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Perception of low frequency components contained in wind turbine noise

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Summary

To investigate the human auditory sensation to low frequency components contained in wind turbine noise, we have been performing a series of auditory experiments by using a test facility capable of reproducing low frequency sounds including infrasound. As the first experiment, audibility of low frequency components contained in wind turbine noise (WTN) was tested by changing the low frequency components by low-pass filtering with 10 different cut-off frequencies from 10 Hz to 125 Hz. As a result, it has been confirmed that the low frequency components in infrasound frequency range of general wind turbine noises can not be heard nor sensed. As a succeeding experiment, hearing thresholds for low frequency band noises were tested by changing the frequency band width in 7 variations. As a result, the critical spectral characteristics in 1/3 octave bands for hearing threshold have been found. Furthermore, a loudness test was performed by using an artificial noise modelling general WTNs, in which the frequency characteristic of the test sound was changed by high-pass filtering in 9 steps from 16 Hz to 1 kHz. As a result, it has been confirmed that A-weighted sound pressure level is the most suitable and convenient indicator for loudness impression.

1. Introduction

The authors have conducted a synthetic research program on wind turbine noise titled “Research on the Evaluation of Human Impact of Low Frequency Noise from Wind Turbine Generators” in the past three years from the 2010 fiscal year [1-3]. This research program consists of field measurement, social survey on the response of nearby residents, and laboratory experiments. Regarding the third topic, we have conducted a series of subjective experiments regarding human audibility of low frequency sounds. In these experiments, hearing thresholds for pure tones in low frequency range and hearing sensation to WTN have been examined.

In the experiments on human audibility for low frequency components contained in WTNs, actual WTNs recorded on sites and an artificially synthesized sound modelling general WTNs were used. In Experiments 1 and 2, the frequency components of the test sounds were limited in steps by low-pass filtering processing and audibility was examined. In Experiment 3, the frequency components of the model sound were modified by high-pass filtering processing and the contribution of the low frequency components to loudness sensation was examined.

2. Experimental system

In this study, an experimental facility constructed for the experiments on human audibility to low frequency sounds [4] was used. As shown in Figure 1 and Picture 1, it consists of a couple of rooms and 16 woofers with a diameter of 40 cm (FOSTEX, FW405N, lowest resonance frequency: 27 Hz) were installed on the partition wall between the two rooms. For the production of mid/high frequency components up to 8 kHz, a wide-range loudspeaker was set at the centre point of the 16 woofers. The cross-over frequency between the two systems was set at 224 Hz. The listening position was set at a point of 3.5 m away from the centre position of the loudspeakers. To correct the frequency characteristic of the total system, the digital inverse-filtering technique was applied.

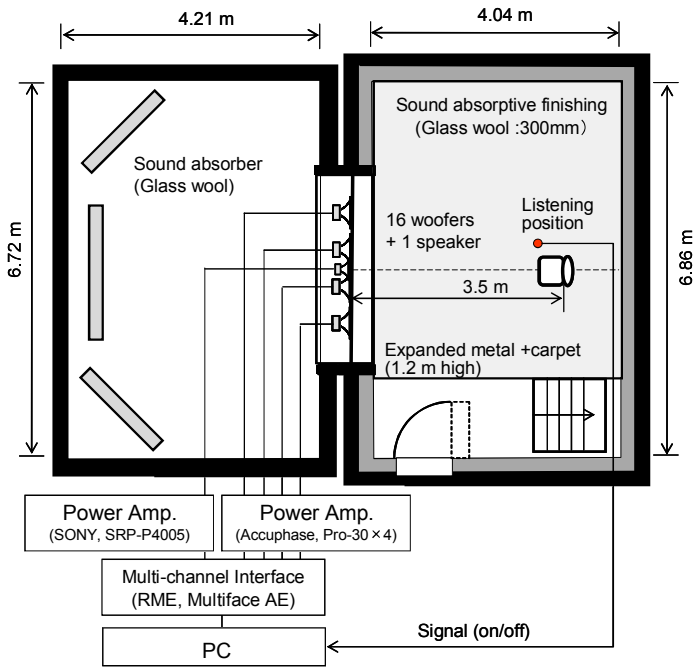


Figure 1: Experimental system.

Picture 1: Loudspeaker system and the listener's position in the receiving room.

3. Experiment-1: Audibility to low frequency components contained in WTN

By using actual WTNs recorded on sites and a model noise, the audibility to their low frequency components was investigated by applying low-pass filtering processing [5].

3.1 Experimental conditions

In this experiment, four test sounds shown in Table 1 were used. The sounds No.1, No.2 and No.3 are actual WTNs recorded around the wind farms in Japan. The sound No.1 was recorded at a point close to a wind turbine and had relatively high level (55 dB in A-weighted sound pressure level). The sound No.2 is a typical WTN observed outside in residential areas around wind farms. The sound No.3 is an example of WTN observed indoors. In addition to these actual WTNs, an artificial sound with a frequency characteristic of -4 dB/octave (in band spectrum) was used as a model noise representing general WTNs. The presentation level of this model noise was varied at three steps of 35 dBA, 45 dBA and 55 dBA. Figure 2 shows the sound pressure levels in 1/3 octave bands of these test sounds which were measured in the absence of the listener at the position where the centre of the listener's head would be. In order to investigate the "audibility" of the low frequency components contained in WTNs, the test sounds were modified by low-pass filtering with different cut-off frequencies. As shown in Figure 3, the center frequency (f_{center}) was used as the nominal cut-off frequency in this study.
The cut-off frequencies were set at 125 Hz and the 1/3 octave series from 63 Hz to 10 Hz, inclusive (10 in total). As an example, Figure 4 shows the original test sound No.1 and its variations made in such a way mentioned above. These experiments were performed according to the ethical code of The University of Tokyo.

