultaneously draw, also creating a periodic swish). On the website of MAIWAG, a group of

citizens from villages near four wind farms in the south of Cumbria (UK), the sound is described as 'an old boot in a tumble dryer', and also as 'Whumph! Whumph! Whumph!' (see text box in section III.4). Several residents near single wind turbines remarked that the sound often changed to clapping, thumping or beating when night falls: 'like a washing machine'. It is common in all descriptions that there is noise ('like a nearby motorway', 'a B747 constantly taking of') with a periodic fluctuation superimposed. In all cases the sound acquires this more striking character late in the afternoon or at night, especially in clear nights and downwind from a turbine.
Part of the relatively high annoyance level and the characterisation of wind turbine sound as lapping, swishing, clapping or beating may be explained by the increased fluctuation of the sound. Our results in table V.2 show that in a stable atmosphere measured fluctuation levels are 4 to 6 dB for single turbines, and in long term measurements (over many 5 minute periods) near the Rhede wind farm fluctuation levels of approx. 5 dB are common but may reach values up to 9 dB.

The level difference associated with an amplitude modulation (AM) factor mf is:

$$\Delta L \quad 20\cdot\log((1+mf)/(1-mf)) \qquad \text{(V.2a)}$$

The modulation factor mf is the change in sound pressure amplitude due to modulation, relative to the average amplitude. For $\Delta L < 9$ dB a good approximation (±5%) is:

$$mf \quad 0.055\cdot\Delta L \qquad \text{(V.2b)}$$

Now when ΔL rises from 3 dB, presumably a maximum value for a daytime (unstable or neutral) atmosphere, to 6 dB, mf rises from 17% to 33%. For a maximum value of $\Delta L \quad 9$ dB, mf is 50%.

Fluctuations are perceived as such when the modulation frequencies are less than 20 Hz. Human sensitivity for fluctuations is highest at $f_{mod} \quad 4$ Hz, which is the frequency typical for rhythm in music and speech [Zwicker *et al* 1999], and for frequencies of the modulated sound close to 1 kHz. For wind turbines we found that a typical modulation frequency is 1 Hz, modulating the trailing edge sound that itself is at frequencies of 500 1000 Hz. So human sensitivity for wind turbine sound fluctuations is relatively high.

Fluctuation strength can be expressed in a percentage relative to the highest perceptible fluctuation strength (100%) or as an absolute value in the unit vacil [Zwicker *et al* 1999]. The reference value for the absolute fluctuation strength is 1 vacil, equalling a 60 dB, 1 kHz tone, 100% amplitude-modulated at 4 Hz [Zwicker *et al* 1999].
For an AM pure tone as well as AM broad band noise, absolute fluctuations strength is zero until $\Delta L \approx 3$ dB, then increases approximately linearly with modulation depth up to a value of 1 vacil. For a broad band noise level L_A the fluctuation strength F_{bb} can be written as [Zwicker *et al* 1999]:

$$F_{bb} \quad \frac{5.8\cdot(1.25\cdot mf-0.25)\cdot(0.05\cdot L_A \quad 1)}{(f_{mod}/5\text{ Hz})^2 + (4\text{ Hz}/f_{mod}) + 1.5} \text{ vacil} \qquad \text{(V.3a)}$$

With typical values for wind turbine noise of f_{mod} 1 Hz and L_A 40 dB(A), this can be written as F_{bb} $1.31\cdot(mf-0.2)$ vacil or, when $\Delta L < 9$ dB:

$$F_{bb} \quad 0.072\cdot(\Delta L - 3.6) \quad \text{vacil} \qquad \text{(V.3b)}$$

When ΔL increases from 3 to 5 dB, F_{bb} increases from negligible to 0.1 vacil. For the high fluctuation levels found at locations A and B (ΔL 8 to 9 dB), F_{bb} is 0.3 to 0.4 vacil.

It can be concluded that, in a stable atmosphere, the fluctuations in modern wind turbine sound can be readily perceived. As yet it is not clear how this relates to possible annoyance. However, the sound can be likened to the rhythmic beat of music: pleasant when the music is appreciated, but distinctly intrusive when the music is unwanted.
The hypothesis that these fluctuations are important, is supported by descriptions of the character of wind turbine sound as ‘lapping’, ‘swishing’, ‘clapping’, ‘beating’ or ‘like the surf’. Those who visit a wind

turbine in daytime will usually not hear this and probably not realise that the sound can be rather different in conditions that do not occur in daytime. This may add to the frustration of residents: “Being highly affected by the wind turbines was hard to explain to people who have not had the experiences themselves and the informants felt that they were *not being believed*” [Pedersen *et al* 2004]. Persson-Waye *et al* [2002] observed that, from five recorded different turbine sounds “the more annoying noises were also paid attention to for a longer time”. This supported the hypothesis that awareness of the noise and possibly the degree of annoyance depended on the content (or intrusive character) of the sound.

Fluctuations with peak levels of 3 9 dB above a constant level may have effects on sleep quality. The Dutch Health Council [2004] states that "at a given L_{night} value, the most unfavourable situation in terms of a particular direct biological effect of night-time noise is not, as might be supposed, one characterised by a few loud noise events per night. Rather, the worst scenario involves a number of noise events all of which are roughly 5 dB(A) above the threshold for the effect in question." For transportation noise (road, rail, air traffic) the threshold for motility (movement), a direct biological effect having a negative impact on sleep quality, is a sound exposure level per sound event of SEL 40 dB(A) in the bedroom [Health Council 2004]. The pulses in figure V.4 have SEL-values up to 50 dB(A), but were measured on the façade. With an open window facing the wind turbines indoor SEL-values may exceed the threshold level. In other situations this of course depends on distance to and sound power of the turbines and on the attenuation between façade and bedroom. It is not clear whether the constant and relatively rapid repetition of wind turbine sound beats will have more or less effect on sleep quality, compared to vehicle or airplane passages. Pedersen and Persson Waye [2004] found that at dwellings where the (outdoor) sound level due to wind turbines exceeded 35 dB(A), 16% of 128 respondents reported sleep disturbance by this sound, of whom all but two slept with a window open in summer.

V.4 Conclusion

Atmospheric stability has a significant effect on the character of wind turbine sound. The change in wind profile causes a change in angle of attack on the turbine blades. This increases the thickness (infra)sound level as well as the level of trailing edge (TE) sound, especially when a blade passes the tower. TE sound is modulated at the blade passing frequency, but it is a high frequency sound, well audible and indeed the most dominant component of wind turbine noise. The periodic increase in sound level dubbed blade swish, is a well known phenomenon. Less well known is the fact that increasing atmospheric stability creates greater changes in the angle of attack over the rotor plane that add up with the change near the tower. This results in a thicker turbulent TE boundary layer, in turn causing a higher swish level and a shift to somewhat lower frequencies. It can be shown theoretically that for a modern, tall wind turbine in flat, open land the angle of attack at the blade tip passing the tower changes with approx. 2° in daytime, but this value increases with 2° when the atmosphere becomes very stable. The calculated rise in sound level during swish then increases from 2 dB to 5 dB. This value is confirmed by measurements at single turbines in the Rhede wind farm where maximum sound levels rise 4 to 6 dB above minimum sound levels within short periods of time.

Added to this, atmospheric stability involves a decrease in large scale turbulence. Large fluctuations in wind velocity (at the scale of a turbine) vanish, and the coherence in wind velocity over distances as great as or larger than the size of an entire wind farm increases. As a result turbines in the farm are exposed to a more constant wind and rotate at a more similar speed with less fluctuations. Because of the near-synchronicity, blade swishes may arrive simultaneously for a period of time and increase swish level. The phase difference between turbines determines where this amplification occurs: whether the swish pulses will coincide at a location depends on this phase difference and the propagation time of the sound. In an area where two or more turbines are comparably loud the place where this amplification occurs will sweep over the area with a velocity determined by the difference in rotational frequency. The magnitude of this effect thus depends on stability, but also on the number of wind turbines and the distances to the observer. This effect is in contrast to what was expected, as it seemed reasonable to suppose that turbines would behave independently and thus the blade swish pulses from several turbines would arrive at random, resulting in an even more constant level than from one turbine. Also, *within* a wind farm the effect may not be noticed, since comparable positions in relation to two or more turbines are less easily realised at close distances and the position relative to a turbine rotor is quite different.

Sound level differences L_{Amax}-L_{Amin} (corresponding to swish pulse heights) within 5 minute periods over long measurement periods near the Rhede wind farm show that level changes of approximately 5 dB occur for an appreciable amount of time and may less often be as high as 8 or 9 dB. This level difference did not decrease with distance (from 400 m to 1500 m). The added 3-5 dB, relative to a single turbine, is in agreement with simultaneously arriving pulses from two or three approximately equally loud turbines.

The increase in blade swish level creates a new percept, fluctuating sound, that is absent or weak in neutral or unstable atmospheric conditions. Blade passing frequency is now an important parameter as a modulation frequency (not as an infrasound frequency). Human perception is most sensitive to modulation frequencies close to 4 Hz of sound with a frequency of approximately 1 kHz. The hypothesis that fluctuations are important is supported by descriptions given by naïve listeners as well as residents: turbines sound like ‘lapping’, ‘swishing’, ‘clapping’, ‘beating’ or ‘like the surf’. It is not clear to what degree this fluctuating character determines the relatively high annoyance caused by wind turbine sound and to a deterioration of sleep quality. Further research is necessary into the perception and annoyance of wind turbine sound, with correct assumptions on the level and character of the sound. Also the sound exposure level of fluctuations in the sound in the bedroom must be investigated to be able to assess the effects on sleep quality.

VI STRONG WINDS BLOW UPON TALL TURBINES: wind statistics below 200 m altitude

VI.1 Atmospheric stability in wind energy research

In the European Wind Atlas model ('Wind Atlas Analysis and Application Program' or WAsP) [Troen *et al* 1989] wind energy available at hub height is calculated from wind velocities at lower heights. The Atlas states that "modifications of the logarithmic wind profile are often neglected in connection with wind energy, the justification being the relative unimportance of the low wind velocity range. The present model treats stability modifications as small perturbations to a basic neutral state." With the increase of wind turbine heights this quote is now an understatement. In recent years atmospheric stability is receiving gradually more attention as a determinant in wind *energy* potential, as demonstrated by a growing number of articles on stability related wind profiles in different types of environments such as Danish offshore sites [Motta *et al* 2005], the Baltic Sea [Smedman *et al* 1996], a Spanish plateau [Pérez *et al* 2005] or the American Midwest [Smith *et al* 2002]. Recently Archer and Jakobsen [2003] showed that wind energy potential at 80 m altitude in the contiguous US 'may be substantially greater than previously estimated' because atmospheric stability was not taken into account: on average 80-m wind velocities appear to be 1.3 1.7 m/s higher than assumed from 10-m extrapolated wind velocities in a neutral atmosphere.

VI.2 The Cabauw site and available data

To investigate the effect of atmospheric stability on wind, and thence on energy and sound production, data from the meteorological research station of the KNMI (Royal Netherlands Meteorological Institute) at Cabauw in the western part of the Netherlands were kindly provided by dr Bosveld of the KNMI. The site is in open pasture for at least 400 m in all directions. Farther to the west the landscape is open, to the distant east are trees and low houses. More site information is given in [KNMI 2005, Van Ulden *et al* 1996]. The site is considered representative for the flat western and

northern parts of the Netherlands. These in turn are part of the low-lying plain stretching from France to Sweden.
Meteorological data are available as half hour averages over several years. Here data of the year 1987 are used. Wind velocity and direction are measured at 10, 20, 40, 80, 140 and 200 m altitude. Cabauw data are related to Greenwich Mean Time (GMT); in the Netherlands the highest elevation of the sun is at approximately 12:40 Dutch winter time, which is 20 minutes before 12:00 GMT.

An indirect measure for stability is Pasquill class, derived from cloud cover, wind velocity and position of sun (above or below horizon). Classes range from A (very unstable: less than 50% clouding, weak or moderate wind, sun up) to F (moderately to very stable: less than 75% clouding, weak or moderate wind, sun down). Pasquill class values have been estimated routinely at Dutch meteorological stations [KNMI 1972].

Figure VI.1: the Cabauw site with 200 m mast for meteorological research (photo:Marcel Schmeier)

VI.3 Reference conditions

To relate the meteorological situation to wind turbine performance, an 80 m hub height wind turbine with three 40 m long blades will be used as reference for a modern 2 to 3 MW, variable speed wind turbine. To calculate electrical power and sound power level, specifications of the 78 m tall Vestas V80 2MW wind turbine will be used. For this turbine cut-in

(hub height) wind velocity is 4 m/s, and highest operational wind velocity 25 m/s.
Most data presented here will refer to wind velocity at the usual observation height of 10 m and at 80 m hub height. Wind shear will be presented for this height range as well as the range 40 to 140 m where the rotor is. The meteorological situation is as measured in Cabauw in 1987, with a roughness height of 2 cm. The year will be divided in meteorological seasons, with spring, summer, autumn and winter beginning on the first day or April, July, October and January, respectively.

We will consider four classes of wind velocity derived from Pasquill classes A to F and shown in table 1: unstable, neutral, stable and very stable. In table VI.1 (the same as table III.1, but written slighly different to show boundaries between stability classes in terms of m) this is also given in terms of the shear exponent, but this is tentative as there is no fixed relation between Pasquill classification and shear exponent or stability function Ψ. This classification is in agreement with that in chapter III, though there typical mid-class values of m were given, not values at the boundaries between classes. In our reference situation 'very stable' ($m > 0.4$) corresponds to a Monin-Obukhov length $0 < L < 100$ m, 'stable' ($0.25 < m < 0.4$) refers to $100 \text{ m} < L < 400$ m, near neutral to $|L| > 400$ m.
This is somewhat different from the Monin-Obukhov length based classification used by Motta *et al* [2005] for a coastal/marine environment. Motta *et al* qualified $0 < L < 200$ m as very stable, $200 \text{ m} < L < 1000$ m as stable and $|L| > 1000$ m as near-neutral, so they considered a wider range of conditions as (very) stable when compared to table 1.

Table VI. 1: stability classes and shear exponent m

Pasquill class	name	shear exponent
A – B	(very – moderately) unstable	$m \leq 0.21$
C	near neutral	$0.21 < m \leq 0.25$
D – E	(slightly – moderately) stable	$0.25 < m \leq 0.4$
F	very stable	$0.4 < m$

VI.4 Results: wind shear and stability

VI.4.1 Wind velocity shear

In figure VI.2 the average wind velocities at altitudes of 10 m to 200 m are plotted versus time of day. Plotted are averages per half hour of all appropriate half hours in 1987. As figure VI.2 shows, the wind velocity at 10 m follows the popular notion that wind picks up after sunrise and abates after sundown. This is obviously a 'near-ground' notion as the reverse is true at altitudes above 80 m. Figure VI.2 helps to explain why this is so: after sunrise low altitude winds are coupled to high altitude winds due to the vertical air movements caused by the developing thermal turbulence. As a result low altitude winds are accelerated by high altitude winds that in turn are slowed down. At sunset this process is reversed. In figure VI.2 also the wind velocity V_{80} is plotted as calculated from the measured wind velocity V_{10} with equation III.3 (z_o 2 cm, equivalent to equation III.1 with m 0.14), as well as the shear exponent *m* calculated with equation III.4. The logarithmically extrapolated V_{80} approximates actual V_{80} in daytime when the shear exponent has values close to 0.14. However, the prediction is very poor at night time, when *m* rises to a value of 0.3, indicating a stable atmosphere.

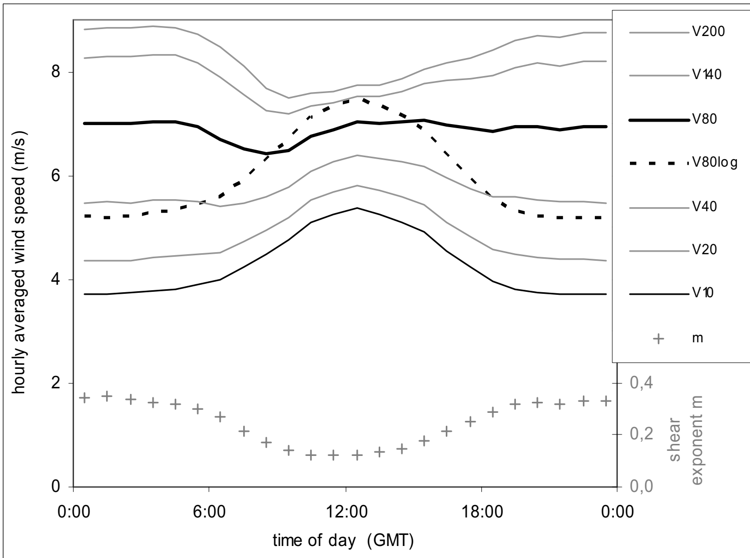

Figure VI.2: solid lines, bottom to top: 1987 wind velocity per clock hour at heights 10 to 200 m; dotted line: logaritmically extrapolated V_{80};

+: shear exponent $m_{10,80}$

For the hourly progress of wind velocities large deviations from the average wind profile occur. This is illustrated in figure VI.3 for a week in winter and a week in summer with measured V_{10} values and measured as well as logarithmically extrapolated V_{80} values. In the winter week in January 1987 ground and air were cold for a long time (below freezing point) with very little insolation. Temperature varied from night to day (diurnal minimum to maximum) with 7 °C on the first day and 5 °C or less on the next days, and the atmosphere was close to neutral with measured V_{80} more or less equal to the extrapolated V_{80}. In the summer week in July 1987 there was little clouding after the first two days; insolation was strong in daytime, and nights were 10 to 14 °C cooler than days, resulting in a stable to very stable night time atmosphere. Here, night time wind velocity was rather higher than predicted with the logarithmic wind profile.

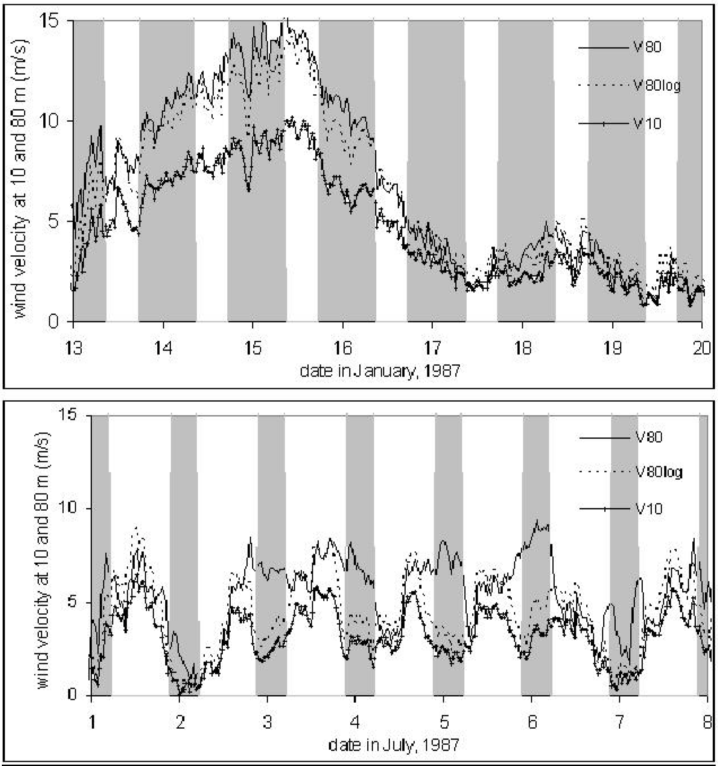

Figure VI.3: wind velocity at 10 and 80 m (solid lines), and logarithmically extrapolated V_{80log} (dotted line) over 7 days in January (top) and July (bottom); grey background: time when sun is down

In figure VI.4 wind velocities per half hour are again plotted for different heights, as in figure VI.2, but now averaged per clock half hour and per meteorological season. In spring and summer differences between night and day seem more pronounced than in autumn or winter. In fall and winter wind velocities are on average higher.

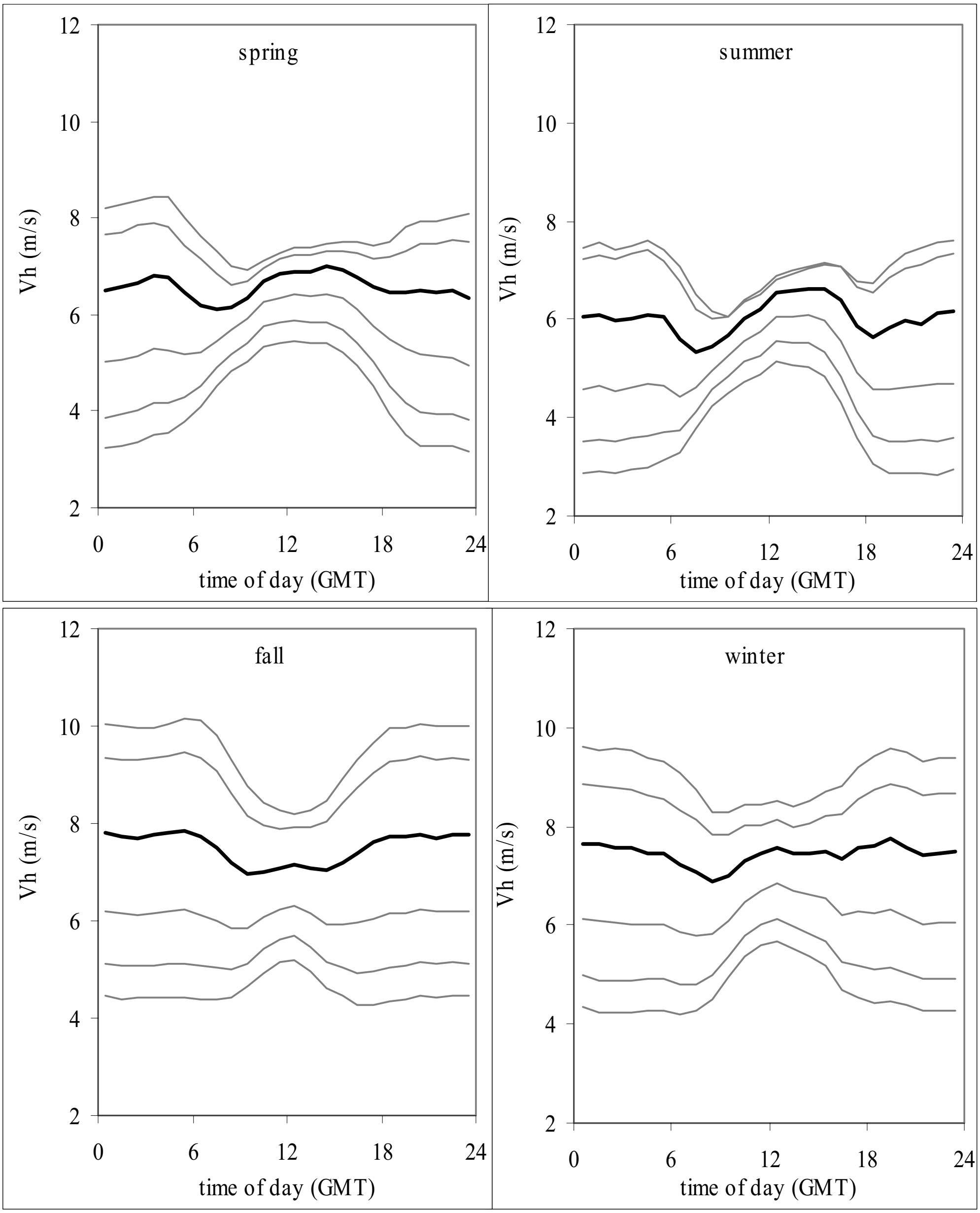

Figure VI.4: wind velocity per hour GMT at heights of 10, 20, 40, 80, 140 and 200 m (bottom to top; 80 m is bold) in the meteorological seasons in 1987

In figure VI.5 the frequency distribution is plotted of the half-hourly wind velocities at five different heights. Also plotted is the distribution of wind velocity at 80 m as calculated from the 10-m wind velocity with the logarithmic wind profile (equation III.3, m 0.14). Wind velocity at 80 m has a value of 7 ± 2 m/s for 50% of the time. For the logarithmically extrapolated wind velocity at 80 m this is 4.5 ± 2 m/s.

In figure VI.6 the prevalence of the shear exponent in the four meteorological seasons is plotted, determined from the half-hourly 10-m and 80-m wind velocities. It shows that, relative to autumn and winter, a neutral or mildly stable atmosphere occurs less often in spring and summer, whereas an unstable as well as in summer- a very stable atmosphere occurs more often . As summer nights are short this means that a relatively high percentage of summer night hours has a stable atmosphere.

