A Methodology for Assessment of Wind Turbine Noise Generation

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The detailed analysis of a series of acoustic measurements taken near several large wind turbines (100 kW and above) has identified the maximum acoustic energy as being concentrated in the low-frequency audible and subaudible ranges, usually less than 100 Hz. These measurements have also shown any reported community annoyance associated with turbine operations has often been related to the degree of coherent impulsiveness present and the subsequent harmonic coupling of acoustic energy to residential structures. Thus, one technique to assess the annoyance potential of a given wind turbine design is to develop a method which quantifies this degree of impulsiveness or coherency in the radiated acoustic energy spectrum under a wide range of operating conditions. Experience has also shown the presence of annoying conditions is highly time dependent and nonstationary, and, therefore, any attempts to quantify or at least classify wind turbine designs in terms of their noise annoyance potential must be handled within the proper probabilistic framework. A technique is described which employs multidimensional, joint probability analysis to establish the expected coincidence of acoustic energy levels in a contiguous sequence of octave frequency bands which have been chosen because of their relationship to common structural resonant frequencies in residential buildings. Evidence is presented to justify the choice of these particular bands. Comparisons of the acoustic performance and an estimate of the annoyance potential of several large wind turbine designs using this technique is also discussed.

Introduction

Until the fall of 1979, noise from large wind turbines had not been a major concern. The situation changed however as the 2 MW, MOD-1 turbine installed near Boone, North Carolina began to undergo a series of operational tests which resulted in a number of sporadic and totally unexpected noise complaints from a few residents living within 3 km of the installation. Since that time, a considerable effort has been undertaken by a number of organizations who have studied the phenomena to find out the exact nature of the noise responsible for annoying the neighbors, its origin and production mechanism, its propagation path, and what could be done to eliminate or at least reduce it to below perceptible levels. Some of the results of these studies have been reported previously [1].

To date, acoustically-related annoyance from large wind turbines has been confined to a dozen families living within 3 km of the MOD-1. There have been no documented complaints of noise the author is aware of with any of the four MOD-OA turbines currently operating, and two surveys of the MOD-2 turbine have failed to find a tendency for impulsive noise generation similar to the MOD-1 in the measurements taken so far [3, 4]. Some impulsive noise has been detected in a recent survey of the 17-m Darrieus/VAWT [5]. The situation in Boone, however, has been severe enough to warrant a close examination of the details of the MOD-1 experience. The causal factors responsible for the noise had to be identified; this information would then be used to develop a methodology to assess the annoyance potential of other wind turbine designs by measuring their acoustic radiation with reference to the MOD-1 data.

Characteristics of Large Wind Turbine Noise

Figure 1 summarizes the acoustic pressure spectrum associated with large wind turbines and indicates the dominate noise sources as a function of frequency. Not all wind turbines will exhibit the features of the spectrum shown. The ultimate cause of aerodynamically generated sound is the unsteady loading of the blades. The degree of this unsteadiness, for the most part, is responsible for the distribution of acoustic energy across the spectrum of Fig. 1.

Conventional classifications of rotor noise include rotational, broadband or vortex, and impulse noise. Rotational noise is characterized by the large number of discrete frequency bands which are harmonically related to the blade passage frequency. The amplitude of these bands is determined by the sum of the steady load, which is a function of the commanded level of operation of the machine, and the unsteady loading at any moment arising from such sources as inflow turbulence and upstream wakes. Broadband or vortex noise results from the slightly viscous interaction of the unsteady lift and the blade boundary layer and is responsible for such mechanisms as flow separation and tip-and trailing-edge vortex shedding. Broadband noise, which is described as

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Contributed by the Solar Energy Division and presented at the 5th Biennial Wind Energy Conference and Workshop, Washington, D.C., October 5-7, 1981. Manuscript received by the Solar Energy Division March 4, 1982.

