Springer

KSME

Journal of Mechanical Science and Technology 30 (10) (2016) 4503~4509
www.springerlink.com/content/1738-494x(Print)/1976-3824(Online)
DOI 10.1007/s12206-016-0918-7

Effects of amplitude modulation on perception of wind turbine noise †

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(Manuscript Received December 22, 2015; Revised May 8, 2016; Accepted May 17, 2016)

Abstract

Wind turbine noise is considered to be easily detectable and highly annoying at relatively lower sound levels than other noise sources. Many previous studies attributed this characteristic to amplitude modulation. However, it is unclear whether amplitude modulation is the main cause of these properties of wind turbine noise. Therefore, the aim of the current study is to identify the relationship between amplitude modulation and these two properties of wind turbine noise. For this investigation, two experiments were conducted. In the first experiment, 12 participants determined the detection thresholds of six target sounds in the presence of background noise. In the second experiment, 12 participants matched the loudness of modified sounds without amplitude modulation to that of target sounds with amplitude modulation. The results showed that the detection threshold was lowered as the modulation depth increased; additionally, sounds with amplitude modulation had higher subjective loudness than those without amplitude modulation.

Keywords: Amplitude modulation; Wind turbine noises; Detection threshold; Subjective loudness

1. Introduction

As eco-friendly energy is in the spotlight, many countries aim to develop and disseminate renewable energy. However, the growth of wind energy utilization evoked many environmental problems, such as visual interference because of the size and location of wind turbines and the tower shadow problem related to the blocking of the sun lay [1]. One of crucial problems concerning wind energy that has attracted considerable attention is the ‘wind turbine noise problem’. Wind turbine noise can directly affect people living in the vicinity of wind turbines and can cause even serious health problems, such as hypoacusis, insomnia, and loss of appetite [1, 2]. Although these effects are identified as physical phenomena, many of these symptoms are fundamentally based on psychological problems. Furthermore, as many previous studies have inferred, such physical phenomena are mainly caused by the annoyance by wind turbine noise.

Studies on the annoyance by wind turbine noise have been conducted since the early 21th century. Most of the studies about the annoyance of wind turbine noise could be categorized as two groups. First, many studies have been performed to obtain more precise prediction results of ‘wind turbines noise’ and to more properly evaluate the characteristic of wind turbine noise. In 2007, Oerlemans et al. conducted several experiments and simulations to reveal the dominance of the broadband trailing edge noise of the wind turbine [3]. Also, Cheong and Joseph proposed the way of measuring and predicting the swishing noise of wind turbine by using cyclostationary spectral analysis in 2014 [4]. Furthermore, Lee and Cheong predicted noise characteristic of horizontal axis wind turbine by using statistical wind speed model in the same year [5]. In 2016, Lenchine proposed the way of estimating environmental noise which has poor modulation pattern or signal to noise ratio [6]. These studies were not conducted to ‘directly’ verify the relationship between the annoyance and the characteristic of wind turbine noise. Nevertheless, these studies have significant importance not only as their own academic achievements but also as basic studies of further ‘annoyance’ related researches.

In secondly group, many studies have been conducted to directly verify the relationship between the annoyance and the characteristic of wind turbine noises. In 2004, Pedersen and Waye attempted to reveal the dose-response relationship be-

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tween annoyance and wind turbine noise [7]. The result showed that people reported higher annoyance by wind turbine noise than other transportation noise. Furthermore, Janssen et al., in 2011, reported that the percentage of people who could detect wind turbine noise at low exposure levels or were annoyed by it at relatively lower sound pressure levels were higher than those who described these effects from other community noise sources, although wind turbine noise was measured to be quieter than other community noise sources [8]. By reviewing these studies, it is reasonably concluded that wind turbine noises are easily detectable and highly annoying compared with other noise sources.

Most of the previous studies interpreted their results in terms of amplitude modulation and used the basic assumption that it is the key factor causing high detectability and annoyance [7-9]. However, none of these studies confirmed whether amplitude modulation is really the main cause of the special characteristics of wind turbine noise and, if so, how much it can affect the perception of wind turbine noise. Therefore, it is important to investigate the effect of amplitude modulation on the perception of wind turbine noise. By conducting such fundamental research, it is expected to obtain a more precise estimation method of the harmful effects of wind turbine noise and establish techniques for wind turbine noise reduction.