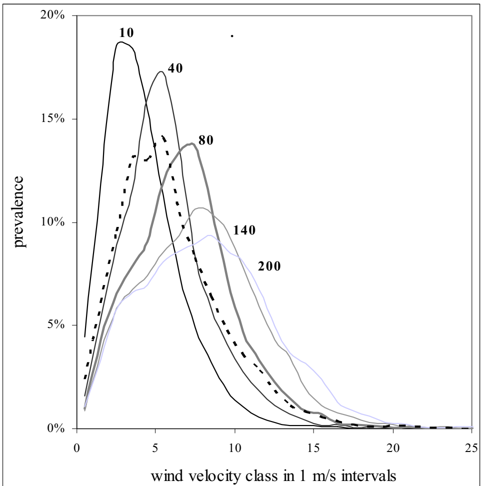

Figure VI.5: distribution of measured wind velocities at 10, 40, 80, 140 and 200 m;dashed line: V_{80} extrapolated from V_{10}

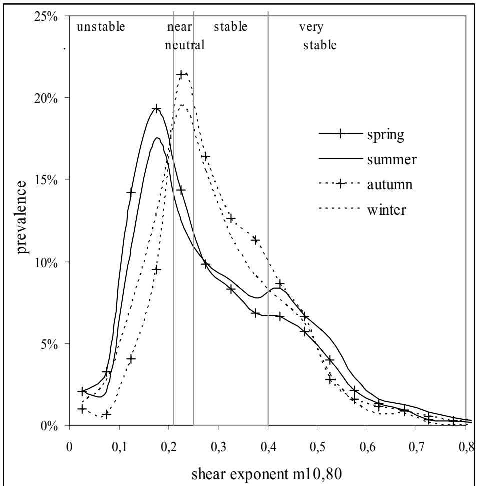

Figure VI.6: distribution of shear exponent per meteorological season, determined from V_{80}/V_{10}

VI.4.2 Shear and ground heat flux

Figure VI.7 shows how the shear exponent depends on the total heat flow to the ground for two different height ranges: 10   80 m in the left panel, 40   140 m in the right panel. The shear exponent is calculated from the wind velocity ratio with equation III.1. The heat flow at Cabauw is determined from temperature measurements at different heights, independent of wind velocity. Total heat flow is the sum of net radiation, latent and sensible heat flow, and positive when incoming flow dominates. For heat flows above approximately 200 W/m^2 the shear exponent m is between 0 and 0.21, corresponding to an unstable atmosphere, as expected. For low or negative (ground cooling) heat flows the range for m increases, extending from -1 up to +1.7. These values include conditions with very low wind velocities. If low wind velocities at 80 m height (V_{80} < 4 m/s, occurring for 19.7% of the time) are excluded, $m_{10,80}$ varies (with very few exceptions) between 0 and 0.6, and $m_{40,140}$ varies between -0.1 and +0.8. A negative exponent means wind velocity decreases with height. The data show that below 80 m this occurs in situations with little wind (V_{80} < 4 m/s), but at greater heights also at higher wind velocities. In fact, V_{140} was lower than V_{80} for 7.5% of all hours in 1987, of which almost half (3.1%)

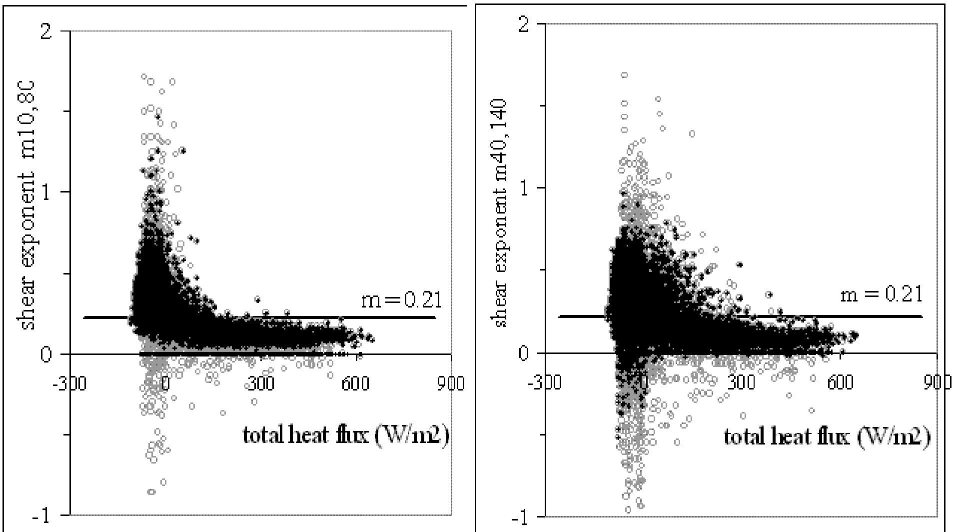

Figure VI.7: shear exponent m from wind velocity gradient between 10 and 80 m (left), and 40 and 140 m (right) vs. total ground heat flow; grey circles: all data, black dots: V_{80} > 4 m/s when V_{80} was over 4 m/s. Such a decrease of wind velocity with height occurs at the top of a 'low level jet' or nocturnal maximum; it occurs at night when kinetic energy of low altitude air is transferred to higher altitudes.

For V_{80} > 4 m/s both shear exponents ($m_{10,80}$ and $m_{40,140}$) are fairly strongly correlated (correlation coefficient 0.85), showing that generally there is no appreciable change between both altitude ranges. For low wind velocities (V_{80} < 4 m/s) both shear exponents are less highly correlated (correlation coefficient 0.62).

VI.4.3 Wind direction shear

When stability sets in the decoupling of layers of air also affects wind direction. The higher altitude wind more readily follows geostrophic wind and therefore can change direction when stability sets in, while lower altitude winds are still influenced by the surface following the earth's rotation. In the left panel of figure VI.8 the change in wind direction at 80 m relative to 10 m is plotted as a function of the shear exponent as a measure of stability. A positive change means a clockwise change (veering wind) at increasing altitude. The right panel shows the wind direction change from 40 to 140 m as a function of the shear exponent determined from the wind velocities at these heights. In both cases the prevailing change from m 0 to m 0.5 is 30°, but with considerable variation.

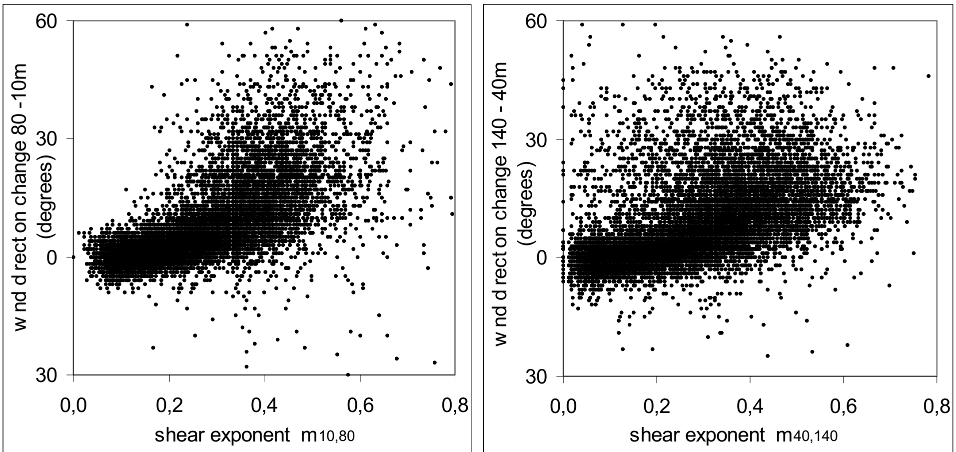

Figure VI.8: wind direction change between 10 and 80 m (left) and 40 and 140 m (right) vs. shear exponent m between same heights for V_{80} > 4 m/s

VI.4.4 Prevalence of stability

In figure VI.9 the percentages are given that the atmosphere is very stable, stable, neutral and unstable respectively (as defined in table VI.1) for 1987 as a whole and per meteorological season. Prevalence is given for heights from 10 and 80 m (upper panel figure VI.9) and for heights from 40 to 140 m (lower panel). The upper panel is in fact a summation over the four ranges of the shear exponent indicated in figure VI.6. It appears that in autumn the atmosphere is most often stable, and least often unstable. In spring the opposite is true: instability occurs more often than stability. Overall the atmosphere up to 80 m is unstable (m < 0.21) for 47% of the time and stable (m > 0.25) for 43% of the time. At higher altitudes (40 to 140 m) percentages are almost the same: 44% and 47%, respectively. This means that for most of the daytime hours the atmosphere is unstable, and for most of the night time hours stable. For the rest (9 to 10%) of the time the atmosphere is near neutral.

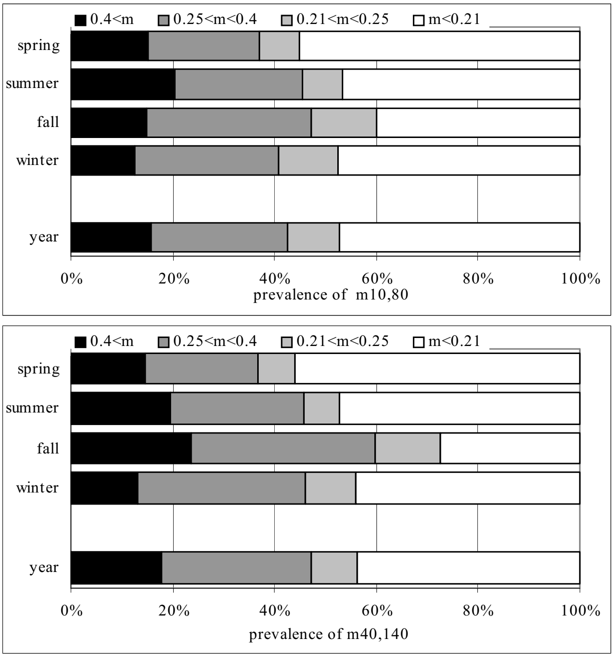

Figure VI.9: prevalence of shear exponent m between 10 and 80 m (top) and 40 and 140 m (bottom) in four seasons and year of 1987

Climatological observations can put the Cabauw data in national perspective. In figure VI.10 the prevalence of Pasquill classes E and F (corresponding to approximately m > 0.33) are given as observed at 12 meteorological stations all over the Netherlands over the period 1940 - 1970 [KNMI 1972], ordered according to yearly prevalence. Three of the dunes on the North Sea coast, Vlissingen is at the Westerschelde estuary and Den Helder is on a peninsula between the North Sea and the Wadden Sea. At Den Helder a stable atmosphere occurs for only 8% of the time per year, whereas at both other coastal stations this is 13% to 16% and at the other landward stations 15% to 20% of the time. At Cabauw a value of $m > 0.33$ occurs for 27% of the time.

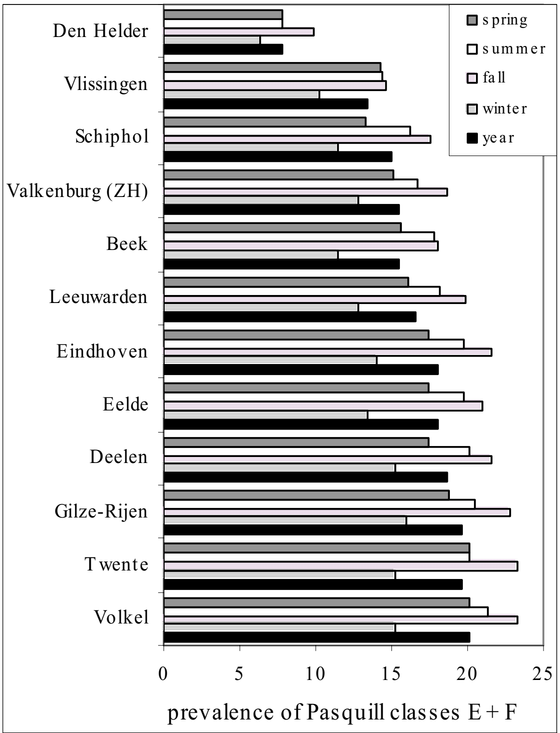

Figure VI.10: prevalence of observed stability (Pasquill classes E and F) per season and per year at 12 different Dutch stations over 30 years (data from [KNMI

VI.5. Results: effects on wind turbine performance

VI.5.1 Effect on power production

The effect of atmospheric stability can be investigated by applying the Cabauw data to a reference wind turbine, the Vestas V80-2MW [Vestas 2003, Jorgensen 2002]. This turbine has an ‘Optispeed’ sound reduction possibility to reduce sound power level (by adapting the speed of the rotor and generator). We will present data for the highest (‘105.1dB(A)’) and lowest (‘101.0dB(A)’) sound power curve. To calculate the electric power P80 as a function of wind velocity V_h at hub height the factory ‘105.1dB(A)’ highest power (‘hp’) curve is approximated with a fourth power polynome:

$$P_{h,hp} \quad 0.0885 \cdot V_h^4 \quad 8.35 \cdot V_h^3 + 186 \cdot V_h^2 - 1273 \cdot V_h + 2897 \text{ kW} \qquad \text{(VI.1a)}$$

which is valid for $4 < V_h < 14.3$ m/s. In figure VI.11 this fitted curve is plotted as diamonds on top of the manufacturer's specification [Vestas 2003]. For higher wind velocities (>14.3 m/s; 2% of time at Cabauw) electric power is constant at 2000 kW, for lower wind velocities (< 4 m/s; 20% of time) electric power is set to zero.

A fourth power relation is used as this is convenient to fit the power curve at 12 m/s where maximum power is approached. For lower wind velocities (V_h < 11 m/s) the power curve can be fitted with a third power ($P_h \quad 1.3 \cdot V_h^3$) in agreement with the physical relation between wind power and wind velocity.

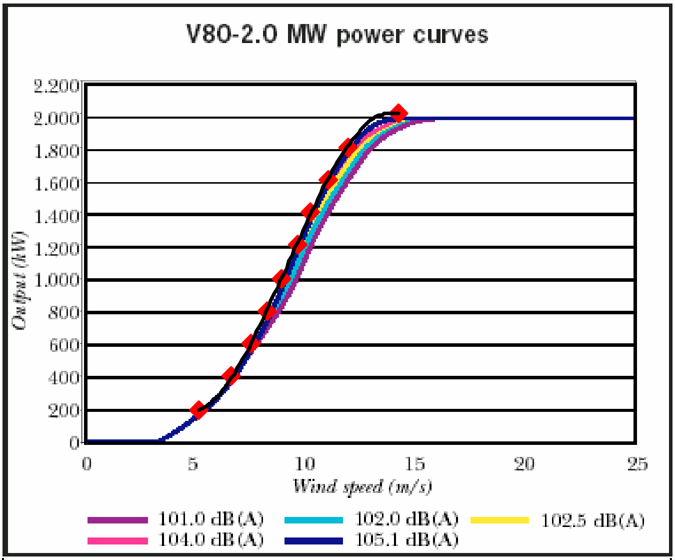

Figure VI.11: lines: Vestas V80 power curves vs. hub height wind speed; diamonds: best fit to 105.1dB(A) curve (figure adapted from [Vestas 2003])

Electric power can thus be calculated from real wind velocities as measured each half hour at 80 m height, or from 80-m wind velocities logarithmically extrapolated from wind velocity at 10 m height. The result is plotted in figure VI.12 as an average power versus time of day $P_{80,hp}$ (the power averages are over all hours in 1987 at each clock hour). Actual power production appears to be more constant than estimated with extrapolations from 10-m wind velocities. When using a logarithmic extrapolation, daytime power production is overestimated, while night time power production is underestimated. The all year average is plotted with large symbols at the right side of the graph in figure VI.12: 598 kW when based on measured wind velocity or a 30% annual load factor, 495 kW when based on extrapolated wind velocity or a 25% load factor. In figure VI.12 also the wind power is plotted when the turbine operates in the lowest '101.0dB(A)' power curve ('lp') where the best fit is:

$$P_{h,lp} \quad 0.089 \cdot V_h^4 + 0.265 \cdot V_h^3 + 43 \cdot V_h^2 \quad 326 \cdot V_h + 749 \text{ kW} \qquad \text{(VI.1b)}$$

The year average is now 569 kW, corresponding to a 28% annual load factor. The 4 dB lower sound level setting thus means that yearly power production has decreased to a factor 0.94.

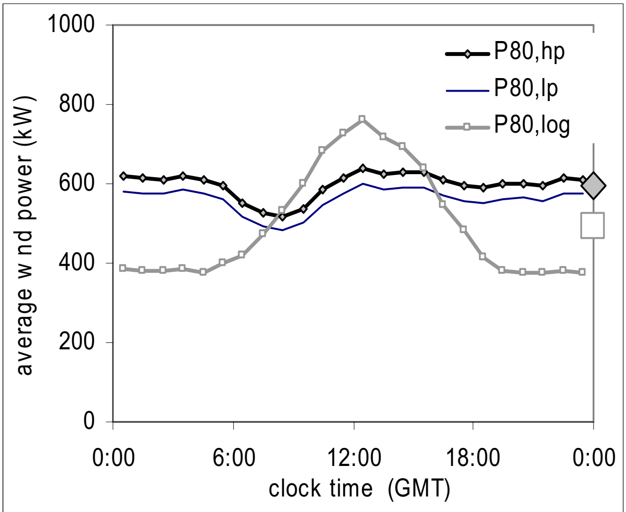

Figure VI.12: hourly averaged estimated (log) and real wind power at 80 m height per clock hour in 1987

In the calculations it was implicitly assumed that the wind velocity gradient over the rotor was the same as at the time the power production was determined as a function of hub height wind velocity. In stable conditions however, the higher wind gradient causes a non-optimal angle of attack at the blade tips when the tips travel far below and above the hub. This will involve some loss, which is not determined here.

VI.5.2 Effect on sound production

Figure VI.13 shows 'theoretical' sound power levels for the Vestas turbine [Vestas 2003, Jorgensen 2002]; in fact for $V_h < 8$ m/s measured levels are somewhat lower, for $V_h > 8$ m/s somewhat higher [Jorgensen 2002]. To calculate the sound power level L_W as a function of hub height wind velocity V_h the factory '105.1dB(A)' high power curve is approximated with a fourth power polynome:

$$L_{W,hp} \quad -0.0023 \cdot V_h^4 + 0.146 \cdot V_h^3 - 2.82 \cdot V_h^2 + 22.6 \cdot V_h + 39.5 \quad \text{dB(A)} \text{(VI.2a)}$$

for $4 < V_h < 12$ m/s and $L_{W,hp}$ 107 dB(A) for $V_h >$ 12 m/s. In figure VI.14 the result per clock hour is plotted when using actual and extrapolated (from 10 m) wind velocities. Averaged over all 1987 the sound power level in daytime is overestimated by 0.5 dB, but at night underestimated by 2 dB. In the ‘101.0dB(A)’ low power curve setting the best fourth power polynomal fit is (in figure VI.13 plotted as diamonds over the Vestas curve):

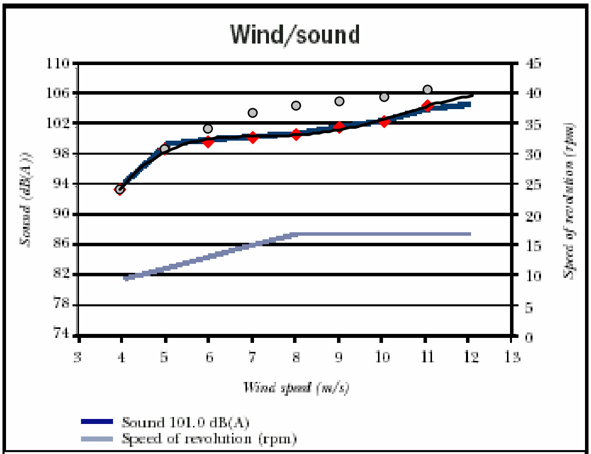

Figure VI.13: Vestas V80 sound power level at ‘101.0dB(A)’ (diamonds and upper line) and ‘105.1dB(A)’ power curve (circles); lower line: speed of rotation vs. hub height

$$L_{W,lp} \quad -0.022\cdot V_h^4 + 0.78\cdot V_h^3 \quad 10\cdot V_h^2 + 55.3\cdot V_h - 12.3 \quad \text{dB(A)} \qquad \text{(VI.2b)}$$

for $4 < V_h < 12$ m/s and $L_{W,hp}$ 105 dB(A) for $V_h > 12$ m/s. The sound power levels in this setting are, for $6 < V_h <$ 12 m/s, on average 3 dB lower than in the high power setting.

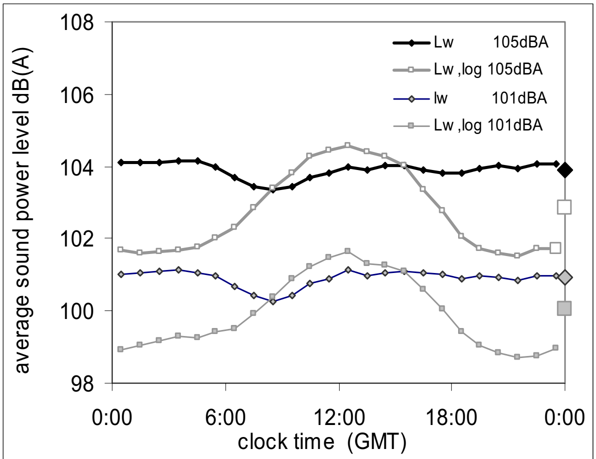

Figure VI.14: hourly averaged real and estimated (log) sound power level at ‘105.1dB(A)’ and ‘101.0dB(A)’ power curves

The differences between actual and logarithmically predicted sound power levels can be bigger than the over one year hourly averaged values in figure VI.14 show. This is illustrated in figure VI.15 for two days each in January and July 1987 (also shown in figure VI.3) where actual and predicted half-hour sound power levels are plotted as a function of 10-m wind velocity. On both winter days actual sound power agrees within 1 dB with the predicted sound power for wind velocities $V_{10} > 5.5$ m/s; at lower 10-m wind velocities actual levels are rather higher for most of the time. On both summer days the 10-m wind velocities are lower than in winter, and sound power level now is more often higher than predicted and can reach near maximum levels even at very low (2.5 m/s) 10-m wind velocities (when at ground level people will probably feel no wind at all). In these conditions residents in a quiet area will perceive the highest contrast: hardly or no wind induced sound in vegetation, while the turbine(s) are rotating at almost top speed. In these conditions also an increased fluctuation strength of the turbine sound will occur (see chapter V), making the sound more conspicuous.

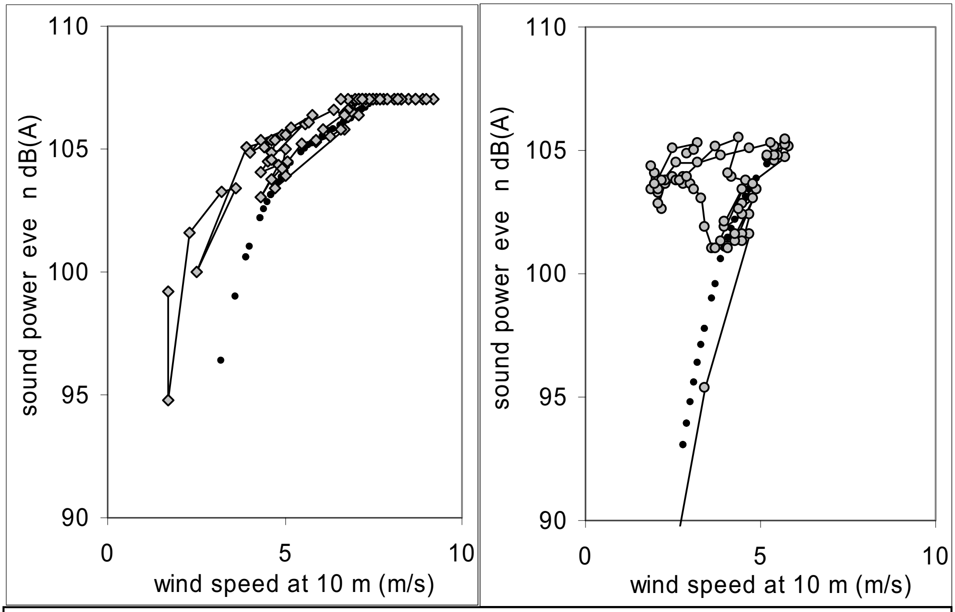

Figure VI.15: half-hourly progress of actual (grey diamonds) and logaritmically predicted (black dots) sound power level plotted vs. 10-m wind speed over 48 hours; left: January 13-14; right: July 2-3

VI.6 Other onshore results

Values of wind shear have been reported by various authors, showing similar results. Pérez *et al* [2005] measured wind velocities up to 500 m above an 840 m altitude plateau north of Valladolid, Spain, for every hour over sixteen months. The shear exponent, calculated from the wind velocity at 40 m and 220 m, varied from 0.05 to 0.95, but was more usual between 0.1 and 0.7. High shear exponents occurred more often than in Cabauw: $m > 0.48$ for 50% of the time. This is likely the result of the more southern position: insolation is higher, causing bigger temperature differences between day and night, and the atmosphere above the plateau is probably drier causing less reflection of outward infrared radiation at night. There was a distinct seasonal pattern, with little day-night differences in January, and very pronounced differences in July.

Smith *et al* [2002] used data from wind turbine sites in the US Midwest over periods of 1.5 to 2.5 years and calculated shear exponents for wind velocities between a low altitude of 25 - 40 m and a high altitude of 40 123 m. At four sites the hourly averaged night time (22:00 6:00) shear exponent ranged from 0.26 to 0.44, in daytime from 0.09 to 0.19. The fifth station (Ft. Davis, Texas) was exceptional with a day and night time wind shear below 0.17 and a very low day time wind shear (*m* 0.05).

Archer *et al* [2003] investigated wind velocities at 10 m and 80 m from over 1300 meteorological stations in the continental USA. No shear statistics are given, but for 10 stations the ratio V_{80}/V_{10} is plotted versus time of day. At all these stations the ratio is 1.4 ± 0.2 in most of the daytime and 2.1 ± 0.3 in most of the night time. Using equation III.4, it follows that the shear exponent has a value of 0.15 ± 0.07 and 0.35 ± 0.07, respectively.