Table 1: Test sounds used in this experiment.

Test sounds	Distance from the nearest wind turbine	Measurement point	A-weighted sound pressure level
No.1	48 m	outdoor	56 dB
No.2	436 m	outdoor	44 dB
No.3	328 m	indoor	27 dB
No.4	A model noise representing general WTNs (- 4 dB/octave)		55 dB
No.5			45 dB
No.6			35 dB

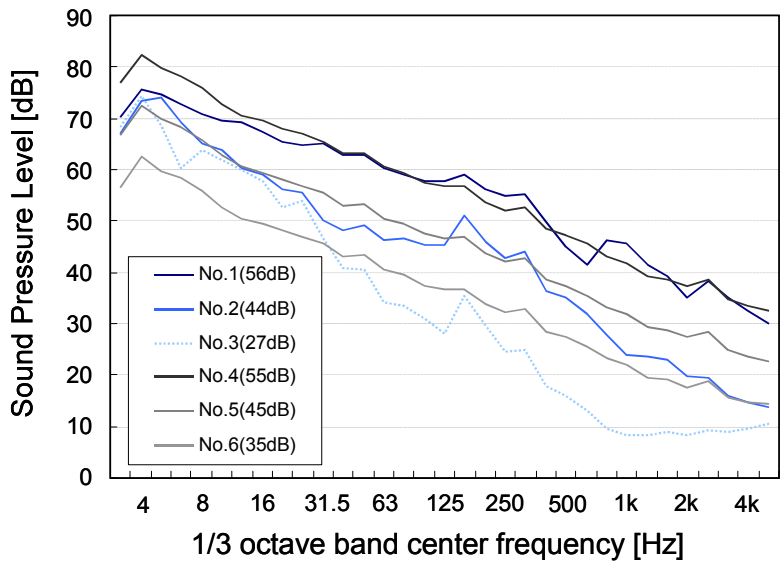


Figure 2: Frequency characteristics of the test sounds (in 1/3 octave bands).

3.2 Experimental procedure

In the preliminary experiment, it was found that the subject had a difficulty to judge the audibility of the test sounds, especially in low frequency range. To reduce such a stress of the subjects and to avoid their guess work, the MLS-signal modulation method [6] was applied in this experiment. This method was originally developed for the measurement of sound propagation characteristics and this is the first time to apply this method to psychological experiment. That is, a test sound was modulated (ON/OFF) by one sequence of a binary MLS-signal (5th order, clock period: 4 s, total time: 124 s). Figure 5 shows an example of the time pattern of the modulated test signal. When the signal was turned ON/OFF, it was gradually risen/fallen with a time of 0.5 s, respectively, to avoid click sounds.

The subject was asked to push the response button while he/she could hear or feel something about his/her ears and to release the button when such sensations ceased. To investigate the "audibility" judged by the subject, the cross-correlation coefficient between the MLS-signal used for the modulation of the test sound and the subject's response (binary signal of on/off) was calculated. Besides, the subject was asked to answer the subjective impression of his/her judgement in three-step category (1: easily judged, 2: rather difficult to judge, and 3: couldn't judge at all) after each test. Before the experiment, the subject was informed that the test sounds might include some inaudible sounds and experienced trial tests.

In the experiment, the subject was asked to sit straight on a chair to keep his/her head near the headrest. The total time to complete the listening test of 66 test sounds (the test sounds No.1 to No.6; 10 modified sounds processed by the low-pass-filtering and original sound) was about 3.5 hours including rest times in between. In this experiment 10 subjects of age range from 21 years to 25 years (7 males and 3 females) with otologically normal hearing abilities participated.

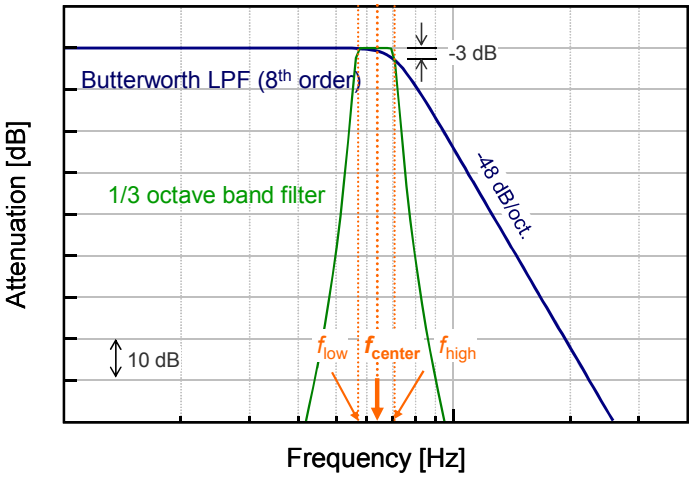


Figure 3: Frequency characteristics of the low-pass filter.