In the present study, two experiments were conducted by using three original wind turbine noises with different modulation depth and three modified wind turbine noises with identical spectral property to the three original ones but no amplitude-modulated component. In the following section, the materials and methods used in the two experiments are explained. At first, basic information about stimuli used on the two experiments is described. Then, the design methods of each experiment are introduced. The specific information about stimuli, information of participants and procedure of the test are described. In Sec. 3, the empirical results of the two experiments are presented. The effect of amplitude modulation on the perception of wind turbine noise is identified. In Sec. 4, the empirical results are compared with two prediction models of Grasberg and Moore's and discussed in terms of perception of amplitude modulation. Finally, a summary of the present study is presented in Sec. 5.

2. Materials and methods

2.1 Stimuli

To investigate the effect of the presence of amplitude modulation and the magnitude of modulation depth on the perception of wind turbine noise, it is necessary to use stimuli that have similar sound characteristics except the properties related to amplitude modulation. On the previous study of Lee, the method of generating wind turbine noises with different modulation depths that depend on the azimuth angle of the recording location was introduced [10]. This method was adopted to generate the stimuli used in the following experiments in order to avoid measurement errors [10]. By using the above method, it is possible to conduct experiments with ideal signal, without other unwanted noise.

Table 1. Modulation depth of original wind turbine noises.

	Modulation depth (dB)
Sound 1 (0°)	8.97
Sound 2 (30°)	12.77
Sound 3 (60°)	18.48

Six artificially generated signals were used in the experiments: three original wind turbine noises and three modified wind turbine noises. The three original wind turbine noises were estimated by using the numerical modeling method that was employed in the previous study of Lee [10].

The selection criteria for the number of original wind turbine noises were based on the directions of the wind flow with respect to the wind turbine. Each original wind turbine noise was estimated at three azimuth angle locations (0°, 30° and 60°) and at 500 m [10]. The results of the measurements are presented in Table 1 and demonstrate that the sound from the 0° direction had the smallest modulation depth and that from the 60° direction had the largest one.

In contrast to the three original wind turbine noises, the three modified wind turbine noises were generated by applying a random-phase filter to the original wind turbine noises. The random-phase filter randomly mixed a phase component of the signal and then created a new signal that was perceived as 'white noise' but had identical spectral properties. Thus, the amplitude-modulated component of the original wind turbine noise could be erased. Likewise, with the application of the random-phase filter, the original wind turbine noises were changed to modified wind turbine noises with equivalent spectral properties but without an amplitude-modulated component. These three modified wind turbine noises were used to determine the relationship between the experimental results of the original and modified wind turbine noises.

2.2 Experiment 1: Detection threshold estimation

The objective of the first experiment is to investigate whether the amplitude modulation is really the main cause of the high detectability of wind turbine noise. For this test, the detection thresholds of experimental sounds (some of which had amplitude modulation) were estimated. Furthermore, the empirical results were compared with the predictions of Moore's and Glasberg's partial-loudness models to assess the effect of amplitude modulation on the variation of the detection threshold.

2.2.1 Experimental design

2.2.1.1 Stimuli

The first experiment was conducted with six target sounds (three original wind turbine noises and three modified wind turbine noises), as described above, and one background noise. The six target sounds were defined as sounds 1-6 (sound 1

(0°), sound 2 (30°), sound 3 (60°), sound 4 (0° and random-phased), sound 5 (30° and random-phased) and sound 6 (60° and random-phased). The background noise was natural ambient sound that was recorded in a rural area located far from other complex noise sources. The sound was recorded on a digital analyzer 2250 (B&K) using an omni-directional 1/2-inch free-field microphone type 4189. The microphone was placed 1.5 m above ground level. In order to decrease the pseudo-noise generated by the wind into the microphone, a 10-cm-diameter windscreen was used. To record sufficiently high sound pressure levels of sound samples, the recordings were conducted when the wind speed exceeded 5 m/s. The recorded background noise was 95.8 dB in equivalent sound level and 60.1 dB in A-weighted equivalent sound level.

2.2.1.2 Jury test conditions

The jury tests were conducted in an insulated anechoic room measuring 3.2×3.2×2.1 m^3. The background noise level was approximately 20 dB(A) and the cut-off frequency was 200 Hz. Twelve listeners were guided to participate in the study. Their ages varied between 25-39 years with an average of 29.8 years; one was female and 11 were men.

2.2.1.3 Test procedure

The first experiment was conducted using the four-alternative forced-choice method with the 1-up 1-down stepping rule. This method was used to avoid biased experimental results. Additionally, some previous studies involving auditory detection experiments reported that it is preferable to use more than two alternatives in the test method [11].

The participants were asked to determine which of four signals contained the target sound. In a random signal, the target sound was mixed with the background noise (masker) whereas the other three signals contained only the background sound. The gain factor of the 'correct' signal (which contained the target sound and masker) changed between trials depending on the participant's previous response.