At the 2005 Berlin Conference on Wind Turbine Noise two presentations added to these wind shear data, now (also) from a noise perspective. Harders *et al* [2005] showed hourly wind velocity averaged over the year 2000 at altitudes between 10 and 98 m from the Lindenberg Observatory near Berlin. The results are very much like those in figure VI.2, with a wind velocity ratio V_{80}/V_{10} 1.3 at noon, increasing to 1.9 in night time

hours. This corresponds to an avarage shear exponent of 0.13 and 0.3, respectively.
Botha [2005] presented results from 8 to 12 months measurements at sites in two flat Australian areas and two sites in more complex (non flat) New Zealand terrain. On the Australian sites the average day time wind velocity ratio V_{80}/V_{10} was 1.5, in night time 1.7 and 1.8. This corresponds to shear exponents of to 0.19 and 0.26 to 0.28, respectively. In the hilly New Zealand areas the average wind velocity ratio was between 1.2 and 1.25 in day as well as night time, from which the shear exponent can be calculated as 0.1.

From the measurements at the Rhede wind farm the shear exponent could be calculated from the 10-m and 100-m wind velocity, the latter determined from the sound level and the relation between sound power level and hub height (100 m) wind velocity. This was done for all (892) five minute periods when wind turbine sound was dominant between 23:00 and 04:00 hours within the measurement period (May and June; location A in figure IV.2). From the Cabauw data the same period and time was selected and all values of the half-hour shear exponent $m_{10,80}$ were determined. For both locations the resulting frequency distributions of the shear exponent are plotted in figure VI.16. The distributions are rather similar and show that a stable atmosphere (m > 0.25) occurred for over 95% of the time in night time hours (23 4 o'clock) in spring (May June) at Cabauw as well as at Rhede.

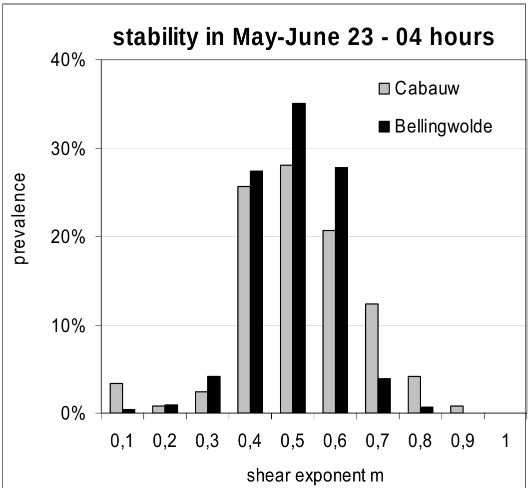

Figure VI.16: frequency distribution of the shear exponent at Cabauw and in the measurement period near the Rhede wind farm in the same period of time

VI.7 Conclusion

Results from various landward areas show that the shear exponent in the lower atmospheric boundary layer (< 200 m) in daytime is 0.1 to 0.2, corresponding to a wind velocity ratio V_{80}/V_{10} of 1.25 to 1.5. The associated wind profile is comparable to the profile predicted by the well-known logarithmic wind profile for low roughness lengths (low vegetation).

At night the situation is quite different and in various landward areas the shear exponent has a much wider range with values up to 1, but more usually between 0.25 and 0.7. Near the Rhede wind farm the same range of wind shear occurred, showing that the site indeed was suitable to study the effect of atmospheric stability on wind turbine performance and representative for many other locations.

A shear exponent $0.25 < m < 0.7$ means that the ratio V_{80}/V_{10} varies between 1.7 and 4.3. High altitude wind velocities are thus (much) higher than expected from logarithmic extrapolation of 10-m wind velocities.

A high wind shear at night is very common and must be regarded a standard feature of the night time atmosphere in the temperate zone and over land. In fact the atmosphere is neutral for only a small part (approximately 10%) of the time. For the rest it is either stable (sun down) or unstable (sun up).

As far as wind power concerns, the underestimate of high altitude night time wind velocity has been compensated somewhat by the overestimate of high altitude daytime wind velocity. This may partly explain why, until recently, atmospheric stability was not recognized as an important determinant for wind power.

To assess wind turbine electrical and sound power production the use of a neutral wind profile should be abandoned as it yields data that are not consistent with reality.

VII THINKING OF SOLUTIONS: measures to mitigate night time wind turbine noise

VII.1 Meeting noise limits

Sound from modern wind turbines is predominantly the result of turbulence on the blades; reduction of this source is the topic of dedicated research, such as the SIROCCO (*Si*lent *ro*tors by a*c*oustic *o*ptimisation) program which seeks to improve the design of the wind turbine blade; in the near future a reduction of approximately 2 dB might be achieved [Schepers *et al* 2005]. Sound reduction by reducing blade speed is an option already available in modern turbines.

In this chapter we will deal with the ('added') sound produced by a wind turbine due to increased atmospheric stability. To address this problem two types of mitigation measures can be explored:

1. reduce the sound level down to to the pertinent (legal) limit for environmental noise;
2. reduce the level variations due to blade swish/beating.

The first measure of course must be pursued as it is a legal obligation. The need for reduction depends on the type of limit. *E.g.*, in Germany the limit applies to the maximum sound immission level (the level produced at nominal maximum power), regardless of wind velocity as such. In many countries the limit is based on the wind velocity related background ambient sound level (L_{95} or L_{90}). In the UK and elsewhere the limit is a constant at low 10-m wind velocities and 5 dB above ambient background level (L_{90} + 5 dB) at higher 10-m wind velocities. In the Netherlands the standard limit is a reference curve constructed from a constant value at low 10-m wind velocities and a wind velocity dependent part at higher 10-m wind velocities (see figure VII.1). For wind farms over 15 MW other limit values may apply, and local authorities may enforce other limits in 'non-standard' local conditions.

In assessments of wind turbine noise immission the effect of atmospheric stability has usually been disregarded and the 10-m wind velocity was erroneously used for all atmospheric conditions. In that case high sound levels only occur at high wind velocities and this can be accommodated by limit values as in figure VII.1. In reality however these limits are not always met as high immission sound levels already occur at a lower 10-m wind velocity. This implies that an extra effort to reduce the immission level may be necessary.

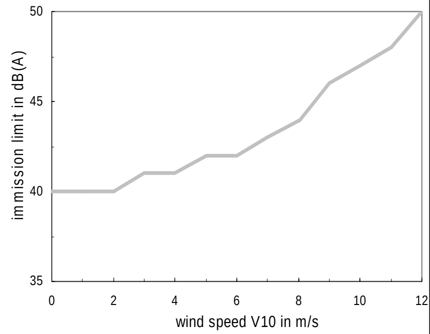

Figure VII.1: standard Dutch limit for night time wind turbine immission sound level

In hilly and certainly in mountainous terrain this change in wind profile may be influenced or even overridden by relief related changes. For example: in a valley a down flowing (decelerating) wind may enhance the effect of stability, whereas an up flowing (accelerating) wind may compensate the effect of stability. Furthermore the wind profile as well as the temperature profile will simultaneously influence the propagation paths of sound. Combined effects are therefore complex and, though readily understood qualitatively, not easily predicted quantitatively.

The second measure is worth considering when the noise limit incorporates a penalty for a sound having a distinctive (impulsive or fluctuating) character. In that case either the sound immission level should be reduced by a value equal to the penalty (usually 5 dB) or the sound character must change.

VII.2 Reduction of sound level

When the sound immission level is limited to a value depending on the 10-m wind velocity or the (supposedly 10-m wind velocity dependent) ambient sound level, the problem is that hub height wind velocity is not uniquely related to 10-m wind velocity and the sound emission as well as immission level can have a range of levels depending on atmospheric stability. The turbine thus operates at hub height wind velocity, but must be controlled by a 10-m based wind velocity. To decrease the sound level from a given turbine the speed of rotation can be decreased, either by directly changing blade pitch or indirectly by changing the mechanical load (torque) on the rotor. This implies a lower efficiency at the turbine as the tip speed ratio $\Omega \cdot R/Vo$ will decrease and deviate from its value optimized for produced power. It is necessary to find a new optimum that also takes noise production into account.

VII.2.1 Wind velocity controlled sound emission

As a result of opposition to wind farm proposals in the relatively densely populated central province of Utrecht in the Netherlands all proposals were cancelled but one. The exception is in Houten (incidentally 8 km east of Cabauw; see previous chapter), where the local authorities want to stimulate wind energy by allowing the constructing of several 3 MW turbines, at the same time ensuring that residents will not be seriously annoyed. Atmospheric stability is taken into account by not accepting the usual logarithmic relation between 10-m and hub height wind velocity. The official permission will require that the immission sound level at specified locations must not exceed the background level of all existing ambient sound. Of course ambient sound level depends on wind velocity if the wind is sufficiently strong, but in this area it also depends on wind direction as that determines audibility of distant sources: a motorway to the west, the town to the north-east and relatively quiet agricultural land to the south-east. So the ambient background level, measured as L_{95}, must be measured in a number of conditions: as a function of wind velocity (1 m/s classes), wind direction (4 quadrants) and time of day (day, evening, night). These values equal the limit values for the immission level L_{imm}, and from this it can be calculated what the maximum allowable sound power level L_{Wmax} per turbine is at every condition, presuming all (or perhaps a selection of) turbines produce. It is advisable to determine wind characteristics and turbine performance over a period of at least five minutes, as wind velocity variations are relatively strong at frequencies above approximately 3 mHz (inverse of 5 min) and weak at lower frequencies down to the order of 0.1 mHz (inverse of several hours) [Wagner *et al* 1996]. On the other hand it is desirable to adapt to changing conditions, so averaging over 5 minutes seems a good choice.

Control will thus be achieved in a number of steps:

1. measure wind direction D_{10} and wind velocity V_{10} in open land over a 5-minute period; from this determine the ambient back ground level from the previously established relation $L_{95}(D_{10},V_{10})$.
2. determine the limit value for the sound power level L_{Wmax} from the previously established relation $L_{imm}(L_W)$; the limit value is determined by L_{imm} L_{95}.
3. determine the actual sound power level $L_{W,5min}$ from wind turbine performance (electric power or speed);
4. if $L_{W,5min} > L_{Wmax}$ (equivalent to $L_{imm} > L_{95}$) the control system must decrease sound power level for the next period; if $L_{W,5min} < L_{Wmax}$ the reverse applies (until maximum speed is attained).

The pro's of this control system are that it is straightforward, simple, easy to implement and directly related to existing Dutch noise limits. However, it is based on the assumption that L_{95} depends on three parameters only: wind velocity, wind direction and diurnal period (day, evening, night). In reality background level will also vary within a diurnal period (*e.g.* traffic: nights are very quiet at around 4 AM and most busy just before 7 AM), and it will depend on the day of the week (*e.g.* Sunday mornings are quieter than weekday mornings), the season (vegetation, holidays), the degree of atmospheric stability (no wind in low vegetation in stable conditions, even when 10-m wind velocity is several m/s) and other weather conditions such as rain. Also sound immission from distant sources will differ with weather conditions.

Measurements show that indeed 10-m wind velocity is not a precise predictor of ambient sound level. These measurements were performed from June 9 through June 20, 2005 at two locations: wind velocity was measured at 10-m height in open terrain, at least 250 m from any obstacles over 1 m height (trees lining the busy and broad Amsterdam-Rhine Canal to the northeast) and over 1000 m from obstacles in any other direction; the sound level was measured close to a farm next to the canal (see figure VII.2). Total measurement time was 220 hours.

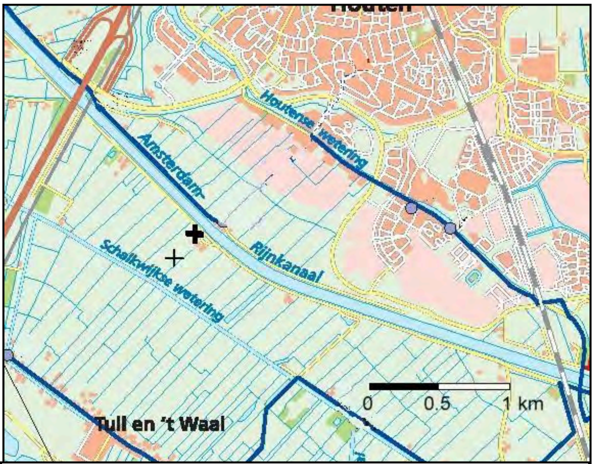

Figure VII.2: measurement locations for wind speed and direction (light cross) and ambient sound level (heavy cross) close to Houten (in upper part of map); top is north

Some results are plotted in figure VII.3: L_{95} per 5-minute period as a function of wind velocity, separately for two opposite wind directions (left and right panel) and two periods (black and blue markers). The periods are night (23 PM 7 AM) and day (7 AM 7 PM), the wind directions southeast (90° - 180° relative to north) and northwest (270° - 360°), where respectively the lowest and highest ambient levels were expected. The northwest data total 675 5-minute periods or 26% of all measurement time, the southeast data cover 511 periods or 19% of the measurement time.

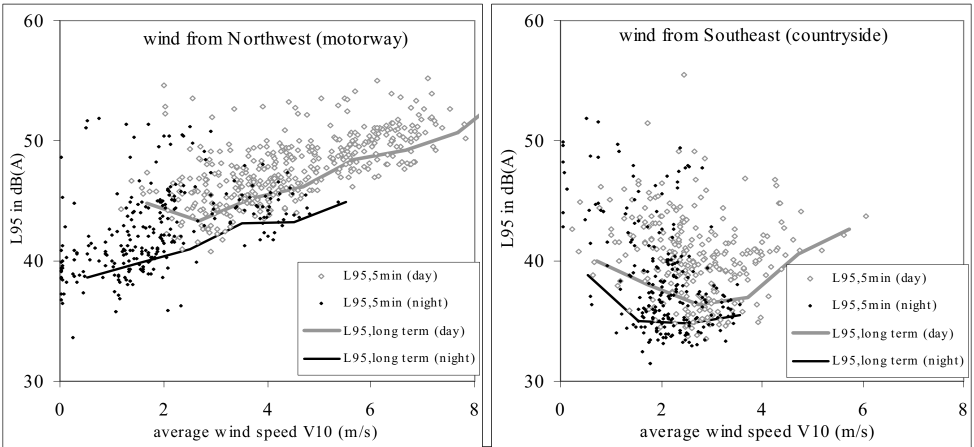

Figure VII.3: 5-minute $L_{95,5min}$ in day (open, grey diamonds) and night time (solid, black dots) and long-term L_{95} (lines) as a function of 10-m wind velocity in open terrain for two different wind directions

The values of $L_{95,5min}$ are calculated from all (300) 1-second samples of the sound pressure level within each 5-minute period, wind velocity is the average value of all 1-second samples of the wind velocity. To determine a long-term background level an appropriate selection (wind direction, period) of all measured 1-second sound levels can be aggregated in 1 m/s wind velocity classes (0-1 m/s, 1-2 m/s, etc.). In figure VII.3 these aggregated values (connected by lines to assist visibility) are plotted for day and night separately. It is clear that in many cases the 5-minute period values of L_{95} are higher, in less cases lower than the long-term value. This means that if the immission limit is based on the measured long-term background sound level, then in a significant amount of time the actual background level will not be equal to the previously established long-term background level. In many instances the actual value of L_{95} is higher than the long-term background level $L_{95,lt}$, which would allow for more wind turbine sound at that time.[1]

VII.3.2 Ambient sound level controlled sound emission

An alternative to a wind velocity controlled emission level is to measure the ambient sound level itself and thus determine the actual limit value directly. If the limit is L_{95}, then the immission level must be $L_{imm} \leq L_{95}$. To achieve this the background ambient sound level can be determined by measurement (*e.g.* in 5-minute intervals) and compared to the immission level calculated from the actual turbine performance. If the immission level L_{imm} would exactly equal the ambient background level L_{95} without turbine sound, it would attain its maximum value $L_{imm,max}$ L_{95}. Then background sound level including turbine sound would be L_{95+wt} log.sum($L_{imm,max}$ + L_{95}) $L_{imm,max}$ + 3 dB or $L_{imm,max}$ L_{95+wt} - 3 dB. If the calculated immission level exceeds the measured ambient level L_{95+wt} - 3, turbine sound apparently dominates the background level and the turbine should slow down.

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[1] perhaps for this reason the approach in the British ETSU-R-07 guideline [ETSU 1996] is to not use the long-term $L_{A90,lt}$, but an average of 10 minute $L_{A90,10min}$ values; this odd statistical construction can be viewed as an inefficient compromise that effectively allows excess of an appropriate limit in half of the time and a too severe limit in the other half

This type of control can also be achieved in several steps. Again assuming 5-minute measurement periods, these are:

1. determine the actual sound power level $L_{W,5min}$ (integrated over 5 minutes) from turbine power production or speed.
2. determine L_{imm} from the previously established relation $L_{imm}(L_W)$.
3. measure actual background level $L_{95+wt,5min}$ at a location where the limit applies;
4. if $L_{imm} > L_{95+wt,5min}$ 3 dB, then $L_{W,5min} > L_{Wmax}$ and the control system must decrease sound power level for the next 5-minute period, if $L_{W,5min} < L_{Wmax}$ the reverse must happen (until maximum speed is attained).

Here it is assumed that the microphone is on a location where immission level must not exceed the ambient background level. If a measurement location is chosen further away from the turbine(s), the immission sound level will decrease with a factor ΔL_{imm} at constant L_W, whereas L_{95} will not change (assuming that 5-minute ambient background sound does not depend on location). In this case a correction must be applied to the measured L_{95+wt} ($L_{imm,max}$ L_{95+wt} $10 \cdot \log(1+10^{0,1 \cdot \Delta L_{imm}})$ to determine what sound power level is acceptable. An advantage of a more distant measurement location is that it is less influenced by the turbine sound. A similar approach may be used if the limit is not L_{95} itself, but L_{95} + 5 dB. In that case, is it not possible to determine L_{95} from measurements at a location where this limit applies, as the turbine sound is allowed to be twice as intense as background sound itself. In that case a measurement location may be chosen where, *e.g.*, ΔL_{imm} 5 dB.

An apparent drawback of this sound based control is that measured ambient sound may be contaminated by local sounds, that is: from a source close to the microphone, increasing only the local ambient sound level. Also, figure VII.3 suggests that there are significant variations in $L_{95,5min}$, which could imply large control imposed power excursions if these variations occur in short time.

The first drawback can be solved by using two or more microphones far enough apart not to be *both* influenced by a local source. The limit value is then either $L_{95,5min}$ determined from all measured sound levels within the previous 5-minute period, or the lowest value of $L_{95,5min}$ from each microphone location. It must be borne in mind that the value of $L_{95,5min}$ is not sensitive to sounds of short duration. Sounds from birds or passing vehicles or airplanes do not influence a measured $L_{95,5min}$ significantly, except when they are present for most of the time within the 5 minute period.

With regard to the second point: large variations in either wind velocity or background sound level are rare, as is shown in figure VII.4 where the difference is plotted between consecutive 5-minute values of L_{95} and average free 10-m wind velocity. The change in wind velocity averaged over consecutive periods of 5 is less than 0.5 m/s in 72% of the time, and less than 1.5 m/s in 99% of the time. The change in background sound level over consecutive periods of 5 minutes is less than 2.5 dB in 88% of the time and less than 3.5 dB in 94% of the time. So, if the adjustment of sound power level is in steps no larger than 3 dB, most changes can be dealt with in a single step. This also holds when a longer averaging period of 15 minutes is chosen: the change in background sound level over

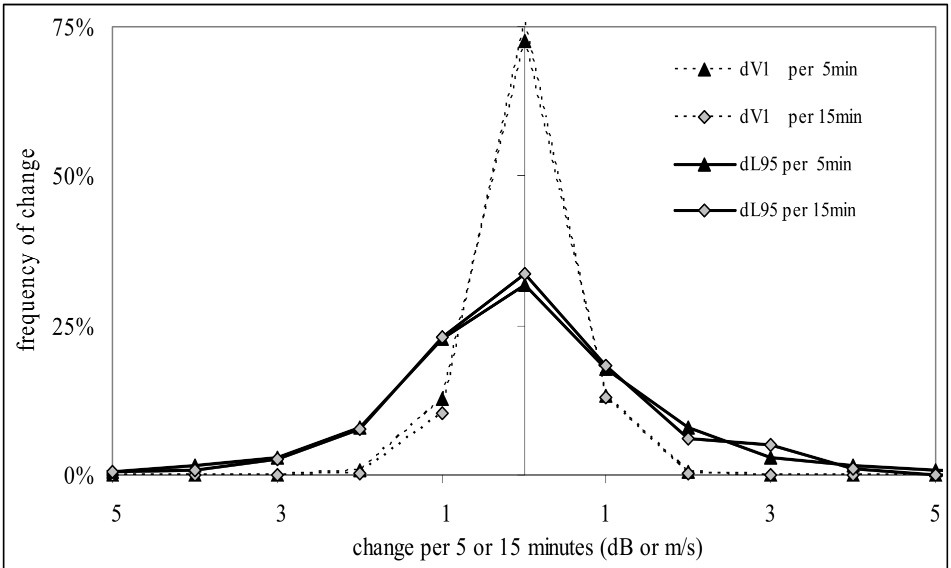


Figure VII.4: frequency distributions of changes per 5 and per 15 minutes of average wind velocity and background ambient sound level in classes of one unit (dB or m/s)

consecutive periods of 15 minutes is less than 2.5 dB in 89% of the time and less than 3.5 dB in 96% of the time.
The frequency of changes between 5-minute periods that are 10 minutes apart (that is: with two 5-minute periods in between) is very similar to the distributions in figure VII.4. This means that when there is a change of 3 dB for two consecutive periods, it is unlikely a similar change occurs within the next one or two periods.

VII.4 Reduction of fluctuations in sound level

The level variation due to blade swish increases when the atmosphere becomes more stable because the angle of attack on the blade changes. As a result the turbulent layer at the trailing edge of the blade becomes thicker and produces more sound. In a wind farm the increased level variations from two or more turbines turbines may coincide to produce still higher fluctuations. The increase of blade swish, or rather: blade beating, may be lessened by adapting the blade pitch angle, the increase due to coincidence (also) by desynchronizing turbines.

VII.4.1 Pitch angle

When a blade rotates in a vertical plane the optimum blade pitch angle α is determined by the ratio of the wind velocity and the rotational speed of the blade. As the rotational speed is a function of radial distance (from the hub), blade pitch changes over the blade length and is lowest at the tip. As the wind velocity closer to the ground is usually lower, the wind velocity at the low tip (where the tip passes the tower) is lower than at the high tip. As a result the angle of attack changes within a rotation if blade pitch is kept constant. For a 100 m hub height and 70 m diameter turbine at 20 rpm this change (relative to hub height) is about 0.5° at the lower tip in an unstable atmosphere, increasing to almost 2° in a very stable atmosphere (see section V.1). Added to this is a further change (of the order of 2°) in the angle of attack in front of the tower due to the fact that the tower is an obstacle slowing down air passing the tower. At the high tip the change in angle of attack is -0.3º (unstable) to -1.7º (very stable).

The optimum angle of attack of the incoming air at every position of the rotating blade can be realized by adapting the blade pitch angle to the local wind velocity. Pitch must then increase for a blade going upward and decrease on the downward flight. Such a continuous change in blade pitch is common in helicopter technology. If the effect of stability on the wind profile would be compensated by pitch control, blade swish due to the presence of the tower would still be left. This residual blade swish can be eliminated by an extra decrease in blade pitch close to the tower. If the variations in angle of attack can be reduced to 1° or less, blade swish will cause variations less than 2 dB which are not perceived as fluctuating sound.

VII.4.2 Rotor tilt

If the rotor is tilted backwards, a blade element will move forward on the downward stroke and backward on the upward stroke, thus having a varying velocity component in the direction of the wind. As a result the angle of attack will change while the blade rotates because the flow angle will depend on blade position. If the tilt angle changes from zero to θ, the flow angle at the low tip increases from φ to φ' (see figure III.2). From geometrical considerations (see figure VII.5) of a blade segment tilted around a horizontal axis, it follows that $C \cdot \sin\varphi + r \cdot \tan\theta \quad r \cdot \tan(\theta + \gamma)$, where $\gamma \quad \arctan(C\sin\varphi/r)$. This leads to:

$$\sin\varphi' \quad S \cdot (\tan[\theta + \arctan(\sin\varphi/S)] \quad \tan\theta) \quad \text{(VII.1)}$$

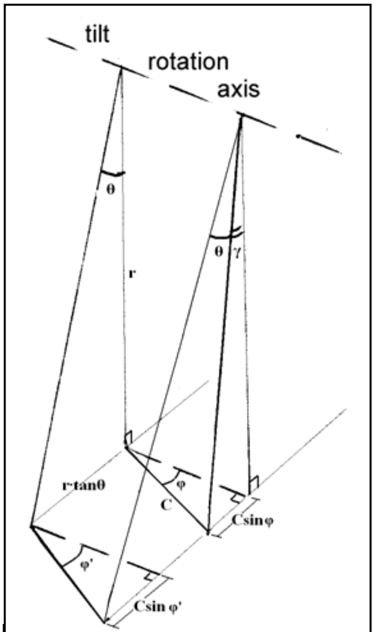


Figure VII.5: change of flow angle φ → φ' when blade is tilted over an angle θ around a horizontal axis

where S r/C is the ratio of radius r and blade width (or chord length) C at radius r. For small blade pitch angles and blade slenderness S between 10 and 40 the increase of blade pitch with tilt (from 0 to θ) can be approximated with:

$$\Delta\varphi \quad \varphi' \quad \varphi \quad 1.1\cdot\varphi\cdot\theta^2 \qquad \text{(angles in radians)} \qquad \text{(VII.2a)}$$

For values of φ, S and θ in the range $\varphi \leq 10°$, $30 \leq S \leq 50$ and $\theta \leq 20°$, the standard deviation of the constant 1.1 is 0.01. With angles expressed in degrees, equation VII.2a reads:

$$\Delta\varphi \quad 33\cdot 10^{\;5}\cdot\varphi\cdot\theta^2 \qquad \text{(angles in degrees)} \qquad \text{VII.2b)}$$

This means that for a tilt angle of 2° and a 6° blade pitch (tip rotational speed 70 m/s, induced wind velocity 10 m/s, angle of attack 2º), the change in angle of attack (relative to a vertical rotor with zero tilt) is negligible (0.008°). Rotor tilt could now compensate a 1° change in angle of attack at the low tip when the tilt angle is 22°. In this case the horizontal distance between the low tip and the turbine tower increases with approximately 15 m. This will in turn lead to a smaller change in angle of attack as at this distance the velocity deficit due to the presence of the tower is lower. For higher values of the blade pitch angle (*ceteris paribus* implying lower values of the angle of attack) increasing the tilt angle has a bigger effect. A substantial tilt however has major disadvantages as it decreases the rotor surface normal to the wind and induces a flow component parallel to the rotor surface which again changes the inflow angle. It therefore does not seem an efficient way to reduce the fluctuation level

VII.4.3 Desynchronization of turbines

When the atmosphere becomes stable, large scale turbulence becomes weaker and wind velocity is more coherent over larger distances. The result is that different turbines in a wind farm are exposed to a wind with less variations, and near-synchronization of the turbines may lead to coincidence of blade beats from two or more turbines for an observer near the wind farm, and thus higher pulse levels (see section V.2.4). To desynchronize the turbines in this situation, the random variation induced by atmospheric turbulence (such as occurs in an unstable and neutral atmosphere) can be simulated by small and random fluctuations of the blade pitch angle or the electric load of each turbine separately.