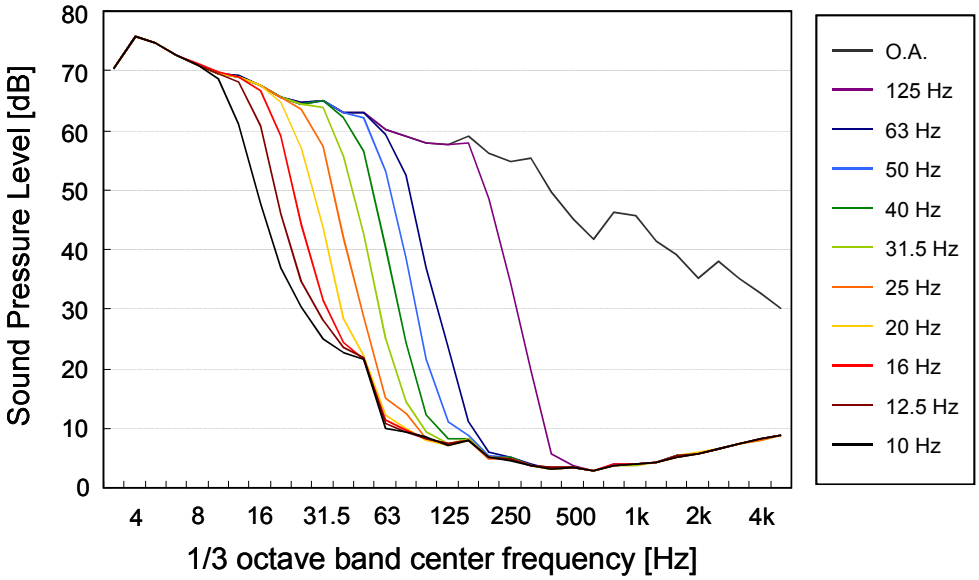


Figure 4: Sound pressure levels in 1/3 octave bands of the original test sound and its variations made by low-pass filtering.

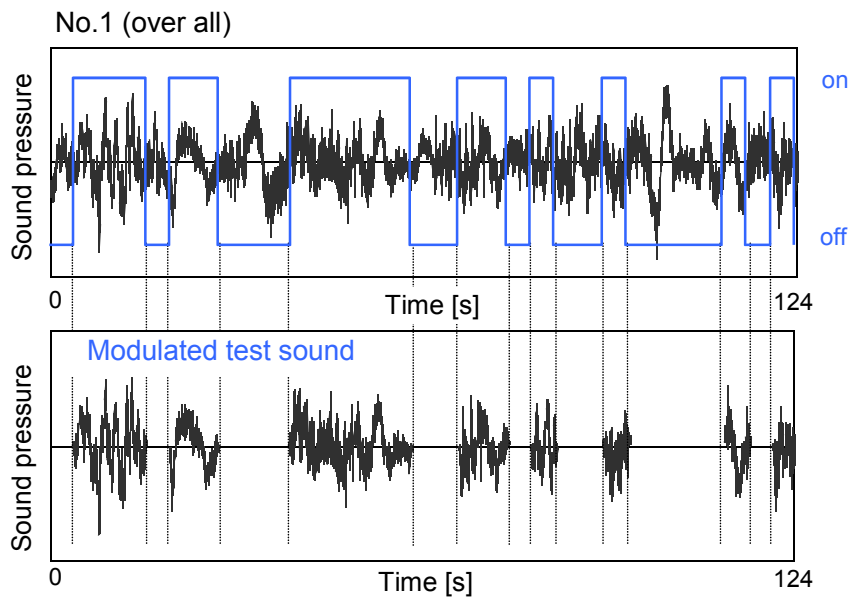


Figure 5: Time pattern of a test sound modulated by the MLS-signal.

3.3 Experimental results

As mentioned above, the cross-correlation coefficient between the MLS-signal and the subject's response was calculated and the maximum value between the time-lag of 4 s was detected. By considering the subjects' impression of his/her judgement, it has been decided that the responses with a cross-correlation coefficient higher than 0.4 can be considered to be "audible/sensible". For respective test sounds, the ratio of the experimental results with cross-correlation coefficients higher than 0.4 is shown in Figure 6. In these results, it is seen that the sounds of over-all and those of 125 Hz cut-off frequency were 100% judged to be "audible/sensible", whereas the response of "audible/sensible" decreased as the cut-off frequency became lower. It is also seen that there is a tendency that the "audible/sensible" judgment increases as the level of the test sound becomes higher. It should be noted that even the cases of the test sound No.1 recorded at a point close to a wind turbine and the test sound No.4 (over-all level is 55 dBA in both cases), the ratio of the judgement of "audible/sensible" was less than 30% under the condition of cut-off frequency of 20 Hz or lower. Regarding the test sounds No.2 and No.5 which correspond to WTN often observed in the residential areas around wind farms (over-all level was about 45 dBA), they were judged "inaudible/insensible" under the condition of cut-off frequency of 25 Hz or lower. Furthermore, regarding the test sounds No.3 recorded in a residential house around a wind turbine (over-all level was 27 dBA) and the test sound No.6 (over-all level was 35 dBA), they were judged "inaudible/insensible" under the condition of cut-off frequency of 31.5 Hz or lower.

From these results, it has been indicated that the low frequency components (infrasound and low frequencies in audible frequency range) themselves are not "audible/sensible".

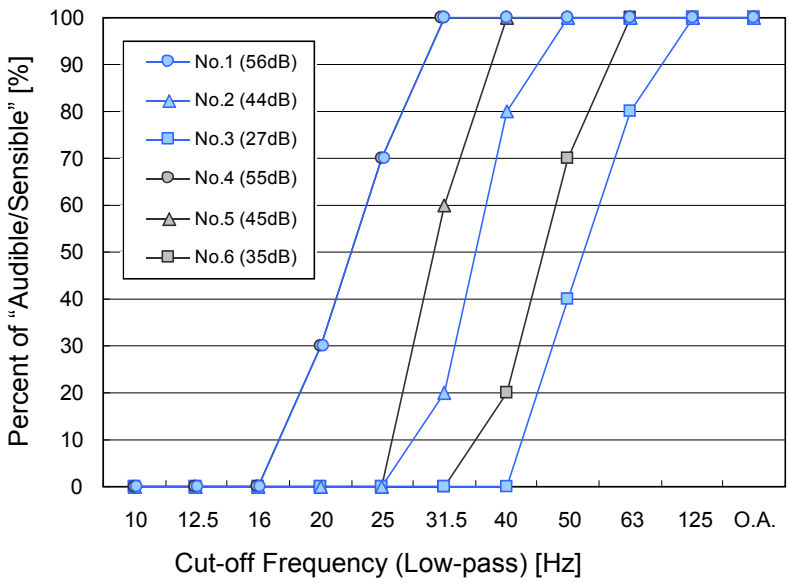


Figure 6: The ratio of the experimental results with cross-correlation coefficients higher than 0.4.

