

TECHNICAL REPORT

Experimental study on hearing thresholds for low-frequency pure tonesShinichi Sakamoto^{1,*}, Sakae Yokoyama¹, Hiroo Yano² and Hideki Tachibana²¹*Institute of Industrial Science, The University of Tokyo,
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Abstract: To investigate the effect of wind turbine noise, a study project has been conducted in the three years from fiscal year 2010 under the sponsorship of the Ministry of the Environment, Japan. One of the key aims in this study was to examine the effects of low-frequency components contained in wind turbine noise, and a series of auditory experiments have been conducted using an experimental facility composed of two adjacent rooms, where low-frequency sounds down to infrasound frequency range could be produced. As the first experiment using this facility, human hearing thresholds for pure tones were examined in the frequency range from 10 Hz to 200 Hz with 97 participants in a wide age range from 20 to 60 years.

Keywords: Wind turbine noise, Low-frequency sound, Hearing threshold

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1. INTRODUCTION

Wind power generation is highly promising as a source of renewable energy and many wind generation plants have been constructed all over the world. However, the noise generated by wind turbines has become an environmental noise problem in areas around power plants. Also, in Japan, after the commencement of the construction of wind generation plants from about 2000, there have been many complaints from nearby residents regarding noise pollution. This new type of noise problem has often been reported by the mass media as an issue of low-frequency noise and it has increased residents' anxiety about the effect of wind turbine noise on human health.

Concerning the above kind of noise problem, scientific knowledge is insufficient and no standard method for measuring and assessing such noise has been established. To overcome this situation, a study project, "Research on the evaluation of human impact of low-frequency noise from wind turbine generators" has been conducted in the three years from fiscal year 2010 under the sponsorship of the Ministry of the Environment, Japan. This project consisted of three main tasks: (1) physical research on wind turbine noise by field measurement, (2) social survey on the response of nearby residents, and (3) auditory experiments

on human response to noise containing low-frequency components.

Regarding the third task, the authors conducted a series of laboratory experiments [1–5]. For those studies, an experimental facility capable of producing low-frequency sounds including infrasound was constructed and the hearing threshold levels (HTLs) for pure tones between 10 Hz and 200 Hz were investigated as the first experiment using the facility. In this paper, the specifications and function of the facility and the results of the experiments on HTLs conducted with 97 participants in a wide age range from 20 to 60 years are reported.

2. EXPERIMENTAL FACILITY

For the experiments on human HTLs for low-frequency sounds, various devices have been made to reproduce sounds down to the infrasound region. Yeowart and Evans constructed low-frequency headphones using loudspeaker units [6]. They also constructed a low-frequency chamber with an enclosed volume of 1,250 liters [6]. Such pressure-box-type apparatuses were also used in the studies by Tokita [7] and Watanabe and Møller [8]. These apparatuses with relatively small air volumes are advantageous in realizing a uniform pressure field in the box. In this study, however, we used an anechoic room as the test room since we planned to perform various experiments on auditory sensation to various environmental noises in a wide

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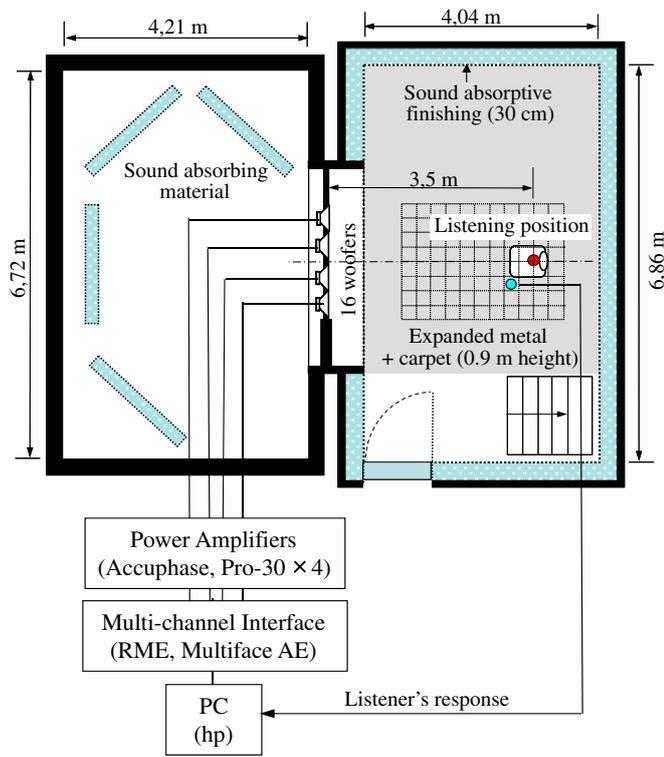


