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Perception of low-frequency components contained in general environmental noises including wind turbines

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ABSTRACT

The influence of low frequency components in noises including wind turbine noise has become a serious problem and various researches are being made in many countries. Also in Japan, synthetic study programs mainly targeted for wind turbine noise had been performed, in which field measurements, social survey on the response of nearby residents and laboratory experiments on audibility of low frequency sounds were conducted. In parallel to these studies, field measurements on general environmental noises including transportation noises inside and outside of various vehicles were performed by paying attention to low frequency components. As a result, it has been found that low frequency components are included not only in wind turbine noise but also in general environmental noises. The environmental sounds recorded on sites were reproduced by a test facility which can reproduce low frequency components including infrasound and auditory tests were performed. As a result, it has been found that the A-weighted sound pressure level is robustly applicable to the assessment of loudness for such kinds of environmental sounds and the low frequency components contained in wind turbine noise around residential area is not audible.

Keywords: Low-frequency, Wind turbine noise, Loudness, Annoyance, auditory experiment

1. INTRODUCTION

To investigate wind turbine noise problem from a psycho-acoustical viewpoint, the authors have conducted several kinds of subjective tests focusing on the low frequency sound using WTN recorded on-site and electrically synthesized sounds [1-5]. In addition to WTNs, a variety of environmental noises such as ambient sounds in natural environments and urban residential areas, transportation noises inside and outside of various vehicles, machine noises, construction noises, etc. were also recorded including low frequency components down to 1 Hz. In order to investigate the method of assessing these general environmental noises including WTN uniformly, the authors have conducted an auditory experiment on loudness sensation by using an experimental facility which is capable of reproducing low frequency sounds including infrasound.

2. EXPERIMENTAL FACILITY

To investigate the effects of low-frequency components contained in various environmental noises including WTN, the experimental facility shown in Figs 1 and 2 was constructed at the Institute of Industrial Science, The University of Tokyo [1]. On the partition wall between the two rooms, 16 woofers of 40 cm diameter (Fostex: FW405N) were installed to reproduce low-frequency sounds down to 4 Hz. In addition, a full-range loudspeaker of 20 cm diameter (Fostex: FE206En) was added at the center position of the woofers to cover the middle- and high-frequency sounds up to 16 kHz. The crossover frequency between the two loudspeaker systems was set at 224 Hz. The listening position was located 3.5 m from the center point of the loudspeaker system. To correct the frequency characteristic of the total reproduction system, the digital inverse-filtering technique was applied using a linear-phase FIR filter calculated from the trans-fer function from the input of the amplifier to the listening point measured in the frequency range from 4 Hz to 16 kHz in 1/12-octave-bands.

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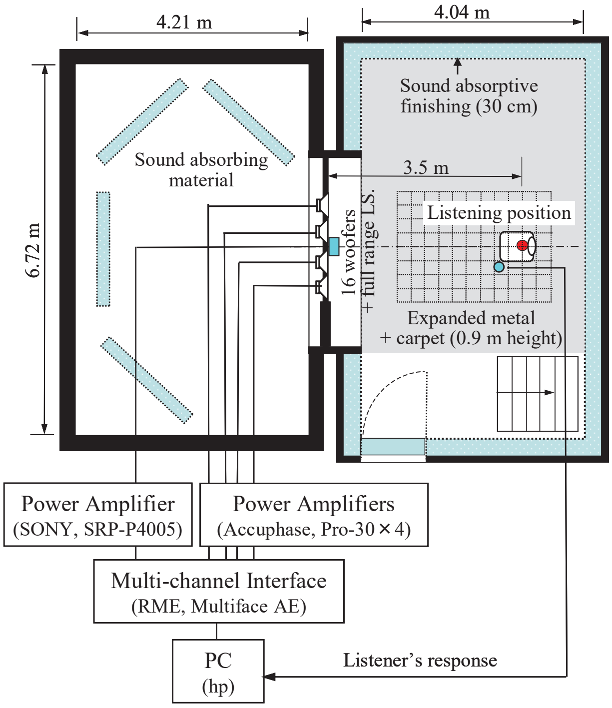