The experiment always started with a series of descending trials and changed to an ascending trial if the participants chose a signal that contained the target sound; accordingly, it changed from an ascending to a descending trial if the participants selected a signal that did not contain the target sound. The experiment ended after three modifications. In the first stage of the descending trials, the experiment began with a gain factor of -10 dB and a step size of 5 dB. The step size changed to 3 dB in the first stage of the ascending trials and then to 1dB in the second stage of the descending trials. The experiment continued in a similar way until the participants correctly chose the signal that contained the target sound in the ascending trials with step size 1 dB.

Instructions on how to perform the experiment were displayed on the screen during the test. Each signal consisted of four intervals. The participants could listen to the target sound separately before and after all four signals had been played. Additionally, participants could choose to listen to all four signals again. The experiment was conducted for all target sounds. The playback time of the experimental sounds was set at 5 s.

2.3 Experiment 2: Subjective loudness-matching test

The objective of the second experiment is to establish whether the reason why wind turbine noise is more annoying than other noise sources is its amplitude modulation or not. To test this, the subjective loudness of the modified wind turbine noise was matched to that of the original wind turbine noise. Furthermore, predictions of the subjective loudness derived using the loudness model are presented and compared with empirical results to identify the effect of amplitude modulation on the variation of subjective loudness. Considering the results of the comparison and those of previous studies, the relationship between amplitude modulation of the sound and associated annoyance are discussed.

2.3.1 Experimental design

2.3.1.1 Stimuli

The three original and three modified wind turbine noises used as target sounds in the first experiment were also employed in the second experiment. However, the test was not conducted by just using each wind turbine noise but by using pairs of wind turbine noises (sound 1 and 4, sound 2 and 5, sound 3 and 6). Specifically, if the original wind turbine noise was used in the test, the corresponding modified wind turbine noise was also used. Furthermore, six initial gain factors ranging from -8 dB to 12 dB at intervals of 4 dB were adjusted to each pair of wind turbine noises. Therefore, 18 (3 pairs × 6 gains) pairs of wind turbine noises were used in the test.

2.3.1.2 Jury test conditions

The second experiment was also conducted in the previously mentioned anechoic room. Twelve listeners were guided to participate in the study. Their ages varied between 25-30 years with an average of 28.1.

2.3.1.3 Test procedure

For each pair of wind turbine noises, the participants were asked to match the subjective loudness of the modified wind turbine noises to that of the original wind turbine noises. In contrast to the first experiment, the four-alternative forced-choice method was not used because no background noise was used in the assessment of subjective loudness. Therefore, the test was conducted by using the 1-up 1-down stepping rule and the gain factor of the modified sound was changed depending on the participant's previous response [12]. The test ended after three modifications like the first experiment. However, the step sizes of each modification were different from the first experiment. The test started with the initial gain factors, and the step size of the first ascending trial was 5 dB. The step size was changed to -2 dB in the first descending trial and then to 1 dB in the second ascending trial. The test continued in a similar way until the last descending trial had a

Table 2. Empirical results and predictions of detection thresholds in LAeq.

	Empirical	Prediction (Stationary)	Prediction (Time-varying)
Sound 1	46.4	41.0	37.4
Sound 2	43.7	40.8	36.2
Sound 3	43.1	42.6	36.1
Sound 4	51.6	40.9	38.1
Sound 5	51.8	43.1	37.2
Sound 6	53.1	42.5	39.1

step size of 1 dB.

Instructions on how to perform the experiment were displayed on the screen, like in the first experiment. However, the participants could stop stepping if he or she thought that the two wind turbine noises of the pair had equal subjective loudness. The playback time of these sounds was 5 s.

3. Results

3.1 Detection threshold estimation test

The empirical results of the first experiment are shown in terms of the average value of LAeq in Table 2. From the comparison between sound 1 (0°) and sound 4 (0° and random-phased) pair, sound 2 (30°) and sound 5 (30° and random-phased) pair, and sound 3 (60°) and sound 6 (60° and random-phased) pair, it is shown that the wind turbine noises with amplitude modulation have 5.2-10 dB(A) lower detection thresholds than those without amplitude modulation. Furthermore, from the comparison of sounds 1, 2, and 3, it is inferred that a sound with larger modulation depth has a smaller detection threshold.

3.2 Subjective loudness-matching test

The empirical results of the second experiment are shown in Fig. 1. First of all, it is easily inferred that the subjective loudness of the original wind turbine noises was estimated to be higher than that of the modified wind turbine noises. Quantitatively, the original wind turbine noises had 2.63-7.1 dB higher subjective loudness than the modified ones. Furthermore, the differences between the subjective loudness of the original and modified wind turbine noises seem to be affected not only by the modulation depth but also by the gain factors of the original sounds. When the initial gain factors increase, these differences decrease. This means that the participants perceived the original wind turbine noises as louder than the modified ones. Additionally, this tendency becomes clearer when the gain factor of the original wind turbine noise decreases.