In an unstable atmosphere turbulence strength peaks at a non-dimensional frequency n $fz/V \approx 0.01$, where V is the mean wind velocity and z is height (this is according to custom in acoustics; in atmospheric physics traditionally f is non-dimensional and n physical frequency). At z 100 m and V 10 m/s this corresponds to a physical frequency f nV/z 1 mHz. At higher frequencies the turbulence spectral power density decreases with $f^{\ 5/3}$. When atmospheric instability decreases, the maximum shifts to a higher frequency and wind velocity fluctuations in the non-dimensional frequency range of 0.01 to 1 tend to vanish. So, to simulate atmospheric turbulence the blade pitch setting of each turbine (or the load imposed by the generator) must be fed independently with a signal corresponding to noise such as pink ($f^{\ 1}$) or brown ($f^{\ 2}$) noise, in the range of appr. 1 to 100 mHz. The (total) amplitude of this signal must be determined from local conditions, but is of the order of 1°.

VII.5 Conclusion

Wind turbine noise has shown to be a complex phenomenon. In the future quieter blades will be available, reducing sound emission by some 2 dB. The only presently available effective measures to decrease the sound impact of modern turbines are to create more distance or to slow down the rotor.

In existing turbines the sound immission level can be decreased by controlling the sound emission, which in turn is decreased by slowing down the rotor speed. When the limit is a single maximum sound immission level, this in fact dictates minimum distance for a given turbine and there is no further legal obligation to control.

In other cases the control strategy will depend on whether the legally enforced limit is a 10-m wind velocity or an ambient background sound level dependent limit. The 10-m wind velocity or the background sound level act as the control system input, blade pitch and/or load on the rotor is the controlled parameter. In both cases a suitable place must be chosen to measure the input parameter. For background sound level as input it is probably necessary to use two or more inputs to minimize the influence of local (near-microphone) sounds. It may however be the best strategy in

relatively quiet areas as it controls an important impact parameter: the level above background or intrusiveness of the wind turbine sound.
Controlling sound emission requires a new strategy in wind turbine control: in the present situation there is usually more room for sound in daytime and in very windy nights, but less in quiet nights.

A clear characteristic of night time wind turbine noise is its beating character. Even if the sound emission level does not change, annoyance may decrease by eliminating the rhythm due to the blades passing the tower. Again, a lower rotational speed will help as this reduces the overall level including the pulse level. A better solution is to continuously change the blade pitch, adapting the angle of attack to local conditions in each rotation. This will also be an advantage from an energetic point of view as it optimizes lift at every rotor angle, and it will decrease the extra mechanical load on the blades accompanying the sound pulses.
When the impulsive character of the sound is heightened because of the interaction of several turbines in a wind farm, this may be eliminated by adding small random variations to the blade pitch, mimicking the random variations imposed by atmospheric turbulence in daytime when this effect does not occur.

Figure VIII.0: foam wind screens

VIII RUMBLING WIND: wind induced sound in a screened microphone

VIII.1 Overview of microphone noise research

It is commonly known that a wind screen over a microphone reduces 'wind noise' that apparently results from the air flow around the microphone. An explanation for this phenomenon has been addressed by several authors. According to a dimensional analysis by Strasberg [1988] the pressure within a spherical or cylindrical wind screen with diameter D in a flow with velocity V, depends on Strouhal number Sr $\quad fD/V$, Reynolds number Re $\quad DV/\nu$ and Mach number M $\quad V/c$ (where ν is the kinematic viscosity of air and c the velocity of sound). Writing the rms pressure in a relatively narrow frequency band centered at frequency f as p_f, and in dimensionless form by division with ρV^2, Strasberg found: $p_f/\rho V^2 \quad$ *function*(Sr, Re, M). Comparison with measured 1/3 octave band levels from four authors on 2.5 - 25 cm diameter wind screens, in air velocities ranging from 6 to 23 m/s yielded a definite expression for 1/3 octave frequency band:

$$20 \cdot \log_{10}(p_{1/3}/\rho V^2) \qquad 23 \cdot \log_{10}(f_m D/V) \quad 81 \qquad \text{(VIII.1)}$$

where f_m is the middle frequency of the 1/3 octave band. The data points agreed within appr. 3 dB with equation VIII.1 for $0.1 < fD/V < 5$, except for one of the fourteen data series where measured values diverged at $fD/V > 2$. Equation VIII.1 can also be written in acoustical terms by expressing the rms pressure as a sound pressure level relative to 20 µPa:

$$L_{1/3} \quad 40 \cdot \log_{10}(V/V_o) \quad 23 \cdot \log_{10}(f_m D/V) + 15 \qquad \text{(VIII.2)}$$

Here V_o is a reference velocity of 1 m/s and $\rho \quad 1.23$ kg/m^3 is used (air density at 1 bar and 10 °C). Equation VIII.2 is slightly different from the expression given by Strasberg because SI-units are used and terms in logarithms have been non-dimensionalized.

Morgan and Raspet pointed out that all measurements reported by Strasberg were made in low turbulence flows, such as wind tunnel flow [Morgan *et al* 1992]. Strasberg's result thus referred to the wake created by a wind screen and excluded atmospheric turbulence (as Strasberg had noted himself in his concluding remarks [Strasberg 1988]). Outdoors, however, the flow is turbulent, and induced pressure variations are expected to depend on meteorological parameters also. Morgan & Raspet applied Bernoulli's principle by decomposing the wind velocity U in a constant time-averaged velocity V and a fluctuation velocity u with a time average u   0, to obtain the rms pressure fluctuation $p \quad \rho V u$ [Morgan *et al* 1992] (in this chapter italics are used to denote the rms value x of a variable x: $x \quad \sqrt{x^2}$). This method can be compared to Strasberg's model for a microphone in turbulent water flow [Strasberg 1979]. Measurements in wind velocities of 3   13 m/s at 30.5 m and 1.5 m height for different screen diameters (90 and 180 mm) and screen pore sizes (10, 20, 40 and 80 ppi) yielded:

$$p \quad \alpha \cdot \rho (V u)^k \tag{VIII.3}$$

with α ranging from 0.16 to 0.26 and k from 1.0 to 1.3 [Morgan *et al* 1992]. For some measurements Morgan *et al* showed spectra over almost the same frequency range where equation VIII.1 is valid ($0.1 < fD/V < 5$). The spectra have a positive slope up to 3 Hz, possibly due to a non-linear instrumental frequency response. At higher values the slope is roughly comparable to what Strasberg found, but values of $20 \cdot \log_{10}(p_{1/3}/\rho V^2)$ are generally 8   20 dB higher as predicted by equation VIII.1, implying that atmospheric turbulence dominated expected wake turbulence.

Zheng and Tan tried to solve this problem analytically [Zheng *et al* 2003]. Their analysis applies to low frequency variations, so the velocity variation u is uniform over the wind screen. Zheng & Tan state that this assumption seems to be valid for a low screen number D/λ (< 0.3), the ratio between screen diameter and wavelength. Ignoring viscous effects (*i.e.* infinite Reynolds number), and calculating the pressure variation p(0) at the center of a spherical wind screen caused by pressure variations at the surface induced by a wind velocity U   V + u, they found p(0)   -½·ρVu or:

$$p(0) \quad \tfrac{1}{2}\rho V u \tag{VIII.4}$$

Comparison with equation VIII.3 shows that now α   0.5 and k   1.

Finally, in this overview, Boersma [1997] found that sound spectra due to wind measured at 1.5 m above flat, open grassland were in good agreement with Strasberg's results. However, Boersma used 95 percentile levels (L_{95}) which he estimated to be 6 to 13 dB lower than equivalent sound levels in the range considered ($30 < L_{95} < 70$ dB) [Boersma 1997], but he did not apply a level correction. So, in fact he found that his wind related spectra had slopes comparable to Strasberg's, but with a 6 13 dB higher value, not unlike the Morgan & Raspet spectra.

So, from literature we conclude that air turbulence creates pressure fluctuations especially at low frequencies, but the origin -wake or atmospheric turbulence- has not been definitely resolved.

In this chapter we will try to estimate the level of pressure variations due to atmospheric turbulence, *i.e.* the 'sound' pressure level taken from a sound level meter caused by turbulence on the microphone wind screen. First we will describe the spectral distribution of atmospheric turbulence and the effect this turbulence has on a screened microphone. Then we will turn to measured spectra related to wind, obtained by the author as well as by others. Finally the results will be discussed.

VIII.2 Atmospheric turbulence

A wind borne eddy that is large relative to the microphone wind screen (hence the change of wind velocity is nearly the same all over the wind screen) can be regarded as a change in magnitude and/or direction of the wind velocity [Zheng *et al* 2003]. The change in the magnitude of the velocity causes a change in pressure; the change in direction is irrelevant for a spherical wind screen as nothing changes relative to the sphere. As we saw in the previous section, when the velocity U is written as a constant (average) wind velocity V and a fluctuating part u, and similarly P $P_{average}$ + p, the relation between the rms microphone pressure fluctuation p and the rms wind velocity fluctuation u is p $\alpha\rho V u$. For inviscid flow α 0.5. For finite Reynolds numbers ($Re/10^4 \approx 0.5$ 15 for wind screens of 4 20 cm and wind velocities of 2 12 m/s), screening is better [Zheng *et al* 2003], and $\alpha \leq 0.5$; Morgan & Raspet [1992] found α 0.16 0.26. The pressure level due to atmospheric turbulence can be expressed as a sound pressure level L_{at} (with reference pressure p_{ref} 20 μPa):

$$L_{at}(u) \quad 20\cdot\log_{10}(\alpha\rho V u/p_{ref}) \qquad \text{(VIII.5)}$$

which is frequency dependent because of u.

VIII.2.1 Turbulence spectra

Turbulent velocity fluctuations v and w also exist perpendicular to the average wind velocity, in the vertical (w) as well as horizontal (v) direction, and are of the same order of magnitude as in the longitudinal direction [Jensen *et al* 1982]. Zheng & Tan [2003] showed that the effect of these fluctuations on the pressure at the microphone can be neglected in a first order approximation, as it scales with v^2 and w^2 and is therefore second order compared to the effect of the component u in line with the average wind velocity V that scales as Vu.

Atmospheric turbulence is treated in many papers and textbooks (such as [Jensen *et al* 1982, Zhang *et al* 2001]), also in reference to acoustics (see, *e.g.*, [Wilson *et al* 1994]). Here a short elucidation will be presented, leading to our topic of interest: turbulence spectra.

Atmospheric turbulence is created by friction and by thermal convection. Turbulence due to friction is a result of wind shear: at the surface the wind velocity is zero whereas at high altitudes the geostrophic wind is not influenced by the surface but a result of large scale pressure differences as well as Coriolis forces resulting from earth's rotation. In between, in the atmospheric boundary layer wind velocity increases with height z, equation III.2 is valid and for convenience repeated here :

$$V \quad (u_*/\kappa)\cdot[\ln(z/z_o) \quad \Psi] \qquad \text{(VIII.6)}$$

For $-1 < \zeta < 1$, $\Psi(\zeta)$ is of the same order of magnitude as the logarithmic term in equation VIII.6 ($2<\ln(z/z_o)<6$ for $1<z<5$ m, $1<z_o<10$ cm). Hence, at the same height and roughness length, V may still change appreciably due to (in)stability.

The friction created by wind shear produces eddies over a range of frequencies and lengths, their size determined by z and V. These eddies break up in ever smaller eddies and kinetic turbulent energy is cascaded to smaller sizes at higher frequencies, until the eddies reach the Kolmogorov size η_s (≈ 1 mm) and dissipate into heat by viscous friction. It has been shown by Kolmogorov that for this energy cascade, in the so-called inertial subrange of the turbulent spectrum, the frequency dependency follows the well known 'law of 5/3': the spectrum falls with $f^{\ 5/3}$.
It is customary in atmospheric physics to express turbulence frequency in dimensionless form n, with n fz/V (in fact n and f are usually interchanged, but we will use f for dimensional frequency, as is usual in acoustics). The seminal Kansas measurements showed that the squared longitudinal velocity fluctuation u_f^2 per unit frequency in a neutral atmosphere depends on frequency as [Kaimal *et al* 1972]:

$$f{\cdot}u_f^2/u_*^2 \quad 105n{\cdot}(1+33n)^{\ 5/3} \qquad \text{(VIII.7)}$$

The experimentally determined constants in this equation, the non-dimensional turbulent energy spectrum, are not exact, but are close to values determined by others [Garrat 1992, Zhang *et al* 2001]. For n << 1, the right-hand side approximates 105n, which, with n fz/V and equation VIII.6, leads to $u_f^2 \quad 105{\cdot}u_*^2{\cdot}z/V \quad 105\kappa^2 zV{\cdot}[\ln(z/z_o) \quad \Psi]^{\ 2}$. Applying this to VIII.5, the induced pressure level per unit of frequency appears to be independent of frequency, but increases with wind velocity (~ 30·logV).
For n >> 1 the right-hand side of equation VIII.7 reduces to $3.2{\cdot}(33n)^{\ 2/3}$, leading to $u_f^2 \quad 0.3{\cdot}u_*^2{\cdot}(V/z)^{2/3}{\cdot}f^{\ 5/3}$, which describes the inertial subrange. The frequency where the wind velocity spectrum VIII.7 has a maximum is $n_{max} \quad 0.05$ or $f_{max} \quad 0.05V/z$. As sound measurement are usually at heights $1 < z < 5$ m, f_{max} is less than 1 Hz for wind velocities V < 20 m/s,

When insolation increases the surface temperature, the atmosphere changes from neutral to unstable and eddies are created by thermal differences with sizes up to the boundary layer height with an order of magnitude of 1 km. Turbulent kinetic energy production then shifts to lower frequencies. In contrast in a stable atmosphere, where surface temperature decreases because of surface cooling, eddy production at low frequencies (corresponding to large eddy diameters) is damped and the spectral maximum shifts to a higher frequency up to appr. n 0.5 for a very stable atmosphere. As low-altitude wind velocities (z < 5 m) in a stable atmosphere are restricted to relatively low values (for higher wind velocities, stability is disrupted and the atmosphere becomes neutral), the spectral maximum may shift up to $0.5V/z \approx 3$ Hz. The inertial subrange thus expands or shrinks at its lower boundary, but its frequency dependency follows the 'law of 5/3'.

VIII.2.2 Effect on microphone in wind screen

The spectrum of longitudinal atmospheric turbulence in the inertial subrange was described in the previous section with the (squared) rms value of velocity variation per unit frequency $u_f^2 \;\; 0.3 \cdot u_*^2 \cdot (V/z)^{2/3} \cdot f^{\;\;5/3}$. It is convenient to integrate this over a frequency range f_1 - f_2 to obtain a 1/3-octave band level ($f_m \;\; 2^{\,1/6} \cdot f_2 \;\; 2^{1/6} \cdot f_1$) with centre frequency f_m: $u_{1/3}^{\;2} \;\; 0.046 \cdot u_*^2 \cdot (f_m \cdot z/V)^{\,2/3} \qquad [0.215 \cdot u_* \cdot (f_m \cdot z/V)^{\,1/3}]^2$. Substituting u_* from equation VIII.6 and applying the result to equation VIII.5 for 1/3 octave band levels $L_{at,1/3}(f_m) \;\; 20 \cdot \log(\alpha\rho V u_{1/3}/p_{ref})$, yields:

$$L_{at,1/3}(f) \quad 40 \cdot \log(V/V_o) \quad 6.67 \cdot \log(zf/V) \quad 20 \cdot \log[\ln(z/z_o) - \Psi] + C \qquad \text{(VIII.8)}$$

Here the frequency index m as well as the logarithm index 10 have been dropped, as will be done in the rest of the text. In equation VIII.8 C $20 \cdot \log(0.215\kappa\alpha\rho V_o^{\,2}/p_{ref}) \;\; 62.4$ dB for $\kappa \;\; 0.4$, $\alpha \;\; 0{,}25$, $\rho \;\; 1{,}23$ kg/m^3 and pressure level is taken re $p_{ref} \;\; 20$ µPa. For octave band levels $L_{at,1/1}(f)$ the constant C in the right hand side of VIII.8 is 67.2 dB.

Equation VIII.7 does not apply to frequencies where eddies are smaller then the wind screen. The contribution of small eddies will decrease proportional to the ratio of eddy size (ℓ^2, where ℓ is the eddy length scale and $f \;\; V/\ell$) and wind screen surface πD^2. When this ratio decreases more eddies will simultaneously be present at the screen surface and resulting pressure fluctuations at the surface will more effectively cancel one another in the interior of the wind screen. The pressure variation in the wind screen centre resulting from one eddy is proportional to the size of

the eddy relative to the screen surface, *i.e.* ℓ^2/D^2, but also the screen centre pressure resulting from the random contributions of all N eddies on the screen surface is proportional to $\sqrt{N}$, where $N \sim D^2/\ell^2$. The resulting screen centre pressure is thus proportional to individual eddy pressure p_f and $(\ell^2/D^2)\cdot\sqrt{(D^2/\ell^2)} \quad \ell/D \quad V/fD$. Consequently a factor $-20\cdot\log(fD/V)$ must be added to the resulting rms pressure level.
In wind noise reduction measured by Morgan there is a change in frequency dependency at screen number $D/\ell \approx 1/3$ ([Morgan 1993], see also [Zheng *et al* 2003]). We therefore expect at sufficiently high frequencies the pressure level at the microphone to decrease proportional to $20\cdot\log(D/\ell)$, relative to the level in equation (VIII.8), and this decrease must vanish when $D/\ell \quad Df/V < 1/3$, *i.e.* below the cut-off frequency $f_c \quad V/(3D)$. As the change will be gradual, a smooth transition can be added to equation VIII.8:

$$L_{at,1/3}(f) \quad 40\cdot\log(V/V_o) \quad 6.67\cdot\log(zf/V) \quad 20\cdot\log[\ln(z/z_o)-\Psi] +$$

$$10\cdot\log(1+(f/f_c)^2) + C \qquad \text{(VIII.9a)}$$

With usual screen diameters 5 25 cm and wind velocities 1 - 20 m/s, the cut-off frequency is in the range of 1 to 100 Hz. With the common 10 cm diameter wind screen f_c will usually be in the infrasound region. Equation VIII.9a can be rewritten with Strouhal number $Sr \quad fD/V$ as independent variable of a 'meteorologically reduced' 1/3 octave band level L_{red}:

$$L_{red,1/3} \quad L_{at,1/3} \quad 40\cdot\log(V/V_o) + 20\cdot\log[(z/D)^{1/3}\cdot(\ln(z/z_o)-\Psi)]$$

$$6.67\cdot\log(Sr) \quad 10\cdot\log[1+(3Sr)^2] + C \qquad \text{(VIII.9b)}$$

The levels according to equation VIII.9 have been plotted in figure VIII.1 for different wind velocities and with $z \quad 20\cdot D \quad 40\cdot z_o \quad 2$ m, $\Psi \quad 0$. For $f < 0.5\cdot f_c$ the term before C is less then 1 dB and equation VIII.9a reduces to equation VIII.8. For frequencies $f \gg f_c$ the term before C in equation VIII.9b reduces to $-20\cdot\log(3Sr)$ and equation VIII.9b can be written as:

$$L_{red,1/3} \qquad 26.67\cdot\log(Sr) + C - 9.5 \qquad \text{(VIII.10a)}$$

This can be rewritten in a aerodynamic terms as:

$L_{p,1/3}$ $20\cdot\log(p_{1/3}/\rho V^2)$ $26.67\cdot\log(Sr) + F(z) + C_p$ (VIII.10b)

where and $F(z)$ $20\cdot\log[(z/D)^{1/3}\cdot(\ln(z/z_o)-\Psi)$ and C_p $20\cdot\log(0.215\kappa\alpha)$ 9.5 -43 dB. For $F(z)$ -20 dB (*e.g.* a 10 cm diameter wind screen at a z 2 m, z_o 5 cm and Ψ 0) the right hand side of equation VIII.10b is $-26.67\cdot\log(Sr)$ 63. Comparing this with Strasberg's result (equation VIII.1 and gray lines in figure VIII.1) we see that the frequency dependency is slightly different, and levels are 13 - 19 dB higher (0.5 < Sr < 20), which is of the order of what we found in the measurements by Boersma and Raspet *et al* (see section VIII.1). The change in slope, visible at Strouhal number Df_c/V 1/3 in figure VIII.1, is a feature not explained by the earlier authors.

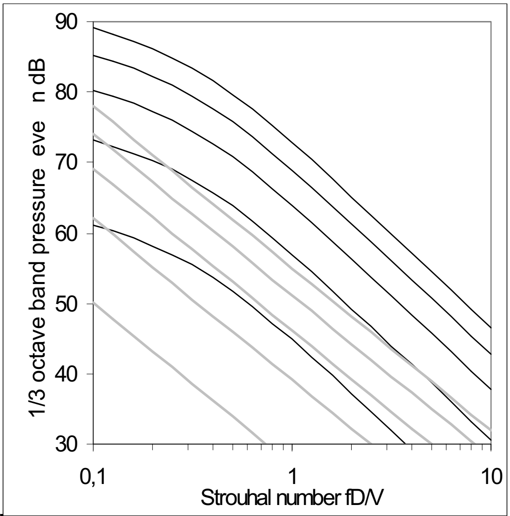


Figure VIII.1: black lines: calculated 1/3 octave band levels $L_{at,1/3}$ due to atmospheric turbulence at wind velocities of (bottom to top) 2, 4, 6, 8 and 10 m/s; F(z) = -18 dB; gray lines: levels at same wind velocities according to Strasberg

VIII.2.3 Frequency regions

From the theory above it can now be concluded that the wind induced pressure level on a (screened) microphone stretches over four successive frequency regions:

i. at very low frequencies (less than a few Hz) the turbulence spectrum is in the energy-producing subrange; 1/3 octave band pressure level $L_{at,1/3}$ is independent of frequency (white noise), but increases with wind velocity;
ii. at frequencies up to f_c 0.3V/D, which is usually in the infrasound region, the turbulence spectrum is in the inertial subrange, $L_{at,1/3}$ ~ $46.7\cdot\log V$ and ~ $6.7\cdot\log f$;
iii. at higher frequencies, but still in the inertial subrange, eddies average out over the wind screen more effectively at increasing frequency

($L_{at,1/3}$ ~ 26.7·log*f*), but pressure level increases faster with wind velocity ($L_{at,1/3}$ ~ 66.7·logV) ;

iv. at frequencies beyond 0.1V/η_s (see [Plate 2000, p. 585]) atmospheric turbulence enters the dissipation range and turbulence vanishes. This is in the range *Sr*   *fD/V* > 0.1*D*/η_s ≈ 100·[*D*/m]   *D*/cm.

The inertial subrange (ii and iii) is of most interest here, as it is within the commonly used range of acoustic frequency and level.