Figure 1 – Plan view of the experimental

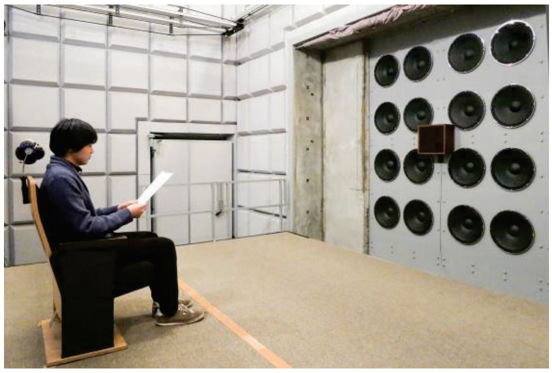

Figure 2 – Interior of the receiving room.

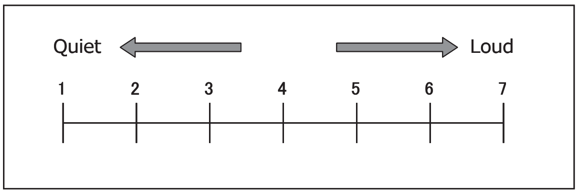

Figure 4 – 7-step category used in loudness

3. SUBJECTIVE EXPERIMENT ON LOUDNESS

The most significant factor in the assessment of noise is loudness. In this study, therefore, a loudness test was conducted by using 38 different environmental sounds containing low frequency components down to infrasound and examined the correspondences between loudness and various noise indicators.

3.1 Test Sounds

As test sounds for this study, sounds in the natural environment, ambient sounds in residential areas, interior and exterior noises of transportation systems, and others shown in Table 1 were collected. All of these sounds can be regarded as stationary and contain no strong tonal components. To record these sounds, including low-frequency components down to infrasound, a wide-frequency-range sound level meter (prototype of RION: NL-62) that had a flat frequency response from 1 Hz to 20 kHz was used, and the sound pressure signals were recorded on an SD card installed in the sound level meter, using the recording function (48 kHz sampling, 16 bits, WAVE-format). To prevent wind-noise at the measurement microphone, a newly designed double-skin type wind-screen set [5] was put on the microphone when recordings outdoors. In addition to the 33 kinds of environmental sounds, an artificial noise with a frequency characteristic of -4 dB/octave in the band spectrum representing the general frequency characteristics of WTNs [5] was used and its level was varied in five steps of 35 dB, 45 dB, 55 dB, 65 dB, and 75 dB in terms of A-weighted SPL. 1/3-octave-band SPLs of the 38 sounds used in this study are shown in Fig. 3. These data were measured when the respective test sounds were reproduced in the experimental facility mentioned below in the absence of the listener at the position where the center of the listener's head would be.

3.2 Test procedure

Each of the test sound was edited to have a duration of 10 s and windowed to incorporate a 1.0 s ramp-up at the beginning and 1.0 s ramp-down at the end of the presentation in order to eliminate click sounds.

The loudness test was conducted by applying the rating scale method using seven-step category. That is, each test sound was presented to the subject and he/she judged the loudness according to the seven-step category presented schematically in a panel (see Fig. 4), and orally gave his/her judgment using the integer shown in the panel. The 38 test sounds were presented in random order. One series of the test took about 30 minutes. To examine the repeatability of the subject's judgments, the test was repeated twice for each subject. Between the two judgment tests, a short break was taken to allow the subject to relax the subject. In this experiment, 20 subjects of the age range from 21 years to 25 years (18 males and 2 females) with otologically normal hearing ability participated. This auditory experiment was performed in accordance with the ethical code of The University of Tokyo.