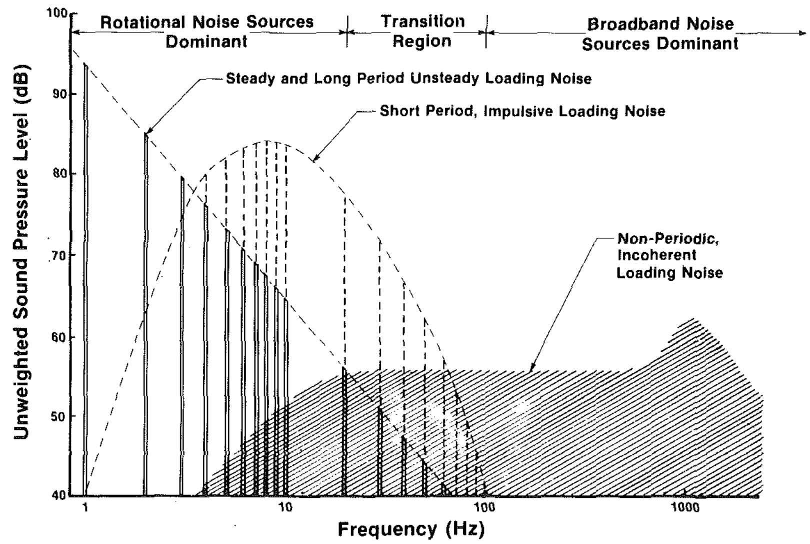

Fig. 1 Schematic representation of wind turbine noise spectrum characteristics

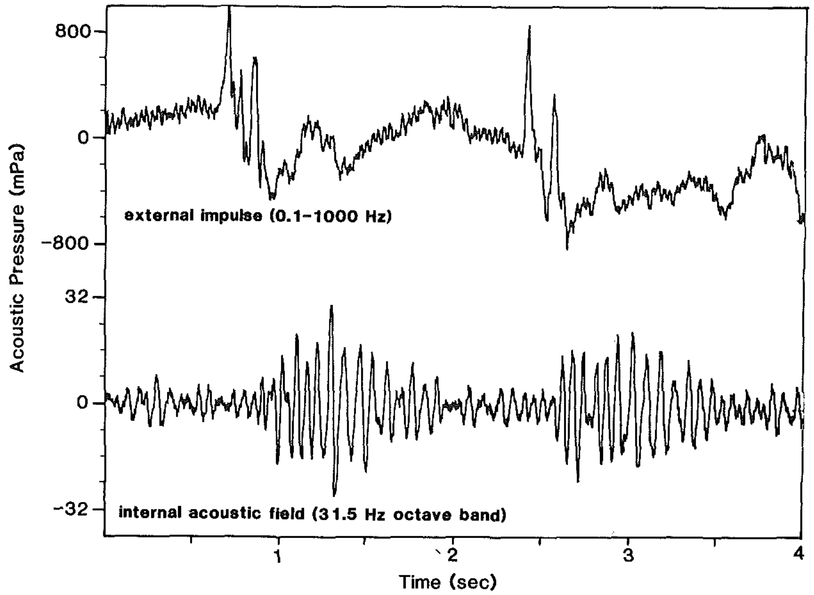

Fig. 2 Pressure-time plots of MOD-1 impulse excitation and internal 31.5 Hz octave band pressure level in house No. 8, Boone, N.C.

the "swishing" sound associated with the turbine operation, is characterized by largely incoherent radiation over a wide frequency range with a spectral "hump" sometimes found at relatively high frequencies. Recent measurements of the MOD-2 turbine have found just such a "hump" in the region shown in Fig. 1 [4]. Impulsive noise, such as has been found with the MOD-1, is identified with short, transient fluctuations in the radiated acoustic field which can contain considerable energy. The dashed lines in the region transcending the rotational and broadband regions of the spectrum in Fig. 1 are indicative of impulsive behavior and reflect the very large number of harmonics necessary to describe the blade loading spectrum which are the sources of the radiation. Impulsive noise tends to be the most annoying because it dominates all other sources due to a high degree of coherence and radiation efficiency. From Fig. 1, the highest levels of acoustic energy can be seen to reside in the low-frequency and subaudible (<20 Hz) ranges in the form of discrete bands. The presence of short period, unsteady blade loads will increase the amount of discrete radiation in the higher rotational harmonics, usually peaking in the 8-15 Hz range.

Low Frequency Sound. The low frequency dominated spectrum of Fig. 1 is a result of the low rotational speed of wind turbines as compared with other forms of turbine machinery. At the present time no adequate standard exists for evaluating impulsive noise, particularly when the sound energy is concentrated below 100 Hz. This gap is due to our limited knowledge of the psychological response and the physical parameters involved with transient sounds which are perceived by humans as annoyance. As part of their program to develop a proposal for wind turbine noise criteria, the psychoacoustics group at the NASA Langley Center has performed a series of tests to establish the perception threshold for low-frequency audible, impulsive-type sounds. Their results are reported in reference [1].

A Possible Low Frequency Annoyance Mechanism

During our March 1980 field measurement program at the MOD-1, we were very fortunate to obtain permission from two very cooperative families living near the machine (who had a history of complaints) to make a series of detailed

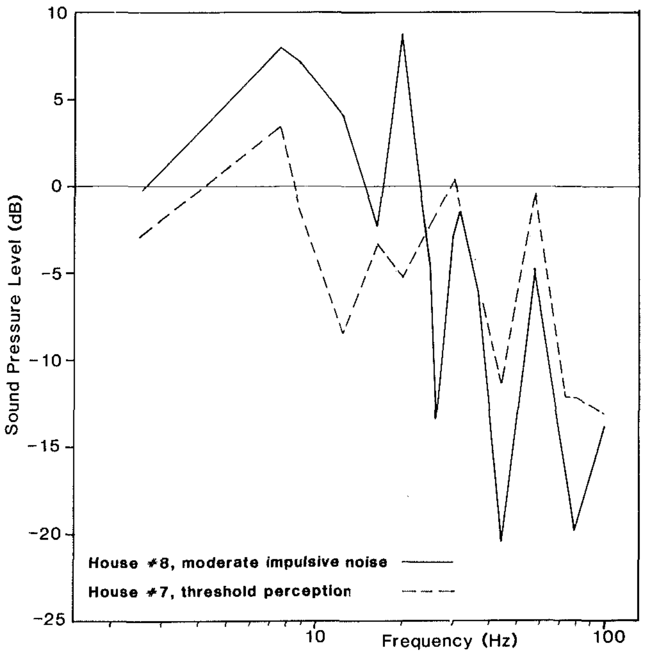

Fig. 3 Peak indoor-outdoor sound pressure level difference for moderate annoyance and threshold perception in houses #7 and #8, Boone, N.C.

