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Short Communication

A New Approach to Assess Low Frequency Noise in the Working Environment

Yukio TAKAHASHI*, Yoshiharu YONEKAWA and Kazuo KANADA

National Institute of Industrial Health, 6–21–1, Nagao, Tama-ku, Kawasaki 214–8585, Japan

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Abstract: To assess high-level low frequency noise in the working environment, adverse extra-aural effects caused by the noise should be taken into account. The human body vibration induced by low frequency noise, 'noise-induced vibration', was measured on the body surface and the equal-acceleration level contours of the vibration were tentatively estimated. With these contours, we can predict the magnitude of noise-induced vibration at every measuring position on the body surface. This is helpful in relating the total dosage of low frequency noise with the physical symptoms caused by the noise. But some important points in the contours remain to be investigated and improved. When these points are dealt with, the equal-acceleration level contours will be useful for assessing high-level low frequency noise in the working environment from the standpoint of predicting the adverse extra-aural effects.

Key words: Low frequency noise, Assessment, Human body vibration, Body surface, Acceleration level, Equal-acceleration level contours

Low frequency noise, the frequency of which ranges below 100 Hz, is generated by many machines commonly used in the working environment, such as fans, blowers, compressors, and so on, and the sound pressure level often exceeds 100 dB(SPL)[1)]. Low frequency noise hardly impairs the human auditory organs because the human equal-loudness levels are quite high in the frequency range below 100 Hz. Hence, in spite of its prevalent generation and high sound pressure level, low frequency noise has not attracted much attention in the working environment where noise-induced hearing loss is the matter of greatest concern[2)].

Apart from adverse effects on the auditory organs, it is known that high-level low frequency noise induces human body vibration, 'noise-induced vibration'. It is speculated that the level of this vibration is not very high, but long-term exposure to it may cause some adverse health effects in a worker. In recent years, Castelo Branco *et al.*[3–7)] have reported the extra-aural symptoms found in workers who have been exposed to high-level low frequency noise for more than 10 years and they have called it 'vibroacoustic disease'. Although the causal relationship and the dose-response relationship have not been clarified in detail, the reporters have pointed out that noise-induced vibration is one of the causes of vibroacoustic disease.

To assess high-level low frequency noise in the working environment appropriately, the adverse extra-aural effects should be taken into account, but the A-weighting curve, which is a standardized weighting curve[2)] for measuring and assessing noise, and some weighting curves focusing on low frequency noise, such as the LF-weighting curve[8)] and the G-weighting curve[9)], are not related to the extra-aural effect, because they are designed on the basis of the human psychological and perceptual responses to noise. Thus it is doubtful whether the frequency-weighting characteristics in these existing weighting curves are suitable for assessing the extra-aural effect. It is desirable to establish a new assessing method on the basis of some index which is closely related to the extra-aural effect. Noise-induced vibration may be useful as an index for this. It directly represents the effect of noise on a part of the body where some physical symptom has occurred, and it is expected not to vary in magnitude in long-term exposure to the noise, contrary to any psychological responses

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*To whom correspondence should be addressed.

which may be reduced in magnitude as habituating. These characteristics of noise-induced vibration are helpful in relating the total dosage of the noise in long-term exposure to the physical symptoms caused by the noise.

We measured noise-induced vibration on the body surface and tentatively estimated the equal-acceleration level contours at every measuring position. With these contours we can predict the magnitude of noise-induced vibration on the body surface. Although some important points in the contours remain to be investigated and improved, it is expected that the contours are useful for assessing the adverse physical effects of high-level low frequency noise. In this article, measurement of noise-induced vibration and estimation of the equal-acceleration level contours are reported.

Nine healthy male subjects whose ages ranged from 24 to 57 (mean=37.0, SD=12.5) participated in the study. We selected five measuring positions on the body surface of a standing subject: on the right anterior chest (2 cm above the right nipple), on the left anterior chest (2 cm above the left nipple), on the right anterior abdomen (5 cm under the pit of the stomach, and 5 cm to the right of the midline), on the left anterior abdomen (5 cm under the pit of the stomach, and 5 cm to the left of the midline), and on the forehead (2 cm above the level of the eyebrow, and on the midline).

The measuring method was approved by the ethics committee of the National Institute of Industrial Health, and before the measurements informed consent was obtained from each subject.

The measurements were carried out in a sound-proof test chamber the capacity of which was 3.16 m × 2.85 m × 2.8 $m^{10)}$. The temperature in the test chamber was initially set at 25 °C at the subject's position and, if he complained, adjusted to within the 23–27 °C range in order to prevent him from sweating. The humidity in the test chamber was maintained at about 40% with a humidifier. To prevent changing the local vibrating system at the measuring position, we used a small (3.56 mm × 6.86 mm × 3.56 mm) and lightweight (0.5 g) accelerometer (EGA-125-10D, Entran, USA), with which we detected the vibration perpendicular to the body surface[11)]. After being low-pass filtered and amplified with a strain amplifier (6M92, NEC San-ei Instruments, Japan), the output signal of the accelerometer was recorded on DAT by a multi-channel data recorder (PC216Ax, Sony Precision Technology, Japan).

Fifteen kinds of low frequency noise stimuli (5 frequencies × 3 sound pressure levels) were reproduced by 12 loudspeakers (TL-1801, Pioneer, Japan) installed in the wall in front of the subject. All the noise stimuli were pure tones the frequencies of which were 20, 25, 31.5, 40 and 50 Hz, and the sound pressure levels of which were 100, 105 and 110 dB (SPL). No noise stimulus in the frequency range higher than 50 Hz was used because the spatial uniformity of the sound pressure levels in the test chamber would deteriorate[10)]. Noise stimuli lower than 20 Hz were not used because the noise-induced vibration was not distinguishable from the vibration inherent in the body surface[11)].