VIII.2.4 Wind induced broad band A-weighted pressure level

In figure VIII.2 1/3-octave band levels according to equation VIII.9 are plotted for different wind velocities for z   50·z_o 20·D   2 m (or F(z)   -20.5 dB with Ψ   0). Also levels are plotted after A-weighting to show the relevance to most acoustic measurements, where wind induced noise may be a disturbance added to an A-weighted sound level. At the frequency where turbulent eddies enter the dissipation subrange (*f* ≈ 0.1V/η_s), no data are plotted as the turbulent velocity spectrum falls very steeply and induced pressure levels are considered negligible. A-weighted pressure levels $L_{at,A}$ can be calculated by summing over all 1/3-octave bands. The wind velocity dependency can then be determined from the best fit of $L_{at,A}$ vs. V:

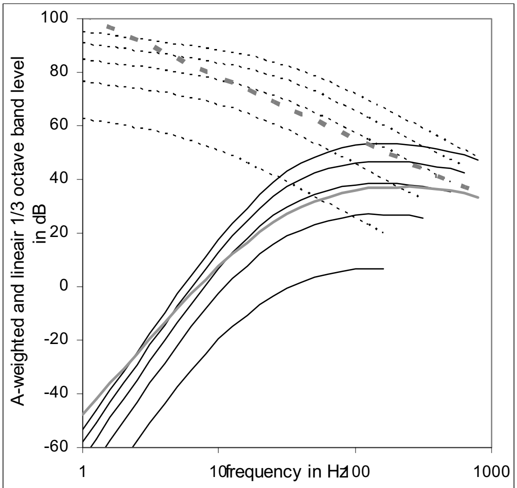


Figure VIII.2: calculated lineair (dashed) and A-weighted (solid lines) 1/3-octave pressure levels due to atmospheric turbulence on a screened microphone with F(z)+C=42 dB, D = 0.1 m and wind speeds 2, 4, 6, 8, 10 m/s (black, bottom to top); bold grey lines: 1/3 octave band levels according to Strasberg for 10 m/s

$$L_{at,A} \quad 69{,}4\cdot\log(V/V_o) \quad 26.7\cdot\log(D/\ell_o) + F(z) + C \quad 74.8 \qquad \text{(VIII.11a)}$$

where ℓ_o 1 m is a reference length. Equation VIII.11a has the same structure as VIII.10a, but a rather higher slope with logV because higher frequencies (with lower A-weighting) are progressively important, and a much smaller constant term as a result of A-weighting. The slope decreases with wind screen diameter and is 65.5 dB when D 1.25 cm (unscreened ½“ microphone), but is constant within 1 dB for 5 < D/cm < 50. Equation VIII.11a is not very sensitive for the cut-off at f 0.1V/η: if spectral levels are integrated over all frequencies, total level does not increase significantly at high wind velocities, and with less than 3 dB at low wind velocities. It will be noted that the slope with wind velocity is slightly higher than for individual spectral levels for $f > f$c (66.7 dB, see equation VIII.10a, due to lower A-weighting at the increasingly higher frequencies.
If we put G(z) F(z) $6.7\cdot\log(D/\ell_o) + 14$ $20\cdot\log[0.2\cdot(z/\ell_o)^{1/3}\cdot(\ln(z/z_o$ $\Psi)]$, and use 10D for convenience, equation VIII.11a becomes:

$$L_{at,A} \quad 69.4\cdot\log(V/V_o) \quad 20\cdot\log(10D/\ell_o) + G(z) + C \quad 68.8 \qquad \text{(VIII.11b)}$$

Now for z_o 2,5 - 6 cm and Ψ 0, G(2 m) 0 ± 1 dB. This means that for a 10 cm wind screen and measurement over a flat area with a low vegetation cover in neutral conditions $L_{at,A} \approx 69.4\cdot\log(V/V_o)$ 6.4 dB(A). Figure VIII.3 is a plot of equation VIII.11 with G(z) 0, C 62 dB. Also plotted in figure VIII.3 is the relation according to Strasberg, obtained by A-weighting and integrating equation VIII.2 over f.

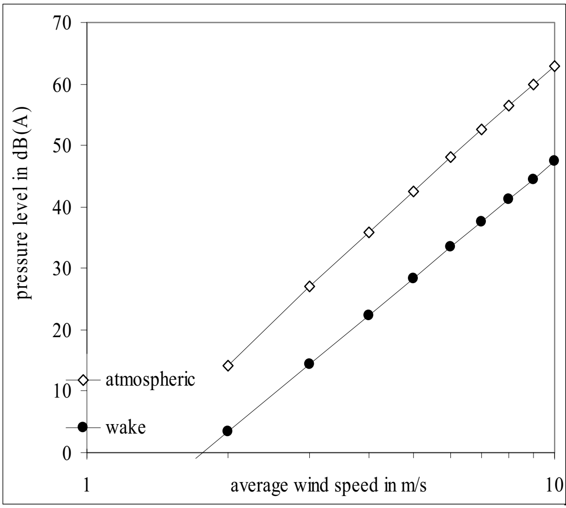


Figure VIII.3: calculated A-weighted broad band pressure level caused by atmospheric or wake turbulence with G(z)+C = 62.4 dB and D = 0.1 m

VIII.3 Comparison with experimental results

VIII.3.1 Measured spectral pressure levels

Several authors have performed measurements to determine spectral levels due to wind, including wind induced sound pressure fluctuations. We will use data from Larsson and Israelsson [1982], Jakobsen and Andersen [1983] and Boersma [1997] from screened as well as unscreened microphones. Table VIII.1 gives an overview of measurement parameters. None of the authors give the degree of stability, but in Jakobsen's data $\Psi \leq 0$ (night), in Boersma's $\Psi \geq 0$ (summer's day). Jakobsen mentions roughness height of the location (a golf course), Boersma grass height (≈ 10 cm), Larsson only mentions measurement height over grass at either 1.25 or 4 m, without specifying which height applies to a measurement result. To prevent using spectra at large values of $|\Psi|$ no data at low wind velocities (< 2 m/s at microphone) are used. This is also recommendable as at low wind velocity sound not related to wind is more likely to dominate. We preferably use L_{eq} data. However, these are not available from Boersma. Boersma used 95 percentile levels (L_{95}), but we have L_{50} values from the original data. Though Boersma quotes $L_{Aeq} \approx L_{A50}$, we will use $L_{Aeq} \approx L_{A50} + 3$, in agreement with long term data on wind noise [Van den Berg 2004b] and assume this to be valid for every frequency band. If measurements yielded octave band levels, 4.8 dB was subtracted to obtain the 1/3 octave band level at the same frequency.

Also L_{eq} values are presented from measurements made by the author at several locations; at one location (Zernike) for the purpose of wind noise measurements, and otherwise (Horsterwold, Kwelder) selected for having little other noise. Here also the degree of atmospheric stability is unknown, as at the time of measurement it was not known to be a relevant factor. The 'Zernike' measurements were done at the university grounds (latitude 53°14'43", longitude 6°31'48") with both the microphone (in a spherical foam screen of 2.5, 3.8 or 9.5 cm diameter) and the wind meter at 1.2 or 2.5 m over grass at least several hundred meters from trees, and an estimated roughness height of 5 cm. They were performed in daytime in December 2003 and august 2004 with a fair wind under heavy clouding.

The ‘Kwelder’ measurements were made in daytime or evening in July and August of 1996 at an open area at the Dutch coast (latitude 53°25’46”, longitude 6°32’40”), consisting of level land overgrown with grass and low weeds and close to tidal water. Sound measurements were taken at a height of 1.5 m at times when no sound could be heard but wind-related sound and distant birds. The microphone was fitted with a spherical 9.5 cm diameter foam wind screen. Wind velocity at microphone height at 1.5 m was estimated from measured wind velocity at 5 m height with equation VIII.6, z_o estimated as 2 cm. Finally the ‘Horsterwold’ measurements were made in December 2001 in an open space with grass and reeds (latitude 52°18’3”, longitude 5°29’38”) between 5 to 10 m high trees at a distance of approximately 30 m but further in the windward direction, in a mostly clouded night. Wind velocity and sound were measured at 2 m height, the wind screen was a 9 cm diameter foam cylinder. Due to the differences in vegetation, roughness length here was difficult to estimate, and was determined by fitting measurement results to the expected level (resulting in 60 cm and a more limited range of values of Ψ to fit).

At very low frequencies in our Zernike measurements the 1/3 octave band levels were corrected for non-linear response. The frequency response of the B&K ½" microphone type 4189 is specified by Brüel & Kjaer [B&K 1995] and is effectively a high pass filter with a corner frequency of 2.6 Hz. The response of the Larson Davis type 2800 frequency analyser is flat (±1 dB) for all frequencies.
To plot spectra we calculate the reduced pressure level $L_{red,1/3}$, leaving only the screen diameter based Strouhal number Sr fD/V as the independent variable. Octave band pressure levels $L_{red,1/1}$ are substituted by $L_{red,1/3}$ + 4.8. As atmospheric stability is as yet unknown, the stability function is set to zero. If wind velocity was not measured at microphone height, the logarithmic wind profile (equation (VIII.6 with Ψ 0, or III.3) is used to determine V_{mic} from the wind velocity at height h.

Linear spectra of 1/3-octave levels are plotted in the left part of figure VIII.4 for the unscreened microphones. Also plotted is the spectrum according to Larsson *et al* [1982], valid for the inertial subrange. Due to the small size of the unscreened microphone (1.25 cm) part of the spectrum lies in the dissipation range at frequencies f > 0.1V/η ≈ 100V/m, corresponding to Sr > 100D/m   1.25.

In figure VIII.4B spectra are plotted from screened microphones, from the data from Larsson, Jakobsen and Boersma. As these spectra were determined with a range of screen diameters, the change from the inertial to the dissipation subrange extends over a range of non-dimensional frequencies (Strouhal numbers). Finally figure VIII.4C shows spectra from the Horsterwold, Zernike and Kwelder measurements. In all figures spectra deviate from the predicted spectrum at high Strouhal numbers because either the lower measurement range of the sound level meter is reached or

Table VIII.1: wind induced noise measurement characteristics

author	period	location	zo (cm)	H_{wind} (m)	H_{mic} (m)	V_{mic} (m/s)	D (cm)	T (min.)	N [1]	F (Hz)	band width [6]
Larsson *et al*	late summer - early autumn	grass lawn	5 [2]	mic	1.25 or 4	2 – 7	no [4] 9.5	6 obs.[5]	9 9	63-8k	1/1
Jakobsen *et al*	summer – dec, night	golf course	2	10	1.5	3 – 7	9.5 / 25	? [5]	5 / 5	63-8k	1/1
Boersma	summer, day	grass land	3 [2]	2	1.5	3 – 7 2 – 9	no [4] 9	160 430	9 7	6-16k 6-16k	1/3
this study:											
Horster-wold	night, clouded	grass, reeds	60 [3]	10	2	4 - 6	9.5	230	4	31-8k	1/1
Kwelder	summer, day	grass, herbs	2 [2]	5	1.5	3 - 5	9.5	40	6	6-16k	1/3
Zernike	summer, clouded day	grass land	5 [2]	1.5	2.5	5	2.5/3.8 /9.5	30	3	6-1k	1/3
	winter, clouded day				1.2	4	3.8/9.5	20	2	1-1k	

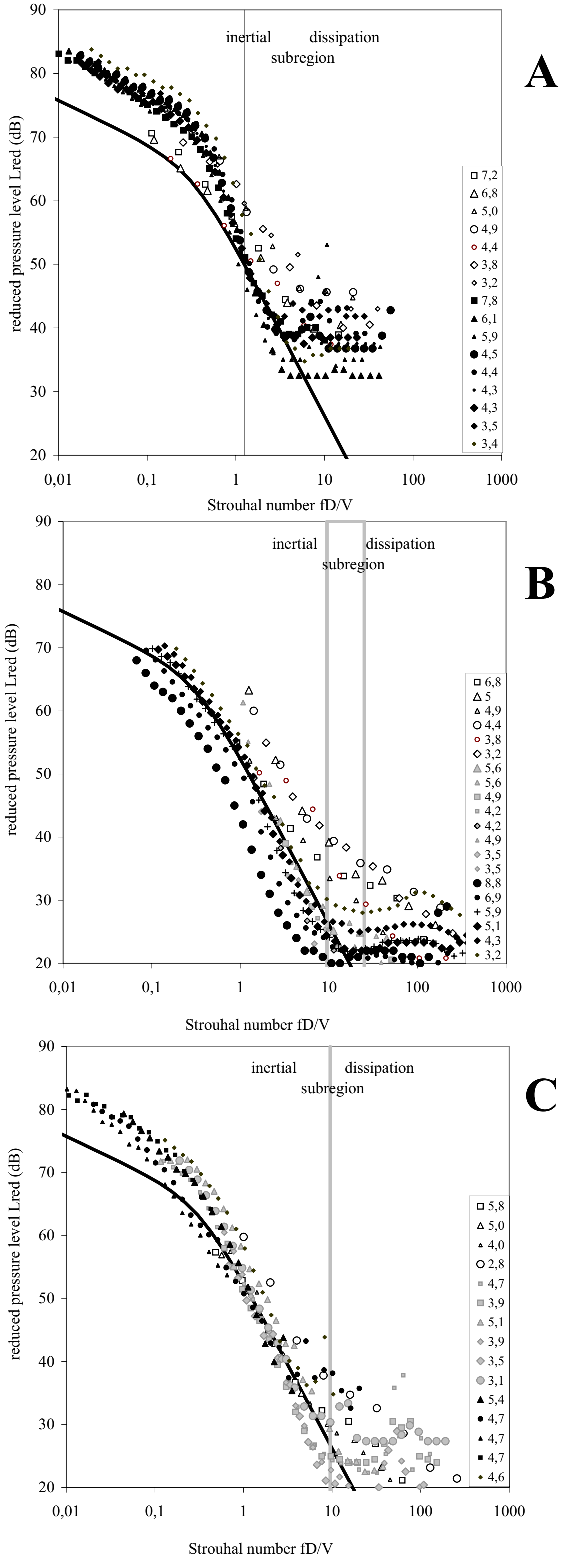
notes: 1: # of measurements 2: estimated; 3: fitted; 4: no = unscreened; 5: observations of unknown length; 6: 1/1 or 1/3 octave band

Figure VIII.4:
reduced 1/3 octave band pressure levels at different wind velocities (in legend: V in m/s), bold line is predicted spectrum;

A: unscreened microphone, from Larsson (open symbols) and Boersma (black symbols);

B: screened microphone, from Larsson (open symbols), Jakobsen (grey) and Boersma (black symbols);

C: screened microphone, measurements in Horsterwold (open symbols), Kwelder (grey) and Zernike (black symbols).



A

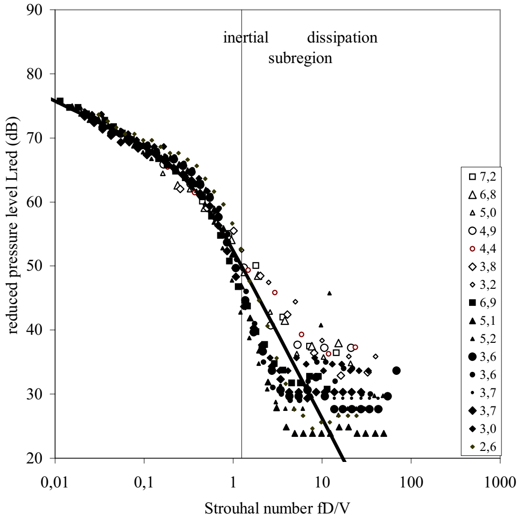
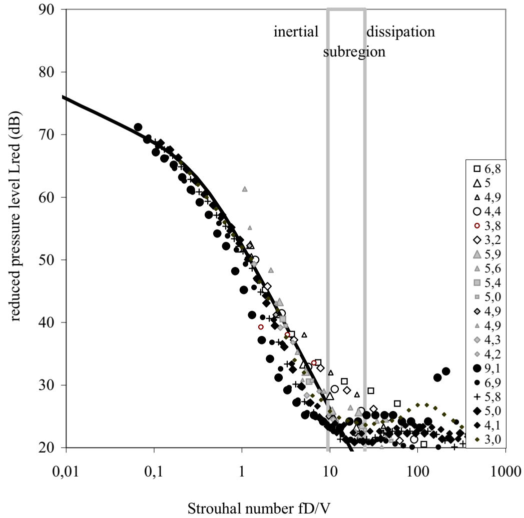
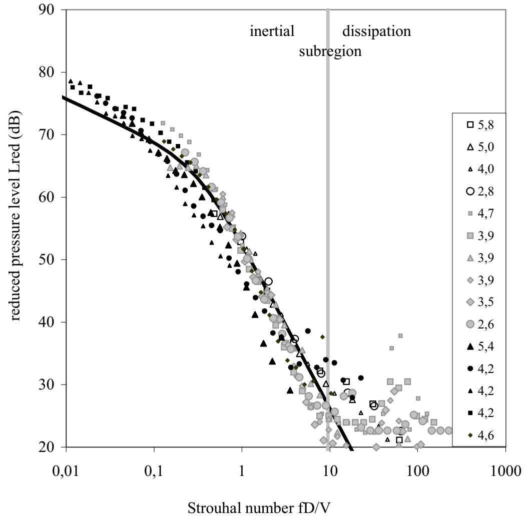


Figure VIII.5:
same as figure VIII.4, but after fitting with stability function

B



C



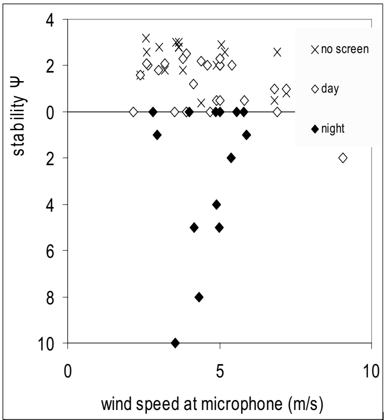


Figure VIII.6: values of the stability function Ψ found by fitting reduced spectral levels L_{red} with theoretical spectrum, for measurements in day or night time, and for unscreened microphones in daytime ambient sound dominates the wind-induced pressure level. Also, at these high Strouhal numbers most values are in the dissipation range where the present model is not valid.

In figure VIII.4 atmospheric stability has not been taken into account yet (in fact Ψ 0 was used), due to lack of data to determine Ψ. In stable conditions ($\Psi < 0$) L_{red} will be higher, in unstable conditions ($\Psi > 0$) lower, causing the plotted spectra to shift vertically if the proper value $\Psi \neq 0$ is applied.
If wind velocity at microphone height is deduced from wind velocity at another height, the shift is more complex, as stability then also affects the term $40 \cdot \log(V/V_o)$ as well as the ordinate value Sr fD/V. The approach taken here is to vary Ψ to obtain a best fit to the theoretical value of the L_{red} levels at non-dimensional frequencies in the inertial subrange. The fitted spectra are plotted in figure VIII.5. The values of Ψ that gave the best fits are plotted in figure VIII.6, categorized in daytime and night time measurements (where one would expect $\Psi \geq 0$ and $\Psi \leq 0$, respectively). Measurements with unscreened microphones are indicated separately, and are in daytime for Boersma's measurements and probably also for Larsson's, so one would expect $\Psi \geq 0$.

VIII.3.2 Measured broad band pressure levels

Several authors give a relation between broad band A-weighted sound pressure level L_A and wind velocity [Boersma 1997, Larsson *et al* 1982, Jakobsen *et al* 1983]. According to Boersma $L_A \sim 22.6 \cdot \log(v)$ (with v measured at 2 m height, L_A at 1.5 m), to Larsson L_A $4.4 \cdot v + 27.5$ (v and L_A measured at the same height), to Jakobsen L_A $6.8 \cdot v$ 2.6 (v measured at 10 m, L_A at 1.5 m). However, as Boersma clearly shows, most of the A-weighted sound is due to ambient wind induced sound, especially at low wind velocities. So we cannot use these relations for just sound induced by wind on the microphone.

A practical situation where the influence of wind on the microphone + wind screen could be investigated directly offered itself when on May 28, 2000 a storm occurred during our 'Wieringerwaard' measurements. The microphone, in a 9 cm foam cylinder, and a wind meter were both placed at a height of 4.6 m, 2 m apart, in front of a big farmer's shed 5 m to the west of the microphone (latitude 52°48’41”, longitude 4°52’23”). A second, 'free wind' windmeter at 10 m height was placed further away to measure undisturbed wind. Around the measurement location were fields with potato plants of 20 - 30 cm height. As it was May, an unstable atmosphere is expected in daytime, leaning to neutral when the wind velocity increases.

Some measurement results are given in figure VIII.7 (all values are 10 minute averages of samples measured at a rate of 1 s^{1}). In the left part of the figure the 'free' wind velocity v_{10} is seen to increase to 20 m/s (72 km/h) in the course of the day after a relatively quiet night. The wind velocity v_{mic} near the microphone increased at practically the same rate between 6 and 12 o'clock, but then abruptly falls from 13 m/s to 2 m/s and thereafter remains at a low value even while the 'free' wind velocity is still increasing. Up to 12 o'clock the sound level (equivalent A-weighted level per 10 minutes) increases in proportion to the wind velocity reaching a maximum of 84 dB(A), but then falls abruptly to 50 dB(A) at the same time the local wind velocity collapses. In this morning the unobstructed wind began in the east and gradually turns south. When at 12 o’clock the wind passes behind the shed, the microphone is suddenly taken out of the wind. There is no reason that the *sound* reaching the microphone changes significantly during this change, but due to the sudden wind velocity reduction the measure sound pressure level drops to 50 dB(A). After that the sound pressure level increases again as long as the storm is gaining strength. The measured pressure level above 60 dB(A) is pure wind-induced ‘pseudo’ sound, that is: sound resulting from moving air, not from airborne sound.

In the right part of figure VIII.7 the A-weighted equivalent (pseudo-) sound pressure level per 10 minutes over the same period as in the left part of figure 7, is plotted as a function of wind velocity at the microphone. There is an obvious direct correlation between pressure level and wind velocity at higher wind velocities ($V \geq 6$ m/s) in contrast to the levels at

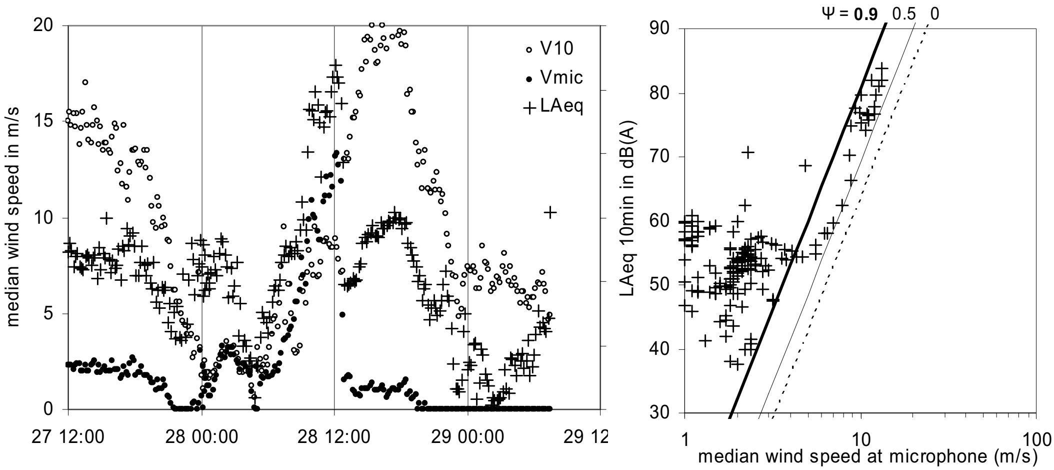


Figure VIII.7: measurements during a storm in front of a big shed; left: 10 minute averages of wind speed at microphone and at 10 m height and sound pressure level Leq; right: Leq as a function of microphone wind speed and predicted sound pressure level (G(4.6) = 8.2 dB)

lower wind velocities. Again, the stability factor Ψ is not known, but in daytime and in strong winds it must be small and positive. The lines in figure VIII.7 show the calculated pressure levels for plausible values $0 < \Psi < 1$ (with z_o 20 cm), encompassing the measured values.

VIII.3.3 Screen reduction

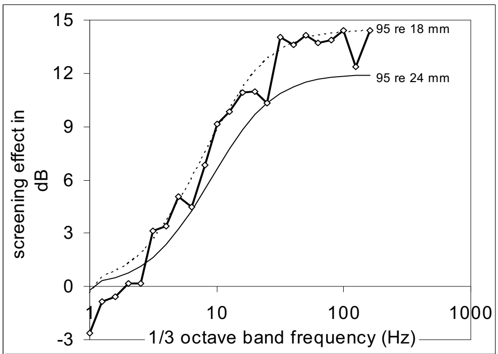


Figure VIII.8: measured (line with markers) and calculated screening effect of a 9.5 cm relative to a 2.4 or 1.8 cm wind screen

For two of our Zernike summer measurements (see table VIII.1) with place and atmospheric conditions unchanged within the measurement period, the difference between 1/3 octave band pressure levels measured with an approximately spherical 2.4 cm wind screen and a spherical 9.5 cm wind screen are plotted in figure VIII.8. Also plotted is the calculated screening effect based on equation VIII.9a, with only both term before C differing between both measurements. It appears that the measured screening effect is on average approximately 1 dB higher than the calculated level. It is not clear why the difference in screening is negative at frequencies below 2 Hz. For a somewhat smaller wind screen (18 mm < D < 24 mm) the average screening effect would agree better with the calculated effect.

VIII.4 Discussion

The model developed in this paper starts with the assumption that wind induced 'sound' pressure levels on a microphone are caused by atmospheric turbulence. Then, at low non-dimensional frequencies (Sr << 0.3) spectral levels are determined entirely by atmospheric turbulence. In this frequency range a wind screen has no effect. At higher frequencies, where pressure fluctuations tend to cancel one another more effectively as their scale decreases relative to the wind screen diameter, a wind screen acts as a first order low pass filter for turbulent fluctuations. In this frequency range (Sr > 0.3) a wind screen diminishes the effect of turbulence, and better so if it is bigger.

Wind induced pressure levels are determined not just by wind velocity and screen diameter, but also by two factors that are relevant for the production of turbulence: atmospheric instability and surface roughness. The stability factor Ψ and roughness height z_o are determinants for thermal and frictional turbulence, respectively. These determinants are usually not taken into account with respect to wind induced noise and are consequently not reported. Atmospheric stability therefore had to be estimated by varying the value of Ψ until a best fit was obtained of measured spectra to the calculated spectrum. Roughness length, when unknown, was assumed to be comparable to vegetation height.