4. Experiment-2: Hearing threshold for low frequency band noises

As an experiment following Experiment-1, hearing thresholds for low frequency band noises were examined by changing the frequency band width in 7 variations.

4.1 Experimental conditions

In this experiment, the model noise used in the former experiment (over-all level was set at 55 dBA) was used again. In order to investigate the threshold of sounds of which frequency components were limited to a certain frequency band, the model noise was modified as shown in Figure 7 by low-pass filtering. The cut-off frequencies (see Figure-3) were set at the 1/3 octave series from 80 Hz to 20 Hz, inclusive (7 in total). To present the test signals at the sound pressure level sufficiently higher than the hearing threshold, the lowest frequency of the signals

were limited at 8 Hz. The sound pressure levels were measured in the absence of the listener at the position where the centre of the listener's head would be.

The test sounds were edited to have a duration time of 5 s. To avoid click sounds, the signals were gradually risen/fallen with a time of 0.5 s, respectively. The experiment was performed by changing the presentation level as shown by the vertical dotted lines in Figure 8. Within the level range, the presentation levels of the test sounds were set at every 1 dB.

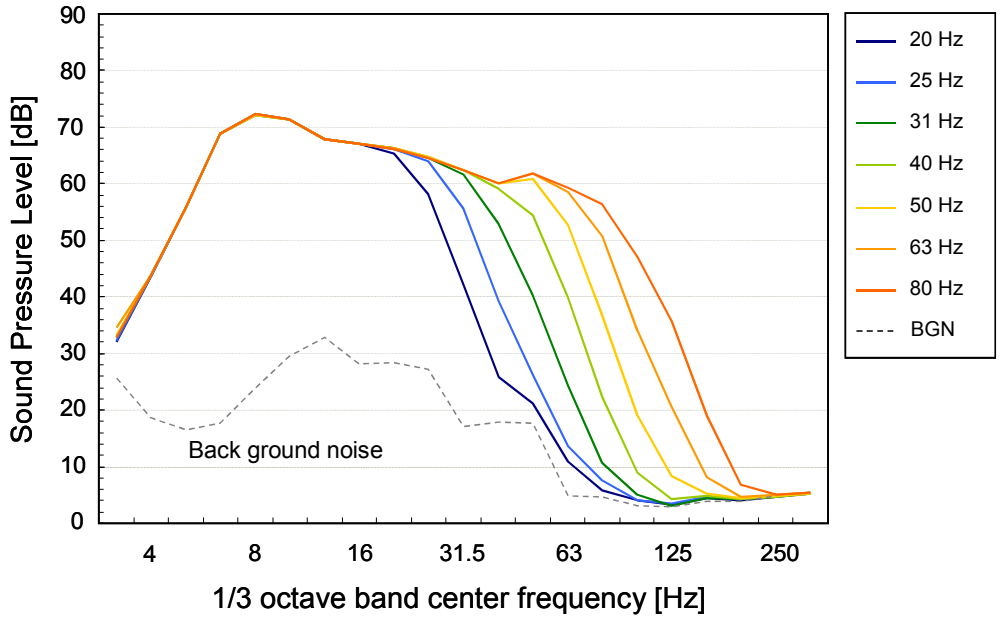


Figure 7: Sound pressure levels in 1/3 octave bands of the variations made by low-pass filtering.

4.2 Experimental procedure

The adaptive method (simple up-down method) was applied in this experiment, and the subject was asked to push the response button while he/she could hear or feel something about his/her ears and to release the button when such sensations ceased. To avoid guess work by a subject, the interval between the respective test sounds was varied at three steps of 1,5 s, 2,0 s and 2,5 s and they were chosen randomly.

For each experimental condition, five trials were performed. Each experiment started with the descending series, in which the test sound was decreased stepwise every 2 dB from the level set as the initial condition. These series continued until the level became one step (2 dB) lower than the level at which the subject's response became negative (no response). Then, the presentation level was further decreased by 7 dB and the ascending series started. In this process, the presentation level was increased stepwise every 1 dB until the level became one step (1 dB) higher than the level at which the subject's response became positive. After that, the presentation level was further increased by 7 dB and the second descending series started, in which the test sound was decreased stepwise every 1 dB. After completing these five series, the lowest levels in the descending series at which the subject could hear or feel something about his/her ears and the highest level in the ascending series at which the subject's response changed to positive were averaged and it was determined as his/her hearing threshold level for each test sound. In this experiment 10 subjects of age range from 21 years to 24 years (7 males and 3 females) with otologically normal hearing abilities participated.

4.3 Experimental results

As the experimental results, the mean values and the plus/minus standard deviations ($\pm\sigma$) for all of the subjects for respective experimental conditions are plotted in Figure 8, in which X-axis indicates the cut-off frequency and Y-axis indicates the hearing threshold level. In this figure, 0 dB (Y-axis; hearing threshold level) means the level of each test signal made by limiting the

frequency components of the model noise (over-all level : 55 dBA). The results show that the hearing threshold became lower as the cut-off frequency became higher. In all the test conditions, the standard deviations are kept constant at about 4 dB.

In Figure 9, the critical spectral characteristics of band-limited low frequency noises in 1/3 octave bands for hearing thresholds are shown. In this figure, the HTL-curve in audible frequency range described in ISO 389-7:2005 [7] and the criterion curve proposed by A.T. Moorhouse *et al*. [8] are quoted for reference. It is seen that the critical spectral characteristics are tangent to the criterion curve in the frequency range from 20 Hz to 50 Hz.