Table 1 – Test sounds used in this study

Categories	No.	Contents	$L_{\mathrm{Aeq,10s}}$ [dB]	Loudness score	
				Average	Std. Dev.
(a) Environmental sounds	1	Environmental sound in a forest	31	1.25	0.54
	2	Sound of soughing through pine trees	61	5.25	0.63
	3	Environmental sound on a seashore : A	61	5.08	0.57
	4	Environmental sound on a seashore : B	54	4.08	0.73
	5	Environmental noise in residential area : A	43	2.73	0.64
	6	Environmental noise in residential area : B	32	1.23	0.42
	7	Environmental noise in residential area : C	38	2.03	0.48
	8	Noise in an industrial estate	49	3.68	0.62
	9	Chirp of cicada in summer	54	4.25	0.78
	10	Chirp of insects in autumn	38	2.00	0.64
(b) Transportation noises	11	Railway noise	76	6.40	0.59
	12	Road traffic noise (distance: 22 m)	76	6.50	0.60
	13	Road traffic noise (distance: 85 m)	63	4.98	0.58
	14	Road traffic noise (distance: 85 m, in house)	43	2.83	0.68
	15	Aircraft noise	65	5.20	0.65
(c) Cabin noises	16	Cabin noise in a super-express train	68	5.80	0.46
	17	Cabin noise in a super-express train in a tunnel	71	6.18	0.38
	18	Cabin noise in a jet-plane A	73	5.98	0.36
	19	Cabin noise in a jet-plane B	81	6.95	0.22
	20	Cabin noise in a car running a highway	72	6.05	0.45
	21	Cabin noise in a conventional train	70	6.05	0.45
	22	Cabin noise in a conventional train running on a	70	6.05	0.50
(d) Wind turbine noises	23	Wind turbine noise (near a wind turbine)	56	4.38	0.67
	24	Wind turbine noise (residential area: outside)	43	3.00	0.64
	25	Wind turbine noise (residential area: inside)	27	1.05	0.22
	26	Wind turbine noise (with insects' sounds)	41	2.65	0.70
	27	Wind turbine noise (insects' sounds were cut off)	37	1.85	0.62
(e) Other environmental noises	28	Air-conditioning equipment : A	40	2.13	0.56
	29	Air-conditioning equipment : B	61	5.15	0.53
	30	Air-conditioning equipment : C	66	5.25	0.54
	31	Structure-borne sound from a subway truck	45	2.95	0.71
	32	Concourse of a railway station	64	5.30	0.56
	33	Construction noise (Concrete breaker)	79	6.93	0.27
(f) Artificial noise modeling WTN	34	Synthesized noise with -4dB/octave : A	35	1.63	0.59
	35	Synthesized noise with -4dB/octave : B	45	3.18	0.59
	36	Synthesized noise with -4dB/octave : C	55	4.40	0.55
	37	Synthesized noise with -4dB/octave : D	65	5.75	0.54
	38	Synthesized noise with --4dB/octave : E	75	7.00	0.00