Fig. 1 Experimental system.

frequency range from infrasound to several kilohertz. Figure 1 shows the experimental facility used in this study, which consists of two adjacent rooms, a reverberation room with an air volume of 220 m³ and an anechoic room of 210 m³ in the acoustic laboratory of the Institute of Industrial Science, The University of Tokyo. These two rooms were originally constructed for the measurement of the sound insulation performances of building materials by the sound intensity technique.

To produce low-frequency sounds in this facility, sixteen woofers with a diameter of 40 cm (FOSTEX, FW405N, lowest resonance frequency: 27 Hz) were installed on the partition wall between the two rooms. In the reverberation room, used as the source room, a large amount of sound-absorbing material was installed to control the reverberation in the room. In the anechoic room, a listening point was located at a point 3.5 m from the centre of the loudspeaker system, at a height of 1.2 m above the floor. The listener sat straight on a chair to keep his/her head near the headrest (see Fig. 2). Here, since the absorption treatment in the anechoic room is only 30 cm thick, which is insufficient to make the room “anechoic” particularly at low frequencies, the interior of the room is not a simple pressure field but a standing-wave sound field. Therefore, the listening point was carefully chosen by checking the sound pressure distribution in the room. Among the measurement results, Fig. 3 shows the sound pressure level distributions on a horizontal plane 1.2 m



Fig. 2 Loudspeaker system and the listener’s position in the receiving room.

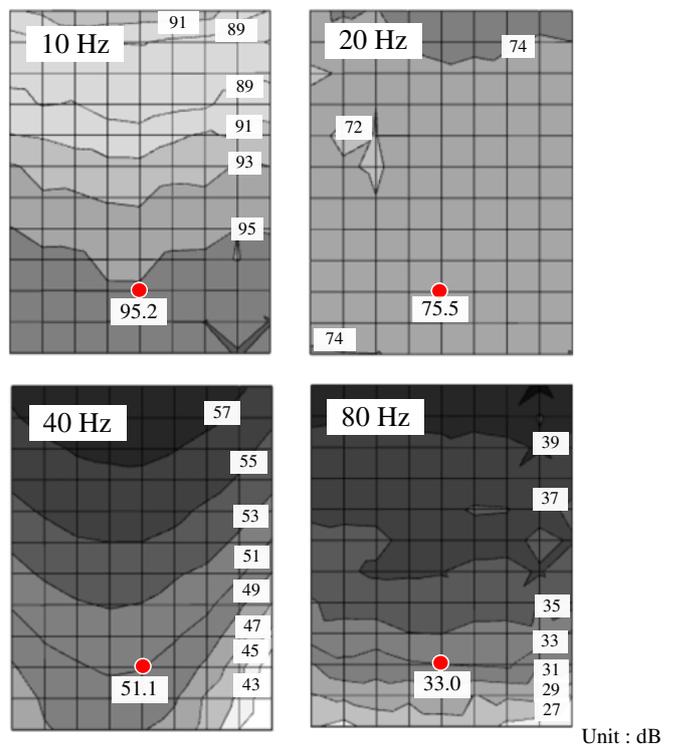


Fig. 3 Sound pressure level distribution on the horizontal plane 1.2 m above the floor in the receiving room.

above the floor measured when pure tones with frequencies of 10, 20, 40, and 80 Hz were reproduced from the woofers in the absence of a listener.

Since HTL becomes higher with decreasing frequency, low-frequency sounds must be produced at high levels from the loudspeaker system. In such cases, harmonic distortion is apt to become a serious problem, especially at frequencies below the lowest resonant frequency of the woofers. Figures 4(a) and 4(d) show the sound pressure levels measured at the listening point in the receiving room when pure tones of 10 Hz and 12.5 Hz were reproduced so