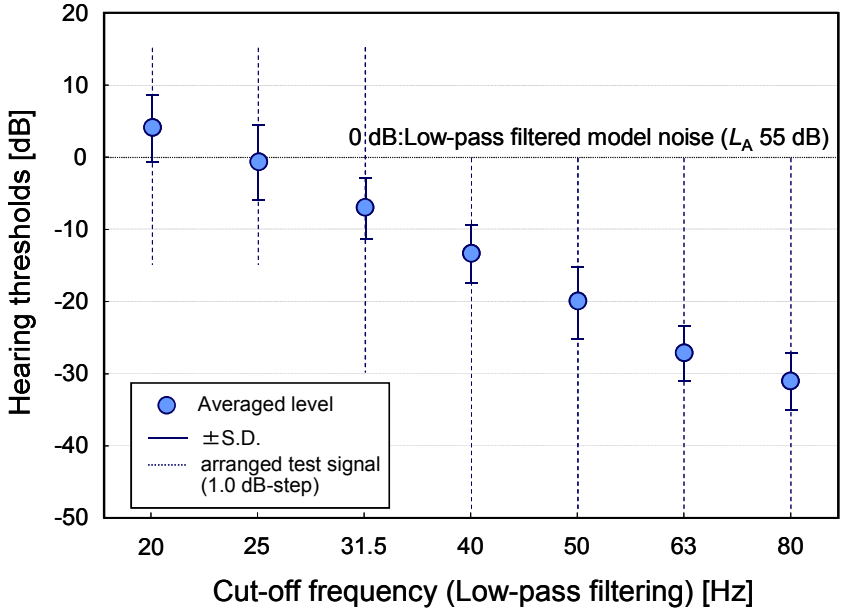


Figure 8: Hearing thresholds.

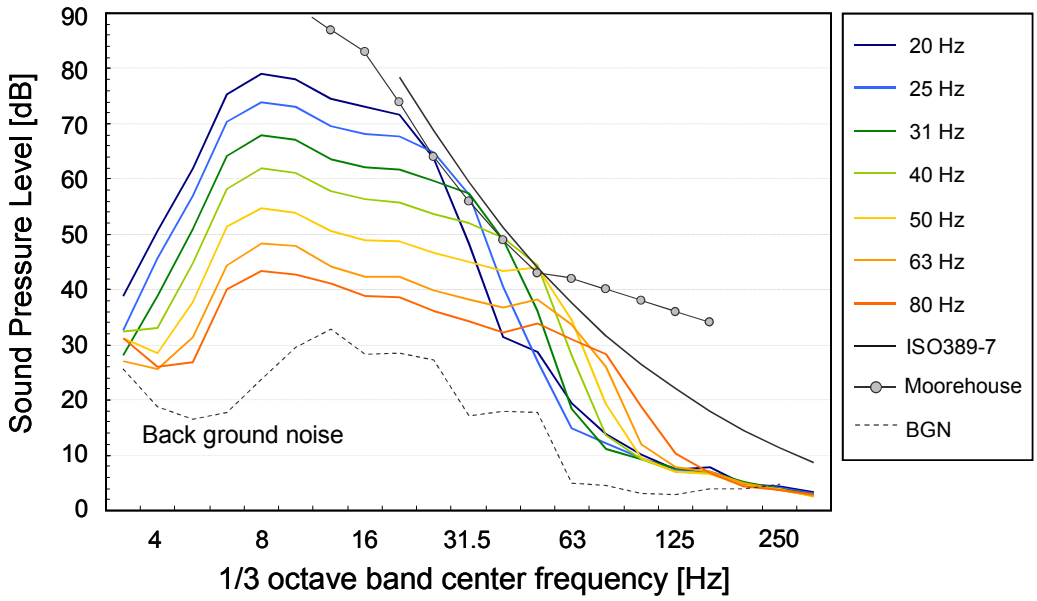


Figure 9: Spectral characteristics of hearing thresholds of band-limited low frequency noises.

To evaluate these critical spectral characteristics, the values in A-, C-, F- and G-weighted sound pressure levels were calculated for the mean value of the hearing threshold for each test sound. In the result shown in Figure 10, it should be noted that the values assessed by A-weighted sound pressure level are almost constant at around 20 dB.

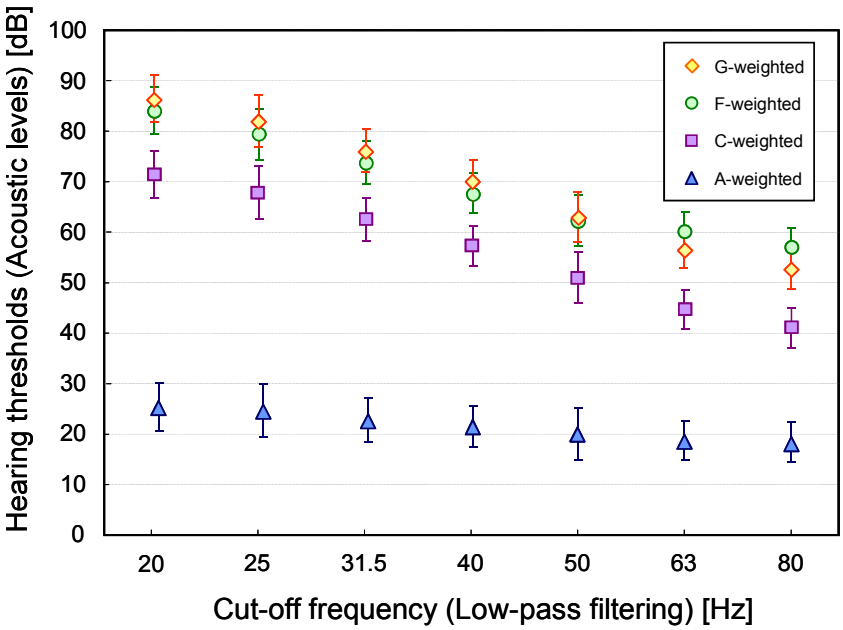


Figure 10: Hearing thresholds (4 kinds of sound levels).