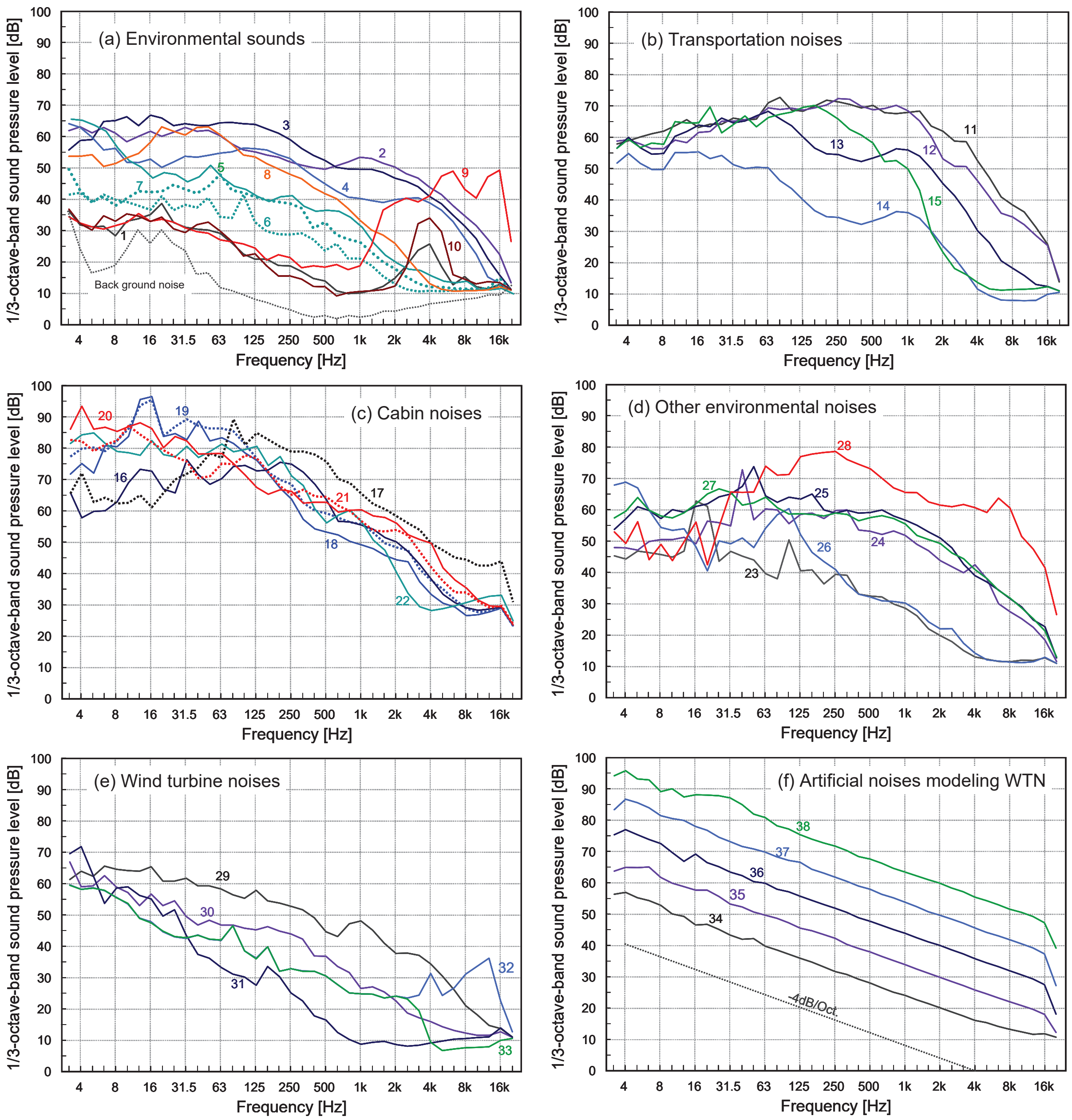

Figure 4 – Spectral characteristics of the test sounds used in this experiment

3.3 Experimental Results

After completing the loudness tests for the 20 subjects, the correlation between the results of the two tests was examined for each subject. As a result, the correlation coefficient ranged be-tween 0.93 and 0.97; indicating that a consider-ably high repeatability was obtained for all of the subjects. Therefore, all of the experimental results of the twice-repeated tests for the 20 subjects were used in the data analysis dis-cussed below.

To examine the equal-interval characteristic of the categories used in this experiment, the method of successive categories was applied, and a correlation coefficient of 0.99 was found between the original categories and those trans-formed into interval scale. Therefore, the arithmetic average of the category numbers given by all of the subjects was determined as the loud-ness score for respective test sounds as shown in Table 1.

Next, the sound pressure measured at the listening position over 10 s (duration of each of the test sounds) shown in Fig. 4 was evaluated using the following six kinds of psycho-acoustical indicators.

(1) L_A: A-weighted sound pressure level (IEC 61672-1 [6])
(2) L_C: C-weighted sound pressure level (IEC 61672-1)
(3) L_G: G-weighted sound pressure level (ISO 7196)
(4) L_Z: Z-weighted sound pressure level (IEC 61672-1)
(5) LL_Z: Zwicker loudness level (ISO 532B [7,8])
(6) LL_{MG}: Moore-Glasberg loudness level (ANSI S3.4-2007 [9])

L_A and L_C were obtained using digital IIR filters with the frequency-weighting functions of A and C, respectively, specified in IEC 61672-1 [6]. L_G was obtained using that with the frequency-weighting functions of G specified in ISO 7196. L_Z was no frequency-weighting. LL_Z was calculated from the time-averaged 1/3-octave-band SPLs from 25 Hz to 12.5 kHz according to the algorithm described in Ref. 7 and 8, and LL_{MG} was calculated from the time-averaged 1/3-octave-band SPLs from 50 Hz to 16 kHz according to Ref. 9.