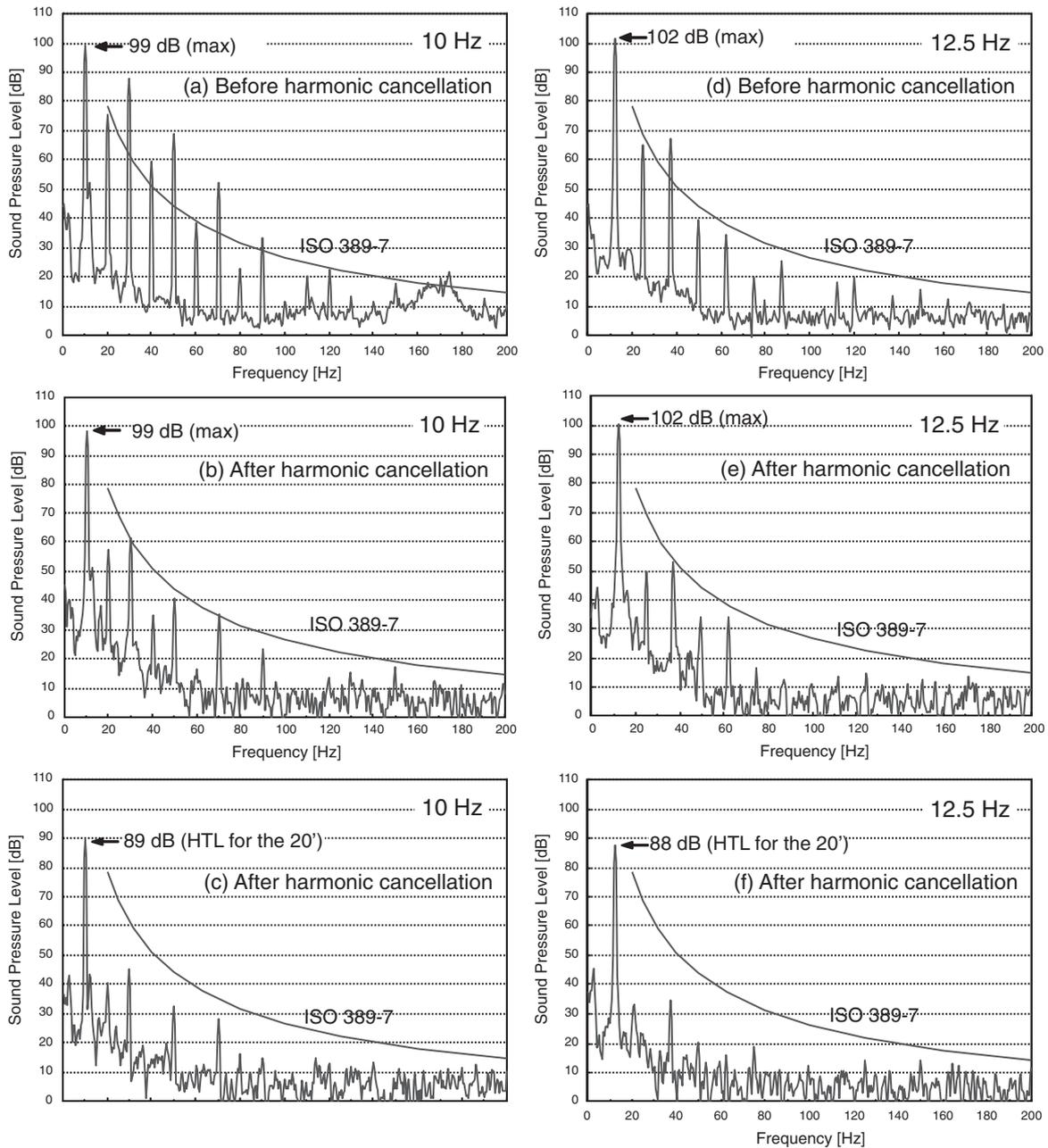


Fig. 4 Suppression of harmonic distortion of the loudspeaker system.

that the sound pressure levels became 99 dB and 102 dB, respectively. In these measurement results, it was clearly seen that harmonics of the fundamental pure tones appeared, and they disturbed the HTL determination of the fundamental tones.

To eliminate the effects of harmonic sounds, the cancelling technique by adding inverse-phase pure tones to the test signal was applied. That is, as shown in Fig. 5, the sum of the source signal ($A \cdot \sin 2\pi ft$: A is the amplitude and f is the frequency) and the harmonic components ($A_n \sin(n \cdot 2\pi ft + \varphi_n)$: n is an integer and φ_n is the phase shift to cancel the n th harmonic component) was synthesized in a computer. In both cases, the 2nd, 3rd, 5th

and 7th harmonics were relatively intense and the cancelling was performed on these harmonics. In this signal processing, respective values for the amplitude A_n and the phase shift φ_n for respective harmonics were determined so that the respective harmonics became minimum by monitoring the sound pressure spectrum at the listening point using a FFT analyzer. In further detail, the sixteen woofers were divided into eight pairs and the cancelling process described above was performed for each pair (two horizontally adjacent woofers). Figures 4(b) and 4(e) show the sound pressure spectra measured at the listening point when pure tones of 10 Hz and 12.5 Hz with the cancellation were produced so that the sound pressure levels became