5. Experiment-3: Frequency weighting for loudness evaluation

As a complementary experiment to the previous experiments, a loudness test was performed using the WTN model noise by changing its frequency characteristic.

5.1 Experimental conditions

As the standard stimulus (Ss), the WTN model noise used in the former experiments was used. In the same way as in Experiment-1, the presentation level of Ss was set at three steps of 35, 45 and 55 dBA. In order to investigate the contribution of low frequency components to loudness sensation, the comparison stimuli (Sc) were made by limiting the frequency components of the model noise by high-pass filtering processing. The cut-off frequencies (see Figure 3) were set at the 1/1 octave series from 1 kHz to 63 Hz and the 1/3 octave series from 31 Hz to 16 Hz, inclusive (9 in total). As an example, Figure 11 shows the model noise (over-all level : 45 dBA) and its variations modified in the way mentioned above. For the experiment, the test sounds were edited to have a duration time of 6 s. To avoid click sounds, the signals were gradually risen/fallen with a time of 0.5 s, respectively.

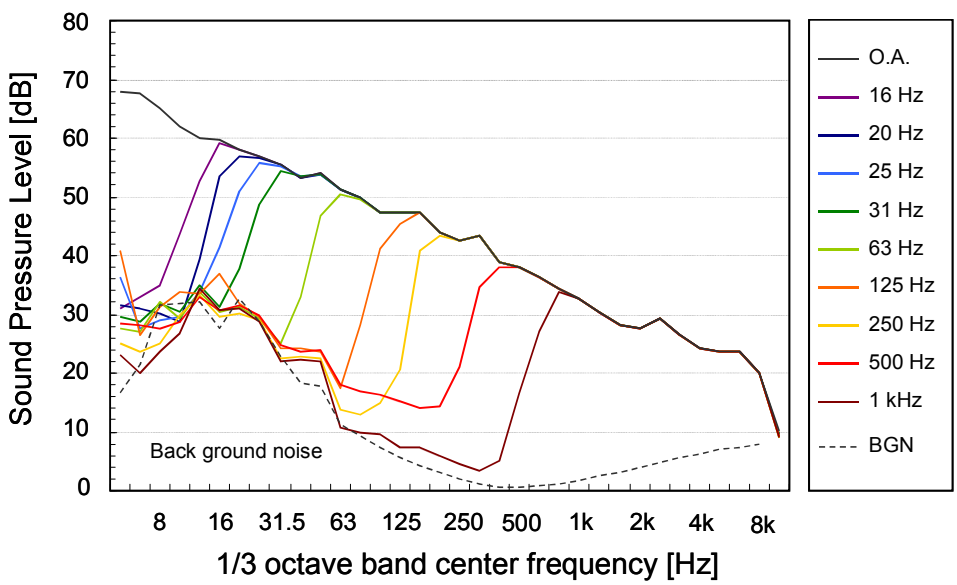


Figure 11: Sound pressure levels in 1/3 octave bands of the original test sound and its variations made by high-pass filtering.

5.2 Experimental procedure

As the test procedure, the method of adjustment by subject was applied. The experimental system was shown in Figure 12. In each condition, the standard stimulus (Ss) was firstly presented and secondly the comparison stimulus (Sc) was presented. After that, the subject was asked to adjust the loudness of Sc to that of Ss by using a volume controller shown in Picture 2. For the ascending/descending series in the case of Ss equal to 45 dBA, the level of Sc was set at 30/60 dB, respectively. The couple of Ss and Sc was repeated until each subject finished the adjustment. For each experimental condition, four trials (ascending/ descending/ascending/descending) were performed. The total time needed to complete the test of 30 test sounds was about 3 hours including rest times in between. In this experiment, the same test subjects in the previous experiments participated again.

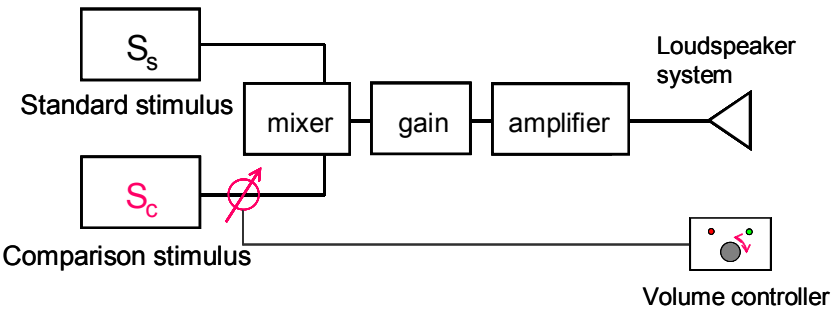
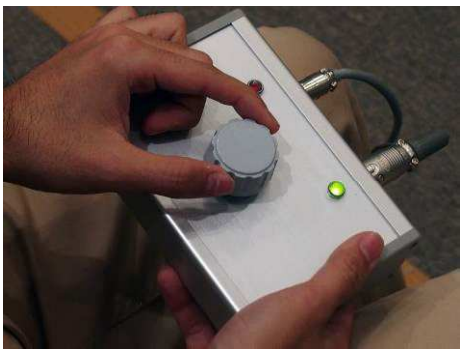


Figure 12: Experimental system for the loudness matching test.



Picture 2: Volume controller used in the matching test.