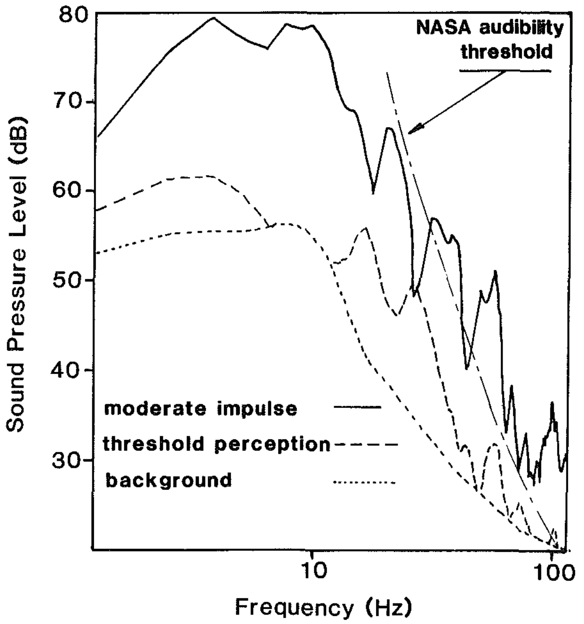

Fig. 4 Peak indoor sound pressure levels

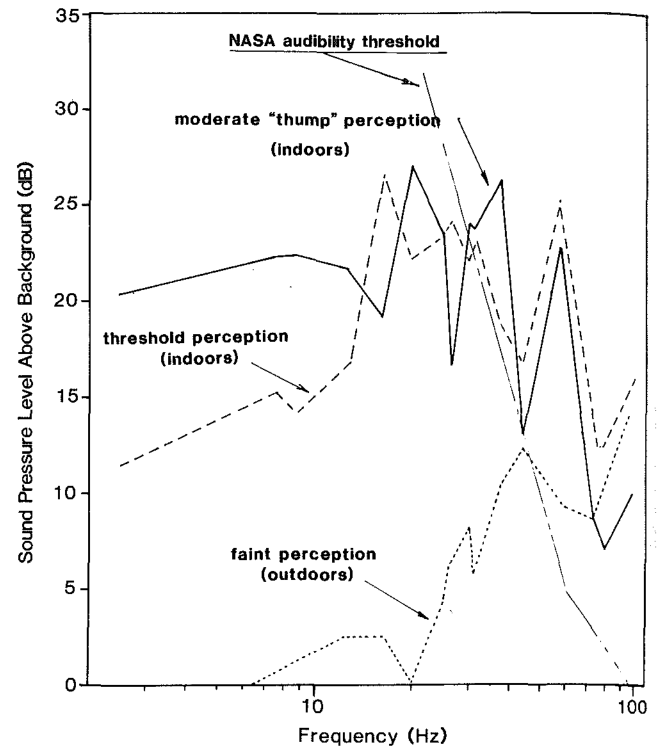

Fig. 5 Peak indoor sound pressure levels above existing background (B_e = 1.25 Hz)

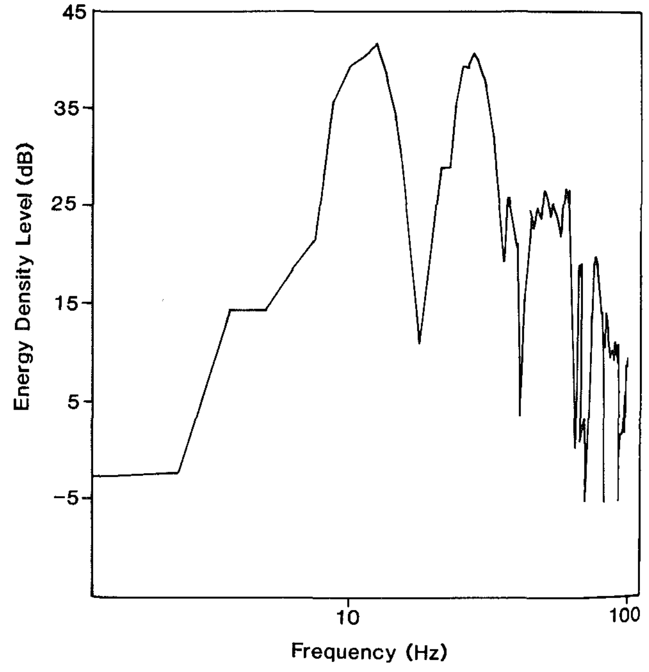

Fig. 6 Moderate-to-severe impulse perception excitation

acoustic and vibration measurements inside and outside of their homes during turbine operations. In addition to the physical measurements, we visited many of the other complaining families and received a description of the annoying sounds. In summary, the complaints centered on the following perceptions:

(*i*) the annoyance was described as a periodic "thumping" sound accompanied by vibrations;

(*ii*) many persons reported they could "feel" more than hear the sounds;

(*iii*) the sounds were louder and more annoying inside their homes than out; and

(*iv*) some experienced the rattle of a loose glass in picture frames mounted on outside walls and small objects such as perfume bottles atop furniture making contact with an inside wall.

In our visits to other complaining homes, we asked in which room the occupants believed the sounds were the most annoying. Without fail, we were shown rooms which had at least one window which faced the turbine. More often than not, the room was a smaller one, usually a bedroom.

Physical Measurement Results. We were able to obtain a range of slight to severe annoyance levels while recording in the conventional two story, frame structure we have identified as house #8, which is located about 1 km and 300 m below the turbine. We also obtained a well-documented measurement of threshold level perception stimuli while recording in the double-wide, mobile home identified as house #7, which is located approximately the same distance from the turbine and less than 0.5 km from house #8. These two data sets have allowed us to compare the impulse excitation levels from both inside and outside the homes. We also have been fortunate to compare these low-frequency impulsive measurements with one involving a slowly varying, broadband source connected with the operation of gas turbine peaking station.

Acoustics. Figure 2 shows the external pressure excitation of the radiated impulse and the resulting indoor pressure trace in the 31.5 Hz octave frequency band. As can be seen, the indoor impulse lasts for a period of over a second compared with the individual impulses outside the house lasting for only a few milliseconds. To compare the moderate annoyance level stimuli with the perception case, we analyzed the differences between indoor and outdoor sound pressure levels and the levels indoors as a function of the existing background. These results are presented in Figs. 3 and 4. Figures 6 and 7 display the acoustic energy density spectra of typical individual impulses striking the homes and invoking moderate-to-severe annoyance and perceptible level responses, respectively. Figure 5 relates this data to local background.

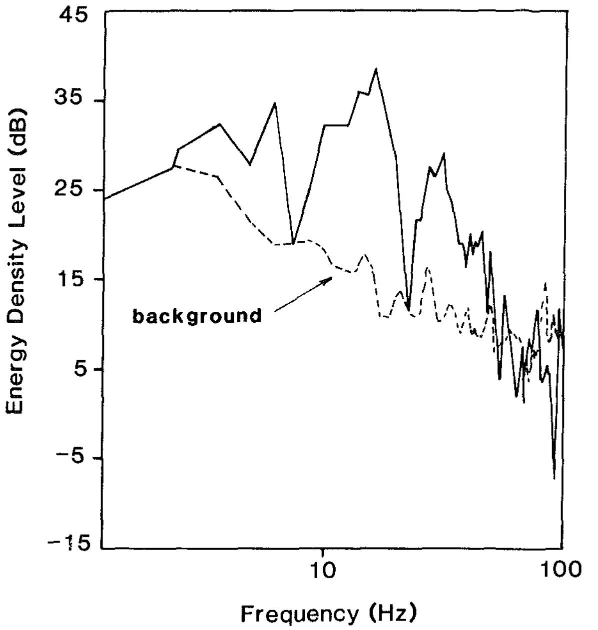

Fig. 7 Threshold level perception impulse excitation (B_e = 1.25 Hz)