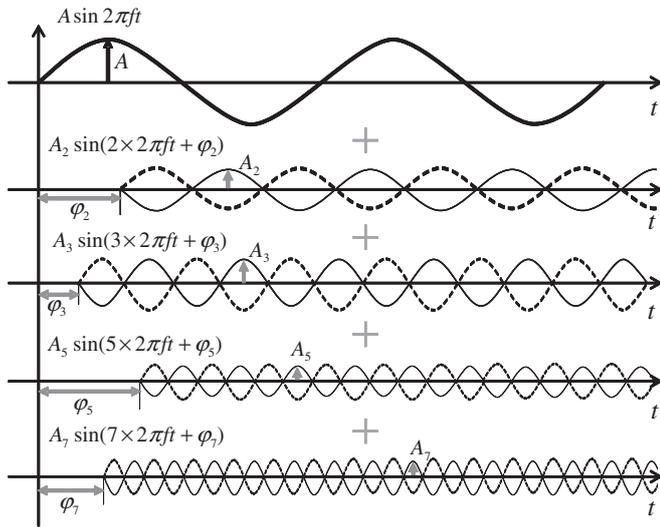


Fig. 5 Method of cancellation of harmonic sounds.

99 dB and 102 dB, respectively, which are the maximum levels that the experimental system used in this study can produce. In both cases, it is seen that the harmonics could be suppressed to levels equal to or lower than the HTLs specified in ISO 389-7:2005 [9]. Figures 4(c) and 4(f) show the sound pressure spectra at the production levels of 89 dB for 10 Hz and 88 dB for 12.5 Hz, respectively, which are the HTLs judged by the subject group in their 20's, as mentioned later. In both cases, the harmonics were suppressed below the HTL curve of ISO 389-7. Since harmonic distortion is a nonlinear phenomenon, this cancelling processing was performed for each of the production levels of the test pure tones of 10 Hz, 12.5 Hz, 16 Hz, and 20 Hz.

3. EXPERIMENTAL PROCEDURES

In the auditory experiment in this study, pure tones with frequencies in the one-third-octave series from 10 Hz to 200 Hz inclusive were used as the test stimuli. The duration and rise/fall times were adjusted for each test sound as shown in Fig. 6(a), to prevent transient click sounds. The interval between respective test sounds was randomly varied at one of the three steps of 1.5 s, 2.0 s, and 2.5 s to avoid guess work by the subjects.

As the test procedure, the adaptive method (simple up-down method) was applied, as shown schematically in Fig. 6(b) and the subject was asked to push a response button while he/she could hear or feel something around his/her ears and to release the button when such sensations ceased. The experiment was started with the descending series in which the test sound was decreased stepwise every 2 dB from a level considered to be sufficiently higher than the assumed HTL. These series continued until the level became one step (2 dB) lower than that at which the

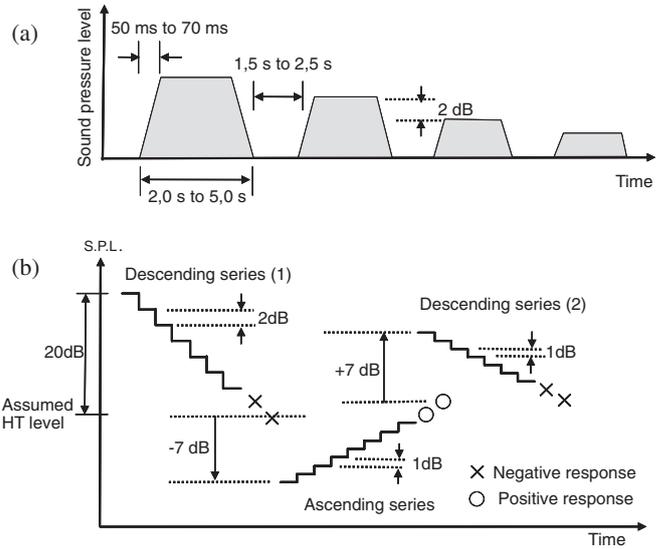


Fig. 6 Time pattern of presentation of test sounds. (a) Presentation of test sounds. (b) Test trials by the adaptive method (simple up-down method).