The values of Ψ that resulted in the best fits are shown in figure VIII.6. They can also be compared to values obtained from long term measurements at the Cabauw measurement site of the Royal Netherlands Meteorological Institute (KNMI). The Cabauw site is in open, flat land west of the central part of the Netherlands (see Chapter VI) and may be considered representative for locations in comparable terrain in the north and central parts of the Netherlands (Boersma's and our measurements), Denmark (Jakobsen *et al*) and the Swedish Uppsala plain (Larsson *et al*). The KNMI provided us with a data file containing 30 minute averages of the Monin-Obukhov length L over one year (1987). From this the dimensionless height ζ z/L can be calculated and then the stability factor Ψ (see text below equation VIII.6). In figure VIII.9 the frequency distribution is shown of all 17520 (2·24·365) values of Ψ, for two altitudes: 2 m and 5 m. Also the frequency distribution is shown of the 42 values of Ψ resulting from our fitting procedure. The distribution of our fitted values resemble the distribution of actually occurring values (in 1987) and thus seems plausible.

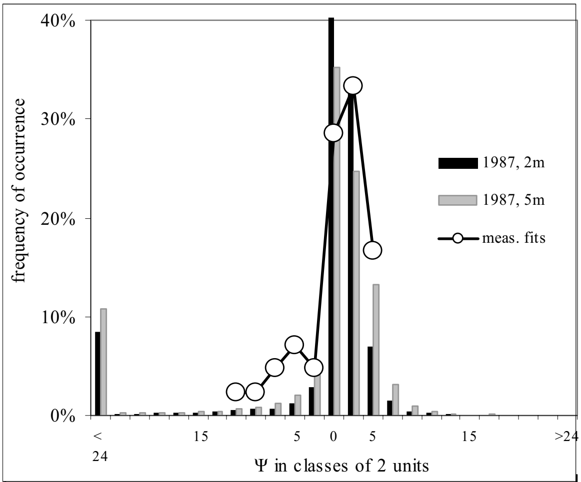


Figure VIII.9: frequency distributions of stability factor Ψ at 2m and 5 m height, based on ½ hour observations over 1987 and resulting from fitted spectra

Two constants are not known accurately: α, assumed to have a value 0.25, and the ratio of screen diameter and eddy size at the corner frequency, where 3 was used. If the Sr-related slopes are as in equation VIII.9b, the best fit of all data points in figure VIII.5 at Sr < 2.5 is a line $L_{red,1/3}$ -6.7·log(Sr) 10·log[1+ (3.8·Sr)^2] + 62.0. This fit is within 2.2 dB of the calculated value (equation VIII.9b). It follows that the ratio ℓ/D (3.8) where screen averaging over eddies sets in may be greater than assumed (*viz.* 3), and the constant term may be somewhat smaller, which could be a result of a lower value of α than assumed (0.24 instead of 0.25.

For 2.5 < Sr < 16 the best fit is on average 2.1 dB above the calculated value. The standard deviation of the measured 1/3 Strouhal octave band levels is less than 3.5 dB at Sr < 2.5 and up to 7 dB at 2.5 < Sr < 16.

VIII.5 Applications

As microphone wind noise appears to be closely correlated to atmospheric turbulence, acoustic measurements can alternatively be used to measure turbulence spectra or turbulence strength, especially in the inertial subrange. This provides a new way to determine (*e.g.*) friction velocity or atmospheric stability. As the measured signal decreases above the corner frequency f_c V/(3D) this frequency is best chosen high, which can be achieved with a small, bare microphone.

The present model can be used to distinguish wind induced noise from other wind related sound. An application is the measurement of wind turbine sound or (without an operating wind turbine) ambient background sound in relatively strong winds. If the measurement is on a wind exposed site it is probable that at high wind velocities wind induced noise influences or even dominates either wind turbine sound or proper ambient sound. A measured level can now be corrected for wind induced sound with a calculated wind noise level. In less exposed sites it is usually not clear in what degree the measured levels are influenced by wind induced noise. To calculate wind induced noise levels additional measurements are necessary to determine roughness height and atmospheric stability. Stability can be estimated from wind velocity measurements on two heights, using equation VIII.6. Roughness height can be estimated from tabulated values or from wind velocity measurement at two heights in a neutral atmosphere, at times when the logarithmic wind profile is valid (equation VIII.6 with Ψ 0). In neutral and stable conditions wind induced noise levels are not very sensitive to errors in roughness height: with an error of a factor of 2 in z_o 10 cm, the level changes less than 2 dB if microphone height is 3 m or more.

VIII.6 Conclusion

Measured spectra, reduced with a term for wind velocity and turbulence strength, coincide well with calculated values for unscreened as well as screened microphones in the range where the theoretical model (equation VIII.9) is valid. To test the model more thoroughly, measurements should include a determination of roughness length and atmospheric stability, in addition to the usual measurement of wind velocity and measurement height.

The model shows that to avoid high wind induced pressure levels, measurements are best performed at low wind velocity and with a large diameter wind screen, which is common knowledge in acoustics. The overall reduction ΔL_A from a bigger wind screen relative to a smaller one is determined by the ratio of the screen diameters D_1 and D_2: ΔL_A $20 \cdot \log(D_2/D_1)$ (from equation VIII.11b, D > 5 cm). A wind screen does not reduce noise from atmospheric turbulence at frequencies $f < V/(3D)$.
The model also shows that, to reduce wind induced sound, it helps to measure over a low roughness surface and at night (stable atmosphere), as both factors help to reduce turbulence, even if the (average) wind velocity on the microphone does not change. With reduced turbulence, wind induced pressure levels will finally reach the level given by Strasberg (equation VIII.1 or VIII.2), where turbulence is the result of the wake caused by the wind screen.
One might be tempted to think that a higher measurement altitude would also help to reduce wind noise (as this would make G(z) in equation VIII.11b more negative, thus reducing $L_{at,A}$). However, in practice increasing altitude will lead to higher wind velocities, especially so in a stable atmosphere, and the first term in equation VIII.11b would more then compensate the decrease in G(z). It is therefore preferable to measure at low altitude if less wind noise is desired.

IX GENERAL CONCLUSIONS

The research aims formulated in the introductory chapter (section I.6) have been addressed separately in the previous chapters. In this chapter we present an overview of all results. The results are presented in a logical order, which is not entirely in the sequence of the previous chapters.

IX.1 Effect of atmospheric stability on wind turbine sound

It is customary in wind turbine noise assessment to calculate the sound level on neighbouring premises by assuming hub height wind velocities predicted using a logarithmic wind profile. This wind profile depends only on surface roughness and is valid in a neutral atmosphere. However, it is not a predictor for wind profiles in either an unstable or stable atmosphere. Especially in a stable atmosphere a wind profile can be very different from the logarithmic, neutral profile and the hub height wind velocity is higher than predicted by the neutral profile. As more wind at hub height makes a variable speed wind turbine rotate at a higher speed, the sound power level may be significantly higher in a stable atmosphere at the same wind 10-m velocity V_{10} (which usually occurs when the sun is down and no strong near-ground wind is present) than in an unstable atmosphere (usually when the sun is up). This is especially relevant for modern, that is: tall and variable speed, wind turbines.
A stability dependent wind profile predicts the wind velocity at hub height more accurately. When a correct wind profile is used, calculated immission sound levels agree with measured night-time sound immission levels.

Sound immission measurements have been made at distances up to 2 km from the Rhede wind farm containing seventeen 98 m hub height, variable speed wind turbines, and at 280 m from a single 45 m hub height, two speed wind turbine at Boazum. Measured immission sound levels at 400 m west of the Rhede wind farm almost perfectly match (average difference: 0.1 dB) sound levels calculated from measured emission levels near the turbines. At distances up to 2 km the calculated level may underestimate the measured level, but the discrepancy is small: 1.5 dB or less.[1] Thus, from the measurements both the emission and immission sound levels could be determined accurately. As both levels can be related through a propagation model, it may not be necessary to measure both: immission measurements can be used to assess immission as well as emission sound levels of an entire wind farm.

The level of aerodynamic wind turbine noise depends on the angle of attack: the angle between the blade and the incoming air flow. Increasing atmospheric stability also creates greater changes in the angle of attack over each rotation, resulting in stronger turbine sound fluctuations. It can be shown theoretically for a modern turbine rotating at high speed that, when the atmosphere becomes very stable, the fluctuation in turbine sound level increases to approximately 5 dB. This value is confirmed by measurements at a single wind turbine where the maximum sound level periodically rises 4 to 6 dB above the minimum sound level within short periods of time. At some distance from a wind farm the fluctuations from two or more turbines may arrive simultaneously for a period of time and increase the fluctuation level further at the observer's position up to approximately 9 dB. This effect develops in a stable atmosphere because the spatial coherence in wind velocity over distances at the size of an entire wind farm increases. As a result turbines in the farm are exposed to a more constant wind and rotate almost synchronously. Because of this near-synchronicity, the fluctuations in sound level will for some time coincide at some locations, causing an amplification of the fluctuation. The place where such an amplification occurs will sweep over the area with a velocity determined by the difference in rotational frequency. The magnitude of this effect thus depends on stability, but also on the number of wind turbines and their distances to the observer.
Blade passing frequency is the parameter determining the modulation frequency of wind turbine sound. Human perception is most sensitive to

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[1] In one night the sound level at over 2 km from the wind farm was much higher than calculated, probably because of an inversion layer adding more downward refracted sound. This apparently rare occurrence at the Rhede wind farm could be more significant where high inversion layers occur more often.

modulation frequencies close to 4 Hz and the modulated sound has a frequency of approximately 1000 Hz. The hypothesis that fluctuations are important is supported by descriptions given by naïve listeners as well as residents: turbines sound like ‘lapping’, ‘swishing’, ‘clapping’, ‘beating’ or ‘like the surf’. It is probable that this fluctuating character is responsible the relatively high annoyance caused by wind turbine sound and a deterioration of sleep quality.

Atmospheric stability also affects the energy yield of wind turbines: relative to the ‘standard’ (neutral) atmosphere, a stable atmosphere increases the yield, especially for modern tall turbines. The reverse is true for an unstable atmosphere, though to a lesser degree. Perhaps atmospheric stability was not recognized as an important determinant for wind power as the underestimated night time yield is compensated partly by the overestimated daytime yield. The annual effect will depend on the average magnitude as well as the prevalence of atmospheric stability.

IX.2 Effect of atmospheric stability on ambient background sound

The change in wind profile at night also results in lower ambient background levels then expected: at night the wind velocity near the ground may be lower than expected from logarithmic extrapolation of the wind velocity at 10 m, resulting in lower levels of wind induced sound from low vegetation. The contrast between wind turbine and ambient sound levels is therefore at night more pronounced.

IX.3 Wind noise on a microphone

To avoid high wind induced pressure levels in windy conditions, outdoor measurements are best performed with a large diameter wind screen. The overall reduction from a bigger wind screen relative to a smaller one is determined by the ratio of the screen diameters. A wind screen does not reduce noise from atmospheric turbulence at very low frequencies.[1]

In a stable atmosphere the low near-ground wind velocity creates less wind noise on the microphone. As a result, sound measurements during a stable night are much less influenced by wind induced microphone noise (and other sounds as well, since nights are usually more quiet) than in a neutral or unstable atmosphere. The results in this book shows that wind turbine sound can be measured accurately at great distances (up to 2 km) if the atmosphere is stable.

The model developed in this thesis shows that, in order to reduce wind induced sound, it helps to measure over a low roughness surface and in a stable atmosphere, as both factors help to reduce turbulence, even if the average wind velocity on the microphone does not change. But in a stable atmosphere near-ground wind velocities will usually be low, decreasing wind induced noise further. With increasing stability, wind induced pressure levels will drop and finally reach a low level determined by turbulence in the wake of the wind screen.

IX.4 Degree of atmospheric stability

Stability is a property of the atmosphere, in principle occurring all over the earth. It depends on surface properties and weather conditions which determine the magnitude and evolution over time of the heat balance in the atmospheric boundary layer. Most important are differences in heat transfer at the surface (water, soil) and in the atmosphere (atmospheric humidity and clouds, wind mixing). With current knowledge, the effects of stability on the wind profile over flat ground can be modelled satisfactorily. In mountaineous areas terrain induced changes on the wind profile influence the stability related changes and the outcome is less easily predicted: these changes can weaken as well as amplify the effect of atmospheric stability.

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[1] frequencies below V/(3D), where V is the wind speed at the microphone and D the wind screen diameter

Results from various onshore, relatively flat areas show that in daytime the ratio of the wind velocity at 80 m (hub height) and the wind velocity at reference height of 10 m is 1.25 to 1.5. This ratio is in agreement with the usual logarithmic wind profile for low roughness lengths (low vegetation). At night the situation is quite different and the ratio has a much wider range with values from 1.7 to 4.3. At night high altitude wind velocities thus can be (much) higher than expected from logarithmic extrapolation of 10-m wind velocities.

IX.5 Measures to mitigate stability related effects

Presently available measures to decrease the immission sound level from modern turbines are to create more distance to a receiver or to slow down the rotor, preferably by an optimized control mechanism. Quieter blades as such will always be advantageous, but expected changes are modest and will not eliminate the beating or thumping character due to atmospheric stability.

Controlling the stability related sound emission requires a new strategy in wind turbine control and wind farm design. In the present situation there is usually more latitude for sound (and energy) production in daytime, but less during quiet nights. A strategy for onshore wind farms might be to use more of the potential in daytime, less at night.

A control strategy may depend on whether the legally enforced limit is a 10-m wind velocity or an ambient background sound level dependent limit. The 10-m wind velocity or the background sound level can act as the control system input, with blade pitch the controlled variable. In both cases a suitable place must be chosen to measure the input parameter. For background sound level as input it is probably necessary to use two or more inputs to minimize the influence of local (near-microphone) sounds. An ambient background controlled emission level may be the best strategy in relatively quiet areas as it controls an important impact parameter: the level above background or intrusiveness of the wind turbine sound.

Even if the sound emission level does not change, annoyance may be diminished by eliminating the rhythm due to the beating character of the sound. A solution is to continuously change the blade pitch, adapting the

angle of attack to local conditions during rotation. This will probably also be an advantage from an energetic point of view as it optimizes lift at every rotor angle, and it will decrease the mechanical load 'pulses' on the blades accompanying the sound pulses.
Increased fluctuation due to the interaction of sound from different turbines can be eliminated by adding small random variations to the blade pitch or rotor load, mimicking the random variations imposed by atmospheric turbulence in daytime when this effect does not occur.

IX.6 Recommendations

When night time is the critical noise period, wind turbine sound levels should be assessed taking into account stable atmospheric conditions. When the impulsive character of the sound is to be assessed, this should be carried out in times of a stable atmosphere, as that is the relevant condition for impulsiveness.

When ambient sound is considered as a sound masking wind turbine sound, neither sound should be related to wind velocity at 10 meter reference height via a (possibly implicit) neutral or 'standard' wind profile. A correct, stability dependent wind profile should be used. In flat and certainly in mountainous terrain one should determine directly the relationship between hub height wind velocity on the one hand and ambient background sound at an immission location on the other hand, in order to eliminate any badly correlated, intermediate wind velocity.

Also, in the assessment of wind turbine electrical power production the sole use of a neutral wind profile (a 'standard atmosphere') should be abandoned as it yields data that are not consistent with reality.

When comparing stable and unstable atmospheric conditions, the difference in sound power as well as in sound limits can lead to new control strategies and onshore wind farm concepts. Presently only distance is a factor used to minimize noise impact. A wind farm can be optimized with a strategy that maximizes power output while keeping sound power within limits. When daytime immission levels do comply with the noise

limits, but nighttime immission levels do not, a control system can be implemented to reduce the turbine speed when necessary.
In new turbine designs continuous blade pitch control could be applied to increase energy yield and reduce annoyance at the same time by eliminating the thumping character of the emitted sound.

X EPILOGUE

This is the end of my tour of discovery, of over two years of reading about and trying to understand atmospheric physics and wind turbines, of measurements and theory, of applying knowledge and expertise in physics and acoustics to a new topic. Of course there is much more to discover: indeed, it looks like wind turbines have become more fascinating now their sound has proved to be more complex than a simple constant noise from the sky, driven only by wind with a constant profile. This may motivate researchers and consultants to put more effort in better predictions of wind turbine noise, and considering again noise exposure to local residents.

This period began with publishing the results of the measurements at the Rhede wind farm and it ended, seemingly symbolically, with the first International Conference on Wind Turbine Noise in Berlin in October 2005. At that conference there was a general acknowledgment that wind turbine sound is not the simple issue we once thought it was. At the conference many delegates agreed that, looking back, the internationally used 'standard wind profile' might have been misleading people by suggesting it was, everywhere and always, the best wind profile. Although the widely used IEC-61400 standard certainly does not state that, a less careful reader might think it did, finding no alternative profile in the standard. Thus, it becomes a question of careful communication and taking into account that acoustic consultants do (did?) not have the knowledge to apply the standard in 'non standard' conditions. Paul Botha [2005] proposed to do away with 10-m wind velocities entirely and relate background sound directly to hub height wind velocity. This is a sensible idea as it relates the two factors that are most relevant, wind turbine sound and ambient sound, without an intermediate variable (10-m wind velocity). It will lead to better insight in the masking capability of background sound: the ability to mask (make inaudible) unwanted sound is not only dependent on wind velocity, but also on atmospheric stability and wind direction.

The Berlin conference helped me solve a riddle. Malcolm Hayes had written me before that according to his observations blade swish is caused by the blade that is going down, not by the blade being in the downward position (passing the mast). This seems contradictory to my conclusion that blade beating is due to blades passing the mast. Oerlemans [2005] showed that close to the tower Malcolm was right, but this could not explain blade swish far away from a turbine. So what we heard depended on the distance to the turbine, which is also true for other sound phenomena: further away from the turbine the sound has a lower pitch, the pulses can be amplified by synchronicity of turbines and it can be louder under an inversion layer. This point again illustrates that one must be careful when generalizing observations.

I don't expect the problem of the distinct, beating character of wind turbine sound to be solved easily. Though I am convinced the sound character is a major factor in wind turbine noise annoyance, a 5 dB penalty for an impulsive character of the sound may indeed impede wind farm projects as a wind farm will need more 'empty space'. Also, the sound is not as impulsive as gun shots or hammering are, giving way to a discussion on whether it is 'really' impulsive (5 dB penalty) or not (no penalty). Is it possible to have a truly independent opinion in a legally created dichotomy with such significant consequences?
Several technical possibilities to minimize the noise have been outlined in this book, but we need not just depend on technical solutions. A change in public relations can also make a difference: proponents must accept that wind turbine noise is not (always) 'benign', that the noise may affect people, and that people who are complaining are not always just a nuisance. And no, we still do not understand wind turbine noise immission entirely, so proponents should watch their WARYDU attitude.

"….. about 80 per cent of the population supports wind power in the surveys investigated in this paper. On the local level the support of wind power in areas with operating wind power plants is equally high. (….) This, however, does not mean that protests will not appear. It takes only one devoted opponent to start for instance a legal procedure against a planning permit. This is one of the reasons why public conflicts over wind power plants have become the rule rather than the exception. Lack of communication between the people who shall live with the turbines, and the developers, the local bureaucracy, and the politicians seems to be the perfect catalyst for converting local scepticism, and negative attitudes into actual actions against specific projects. Conversely, information and dialogue is the road to acceptance."

Steffen Damborg (Danish Wind Industry Association) in "Public Attitudes Towards Wind Power", a "survey of surveys" from several countries, 2002; posted on *http://www.windpower.org/en/news/articles* (consulted December 3, 2005)

ACKNOWLEDGMENTS

I want to express my sincere gratitude to a number of people.
Foremost is Diek (prof dr ir H Duifhuis) who for 20 years has been a true, though most of the time distant colleague, and who immediately responded positive to my request to be my promotor. The same, but for a shorter period, holds for my second promotor Ton (prof dr A J M Schoot Uiterkamp). Both were very confident in my capacities and my work and they also allowed me to change the subject without much ado.[1] "The point is, Frits", they lectured me, "that you demonstrate your scientific capability, the subject as such is not that important". And it is not by obligation that I also mention my wife Luci, who for two years gracefully took most of my share in cooking and household chores.

There are some others I would like to commemorate. My colleague Aart van der Pol who was always interested in new work and new ideas and sharp in his comments. Terry Mazilsky, one of the beleaguered residents, who read the first and the final chapters for language and clarity. My friend Dorothé Faber with whom I discussed my work from a very different, non-technical perspective. And the students and secretaries who had to abide with too little attention devoted to them and me again and again forgetting things. I hope they felt I did try to support them even though I was busy or being elsewhere in my thoughts. Much the same goes for my daughters Inge and Maya, who will meet me at the end of this period as my beloved paranymphs.

Two organizations have supported my research. The province of Groningen has subsidized the measurement project at the Rhede wind farm to support the residents and thus helped to produce a report and after that a scientific publication on the effect of atmospheric stability. The British Renewable Energy Foundation gave a grant to elaborate my thoughts on

[1] Originally my thesis was to be about Sound monitoring in quiet areas, and Diek, Ton and I discussed the nature of sound and quietness and our response to it; this changed when I became ever more involved in wind turbines.

the beating character of wind turbine sound, which led to my second publication on wind turbine noise. The KNMI gave support by providing data that helped me prepare the presentation about the wind statistics.

My Faculty of Mathematics and Natural Sciences allowed me to spend half of my working time for two years on this promotion. Unfortunately there was no money for a substitute, so I had to fit my usual work in the other half of the time. It has been busy sometimes, but I am lucky to have work that I like (well, most of it) and is worthwhile, so I never count the hours from 9 to 5. It is, I think, significant that I have a position in a University based Science Shop, because that position enables me to spend time on projects for the benefit of citizen groups with no net financial return. This book shows that citizens may need the help of science to support their claims and improve their situation, which is not available elsewhere except perhaps at high costs. On behalf of the people I have helped I am grateful our University and Faculty are still firm supporters of the Science Shop idea.[1]

[1] Don't count your chickens before they are hatched! At the time this book was finalized, 21 years after the Science Shop for Physics started, it was announced that because of large financial deficits the Faculty executive board proposed to close down all four faculty science shops.

SUMMARY

Ch. I

This study was started after complaints of residents that the sound of a wind farm was louder and more annoying than predicted, especially when there was little wind in the evening or at night. The explanation appeared to be the occurrence of another wind profile than that used to predict the noise impact (the wind profile describes how the wind velocity increases with height). There are probably several reasons why this was not found earlier: 1) because wind turbines become taller, there is a growing discrepancy between prediction and practice; 2) measurements are usually done in daytime when the wind profile resembles more closely the commonly used standard profile; 3) based on the sound that occurs in daytime, it is hard to imagine the sound can be so different at night; 4) “there are always people complaining”, so complaints are not always a reason for a thorough investigation; 5) at least some wind energy proponents prefer to downplay the disadvantages rather than solve them.

Ch. II

According to Dutch legislation and international guidelines the sound production of a wind farm can only be checked by measurements when the wind farm operator cooperates. The consequence is an implicit partiality in favor of the operator detrimental to independent verification. Because of the level of detail of instructions measurements and assessments are hampered and there is no margin for the very expertise of an investigator. For a lay person understanding the jargon was already utterly impossible and he cannot but hire an expensive expert to argue his case.

From this study one can conclude that through the use of a restricted model of reality, *viz.* a forever neutral atmosphere, experts have lost sight (temporarily) of the true reality in which a neutral atmosphere is not very prevalent. It is precisely the occurrence of complaints that may indicate such errors.

Ch. III

The sound of modern wind turbines is generated mainly by the flow of the wind along the blades. In this process a turbulent boundary layer develops at the rear side of the blade where trailing edge sound of relatively high

frequencies originates and which is radiated into the environment. This turbulent boundary layer becomes thicker and produces more sound when the wind flows in at a greater angle.
The inflowing wind is turbulent itself. The blade cuts through these turbulent movements and as a result again sound is generated: in-flow turbulence sound. Here lower frequencies dominate. Finally a blade also radiates sound when the forces on the blade change because of a local variation in wind velocity. This happens every time the blade passes the tower because there the wind is slowed down by the tower. On the one hand this causes more trailing edge sound due to the change in inflow angle, on the other hand more infrasound is generated because of the sudden sideways movement at the rate of the blade passing frequency.

For all these sounds loudness increases when the speed increases. Because the tip has the highest speed the sound of a wind turbine mainly comes from the blade tips. Moreover, for human hearing the trailing edge sound is most important because it is in an area of frequencies that we can hear well.

It is often assumed that there is a fixed relation between the wind velocity at hub height and at a reference height of 10 meter. This is the relation valid in a neutral or 'standard' atmosphere. No other relations are given in legislation or international guidelines for wind turbine sound that are valid in other conditions of the atmosphere, *viz.* the stable and unstable conditions.
The atmosphere is *unstable* when in daytime the air near the ground is relatively warm from contact with the surface heated by solar insolation. In that case vertical air movements originate and the wind profile is not equal to the profile in a neutral atmosphere, though it does not differ strongly. A *stable* atmosphere however has a markedly different wind profile. The atmosphere is stable when the air close to the ground is relatively cold due to contact with the ground surface when this cools down at night by radiating heat. A stable atmosphere occurs especially in nights with a partial or no cloud cover and the wind is not too strong (close to the ground). In a stable atmosphere the turbulence has decreased substantially

and as a result layers of air are less strongly coupled. The lower layer of air is thus less taken along with the wind that at higher altitudes keeps on blowing, giving rise to greater differences between wind velocities at different heights.

Ch. IV

The present study was performed mainly near the Rhede wind farm close to the Dutch German border. The farm consists of 17 1.8 MW turbines of 98 m hub height and three 35 m blades. The level of the incoming sound has been measured at a number of locations. The sound could be measured up to a distance of 2 km. It proved that, contrary to predictions, already at a weak wind (at 10 m height) the turbines could rotate at almost top speed and consequentially produce much sound.
It appeared that a wind profile proper to stable conditions could explain the measured sound levels excellently. At the same wind velocity at a reference height of 10 meter, wind turbines in a stable atmosphere generate more sound than in a neutral atmosphere, while at the same time the wind velocity near the ground is so low that the natural ambient sound due to rustling vegetation is weaker. As a result the contrast between wind turbine sound and natural ambient sound is more pronounced in stable conditions than it is in neutral conditions.