The relationships between the loudness score and the values assessed by the respective indicators are given in Fig. 5. From these results, it is seen that the loudness score correlated well to all the values assessed using L_A, LL_Z and LL_{MG} exhibiting a high correlation coefficient r larger than 0.99, whereas the correspondence decreased slightly in the case where L_C was applied (r=0.934). In the cases applying L_G and L_Z, it was much deteriorated, whereas L_G.was especially the psycho-acoustical indicator for sounds including low-frequency component.

Here, it should be noted that L_A is in no way inferior to LL_Z and LL_{MG}.

3.4 Discussion

Regarding the A-weighted SPL, many researchers pointed out its shortcoming in the assessment of the loudness or annoyance under the condition that the test sounds contain strong tonal component(s) or dominant spectral component(s) in narrow-band(s) [10-14]. In those cases, the A-weighted SPL is too simple and other sophisticated indicators such as LL_Z and LL_{MG} should be applied. However, the result of this study indicates that the A-weighted SPL is an appropriate indicator of the loudness of general environmental noise even when relatively dominant low-frequency components down to infrasound are included.

Another problem of the A-weighted SPL often pointed out when discussing its applicability to a wide range of sound levels is that the A-weighting function was originally proposed as an inverse characteristic of the 40-phon curve of the equal-loudness contours proposed by Fletcher and Munson [15, 16] (see Fig. 6); therefore, it is unsuitable when assessing intermediate- or high-level sounds. However, when comparing the inverse A-weighting curve to the revised equal-loudness contours specified in ISO 226: 2003 [17], it fits around the 60-phon curve as shown in Fig. 7. This finding means that the A-weighting curve is not necessarily a frequency weighting function for relatively soft sounds.

From the result discussed above, it can be concluded that the A-weighted SPL is a simple and good estimator of the loudness when assessing general environmental noise including WTN. The applicability of the A-weighted SPL to WTN with low-frequency components has also been investigated [14, 18, 19]. However, when assessing noise with dominant tonal or narrow-band spectrum components, there would be a limit to the application of this indicator, and precise loudness evaluation and the consideration of correction factors for tonality as specified in ISO 1996-2 [20] are necessary.

4. CONCLUSIONS

In this study, an auditory experiment on loudness was conducted using a variety of environmental noises including low frequency components and the experimental results were evaluated by six kinds of psycho-acoustical quantities. As a result, it has been found that A-weighted sound pressure level is the best indicator among them. In the problem of wind turbine noise, it is often discussed how to evaluate the low frequency components. As shown in the spectral characteristics of the environmental noises collected in this study, the low frequency components are contained in general environmental noises, not particularly in wind turbine noise. As a conclusion, it is suggested that A-weighted sound pressure level should be uniformly applied to the assessment of general environmental noises including wind turbine noise.