5.3 Experimental results

As the experimental results, the mean values and the plus/minus standard deviations ($\pm\sigma$) for all of the subjects in respective experimental conditions are plotted in Figure 13, in which X-axis indicates the cut-off frequency of Sc and Y-axis indicates the adjusted level in $L_{Aeq,6s}$. In these figures, 0 dB (Y-axis; adjusted level) means the level of Ss. In the results, it is seen that under the conditions where the cut-off frequency was set at 63 Hz or lower, the averaged level of adjusted Sc is less than 1 dB and the standard deviations kept to be small less than 0.5 dB. On the other hand, it is seen that in the cases where the cut-off frequency was set higher than 125 Hz, the adjusted level increased with the increase of the cut-off frequency. Under the condition where the cut-off frequency was set at 1 kHz, the adjusted level was about 6 dB. After the experiment, some subjects remarked that some test signals of which tone colour remarkably differed from that of Ss and it was rather difficult to adjust the loudness of Sc to that of Ss.

The frequency characteristics of the test sounds evaluated to be equal loudness to Ss are shown in Figure 14. In the result, it is seen that the low frequency components lower than 63 Hz did not contributed to loudness.

To find a proper frequency-weighting function, sound levels in A-weighted (L_A) and C-weighted (L_C) and Zwicker's loudness level (LL_z) were calculated for each adjusted level. The results are shown in Figure 15, in which it is seen that A-weighted sound pressure level kept constant (55 dBA). In the results arranged by LL_z, the plots for the sounds with cut-off frequencies higher than 250 Hz lowered a bit. In the figures, it is also seen that the plots assessed by C-weighted sound pressure level gradually decreased as the cut-off frequency became higher.

As a result, it has been confirmed that the frequency components in infrasound range and those lower than a few tens Hertz in audible frequency range hardly contribute to loudness sensation. Furthermore, it has been indicated that the A-weighted sound pressure level is an appropriate indicator for loudness assessment of low frequency sounds like WTN.

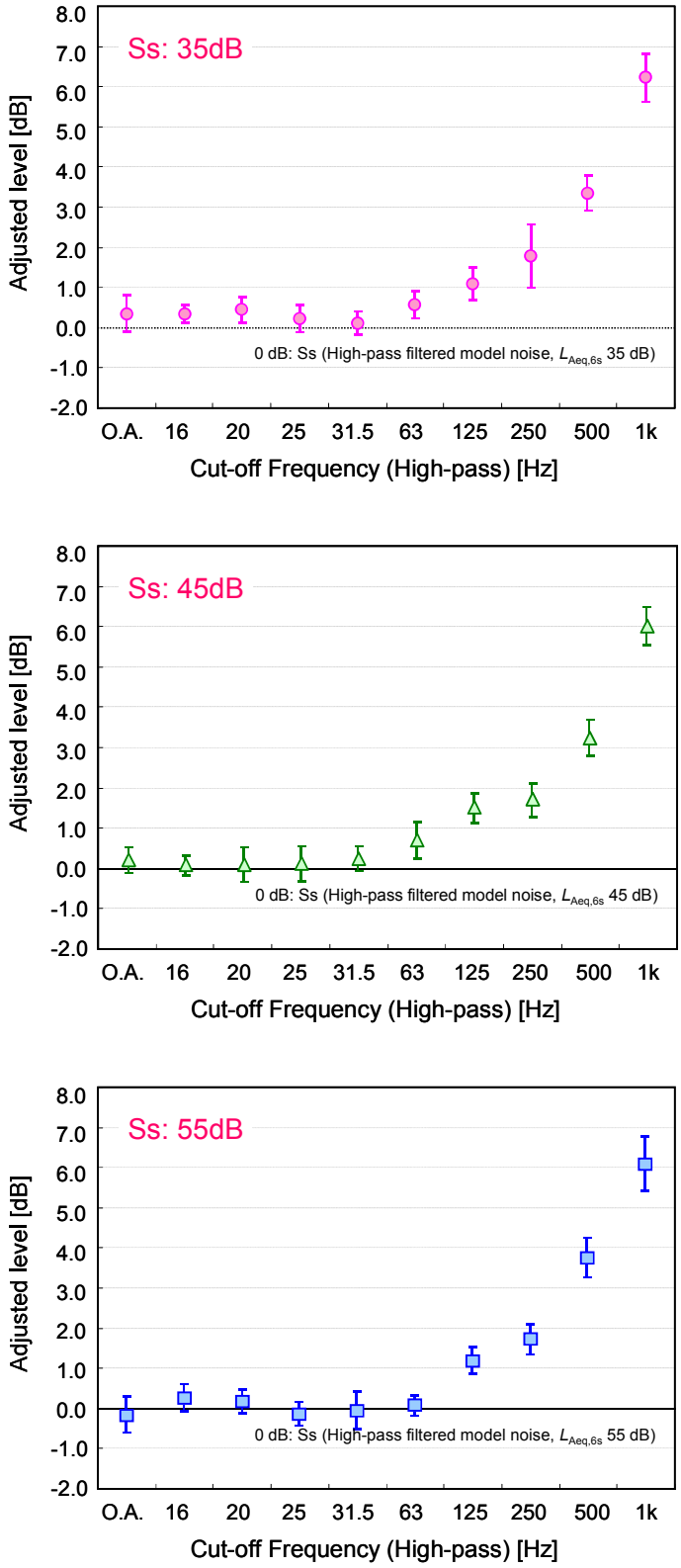


Figure 13: Equal loudness (Adjusted levels).