4. Discussion

4.1 Detection threshold estimation test

Generally, detection thresholds are determined through well-designed experiments or prediction models. Moore's and Grasberg's partial loudness models have been frequently used to predict detection thresholds. Therefore, predictions from the partial loudness models are compared with the empirical results. From the comparison, the effect of amplitude modulation on the change of the detection thresholds and the difference between the predictions and the empirical results are identified.

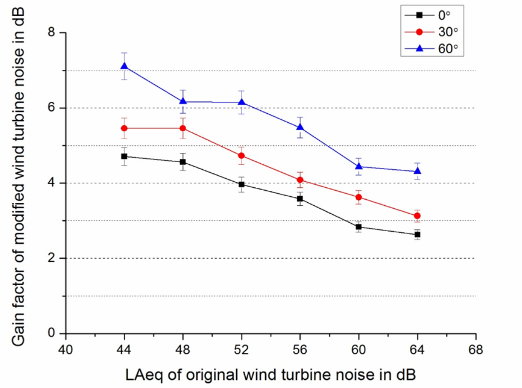

Fig. 1. Empirical results of loudness-matching test as function of modulation depth. X-axis indicates the magnitude of original wind turbine noise in LAeq. Y-axis indicates the magnitude of the gain factor of the modified wind turbine noises that have equal subjective loudness to original ones.

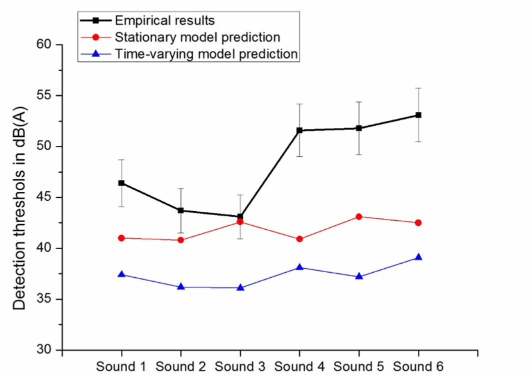

Fig. 2. Empirical results and predictions of detection thresholds in LAeq. Error bars indicate the 95% confidence interval of the empirical results.

In Fig. 2, the detection thresholds of target sounds are presented as averaged LAeq and each error bar indicates a 95% confidence interval around the median. Fig. 2 demonstrates that one of the six predictions of the stationary partial-loudness model and none of the six predictions of the time-varying partial-loudness model are within the 95% confidence interval of the empirical results. This indicates that the detection threshold of the empirical results is not consistent with the predicted one. In other words, both partial-loudness models tend to under-predict the detection threshold.

The difference between the empirical results and the predictions could be explained by the effect of 'informational' mask-

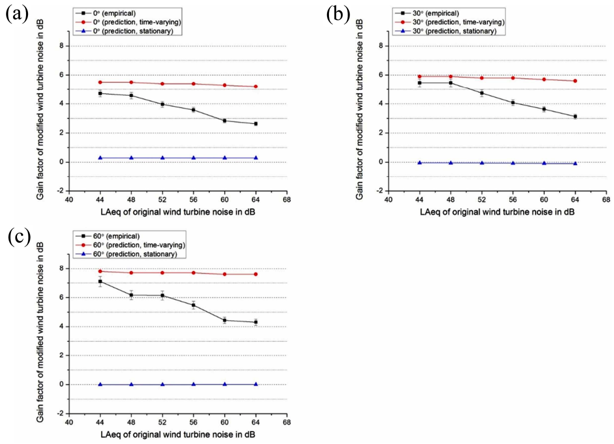

Fig. 3. Empirical results and predications of two loudness models as a function of modulation depth: (a) 0°; (b) 30°; (c) 60°.

ing. Informational masking means a kind of masking effect that is evoked by a fluctuating component of an acoustic signal and is opposed to the energetic masking that is evoked by a stationary component of an acoustic signal. Informational masking effects is difficult to be quantified because of its property. For that reason, the prediction models were developed only to consider the effect of energetic masking. In the present study, the experiment was conducted by using acoustic signals which were changed continually as function of time. The empirical results seem to be affected by informational masking which means the participants might be confused of background noise with target sounds. That is, the participants might be perceived background noise as target sounds incorrectly.