Vibration. Figures 8 and 9 plot the frequency spectra of the horizontal component of the floor vibration under both conditions of perception. In both cases, the sensitive axis of the accelerometer was parallel to the major floor support members and in the direction towards the wind turbine. Figure 10 plots the relative transmissibility function for the acoustic and vibration data which indicates the level of dynamic coupling between the mechanical forcing of the floor vibration and the room acoustic pressure field. As is evident, the horizontal floor vibration is more highly coupled to the pressure field in several frequency bands than is the vertical mode vibration. This is in agreement with the low acceleration levels measured in this orientation.

Comparison with a Non-Impulsive Excitation. Because the strong impulses associated with the MOD-1 may be unique, and evidence from other turbines seems to indicate that partially coherent radiation may be much more common, we needed to find a documented source of low-frequency sound to compare with the measurements taken in Boone. We were fortunate to obtain a data set connected with the operation of a 100-MW gas turbine peaking station located in Southwestern Oregon [6]. The complaints of several homeowners living about 3-5 km north and northeast of the plant paralleled those of the Boone residents. Figure 11 compares typical outdoor sound pressure spectra from the two types of turbines. The characteristic sound of the gas turbine, which was caused by resonances in the exhaust stacks, was not impulsive, but a slow modulation was reportedly evident. While the peak frequencies of the two spectra are different, the levels are about the same at 12 Hz. Figure 12 replots the comparison with interior background of Fig. 5 with the data from one of the homes near the peaking station added. This home reported similar sensations as the

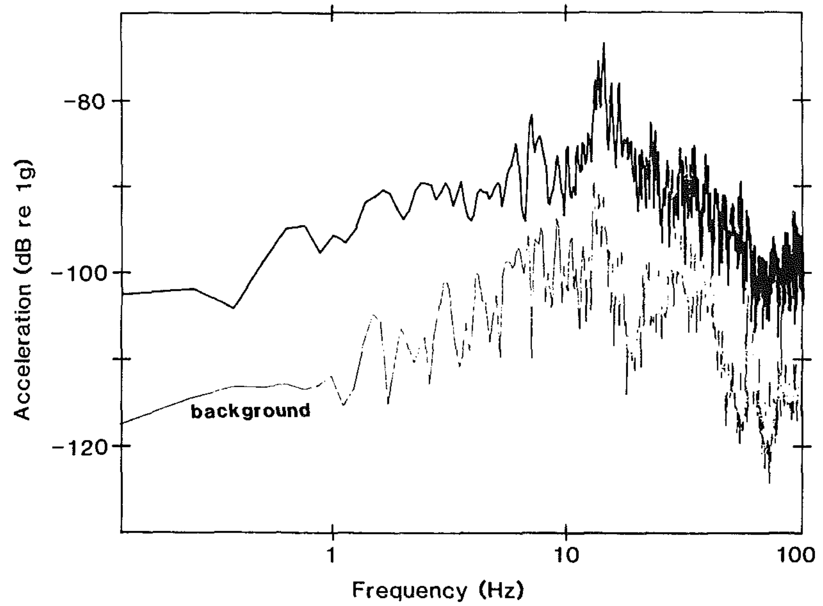

Fig. 8 Background and peak horizontal floor acceleration levels in House #7 under threshold level impulse forcing (B_e = 0.125 Hz)

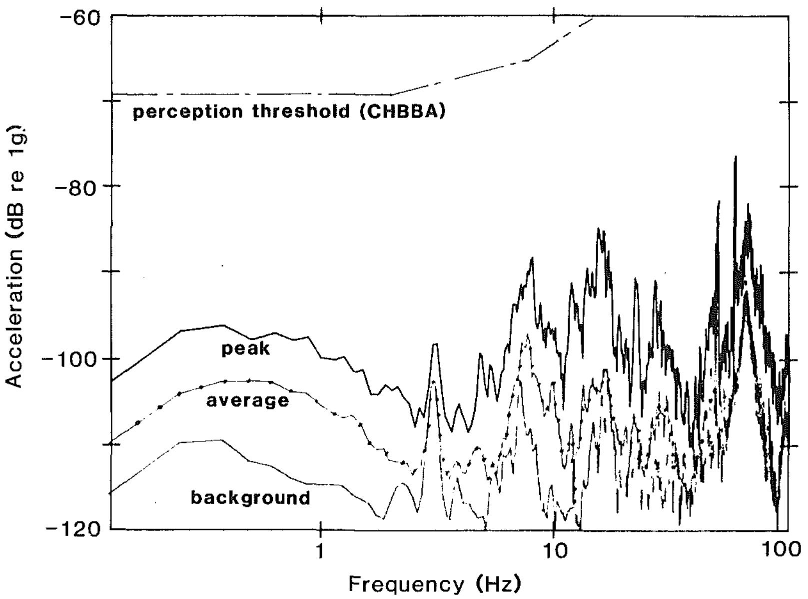

Fig. 9 Horizontal floor acceleration in house #8 under moderate impulsive excitation (B_e = 0.125 Hz)

Boone residents, but very little audible sound, i.e., the feeling of a pressure wave, uneasiness, vibrations, etc.

Interpretation of the Results. The repeated tendencies for both the acoustic pressure field and the vibration data to show discrete peaks at the same frequencies – the room dynamic overpressures shown in Fig. 3 – and the strong resonant behavior of the indoor pressure field when excited by an external impulsive excitation, all point to a complex resonance condition between the volume of air in the rooms and the vibration (displacement) of the walls and floors surrounding it. One of the finest sources of data on the structural dynamics of residential buildings is a NASA Langley study authored by Carden and Mayes [7]. Through the use of sinusoidal excitation and aircraft flyover and sonic boom noise, they determined the characteristic responses of typical frame houses appeared to be largely independent of location and age due to the standardization of building codes which call out such design details as stud and beam spacing, etc. They also found, due to the construction similarities called for by the code, the resonant frequencies associated with the structural elements of most residential buildings fall within the same range but individually depend on the construction details of each house.