Ch. V

When the wind profile after sunset changes while the atmosphere becomes more stable, the difference in wind velocity over the rotor increases. This causes a change in the level of the trailing edge sound. At the low tip this is reinforced because the inflow angle already was less favourable due to the wind being slowed down by the presence of the mast. The differences in wind speed lead to variations in the sound radiated by the blade tips that reach their highest values when a tip passes the mast. For a modern, tall wind turbine the calculated variation is approximately 5 dB at night, whereas it is approximately 2 dB in daytime. This is perceived as a more pronounced fluctuation of the sound.
A more stable atmospheric boundary layer moreover implies that there is less atmospheric turbulence, so wind turbines in a farm will experience a more equal and constant wind. As a result, in a stable atmosphere wind turbines can, more than in daytime, run almost at the same speed and then

diverge again. With several turbines the fluctuations in sound can reinforce one another when they reach the ear of an observer simultaneously. With two turbines (at the same distance) this leads to an increase in level of 3 dB, with three turbines to an increase of 5 dB.
In measurements this reasoned upon effect indeed occurred. With a single 45 m high wind turbine at a distance of 280 m at night variations of 6 dB were found. Near the wind farm the variations were usually 5 dB, but they could rise to approximately 9 dB, as expected when the fluctuations of several turbines coincide.
From other research and from descriptions of residents one can establish that the sound of a wind turbine or wind farm becomes more annoying because of ‘ swishing’, ‘sloshing’, ‘clapping’, ‘beating’ or ‘ thumping’. All descriptions mention a periodic variation on top of a constant noisy sound. This corresponds to the calculated and measured modulation of trailing edge sound. From psycho-acoustic research it has been shown earlier that human sensitivity to sound fluctuations is high at frequencies that occur in the night time sound of modern wind turbines. If this fluctuating sound is sufficiently loud in a bedroom it can cause sleep disturbance.

In the temperate climate zone a stable atmosphere is to be expected between sunset and sunrise over land if there is a -partly- clear sky (because clouds hinder the radiation of heat) and the wind is not too strong (because a strong wind promotes vertical heat exchange). From an analysis of measurements of the KNMI at Cabauw, in the central part of the Netherlands, up to an altitude of 200 m, it appears that there is a diurnal and seasonal pattern in the wind profile that correlates with the diurnal and seasonal variation in the heat exchange between the earth’s surface and the atmosphere. The fact that at sunset the wind often lies down is a consequence of the increasing atmospheric stability, and this decrease in wind velocity close to the ground is accompanied by an increase at higher altitudes. This has significant consequences for the energy production of a wind turbines, where the rotor height plays an important part. If one starts from the measured wind velocities at Cabauw at 10 m height and a forever neutral atmosphere, the annually averaged electrical power generated by a 80 m high, 2 MW (reference) wind turbine would amount to almost

500 kW. However, based on the real, measured wind speed at 80 m height the annual power in reality amounts to 600 kW. So, because of atmospheric stability there is, relative to a neutral atmosphere, a significantly higher yield at night time hours, that even amply compensates for the lower yield in daytime hours.

The higher wind velocity at night on the rotor also causes a higher level of generated sound. If again one starts from the measured wind velocities at Cabauw at 10 m height and an atmosphere assumed to be neutral, the average sound power level generated by the reference wind turbine is 102 dB(A). In reality, however, it is 2 dB higher. This is also an average over an entire year; in separate nights the difference can be substantially higher, *e.g.* when a turbine rotates at (almost) top speed at a time it was expected to not produce at all because of the low 10 m wind velocity.

The degree of atmospheric stability at Cabauw is hardly different from what was observed at the Rhede wind farm. At other locations in countries in the temperate zone stability occurs to a similar extent. The consequences of atmospheric stability as described here, will thus occur at many wind farms that exist or are to be built in the temperate zone. However, above large bodies of water stability is rather a seasonal than a diurnal phenomenon, en in mountainous terrain the consequences of stability on the wind profile can be strengthened as well as weakened due to changes induced by height variations in the area.

The sound of a wind turbine or wind farm can thus become more annoying after sunset for two reasons: it becomes louder and the sound exhibits stronger fluctuations. At a given rotor diameter a blade can only be made less noisy with a different design or by slowing down the speed. A decrease in speed however reduces the generated electrical power and must therefore be applied only when necessary. To achieve this a control can be applied that lowers the speed when a noise limit is exceeded, increasing the speed again when the limit allows. This control could work on the generator and/or the pitch angle of the blades.

By changing the pitch angle while the blades rotate, the wind can flow in at an optimal angle at any position on the rotor, by which the energetic efficiency will increase on the one hand and the fluctuation strength of the sound will decrease on the other hand, even rendering the fluctuations inaudible. The total sound power will then decrease even relative to a neutral atmosphere, because the in-flow turbulence sound level will be lower due to the relative absence of atmospheric turbulence. Tilting the rotor to change the pitch angle during rotation does not appear to be a fruitful strategy: the tilt must be so great that the disadvantages will dominate.
The fluctuations near a wind farm can be stronger due to interference from the fluctuations of several turbines. This can be prevented by desynchronizing the turbines, as it happens in daytime by large scale atmospheric turbulence, by adding small and uncorrelated variations in the load of the rotors or the pitch angle of the blades of the individual turbines.

Controlling the sound production thus requires a new strategy for managing wind turbines: in daytime there is often more margin available for sound production than at night and this margin can be used in daytime in exchange for more restrictions at night.

Finally another, very different problem was addressed: the influence of wind on a microphone in or without a wind screen. When there is sufficient wind the microphone signal contains a low frequency, rumbling sound disturbing the measurement of ambient sound. This rumble is not sound from the environment, but is generated by pressure fluctuations caused by turbulent wind velocity variations. With a pressure sensitive microphone these pressure variations are not distinguishable from acoustical pressure variations. It appears that a wind screen is effective only by damping contributions of small turbulent eddies. A wind screen has no effect when eddies are bigger than the wind screen.
The strength of atmospheric turbulence does not only depend on the (average) wind velocity, but also on the local roughness of the earth surface and the stability of the atmosphere. These last two factors cause friction and thermal turbulence, respectively. The turbulence strength is

well known for an unobstructed wind flow over flat land. Turbulence is weaker in a stable and stronger in an unstable atmosphere.
The 'sound' pressure level based on atmospheric turbulence appears to agree well with measured and published levels of wind induced pressure levels. Thus the influence of wind on a sound measurement in wind can be calculated. In reverse this calculation model yields a new method to measure the strength of atmospheric turbulence.

To conclude, it can be stated that with respect to wind turbine sound an important phenomenon has been overlooked: the change in wind after sunset. This phenomenon will be more important for modern, tall wind turbines and in view of the many wind farms that are planned. If this problem is not recognized and solved it will hamper the expansion of wind energy.

SAMENVATTING

> Bobby vraagt: 'Hoort u de windmolens wel eens?'
> 'Wat voor geluid maken ze?'
> 'Net als op elkaar slaand metaal, maar als er een echt harde wind staat worden de wieken vager en begint de lucht te schreeuwen van pijn.' Hij siddert.
> 'Waar zijn de windmolens voor ?'
> 'Ze zorgen dat alles ‘t doet. Als je je oor tegen de grond houdt kun je ze horen.'
> 'Wat bedoel je met alles?'
> 'De lichten, de fabrieken, de spoorwegen. Zonder de windmolens staat alles stil.' [1]

H. I

Dit onderzoek is tot stand gekomen na klachten van bewoners dat het geluid van een windpark luider en hinderlijker was dan voorspeld, vooral als er ’s avonds of ’s nachts weinig wind was. De verklaring hiervoor bleek het optreden van een ander windprofiel dan werd gehanteerd bij de voorspelling van de geluidsbelasting (het windprofiel beschrijft hoe de windsnelheid toeneemt met de hoogte). Dat dit niet eerder is gevonden heeft waarschijnlijk meerdere redenen: 1) doordat windturbines hoger en groter worden is er een groeiende kloof tussen voorspelling en praktijk; 2) er wordt normaliter overdag gemeten wanneer het windprofiel meer lijkt op het gewoonlijk gebruikte standaardprofiel; 3) men kan zich, op grond van het overdag optredende geluid, moeilijk voorstellen dat het ’s nachts zo anders kan zijn; 4) “er zijn altijd wel mensen die klagen”, dus klachten zijn niet altijd een reden tot grondig onderzoek; 5) tenminste een aantal voorstanders van windenergie bagatelliseert liever de nadelen dan ze op te lossen.

H. II

Volgens de Nederlandse wetgeving en internationale richtlijnen kan de geluidsproductie van een windpark alleen door metingen gecontroleerd worden als de exploitant meewerkt. Het gevolg is een impliciete partijdigheid ten gunste van de exploitant en ten nadele van onafhankelijke

[1] 'The suspect', door Michael Robotham, Time Warner Paperbacks, 2003 (p. 151), vertaling G.P. van den Berg

controle. Ook door de gedetailleerdheid van voorschriften worden metingen en beoordelingen bemoeilijkt en is er geen ruimte meer voor de eigen deskundigheid van een onderzoeker. De burger kan het jargon al helemaal niet meer volgen en moet een dure deskundige inhuren om zijn zaak te beargumenteren.

Bij dit onderzoek kan men constateren dat deskundigen door het gebruik van een beperkt model van de werkelijkheid, namelijk een eeuwig neutrale atmosfeer, (tijdelijk) het zicht hebben verloren op de echte werkelijkheid waarin die neutrale atmosfeer niet zo vaak voorkomt. Juist klachten kunnen helpen om dergelijke dwalingen aan te wijzen.

Het geluid van moderne windturbines wordt vooral opgewekt door de stroming van de wind langs de wieken. Daarbij ontwikkelt zich een turbulente grenslaag aan de achterkant van de wiek waarin relatief hoogfrequent achterrandgeluid (‘trailing edge sound’) ontstaat dat wordt uitgestraald naar de omgeving. Deze turbulente grenslaag wordt dikker en produceert meer geluid als de wind onder een grotere hoek instroomt.
De instromende wind is zelf ook turbulent. De wiek snijdt door deze turbulente bewegingen heen waarbij weer geluid ontstaat: instromings-turbulentiegeluid (‘in-flow turbulent sound’). Hierin domineren lagere frequenties. Tenslotte straalt een wiek ook geluid af als de krachten op de wiek veranderen doordat de windsnelheid lokaal varieert. Dit gebeurt telkens als de wiek de mast passeert omdat daar de wind is afgeremd door de mast. Enerzijds ontstaat daarbij meer achterrandgeluid omdat de instromingshoek verandert, anderzijds ontstaat er ook infrageluid door de plotselinge zijwaartse beweging in het tempo van de wiekpasseerfrequentie.

Bij al deze geluiden neemt de sterkte ervan toe naarmate de snelheid groter is. Omdat de tip de hoogste snelheid heeft is het geluid van een windturbine vooral van de wiektips afkomstig. Voor het menselijk gehoor is bovendien het achterrandgeluid het belangrijkst omdat dat in een frequentiegebied ligt dat wij goed kunnen waarnemen.

Vaak wordt aangenomen dat er een vaste relatie is tussen de wind op ashoogte en op een referentiehoogte van 10 meter. Dit is de relatie die geldig is in een neutrale of ‘standaard’ atmosfeer. Er worden geen andere relaties gegeven in de wetgeving en in internationale richtlijnen die gelden bij andere toestanden van de atmosfeer, namelijk de stabiele en instabiele toestand.
De atmosfeer wordt *instabiel* als overdag de lucht nabij de grond relatief warm is door contact met het door zoninstraling verwarmde aardoppervlak. Er ontstaan dan verticale luchtbewegingen en het windprofiel is niet meer gelijk aan dat in een neutrale atmosfeer, maar wijkt daar niet sterk vanaf. Een *stabiele* atmosfeer kent echter een duidelijk afwijkend windprofiel. De atmosfeer is stabiel als de lucht nabij de grond relatief koud is door contact met het door warmte-uitstraling afkoelende aardoppervlak ’s nachts. Een stabiele atmosfeer treedt vooral op tijdens niet gedeeltelijk of geheel onbewolkte nachten met niet teveel wind (aan de grond). In een stabiele atmosfeer is de turbulentie sterk verminderd met als gevolg dat luchtlagen minder sterk gekoppeld zijn. De onderste luchtlaag wordt daardoor minder meegenomen door de wind die op grotere hoogte gewoon blijft doorwaaien, waardoor er grotere verschillen zijn tussen windsnelheden op verschillende hoogten.

Het hier beschreven onderzoek is grotendeels uitgevoerd bij windpark Rhede vlakbij de Duits-Nederlandse grens. Het park telt 17 1,8 MW turbines met een ashoogte van 98 m en drie wieken van 35 m lengte. Op een aantal punten is het niveau van het invallende geluid langdurig gemeten. Het geluid kon tot op 2 km afstand worden gemeten. Bij een zwakke wind (op 10 m hoogte) bleken de turbines, anders dan voorspeld, al op vrijwel topsnelheid te kunnen draaien en dientengevolge veel geluid te produceren.
Een windprofiel dat bij stabiele omstandigheden past bleek de gemeten geluidsniveaus uitstekend te kunnen verklaren. Bij een gelijke windsnelheid op een referentiehoogte van 10 meter, produceren windturbines in een stabiele atmosfeer meer geluid dan in een neutrale atmosfeer, terwijl dan tegelijkertijd de windsnelheid nabij de grond zo laag is dat het natuurlijke omgevingsgeluid van ruisende vegetatie zwakker is.

Het contrast tussen windturbinegeluid en natuurlijk omgevingsgeluid is daardoor bij stabiele omstandigheden groter dan bij instabiele.

Als het windprofiel na zonsondergang verandert door een stabieler wordende atmosfeer, wordt het verschil in windsnelheid over de rotor groter. Dit veroorzaakt een verandering in de sterkte van het achterrandgeluid. Bij de lage tip wordt dit nog versterkt doordat de instromingshoek al ongunstiger was vanwege de door de mast verlaagde windsnelheid. De verschillen in windsnelheid leiden tot variaties in het door de tips afgestraalde geluid die het grootst zijn als een tip de mast passeert. Voor een moderne, hoge windturbine bedraagt de berekende variatie ongeveer 5 dB 's nachts, terwijl dit overdag ca. 2 dB is. Dit wordt ervaren als een duidelijker fluctuatie van het geluid.
Een stabielere atmosferische grenslaag betekent bovendien dat er minder atmosferische turbulentie is waardoor windturbines in een park een meer gelijke en meer constante wind ervaren. In een stabiele atmosfeer kunnen windturbines daardoor, méér dan overdag, een tijd nagenoeg gelijk lopen en weer langzaam uiteenlopen. Bij meerdere turbines kunnen de fluctuaties in het geluid elkaar versterken als ze het gehoor van een waarnemer gelijktijdig bereiken. Bij twee turbines (op gelijke afstand) leidt dit tot een 3 dB hoger niveau van de fluctuaties, bij drie turbines tot een 5 dB hoger niveau.
Bij metingen bleek dit beredeneerde effect daadwerkelijk voor te komen. Bij een enkele windturbine van 45 m ashoogte werden op een afstand van 280 m 's nachts variaties gevonden van 6 dB. Bij het windpark bedroegen de variaties meestal 5 dB, maar ze konden oplopen tot ongeveer 9 dB, zoals verwacht wordt bij het samenvallen van de fluctuaties van meerdere turbines.
Uit onderzoek elders en uit beschrijvingen van omwonenden kan men constateren dat het geluid van een windturbine of windpark vooral na zonsondergang hinderlijker wordt door het 'zoeven' of 'klotsen', 'klappen', 'slaan' of 'bonken'. De omschrijvingen vermelden steeds een periodieke variatie bovenop een constant ruisachtig geluid. Dit correspondeert met de berekende en gemeten modulatie van het achterrandgeluid. Uit psycho-akoestisch onderzoek is veel eerder al

gebleken dat de menselijke gevoeligheid voor geluidsfluctuaties hoog is bij frequenties die juist voorkomen in het nachtelijke geluid van moderne turbines. Als dit fluctuerende geluid voldoende luid doordringt in een slaapkamer kan het tot slaapverstoring leiden.

In de gematigde klimaatzone kan men tussen zonsondergang en zonsopgang boven land een stabiele atmosfeer verwachten als er een -gedeeltelijk- onbewolkte hemel is (bewolking verhindert de warmte-uitstraling) en een niet te harde wind (veel wind bevordert de verticale warmtevereffening). Uit een analyse van metingen van het KNMI bij Cabauw, in het midden van Nederland, tot op 200 m hoogte blijkt dat er een dagelijkse en jaarlijkse gang is in het windprofiel die samenhangt met de dagelijkse en seizoensvariatie in de warmte-uitwisseling tussen aardoppervlak en atmosfeer. Dat bij zonsondergang de wind vaak gaat liggen is een gevolg van de toenemende atmosferische stabiliteit, en deze windsnelheidsafname nabij de grond gaat gepaard met een toename van de windsnelheid op grotere hoogte.
Dit heeft belangrijke gevolgen voor de energieproductie van een windturbine, waarbij bovendien de rotorhoogte een rol speelt. Als wordt uitgegaan van de gemeten windsnelheden bij Cabauw op 10 m hoogte en een altijd neutrale atmosfeer, dan zou het over een jaar gemiddelde opgewekte elektrische vermogen van een 80 m hoge 2 MW windturbine bijna 500 kW bedragen. Gebaseerd op de werkelijke, gemeten windsnelheid op 80 m hoogte bedraagt het over een jaar gemiddelde vermogen echter 600 kW. Door atmosferische stabiliteit is er dus, ten opzichte van een neutrale atmosfeer, een aanmerkelijk hogere opbrengst in de nachturen, waardoor zelfs de lagere opbrengst overdag ruim wordt gecompenseerd.

De hogere windsnelheid ’s nachts op de rotor veroorzaakt echter ook een hogere geluidsproductie. Als weer wordt uitgegaan van windsnelheden op 10 m hoogte en een neutraal verondersteld atmosfeer, dan bedraagt het geluidsvermogen van de turbine ’s nachts gemiddeld ca. 102 dB(A). In werkelijkheid is het ruim 2 dB hoger. Ook dit is een gemiddelde over een heel jaar; in afzonderlijke nachten kan het verschil veel groter zijn, bijvoorbeeld als een windturbine op (vrijwel) topsnelheid draait, terwijl verwacht was dat deze, gezien de lage windsnelheid op 10 m hoogte, helemaal niet zou produceren. Dit gebeurt vooral in het zomerhalfjaar.

De mate waarin atmosferische stabiliteit optreedt bij Cabauw blijkt nauwelijks te verschillen van wat bij windpark Rhede is waargenomen. Op andere locaties in landen in de gematigde zone blijkt stabiliteit in vergelijkbare mate voor te komen. De beschreven gevolgen van atmosferische stabiliteit zullen dus bij veel windparken optreden die in de gematigde zone staan of nog gebouwd worden. Echter, boven grote wateroppervlakken is stabiliteit eerder een seizoens- dan een dagelijks verschijnsel, en in bergachtig gebied kunnen de gevolgen van stabiliteit op het windprofiel zowel versterkt als verzwakt worden door veranderingen tengevolge van hoogteverschillen in het gebied.

Geluid van een windturbine of windpark wordt dus om twee redenen na zonsondergang hinderlijker: het wordt luider en het geluid vertoont sterkere fluctuaties. Bij een gegeven rotordiameter kan een wiek alleen stiller worden door een ander ontwerp of door de snelheid te verlagen. Snelheidsverlaging gaat echter ten koste van het opgewekte elektrische vermogen en moet daarom liefst alleen worden toegepast wanneer dat nodig is. Daartoe kan een regeling worden toegepast die de snelheid verlaagt wanneer een geluidslimiet wordt overschreden, en deze weer verhoogt wanneer de limiet dat toelaat. De regeling zou kunnen ingrijpen op de generator en/of de vaanstand van de wieken.
Door de vaanstand tijdens de rotatie van de wieken te variëren kan op elke positie de wind onder een optimale hoek de rotor instromen, waardoor enerzijds het energetisch rendement toeneemt en anderzijds de fluctuatiesterkte van het geluid afneemt en de fluctuaties zelfs onhoorbaar kunnen worden. Het totale geluidsvermogen zal afnemen, zelfs ten opzichte van een neutrale atmosfeer, omdat het instromingsturbulentie-geluid zal verminderen door de relatieve afwezigheid van atmosferische turbulentie. Het kantelen van de rotor waardoor tijdens een rotatie de vaanstand verandert lijkt geen vruchtbare strategie: de kanteling moet zo groot zijn dat de nadelen overheersen.

Bij een windpark kunnen de fluctuaties sterker zijn door interferentie van de fluctuaties van meerdere turbines. Dit kan worden voorkomen door de turbines te desynchroniseren, zoals dat overdag gebeurt door grootschalige atmosferische turbulentie, door kleine en ongecorreleerde variaties in de belasting van de rotors of in de vaanstand van de wieken van de afzonderlijke turbines.

Het beheersen van de geluidsproductie vergt derhalve een nieuwe strategie bij de regeling van windturbines: overdag is er vaak meer geluidsruimte beschikbaar dan ’s nachts en die ruimte kan overdag gebruikt worden als er ’s nachts beperkingen worden opgelegd.

Als laatste is nog een geheel ander probleem onderzocht: de invloed van wind op een microfoon, al of niet in een windbol. Bij voldoende wind bevat het microfoonsignaal een laagfrequent, rommelend geluid waardoor de meting van omgevingsgeluid wordt verstoord. Deze ‘rumble’ is geen geluid uit de omgeving, maar ontstaat door drukvariaties tengevolge van turbulente windsnelheidsvariaties. Met een drukgevoelige microfoon zijn deze drukvariaties niet te onderscheiden van akoestische drukvariaties. Het blijkt dat een windbol alleen effectief is doordat de bijdragen van kleine turbulente wervels worden gedempt. Een windbol heeft geen effect bij wervels die groter zijn dan de windbol.
De sterkte van atmosferische turbulentie hangt niet alleen af van de (gemiddelde) wind snelheid, maar ook van de lokale ruwheid van het aardoppervlak en de stabiliteit van de atmosfeer. De twee laatste factoren veroorzaken respectievelijk wrijvingsturbulentie en thermische turbulentie. De turbulentiesterkte is in de literatuur goed bekend bij een vrije aanstroming van wind over vlak land. De turbulentie is zwakker in een stabiele, sterker in een instabiele atmosfeer.
Het op atmosferische turbulentie gebaseerde ‘geluids’drukniveau blijkt goed overeen te komen met gemeten en gepubliceerde niveaus van door wind geïnduceerde drukniveaus. De invloed van wind op een geluidsmeting in wind kan dus worden berekend. Omgekeerd levert het rekenmodel een nieuwe methode om de sterkte van de atmosferische turbulentie te meten.

Tot slot kunnen we concluderen dat er bij het geluid van windturbines een belangrijk fenomeen over het hoofd is gezien: de verandering van de wind na zonsondergang. Dit fenomeen zal belangrijker worden voor moderne, hoge windturbines en met het oog op de vele windparken die worden gepland. Als dit probleem niet wordt onderkend en opgelost zal het de uitbreiding van windenergie bemoeilijken.