4.2 Subjective loudness-matching test

Subjective loudness is determined through experiments or prediction models like detection thresholds. Subjective loudness can be estimated by employing two loudness models of Moore's and Grlasberg's. Therefore, predictions from the models are compared with the empirical results. From the comparison, the effect of amplitude modulation on the change of the subjective loudness and the difference between the predictions and the empirical results are identified.

From Fig. 3, it is observed that the predictions of the two methods of estimating the loudness are not consistent with the empirical results. For all cases, the models seem to over-predict the empirical results of the original wind turbine noises. In contrast to the empirical results, the predictions seem to be affected not by the gain factor of original sound but by the modulation depth. Furthermore, no dependence is observed of the subjective loudness of the original and modified wind turbine noises according to the gain factors of the original wind turbine noises. This means that the loudness model does not well reflect the characteristics of amplitude modulation and must be complemented by current empirical results.

The difference between the empirical results and the predictions might be explained by the limitation of prediction models. The prediction models employed ways of estimating predictions of subjective loudness by matching the maximum STL of each pair of wind turbine noise. However, the employed ways were not helpful for estimating the predictions of an acoustic signal that has a rapidly changing spectral property as function of time. In case of 'rapidly' changing acoustic signal, a calculated excitation pattern used to derive STL does not well represent an actual excitation pattern. In particular, although calculated excitation pattern was derived from short-term spectrum that was estimated by filtering and integrating instantaneous frequency spectrum to calculate STL for a precise prediction, the difference between a calculated excitation pattern and an actual excitation pattern was still exist.

To verify the relationship between amplitude modulation and annoyance, the relationship between loudness and annoyance should be studied. However, the relationship between loudness and annoyance is difficult to be quantified and should be carefully studied in each of noise sources. In case of wind turbine noise, previous study reported that the annoyance by wind turbine noises can be well defined by a numerical index, such as LAmax, LAeq, and loudness [13]. Additionally, loudness is not the most suitable index to represent the property of the annoyance but can describe it quite reasonably. Quantitatively, R2 = 0.6449 was evaluated between the annoyance and loudness of wind turbine noises in a previous study. This means that although they are not exactly described by a linear proportional relationship, quite a linear relationship between annoyance and loudness of wind turbine noises is reported.

Consequently, by using the empirical results and those of previous studies, there is a strong possibility that sounds with amplitude-modulated components have higher annoyance than those without amplitude-modulated components because the former have higher loudness than the latter. However, caution is needed when the results mentioned above are applied to other amplitude-modulated sounds because the current study is only concerns the case of wind turbine noises. Additional studies on other amplitude-modulated sounds are also required to comprehend the exact relationship between amplitude modulation and annoyance.

5. Conclusion

Two experiments were conducted to determine whether amplitude modulation is the main cause of two properties, easily detectable and highly annoying, of wind turbine noise. The results of the first experiments indicated that a sound with larger modulation depth has a smaller detection threshold. The detection thresholds varied between 43.1-53.1 dB(A) according to the magnitudes of modulation depth. The empirical results were compared with prediction results from two types of partial-loudness models which have been frequently used to predict detection thresholds. The empirical results were not consistent with the predictions because of the effect of the informational masking. Consequently, the effect of amplitude modulation on detection threshold was clearly identified from the experiment.

The results of the second experiment indicated that people perceived an original sound to be louder than a modified sound. This tendency is demonstrated more clearly when the A-weighted equivalent sound level of the original sound decreases. The differences between the subjective loudness of the original and modified sounds seemed to be affected by two properties, the modulation depth and the gain factor of the original sound. Namely, when the gain factor or modulation depth of a signal decreases, the subjective loudness decreases. The empirical results were compared with predictions of the loudness models. It was shown that the predictions did not agree with the empirical results because of the limitation of two prediction models. Thus, the effect of amplitude modulation on subjective loudness was clearly shown from the experiment. Furthermore, by using the empirical results of a previous study, it is proposed that sounds with amplitude-modulated components have higher annoyance than sounds without amplitude-modulated components.

Consequently, there is a strong possibility that amplitude modulation is the main cause of the properties of wind turbine noise. However, this does not mean that the properties of wind turbine noise can be perfectly explained by the amplitude modulation and additional studies should be performed to reveal the exact mechanism associating wind turbine noise and human hearing perception.

Acknowledgment

This work was supported by National Space Lab Program (2013M1A3A3A02042024) of Ministry of Future Creation and Science through the National Research Foundation of Korea. This work was also supported by the International Collaborative Energy Technology R&D Program of the Korea Institute of Energy Technology Evaluation and Planning (KETEP), granted financial resource from the Ministry of Trade, Industry & Energy, Republic of Korea (No. 20138520021140).

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