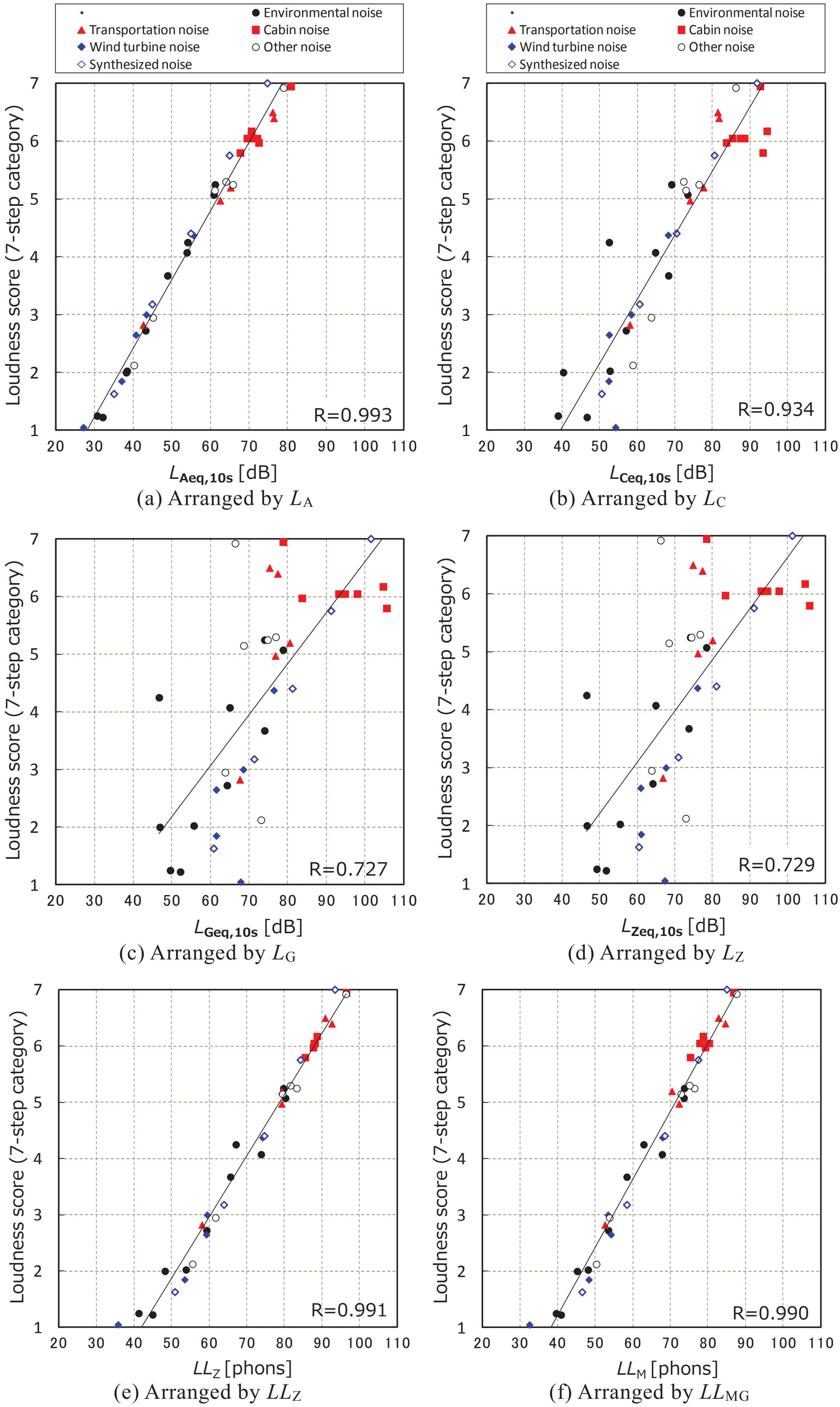

Figure 5 – Relationship between loudness score and noise indicators

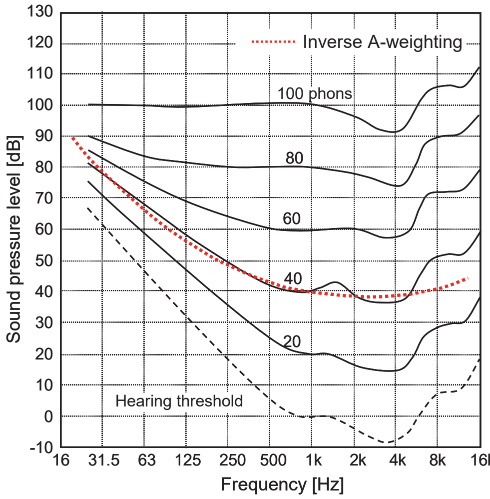

Figure 6 – Inverse A-weighting curve on the equal-loudness contours proposed by Fletcher & Munson.

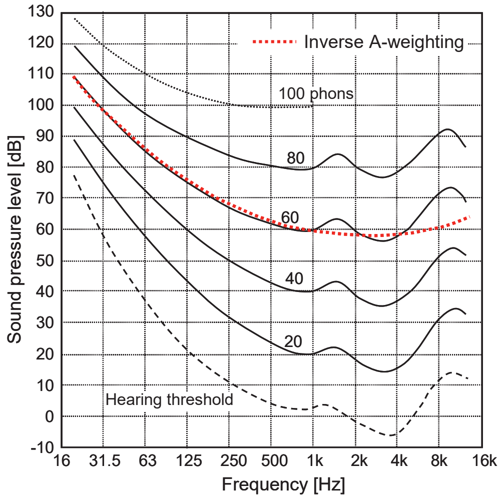

Figure 7 – Inverse A-weighting curve on the equal-loudness contours specified in ISO 226: 2003.

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