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APPENDICES

Appendix A
List of symbols

Symbol: definition [unit]

α:	angle of attack [radian] or [degree];
	also: rotor pitch angel [radian] or [degree]
	also: constant relating wind velocity to pressure [-]
δ_i^*:	displacement thickness of turbulent boundary layer [m]
η_s:	Kolmogorov size [m]
κ:	von Karman's constant [0.4]
ν:	kinematic viscosity of air $[m^2 \cdot s^{\ 1}]$
ρ:	correlation coefficient (1/3 octave band level vs. L_A) [-];
	also: air density $[kg/m^3]$
$\Psi(\zeta)$:	stability function [-]
θ:	rotor tilt angel [radian] or [degree]
ζ:	dimensionless height (h/L) [-]
Ω:	turbine rotor angular velocity $[rad \cdot s^{\ 1}]$
a:	induction factor (1- V_b/V_h) [-]
b:	correction factor for boundary layer thickness (value: 2 4)
c:	velocity of sound in air $[m \cdot s^{\ 1}]$
C:	blade chord length [m]; also: air density dependent constant ($C \quad 20 \cdot \log(0.215 \kappa \alpha \rho V_o^2 / p_{ref})$ [dB])
C_p:	constant ($C_p \quad 20 \cdot \log(0.215 \kappa \alpha) \quad 9.5$) [dB]
D:	diameter [m]
D_h:	directivity function [-]
$D_{j,k}$:	decrease in octave band sound level j of turbine k with distance [dB]
D_{geo}:	decrease in sound level due to geometrical spreading [dB]
D_{air}:	decrease in sound level due to air absorption [dB]
D_{ground}:	decrease in sound level due to ground absorption and reflection [dB]
dB(A):	unit of level after A-weighting

dB(G): unit of level after G-weighting

f: frequency [Hz]

f_{mod}: modulation frequency [Hz]

$f_{peak,TE}$: peak frequency of trailing edge sound [Hz]

$f_{peak,if}$: peak frequency of in-flow turbulence sound [Hz]

f_m : middle frequency of 1/3 octave band [Hz]

f_B: blade passing frequency [Hz]

f_c: screen size related corner frequency (f_c 0.3V/D) [Hz]

f_i: α-dependent factor for TE layer thickness [-]

f_{log}: ratio v_{98}/v_{10} valid in a neutral atmosphere [-]

$f_{(un)stable}$: ratio v_{98}/v_{10} valid in an (un)stable atmosphere [-]

F_{bb}: fluctuation strength [vacil]

F(z): turbulence related function:

$$F(z) \quad 20 \cdot \log[(z/D)^{1/3} \cdot (\ln(z/z_o) - \Psi)] \text{ [dB]}$$

G(z): turbulence related function:

$$G(z) \quad 20 \cdot \log[0.2 \cdot (z/\ell_o)^{1/3} \cdot (\ln(z/z_o \quad \Psi)] \text{ [dB]}$$

h: height [m]

H: turbine height [m]

h_{ref}: reference height for wind velocity (and direction) [m]

k: integer number (of harmonic frequency) [-];
also: exponent of wind velocity in relation with associated turbulent pressure [-]

K_1: constant (128.5 dB)

K_α: α dependent increase in trailing edge sound level [dB]

ℓ: eddy length scale [m]

ΔL: increase in sound level [dB]

L: Monin-Obukhov length [m]

L_A: broad band A-weighted sound level [dB(A)]

L_{A5}: 5-percentile of broad band sound levels over a period [dB(A)]

L_{A95}: 95-percentile of broad band sound levels over a period [dB(A)]

$L_{at}(u)$: pressure level due to atmospheric turbulence [dB]

$L_{at,1/1}(f)$: pressure level due to turbulent wind per octave band [dB]

$L_{at,1/3}(f)$: pressure level due to turbulent wind per 1/3 octave band [dB]

$L_{at,A}$: broad band A-weighted pressure level [dB]

L_{imm}: immission sound level [dB(A)]

L_{eq}: equivalent sound level; $L_{eq,T}$: over time T [dB(A)]

$L_{p,1/3}$: turbulent pressure level at microphone per 1/3 octave band [dB]

$L_{red,1/3}$: ‘meteorologically reduced’ 1/3 octave band pressure level [dB]

$L_{red,1/1}$: ‘meteorologically reduced’ octave band pressure level [dB]

L_W: sound power level [dB(A)]

L_{Wj}: j-th octave band sound power level [dB(A)]

M: Mach number air flow velocity/c (at radius R: M ΩR/c) [-]

m: stability exponent [-]

$m_{h1,h2}$: *m* determined between heights h_1 and h_2 [-]

mf: modulation factor [-]

n: dimensionless frequency (n fz/V) [-]

N: number of blades [-]; rotational speed (ΩR/2π) [s ^{1}]

Ph: Power at height h; Ph,lpp; Ph,hp [W]

p: (sound) pressure [Pa]

$p_{f,}$: rms pressure in narrow frequency band centered at frequency f [Pa]

$p_{f1/3}$: rms pressure in 1/3 octave band [Pa]

p_{ref}: reference (sound) pressure [20 μPa]

p(0): rms pressure at center of wind screen [Pa]

r: distance [m]

R: rotor radius blade length [m]

ΔR: increment in R [m]

R_X: range between maximum and minimum sound levels (X bb or f) [dB]

$R_{X,90}$: range between 5- and 95-percentile of sound levels (X bb or f) [dB]

Re: chord based Reynolds number (Re ΩRC/ν); wind screen diameter based Reynolds number [-]

S: ratio of distance along blade and chord length [-]

Sp_i: 1/3 octave band weighing function for TE sound [dB]

SPL_i: sound pressure level of source i [dB]

Sr: Strouhal number [-]

u: longitudinal (along wind) component of turbulent wind velocity [m·s ^{1}]

u_f : rms longitudinal component of turbulent wind velocity per unit frequency [m·s $^{3/2}$]

u*: friction velocity [m·s ^{1}]

U: instanteneous wind velocity: U <U> + u [m·s ^{1}]

V: air flow velocity or wind velocity [m·s ^{1}]

V_o: reference velocity [1 m·s ^{1}]

V_b: induced wind velocity at turbine blade [m·s ^{1}]

V_h, V_{xx}: wind velocity at height h or height xx m [m·s ^{1}]

$V_{h,b}$, $V_{xx,b}$: induced wind velocity at turbine blade or height h [m·s ^{1}]

V_{hub}: wind velocity at wind turbine hub height h [m·s ^{1}]

V_i: local (induced) velocity at blade ≈ 2V/3 [m·s ^{1}]

V_{ref}: wind velocity at reference height [m·s ^{1}]

<x>: time average of variable x

z_o: roughness height; altitude [m]

Subscripts:

1/1: frequency octave band

1/3: 1/3 frequency octave band

A: A-weighted

at: atmospheric turbulence

bb: broad band

f: at frequency of (1/3) octave band

h: at height h, hub

i: component of TE sound (i p, s, α)

if: in-flow

p: pressure, pressure side

ref: reference

s: suction side

TE: trailing edge

Appendix B
Dominant sources of wind turbine sound

With modern wind turbines there are three important mechanisms that produce sound. These will be reviewed here up to a detail that is relevant to the text in this book.

B.1 Infrasound: thickness sound

When a blade moves through the air, the air on the forward edge is pushed sideways, moving back again at the rear edge. For a periodically moving blade the air is periodically forced, leading to ‘thickness sound’. Usually this will not lead to a significant sound production as the movement is smooth and thus accelerations relatively small.
When a blade passes the turbine tower, it encounters wind influenced by the tower: the wind is slowed down, forced to move sideways around the tower, and causes a wake behind the tower. For a downwind rotor (*i.e.* the wind passes the tower first, then the rotor) this wake causes a significant change in blade loading.
The change in wind velocity near the tower means that the angle of attack of the air on a blade changes and lift and drag on the blade change more or less abruptly. This change in mechanical load increases the thickness sound power level at the repetition rate of the blade passing frequency f_B. For modern turbines f_B $N \cdot \Omega/(2\pi)$ typically has a value of approximately 1 Hz. As the movement is not purely sinusoidal, there are harmonics with frequencies $k \cdot f_B$, where k is an integer. Harmonics may occur up to 30 Hz, so thickness sound coincides with the infrasound region (0 30 Hz). Measured levels at 92 m from the two-bladed 2 MW WTS-4 turbine showed that measured sound pressure levels of the individual blade harmonics were less than 75 dB, and well predicted by calculations of wind-blade interaction near the turbine tower [Hubbard *et al* 2004, Wagner *et al* 1996]. The envelope of the harmonics peaks at the fifth harmonic (k 5 with f_B 1 Hz), indicating a typical pulse time of $(5\ \text{Hz})^{1}$ 0,2 s which is 20% of the time between consecutive blade passages. The WST-4 is a

downwind turbine with an 80 m tubular tower, where the wind velocity deficit was estimated to be 40% of the free wind velocity [Hubbard *et al* 2004]. For modern, upwind rotors the velocity deficit in front of the tower is smaller. As a consequence the change in blade loading is less than for downwind turbines. From data collected by Jakobsen it appears that the infrasound level at 100 m from an upwind turbine is typically 70 dB(G) or less, whereas near downwind turbines it is 10 to 30 dB higher. As 95 dB(G) corresponds to the average infrasound hearing threshold [Jakobsen 2004], infrasound from (upwind) wind turbines does not appear to be so loud that it is directly perceptible.

B.2 Low frequencies: in-flow turbulent sound

Because of atmospheric turbulence there is a random movement of air superimposed on the average wind velocity. The contribution of atmospheric turbulence to wind turbine sound is named 'in-flow turbulence sound' and is broad band sound stretching over a wide frequency range. For turbulent eddies larger in size than the blade this may be interpreted as a change in the direction and/or velocity of the incoming flow, equivalent to a deviation of the optimal angle of attack. This leads to the same phenomena as described in section B.1, but changes will be random (not periodic) and less abrupt. For turbulent eddies the size of the chord length and less, effects are local and do not occur coherently over the blade. When the blade cuts through the eddies, the movement normal to the wind surface is reduced or stopped, given rise to high accelerations and thus sound.

In-flow turbulence sound has a maximum level in the 1/3 octave band with frequency

$$f_{\mathrm{peak,if}} \quad (\mathrm{St}\cdot 0.7R\cdot\Omega)/(H-0.7R) \tag{B.1}$$

where Strouhal number St is 16.6 [Grosveld 1985, Wagner *et al* 1996]. Most sound is produced at the high velocity, outer parts of the blades. For a modern, tall, three-bladed wind turbine with hub height H 100 m, blade length R 35 m and angular velocity Ω $2\pi f_B/3$ 2 rad·s ^{1} (20 rpm), $f_{\mathrm{peak,if}}$ 11 Hz which is in the infrasound region. Measured fall-off from $f_{\mathrm{peak,if}}$ is initially approx. 3 dB per octave, increasing to 12 dB per octave at frequencies in the audible region up to a few hundreds of hertz [Grosveld 1985, Wagner *et al* 1996].

B.3 High frequencies: trailing edge sound

Several flow phenomena at the blade itself or in the turbulent wake behind a blade cause high frequency sound ('airfoil self-noise'). Most important for modern turbines is the sound from the turbulent boundary layer at the rear of the blade surface where the boundary layer is thickest and turbulence strength highest. Trailing edge sound has a maximum level in the 1/3 octave band with frequency

$$f_{peak,TE} \quad 0.02 \cdot \Omega \cdot R \cdot /(\delta^{*} \cdot M^{0.6}) \qquad \text{(B.2)}$$

where Mach number M is based on airfoil velocity. The displacement thickness of the turbulent boundary layer is:

$$\delta^{*} \quad b \cdot 0.37 \cdot C \cdot Re^{\,0.2}/8 \qquad \text{(B.3)}$$

for a zero angle of attack. Re is the chord based Reynolds number [Brooks *et al* 1989]. The experimental factor b accounts for the empirical observation that the boundary layer is a factor 2 to 4 thicker than predicted by theory [Lowson 1995, Wagner *et al* 1996]. For air of 10 °C and atmospheric pressure, a typical chord length C 1 m, and other properties as given above (section B.2), $f_{peak,TE}$ 1700/a Hz. With b 2 to 4, $f_{peak,TE}$ is 450 900 Hz. The spectrum (see Sp_i below) is symmetrical around $f_{peak,TE}$ and decreases with 3 dB for the first octave, 11 dB for the next; the contribution from further octave bands is negligible [Brooks *et al* 1989].

According to Brooks *et al* [1989] trailing edge sound level can be decomposed in components SPL_p and SPL_s due to the pressure and suction side turbulent boundary layers with a zero angle of attack of the incoming flow, and a component SPL_a that accounts for a non-zero angle of attack α. For an edge length ΔR each of the three components of the immission sound level at distance r can be written as [Brooks *et al* 1989]:

$$SPL_i \quad 10 \cdot \log(\delta_i^{*} \cdot M^5 \cdot \Delta R \cdot D_h/r^2) + Sp_i + K_1 - 3 + K_i \qquad \text{(B.4)}$$

and total trailing edge immission sound level as:

$$SPL_{TE} \quad 10 \cdot \log(\Sigma_i\ 10^{SPLi/10}) \tag{B.5}$$

where the index i refers to the pressure side, suction side or angle of attack part (i   p, s, α). The directivity function D_h equals unity at the front of the blade (θ   180°) and falls off with $\sin^2(\theta/2)$. Because of the strong dependence on M (~ M^5, equation B.4) trailing edge sound is dominated by sound produced at the high velocity parts: the blade tips.

Sp_i gives the symmetrical spectral distribution of the trailing edge sound spectrum centered on $f_{peak,TE}$ and is maximum (0 dB) at this centre frequency. The constant K_1 - 3   125.5 dB applies when the chord based Reynolds number exceeds $8 \cdot 10^5$ and the pressure-side turbulent boundary displacement thickness $\delta_i^* > 1$ mm, as is the case for modern tall turbines. K_i is non-zero only if i   α.

For positive angles of attack α < 10° the boundary layer thickness δ^* shrinks with a factor f_p $10^{\ 0.042\alpha}$ at the pressure-side and δ^* grows at the suction-side with a factor f_s $10^{0.068\alpha}$. Because δ_α^* δ_s^*, f_α f_s. K_α has a large negative value for α   0. For 1° < α < 10° and M   0.2 the calculated values of K_α (see formula 49 in [Brooks *et al* 1989] with K_α K_2-K_1+3) are plotted in figure B.1 and these can be approximated by:

$$K_\alpha \quad -0.35 \cdot \alpha^2 + 5.5 \cdot \alpha \quad 14.4 \text{ (α in degrees)} \tag{B.6}$$

With equation B.4, equation B.5 can be rewritten as:

$$SPL_{TE} \quad 10 \cdot \log(\delta^* \cdot M^5 \cdot \Delta R \cdot D_h / r^2) + K_1 - 3 +$$

$$+ 10 \cdot \log(\Sigma_i\ 10^{(10 \bullet \log(fi) + Spi\ +\ Ki)/10}) \tag{B.7}$$

The last term in B.7 is the α-dependent part. For the peak frequency 1/3 octave band level (Sp_i 0) the last term in equation B.7 is 3 dB for α   0 and 3.4 dB for α   1°, then increasing with 1.5 dB per degree to 14.5 dB at α   9°. The level increase $\Delta SPL_{TE}(\alpha)$ $SPL_{TE}(\alpha)$ - $SPL_{TE}(\alpha\ \ 0)$ is given in table B.1 and plotted in figure B.1. The best lineair approximation in the range 1° < α < 10° is:

$$\Delta SPL_{TE}(\alpha) \quad 1.5 \cdot \alpha - 1.2 \text{ (dB)} \qquad \text{(B.8)}$$

with α in degrees (or $\Delta SPL_{TE}(\alpha) \quad 86 \cdot \alpha - 1.2$ dB with α in radians).

Table B1: increase of trailing edge sound level with angle of attack α

A	1º	2º	3º	4º	5º	6º	7º	8º	9º
$\Delta SPL_{TE}(\alpha)$ (dB)	0.4	1.4	2.9	4.6	6.4	8.0	9.4	10.6	11.5

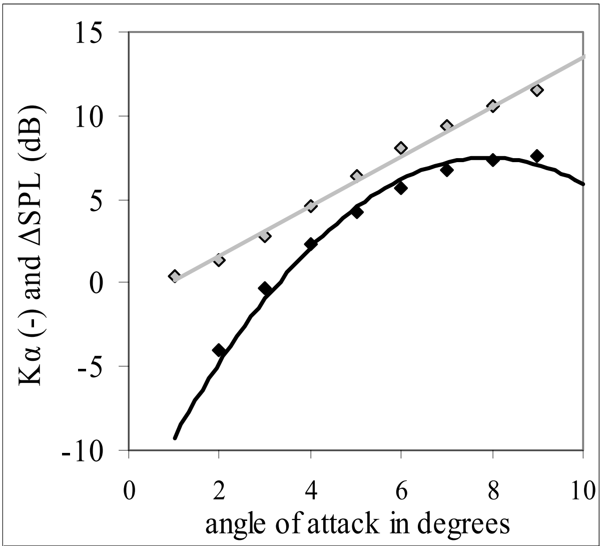


Figure B.1: non-zero angle of attack correction K_α (black diamonds) and resulting added sound pressure level ΔSPL (gray diamonds) with best fits in range $1^o < \alpha < 10^o$

The blade swish that is audible near a turbine is a variation in level of less than 3 dB (in daytime) [ETSU 1996]. It must correspond to a change in sound level of 1 dB to be heard at all. An increase of 1 dB corresponds to an increase in α with 0.7°, an increase of 3 dB corresponds to 2.9°. So, for a swish level of 2 ± 1 dB, we estimate the change in α at the tower passage as 1.8º ± 1.1º. Part of this is due to the lower wind velocity at the lower blade tip relative to the rotor average, the rest is due to the slowing down of the wind by the tower.

For small angles the change of wind velocity with angle of attack α at radius R is $dV_{wind} \quad \Omega \cdot R \cdot d\alpha$, or

$$dV_{wind} \quad 0.017 \cdot \Omega \cdot R \cdot d\alpha \qquad \text{(B.9)}$$

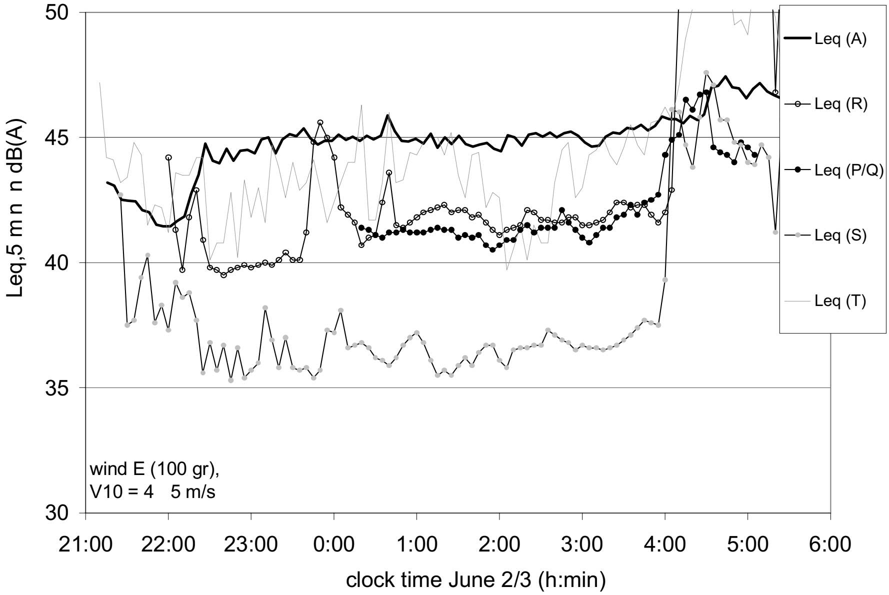
with α in degrees.

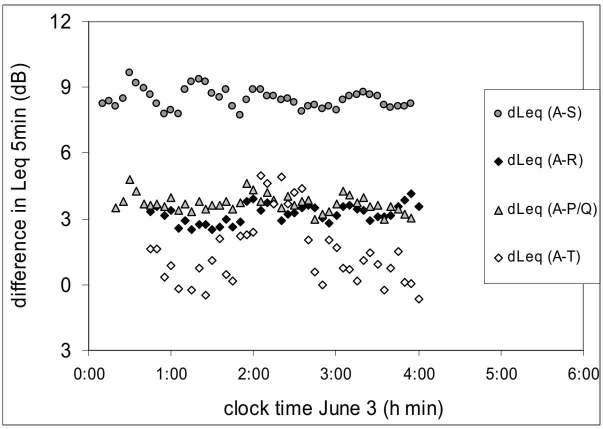
So for a modern turbine at high speed ($\Omega \cdot R \approx 70$ m/s at tip at 20 rpm) the wind velocity deficit where the blade tip passes the tower and α 1° (0.017 radians) is 1.2 m/s. In a free 14 m/s wind, *i.e.* 9.3 m/s at the rotor, this is 13%. This deficit is due to the influence of the tower as well as the (daytime) wind profile.

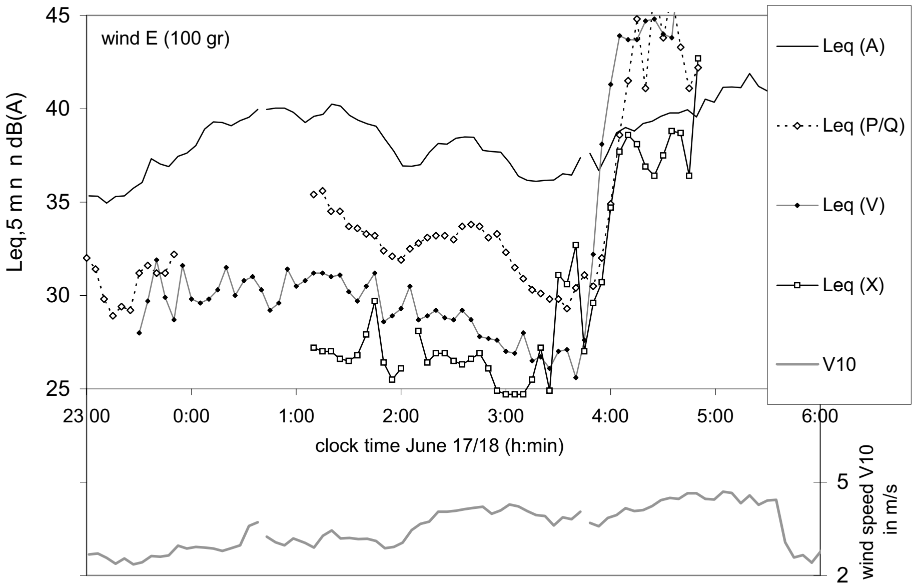
Appendix C

Simultaneous registrations of sound immission level

Additional information to section IV.10: measurements at locations A and P through X (see map figure IV.2) in year 2002. Graphs show measured values of $L_{eq,5min}$ at locations near Rhede wind farm and differences relative to measured value at location A. Wind velocity and wind direction and time of measurement are mentioned in the figures.






wind E (100 gr)
Leq,5 m n n dB(A)
45
40
35
30
25
23:00
0:00
1:00
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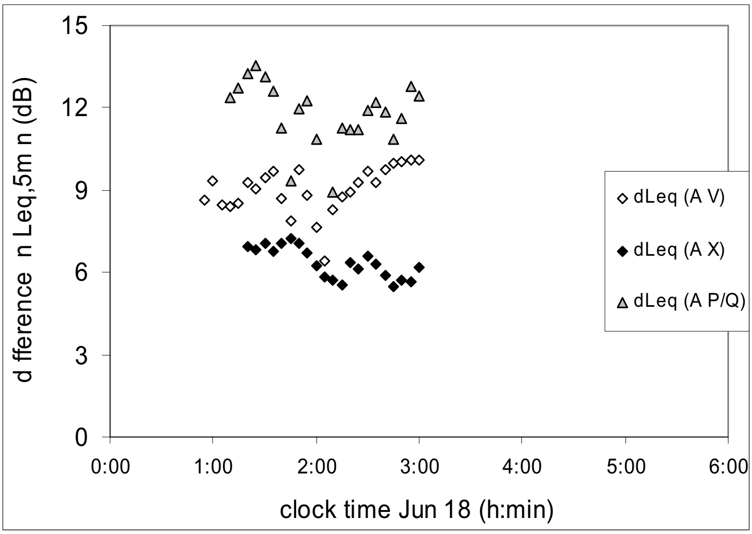
5:00
6:00
clock time June 17/18 (h:min)
Leq (A)
Leq (P/Q)
Leq (V)
Leq (X)
V10
wind speed V10 in m/s
5
2


d fference n Leq,5m n (dB)
15
12
9
6
3
0
0:00
1:00
2:00
3:00
4:00
5:00
6:00
clock time Jun 18 (h:min)
dLeq (A V)
dLeq (A X)
dLeq (A P/Q)

Appendix D
Publications by the author

D1 Published and conference papers

D1.1 Single author

Stiltegebieden, Noorderbreedte juni 1991, pp. 35-39

Onduidelijke stralingsnormen leiden tot onrust, Intermediair vol. 27 nr. 35 (30 augustus 1991), pp. 27-28

Hoogspanningslijnen en overheidsbeleid, NVS-Nieuws 17e jaargang nr. 5 (december 1992), pp. 11-12

Waar of niet: mogelijk of vermeend, NVS-Nieuws 18e jaargang nr. 2 (april 1993) pp. 8-9 (reactie op artikel)

Noise from the Marnewaard shooting range; a review of sound and annoyance measurements, proceedings Internoise93, Leuven, pp. 1145-1148

*A home kit for road traffic noise***,** proceedings Euronoise95, Lyon, pp. 163-168

Laagfrequent geluid-een onderschat probleem, Geluid mrt 1996, pp.14-18

Straling - één pot nat; Psychologische effecten van elektromagnetische straling, NVS-Nieuws, 22e jaargang nr.4, oktober 1997, pp. 11-14

Natural ambient background sound near the Waddensea, proceedings Internoise97, Budapest, pp. 791 - 794

Bommen op Vlieland, Geluid dec. 1997, pp.140-142

Sound exposure measurements in cases of low frequency noise complaints, proceedings Internoise 1998, Christchurch

Long range outdoor propagation and interference of low frequency tonal sound, proceedings Internoise 1998, Christchurch

Case control study in low frequency sound measurements, proceedings Internoise 1999, Fort Lauderdale

Streefwaarden voor laagfrequente geluidsafstraling door trillingen in de woonomgeving, proceedings Geluid en trillingen in Nederland en Europa, Rotterdam 1999

Wiens brood men eet, ... Een pleidooi voor onafhankelijke geluidsadviseurs, Geluid juli 2000, pp. 103-105
Measurement and analysis of natural ambient sound levels and weather parameters, proceedings Internoise 2000, Nice
*Low frequency sounds in dwellings: a case control study***,** Journal of Low Frequency Noise, Vibration and Active Control, Vol. 19 no. 2, 2000
Tinnitus as a cause of low frequency noise complaints, proceedings Internoise 2001, den Haag
Hoorbaar infrageluid door heien in zand Zevenaar zucht onder heislagen, Land + Water juli/augustus (nummer 7/8), 2001
*Last van een lage toon: tinnitus of een motor ?***,** Contactblad Tinnitus & Hyperacusis (nr. 2002 2), NVVS
Low frequency sound and health effects from low noise pile driving, proceedings Internoise 2002, Dearborn
Science and society - the science shop approach (La science et la societe - l'approche "boutique de science"), proceedings CEPAPE workshop, september 2002, Ouagadougou
Wind turbines at night: acoustical practice and sound research, proceedings Euronoise2003, Naples
Effects of the wind profile at night on wind turbine sound, Journal of Sound and Vibration vol. 277 (4-5), pp 955-970 (2004)
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