The acoustic pressure field within a room of a house is dynamically controlled by (*i*) changes in the shape of the room due to diaphragm action from internal and external pressure changes, (*ii*) higher mode resonances in the walls and floors, (*iii*) cavity oscillations (Helmholż-type resonances) from air moving in and out of the room through a door or window, and (*iv*) the resonant modes of the volume of air in the room itself. The ranges of these resonances are plotted on the data of Fig. 1 along with the factors controlling structural mode damping in other frequency ranges in Fig. 13. Table 1 lists the various resonant modes measured and calculated from the dimensions of the two rooms in the Boone homes.

From an examination of Figs. 3, 4, 5, 8, and 9, the peak acoustic and vibration spectra indicate strong resonances at many of the frequencies listed in Table 1, particularly at the 9 and 14 Hz diaphragm modes. Figure 14 presents an illustration from [7] showing the relationship of these modes to the structural features. From the available data, we have concluded the internal pressure field in these rooms and the house in Oregon is being driven primarily through the diaphragm action of the outside walls facing the turbines. The overshoot of the internal pressure levels evident in Fig. 3 indicates a dynamic amplification is taking place and in-

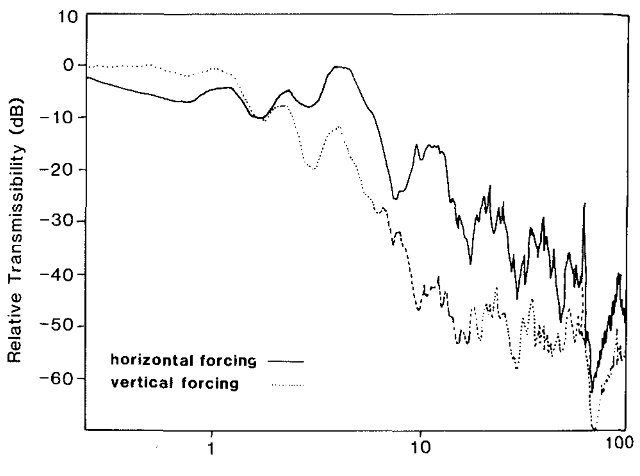

Fig. 10 Acceleration forced acoustic pressure transmissibility

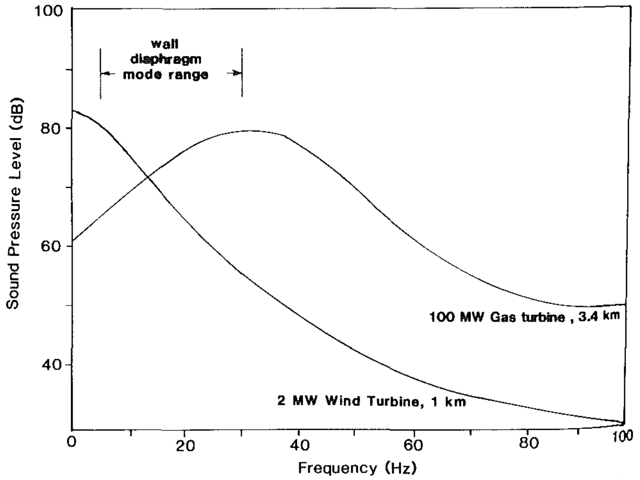

Fig. 11 Comparison of 100-MW gas and 2-MW wind turbine acoustic emissions

tensifying the low-frequency pressure fluctuations in the rooms. Audible sounds are heard in the Boone homes and not in the Oregon house due to the higher wall/floor resonances and room modes being excited by the MOD-1 impulse energy at 12, 25, and 50 Hz (Figs. 6 and 7). The audibility conclusion has been drawn by comparing the above background levels with the NASA perception threshold criteria plotted in Figs. 5 and 12 [1]. Thus the results show the audible sounds are connected with more impulsive-type excitation, but slowly varying, broadband sources with similar levels of sub-audible acoustic energy are also capable of causing annoyance to the residents of exposed homes.

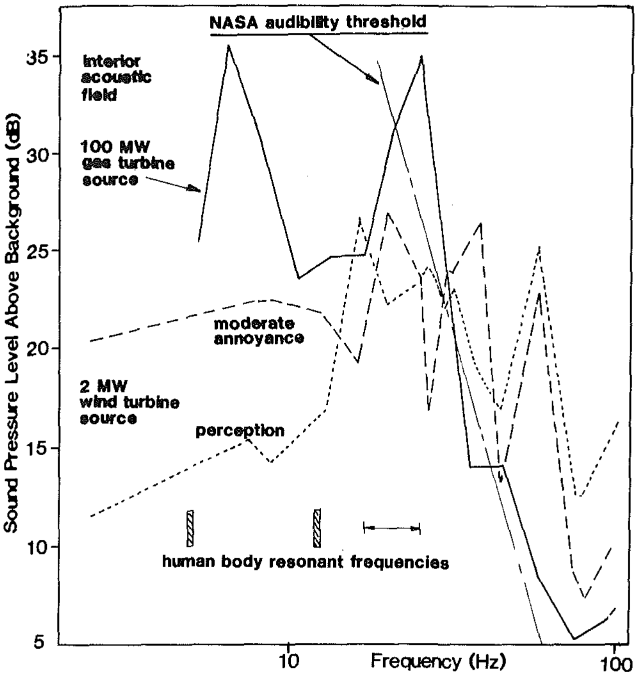

Fig. 12 Same as Fig. 5, with indoor response of home to gas turbine in Oregon

Human Perception. Comparisons of Figs. 3, 4, 5, 8, and 9 show the major difference in the acoustic energy distributions between the moderate annoyance perception (thumping sounds and vibration) and the threshold stimuli (a barely discernible thumping sound but no vibration) appears to be the peak level of subaudible energy present. The first modes of human body resonance (in the direction parallel to long dimension of a standing person) occur at approximately 5, 12, and 17-25 Hz [8]. The position of these frequencies with respect to the room resonant pressure fields is shown in Fig. 12. Some additional supporting evidence for a sensitivity to subaudible sounds is plotted in Fig. 15. This graph shows the threshold/exposure time for continuous sound pressure levels close to the peaks we have measured (see Fig. 4) around the most sensitive frequency of 12 Hz [9].