Table 1 Age composition of the test subjects.

Age ranges	Males	Females	Total
20's	31	13	44
30's	5	5	10
40's	8	8	16
50's	5	4	9
60's	14	4	18
Total	63	34	97

subject's response became nil (no response). Then, the presentation level was further decreased by 7 dB and the ascending series was 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 began to respond. After that, the presentation level was further increased by 7 dB and the second descending series was started, in which the test sound was decreased stepwise every 1 dB. After completing these three series, the lowest levels in the descending series at which the subject could hear or feel something around his/her ears and the highest level in the ascending series at which the subject's response changed to positive were averaged taken to be the subject's HTL for each frequency.

This experiment was performed with the participation of 97 subjects over a wide age range from 20 to 60 years (see Table 1). In advance of the experiment, a hearing ability test was performed for every subject and it was confirmed that all of the subjects had otologically normal hearing abilities suitable for their ages. This auditory experiment was performed according to the ethical code of The University of Tokyo.

Table 2 Experimental results of hearing threshold levels in dB for pure tones.

Age ranges	Frequencies of pure tones [Hz]													
	10	12.5	16	20	25	31.5	40	50	63	80	100	125	160	200
20's	88.9 (3.1)	87.6 (3.8)	83.4 (4.5)	75.5 (4.1)	67.6 (4.2)	58.7 (4.9)	49.9 (4.5)	44.6 (4.4)	36.3 (4.5)	29.3 (3.7)	25.0 (3.6)	20.8 (3.7)	16.3 (3.6)	14.8 (3.7)
30's	88.7 (3.0)	85.3 (3.2)	81.9 (4.7)	73.7 (6.0)	66.7 (4.2)	57.2 (5.4)	48.4 (3.5)	43.6 (3.3)	36.4 (2.9)	28.0 (3.2)	23.2 (4.1)	19.0 (3.0)	14.8 (2.0)	13.4 (3.6)
40's	88.4 (4.1)	85.6 (3.7)	81.8 (5.3)	74.6 (5.2)	66.8 (5.5)	56.1 (4.8)	48.0 (4.0)	44.3 (3.9)	33.4 (4.6)	28.4 (3.6)	23.7 (3.0)	18.1 (3.2)	14.6 (3.8)	12.7 (3.0)
50's	90.3 (4.8)	84.7 (5.7)	82.8 (4.8)	75.6 (6.2)	68.6 (7.4)	58.7 (7.4)	50.2 (6.3)	46.3 (7.1)	39.2 (6.9)	31.4 (7.1)	29.2 (7.8)	23.4 (7.4)	18.7 (8.0)	15.0 (7.1)
60's	93.5 (3.6)	89.2 (2.5)	87.3 (4.7)	80.2 (5.0)	72.1 (5.9)	62.2 (6.4)	53.9 (5.6)	51.1 (6.3)	42.9 (5.8)	36.5 (5.7)	31.6 (6.4)	26.7 (5.8)	21.6 (6.7)	18.9 (5.9)

() : standard deviation in dB.

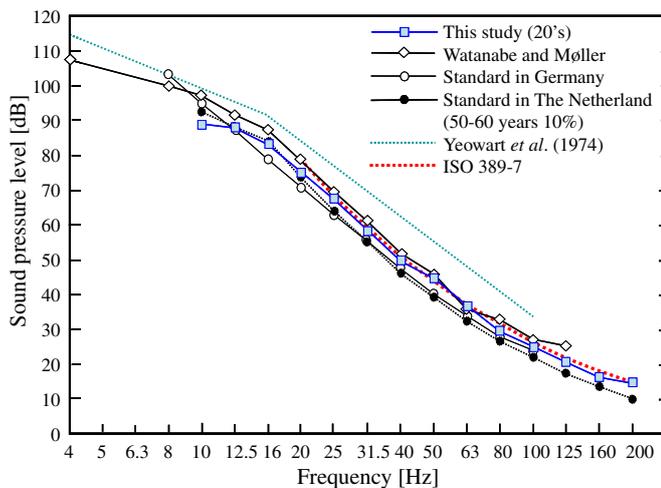


Fig. 7 Experimental results of pure tone HTLs for 44 subjects in their 20's.