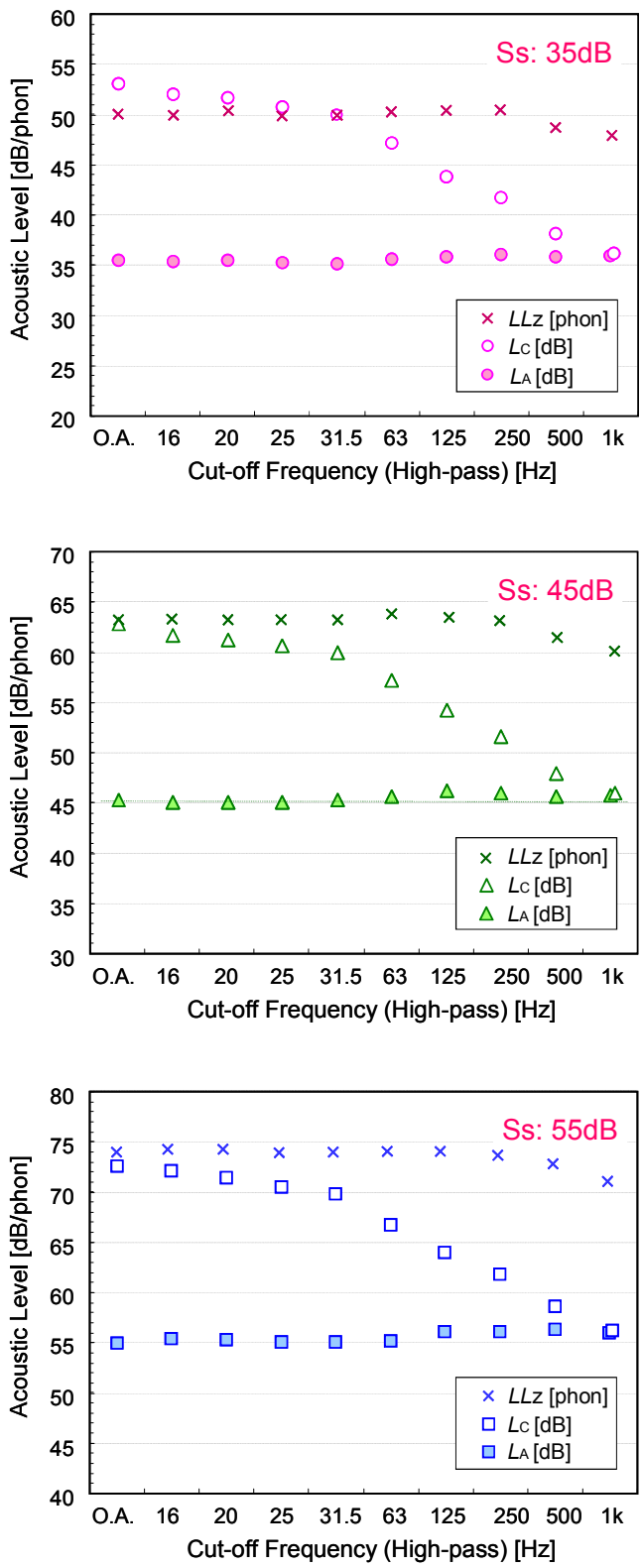


Figure 15: Equal loudness (evaluated by sound levels).

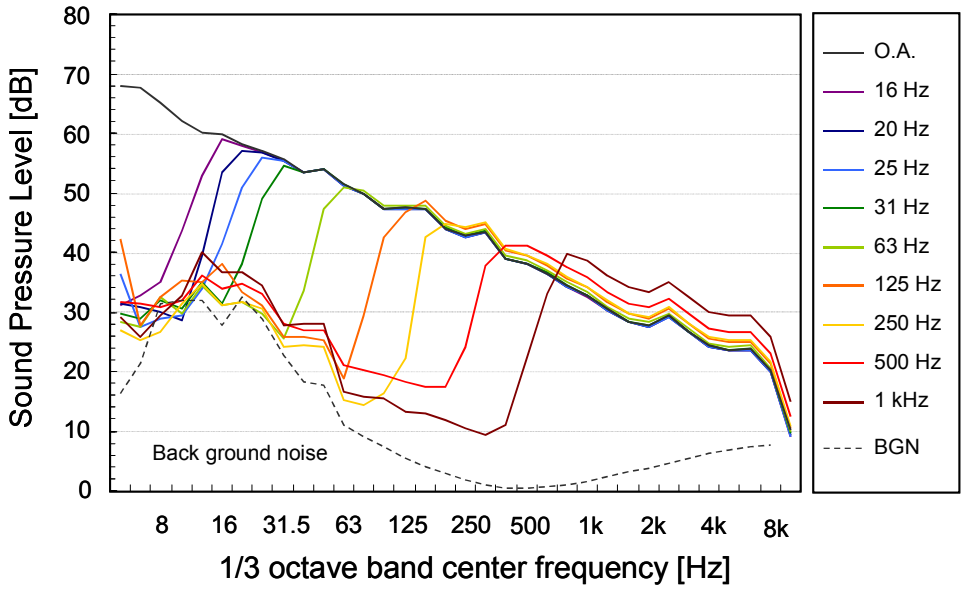


Figure 14: Frequency characteristics of test sound evaluated equal loudness to Ss.

6. Conclusions

In this study, human audibility of low frequency components contained in wind turbine noise was investigated. As a result, the following findings have been obtained.

(1) The low frequency components (infrasound and low frequencies in audible frequency range) themselves are not “audible/sensible”.

(2) The hearing thresholds of band-limited low frequency noises can be assessed by the criterion curve proposed by A.T. Moorhouse *et al*. and these levels are almost 20 dB in A-weighted sound pressure level.

(3) The frequency components in infrasound range and those lower than a few tens Hertz in audible frequency range contained in general wind turbine noises hardly contribute to loudness sensation.

(4) A-weighted sound pressure level is an appropriate indicator for loudness assessment of low frequency sounds like WTN.

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