We hypothesize one of the causal factors related to the annoyance associated with the pulsating pressure fields in the rooms measured is a coupling with human body resonances

Table 1
Resonant modes of rooms in houses 7 and 8 (Hz)

	House #7	House #8
Dimensions (m)	3×3×2.1	3.6×3.5×2.4
Wall/floor resonances (measured)	9,14,20,30,59,79	9,14,21,26,50,60,65
Cavity oscillation frequency (door open)	≃44	≃35
Room mode frequencies	56[100,010][a] 79[110] 80[001] 98[101,011]	47[100,010] 68[110] 70[001] 85[101,011] 98[111]

[a] [ ] give the x,y,z normal modes.

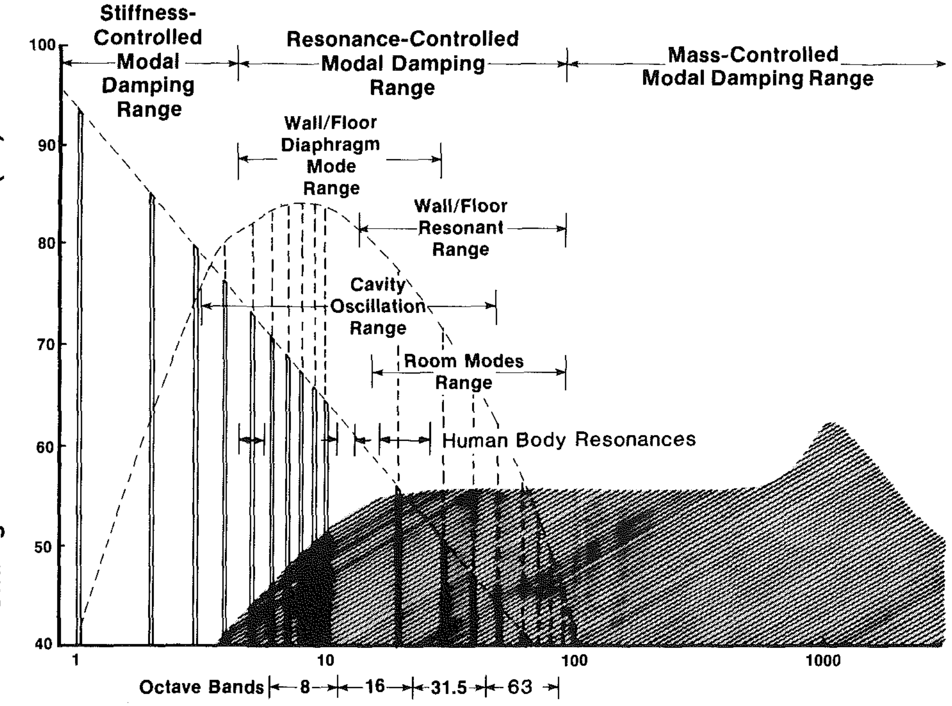

Fig. 13 Same as Fig. 1, with structural, room, and human body resonances added

which in turn are responsible for creating the sensation of a whole-body vibration. This perception is more noticeable indoors due to the increased reverberation time and dynamic overpressures from the interaction between the structural and air volume resonances. From the meager information available from our measurements, we have crudely estimated the perception levels for the body resonance frequencies as 60 dB for 5 Hz, 55 dB for 12 Hz, and 48 dB for the 17–25 Hz band, or +5, 0, and +10 dB above the existing background for the respective frequencies. Such a process as proposed would explain the perceived annoyance within homes when no perceptable sounds could be heard outdoors.

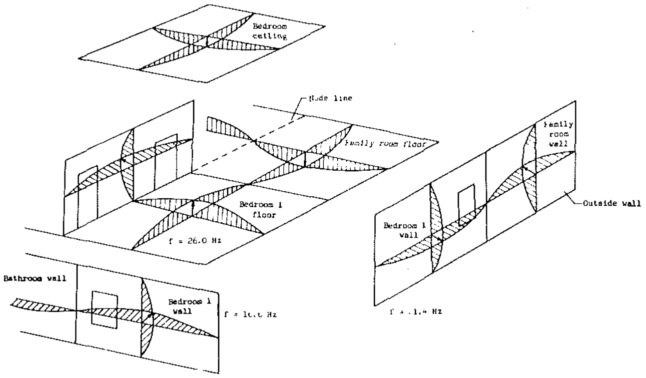

Fig. 14 Example of wall/floor diaphragm modes (source: reference [7])

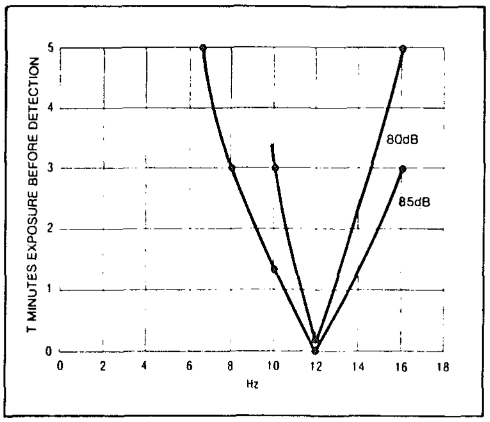

Fig. 15 Threshold/exposure time relationship around most sensitive frequency (source: reference [9])

Assessment Methodology

We have devised a technique by which the potential for community annoyance from the low frequency sound radiated by large wind turbines may be evaluated from recordings or direct measurements. The method allows for a direct comparison of various turbine designs or retrofits. The approach is based on measuring a parameter related to the phase coherence between the discrete frequency bands present in the acoustic energy spectra of wind turbines (see Figs. 6 and 7) and responsible for the level of annoyance perceived by residents in both indoor and outdoor environments.