4. EXPERIMENTAL RESULTS

The experimental results for all of the age ranges obtained in this study are shown in Table 2. Among them, the experimental results for 44 subjects in their 20's are shown in Fig. 7. In this figure, the HTL curve in the audible frequency range specified in ISO 389-7 [9], the generalized HTL curve proposed by Yeowart and Evans [6], the experimental results obtained by Watanabe and Møller [8] and HTL values standardized in Germany [10] and The Netherlands [11] are also given for reference. Comparisons between these data indicate the followings.

(1) At frequencies higher than 12.5 Hz, the results of this study lie between the data obtained by Watanabe and Møller and the values of the standards of Germany and The Netherlands. The result of this study is the lowest at 10 Hz. The harmonic distortion was severest at 10 Hz in this experiment, as shown in Figs. 4(b) and 4(c). The 3rd, 5th and 7th harmonics might influence the subjects' judgments

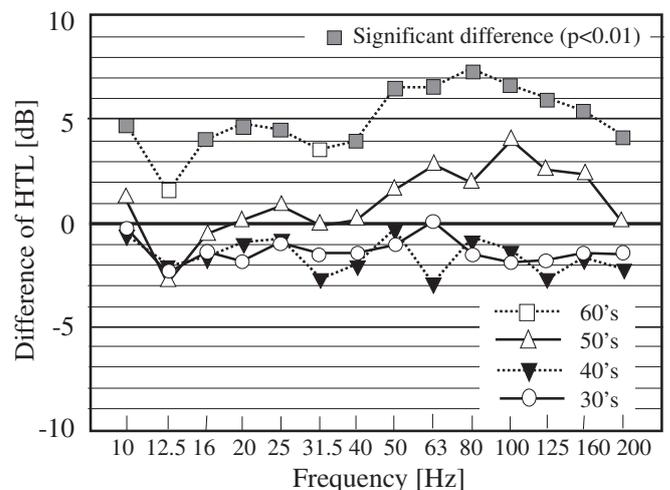


Fig. 8 Pure tone HTLs for various age ranges.

of HTL at this frequency when the stimulus is presented at high levels.

(2) The generalized HTL curve proposed by Yeowart and Evans is above the other data at almost all frequencies. The separations are conspicuous in the audible frequency range above 20 Hz.

Next, the variations of HTLs for each age range of the subjects were examined. Figure 8 shows the relative HTLs for subjects in their 30's, 40's, 50's and 60's compared with those of subjects in their 20's, which was the youngest age group in this study. In the results, HTLs for subjects in their 30's and 40's are slightly lower and those for subjects in their 50's are higher than those of subjects in their 20's at many frequencies, but no statistically significant difference was found between subjects in their 20's and each of the other age ranges ($p < 0.01$). On the other hand, in the comparison of HTLs between the 20's and 60's groups, a significant difference ($p < 0.01$) was found at all frequencies except for 12.5 Hz and 31.5 Hz. Regarding the increase in HTL with age, ISO 7029:2000

[12] describes a statistical method for calculating the HTL deviations for otologically normal persons of a specific age from those for a population of 18-year-olds at the centre frequencies of octave bands from 125 Hz to 8,000 Hz. According to this method, the difference in the HTL values between 18-year-olds and 60-year-olds at 125 Hz is 5.3 dB. In the results of this study, the difference in the HTL values between the 20's and 60's groups at this frequency was 5.9 dB.

5. CONCLUSIONS

To investigate human response to low-frequency sounds, an experimental facility composed of two adjacent rooms was constructed. As the first experiment using this facility, human hearing thresholds for pure tones were examined in the frequency range from 10 Hz to 200 Hz for 97 participants in a wide age range from 20 to 60 years. As a result, it was found that the hearing thresholds of subjects in their 20's were in good agreement with those specified in ISO 389-7 in the audible frequency range above 20 Hz. In the infrasound frequency region below 20 Hz, the experimental results were in fairly good agreement with the data obtained by Watanabe and Møller and those standardized in Germany and The Netherlands, except for 10 Hz, at which the HTL obtained in this study was lower compared to these data.

Regarding the change of the hearing threshold as a result of aging, there were no significant differences among the age ranges from 20 to 50 years in the frequency range under test in this study, whereas the tendency was found that the hearing threshold levels for people in their 60's were significantly higher than those for people in their 20's was observed.

Following the experiment described in this paper, various auditory experiments have been conducted in order to investigate the effects of the low-frequency components contained in wind turbine noise [2–4] and the loudness sensation to various kinds of environmental noise containing low-frequency components [5].

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