The phase coherence between discrete energy bands is determined by computing the joint probability distributions of band sound pressure levels in a series of contiguous octave frequency bands. These bands, which include more than 90 percent of the resonance-controlled frequency range shown in Fig. 13, consist of the 8, 16, 31.5, and 63 Hz octaves. In order to properly take into account the nonstationary nature of wind turbine noise, we have found it is necessary to use the time for one complete rotation of a blade as the analysis period for the computing of distributions.

The actual technique involves the use of an 800-line resolution spectrum analyzer under the control of an external computer. The analyzer acquires a time-series record corresponding to the desired analysis period, transforms it into a narrowband spectrum, and then transfers this spectrum to the computer for calculation of the four octave band levels. The computer, using the method of bins, develops the density functions using a 5 dB increment for the band combinations (8/16), (16/31.5), (31.5/63), and the triple combination (8/16/31.5). The results are then plotted as a series of surfaces containing isopleths of equal joint probability.

Figures 16–19 contain plots of the results of measured joint sound pressure distributions listed above, and a plot reflecting the triple combination and a conditional probability of an 8 Hz band level of 70 dB or more (Fig. 19). These distributions have been derived from on-axis, below the centerline

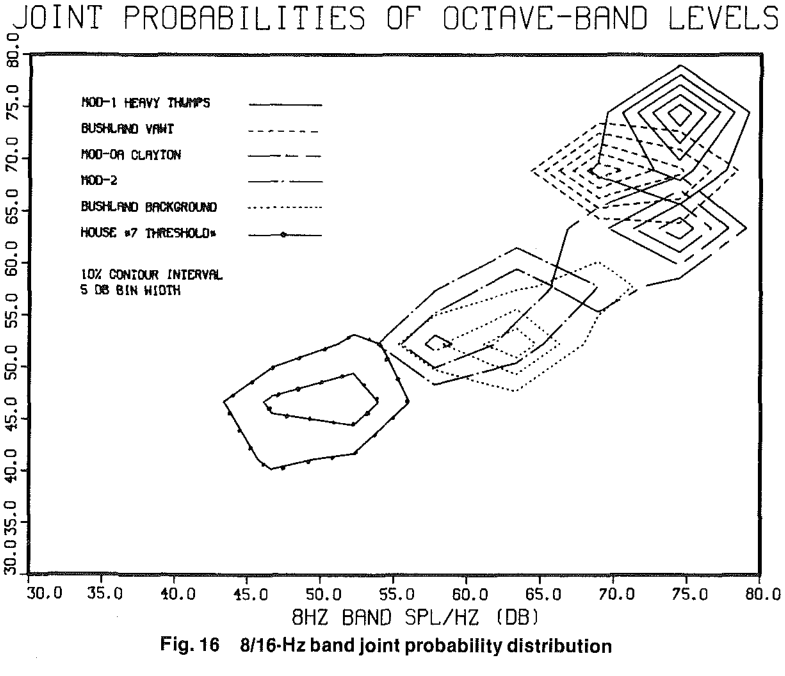

Fig. 16 8/16-Hz band joint probability distribution

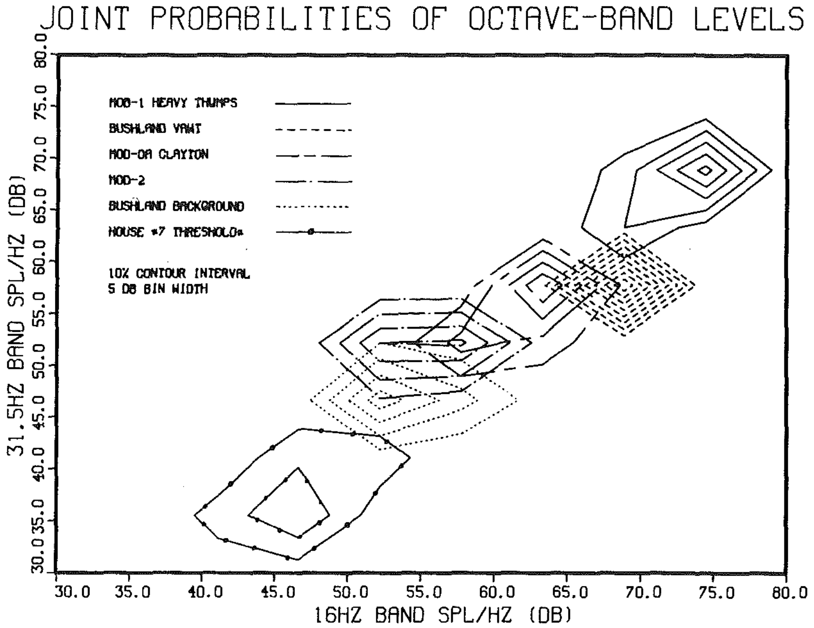

Fig. 17 16/31.5-Hz band joint probability distribution

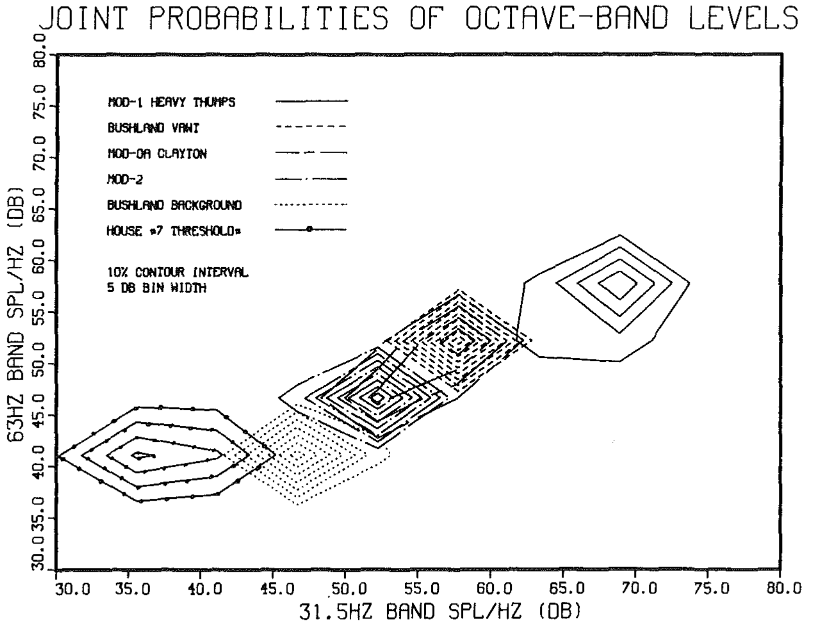

Fig. 18 31.5/63-Hz band joint probability distribution

measurements at a distance of 1.5 rotor dia for the MOD-1, the MOD-OA at Clayton, New Mexico, the unit #1 MOD-2, and the 17-m Darrieus/VAWT at Bushland, Texas. Also plotted in Figs. 16–18 are the reference background levels for Bushland and the threshold perception levels measured outside of house #7 in Boone. Unfortunately, the data from each site were not recorded under similar atmospheric conditions. The MOD-1 data represent the most severe sequence of impulsive noise and the accompanying adverse community reaction we have on tape and corresponds to a period late in the evening. The MOD-2 and MOD-OA surfaces were based on a very limited sample taken in the afternoon at both sites. The VAWT data represents the distribution for a series of measurements recorded right at local sunset when the machine began to exhibit some impulsive noise characteristics.

The results of this analysis indicate the following:

(*i*) The MOD-1 data represent a good measure against which to compare the acoustic performance of other turbines because of the known annoyance levels associated with the record used to compute the distribution.

(*ii*) The shape of the distribution appears to be related to a specific machine design.

(*iii*) The acoustic pressure patterns radiated from large wind turbines have a definite structure as compared with the natural, wind-induced background (as is shown by Fig. 19 in particular) with the radiation from downwind HAWT supported by truss-type towers and the Darrieus/VAWT exhibiting the maximum structural detail.

(*iv*) The importance of the existing background on the detection of turbine noise is graphically illustrated in the comparison of the Bushland background distribution and that associated with the threshold perception in Boone which indicates this would not be heard in Bushland.

(*v*) An interpretation of Figs. 16–19 indicates if the peak coherent radiation from a wind turbine can be held simultaneously at or below 55–65 and 45–55 dB band pressure

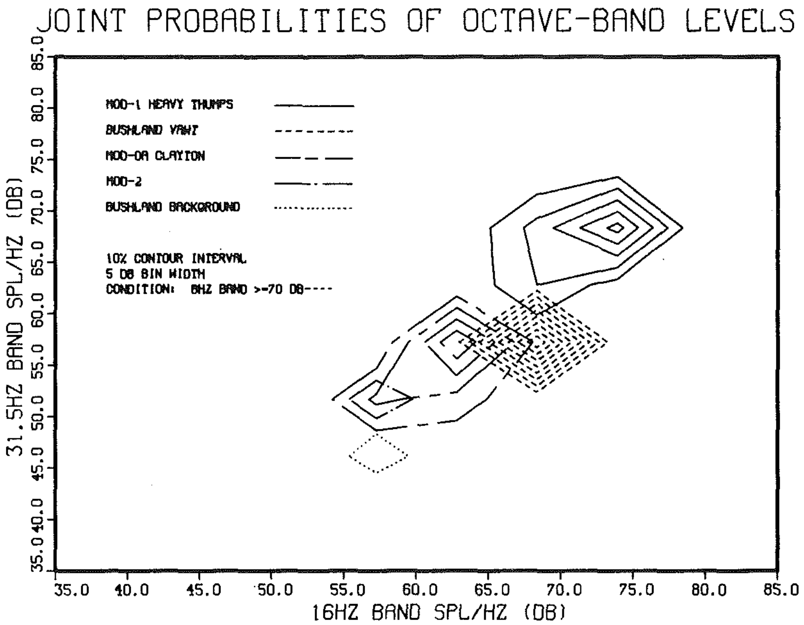

Fig. 19 8/16/31.5 joint distribution with condition of a BPL ≥ 70 dB in the 8-Hz octave band

levels in the 8 and 16 Hz octave bands and under 35-45 dB in the 31.5 and 63 Hz bands at a distance of 1.5 rotor dia, the probability of community annoyance from low-frequency turbine sounds appears remote even under the quietest background conditions.

Conclusions

In this paper we have presented evidence to support the hypothesis that one of the major causal agents responsible for the annoyance of nearby residents by wind turbine noise is the excitation of highly resonant structural and air volume modes by the coherent, low frequency sound radiated by large wind turbines. Further, there is evidence that the strong resonances found in the acoustic pressure field within rooms actually measured indicates a coupling of subaudible energy to human body resonances at 5, 12, and 17-25 Hz, resulting in a sensation of whole-body vibration. The audible sounds indoors associated with the impulsive excitation of the structure appear to be due to the coupling of energy from the higher frequency discrete bands in the impulse to higher frequency room resonances related to the air volume itself.

We have described a turbine noise evaluation technique which, in effect, measures the degree of coherence in the acoustic radiation being emitted from a given turbine under existing atmospheric conditions. The approach is based on computing the joint probability distributions of the band pressure levels in a series of octave frequency bands which are known to encompass the very lightly damped, structural resonances in typical housing construction in the U.S. The results of the analysis for a range of wind turbine designs has shown the MOD-1 to be capable of producing the highest coherent band pressure levels, but the Darrieus/VAWT is capable of the highest probability of coherence over a much narrower range of band pressure levels.

Acknowledgments

The authors gratefully acknowledge Mrs. Carol Etter and Mr. Richard Garrelts for their dedicated assistance and skills. We are indebted to Mr. Scott Turner of the Portland General Electric Company for furnishing us the noise data from the gas turbine measurements and the Robin Towne Associates for their skill in making them. This work was supported by the DOE Wind Energy Technology Division under contract No. EG-77-C-01-4042.

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