The subject wore no clothes on the upper half of the body in order to allow the accelerometers to be attached. For the first measurement, inherent body surface vibration was recorded for 1 min with no noise stimulus. Fifteen kinds of noise stimuli were then used in random order for every subject. The duration of each exposure was 1 min, when the noise-induced vibration was recorded. Between any two recording periods, a rest period (1 min) with neither noise stimulus nor recording was assigned.

Analysis with an FFT analyzer (HP3566A, Hewlett Packard, USA) yielded the power spectrum of the vibration measured for every measuring position and every noise stimulus. A spectral component at the frequency of the noise stimulus was transformed to an acceleration level, AL, defined as[12)]

$$AL = 20\log_{10} (a_{meas}/a_{ref}).$$

Here a_{meas} is the measured acceleration (m/s^2(r.m.s.)) and a_{ref} is the reference acceleration equal to 10^{-5} m/s^2.

At all the measuring positions, the acceleration level of noise-induced vibration was found to increase with the frequency of the noise stimulus. On the other hand, the acceleration level of the inherent vibration was found to decrease as the frequency increased. It was supposed from this that the noise-induced vibration measured in the lower frequency range was more contaminated by the inherent vibration. Accordingly, the acceleration levels measured at 20 Hz were neglected in estimating the equal-acceleration level contours. The increase step in the measured acceleration levels was found to be about 5 dB, which was in good agreement with the increase step (5 dB(SPL)) in the sound pressure levels of the noise stimuli. This proper characteristic of noise-induced vibration was utilized in the following estimation.

In estimating the equal-acceleration level contours, we assumed that noise-induced vibration was a minute one-dimensional oscillation perpendicular to the body surface. Because the measured acceleration, a_{meas}, is a time-averaged one, it is generally expressed as

$$a_{meas} = \omega^2 A(\omega)/\sqrt{[(\omega_0^2 - \omega^2)^2 + (2\zeta\,\omega_0\omega)^2]}.$$

Here ω, ω_0, ζ, and $A(\omega)$ denote an angular frequency, a natural angular frequency, a damping ratio, and a frequencydependent amplitude, respectively. The angular frequency is equal to the frequency multiplied by 2π. If the denominator in the above formula is equal to 1, the vibration has no resonance. According to the definition mentioned before, the measured acceleration level (AL) is expressed as

$$\begin{aligned}\mathrm{AL} = {} & 40\log_{10}(\omega) + 20\log_{10}(A(\omega)) \\ & - 10\log_{10}[(\omega_0^2 - \omega^2)^2 + (2\zeta\,\omega_0\omega)^2] \\ & + (\text{Constant term}).\end{aligned}$$

In this expression, ω_0, $A(\omega)$, and ζ remain unknown.

It has been reported that the acoustic transfer function in the chest is at its maximum in the frequency range higher than 100 Hz[13)], which suggests that the noise-induced vibration measured on the chest has no resonance in the 25–50 Hz range. And it is known that the resonance frequencies of the internal organs, such as the stomach, are lower than 10 Hz[14)]. Accordingly, for noise-induced vibration measured on the chest and abdomen, we assumed that the effect of resonance was negligible in the 25–50 Hz range. We also assumed that the effect of $A(\omega)$ was negligible in this narrow frequency range. Consequently, with a frequency (f) instead of an angular frequency (ω) we adopted an approximate curve,

$$\mathrm{AL} = C_1\log_{10}(f) + \mathrm{SPL} + C_2,$$

for the acceleration level (AL) measured on the chest and abdomen. Here C_1 and C_2 were regression coefficients. The C_1s were not necessarily equal to 40 to compensate for neglecting the $A(\omega)$ and the resonance term. To introduce the proper characteristic of noise-induced vibration, we incorporated the sound pressure level (SPL) of the noise stimulus in the above formula.

With respect to the acceleration level measured on the forehead, the rate of increase with frequency was found to suddenly increase in the 40–50 Hz range. This feature was consistent with the resonance-like behavior found in the vibration transmissibility in the human head[15)]. Assuming that the noise-induced vibration measured on the forehead had a resonance at 50 Hz and that this resonance dominated the behavior of the vibration in the 25–50 Hz range, we adopted an approximate curve,

$$\begin{aligned}\mathrm{AL} = {} & 40\log_{10}(f) - 10\log_{10}[(50^2 - f^2)^2 + (C_3 f)^2] + \mathrm{SPL} \\ & + C_4,\end{aligned}$$

for the acceleration level, AL, measured on the forehead. Here C_3 and C_4 were regression coefficients. The sound pressure level (SPL) of the noise stimulus was also incorporated in this formula.

To reduce the effect of the inherent vibration, we utilized the proper characteristic of noise-induced vibration. The regression coefficients, C_1s, C_2s C_3 and C_4, were determined with the acceleration levels measured for the 110 dB(SPL) stimulus, and we appropriated the same coefficients for 105 and 100 dB(SPL) stimuli.

In Fig. 1, as an example, the approximate curves obtained on the left chest and on the forehead are shown with the mean measured acceleration levels. In Tables 1 and 2, the C_1s C_2s C_3, C_4 and the coefficients of determination (r^2) obtained in the above approximation are listed. Almost all of the r^2s were larger than 0.8, which showed that these approximations were valid in spite of the rough procedure. It was speculated that the smaller r^2s for the lower sound pressure levels were due to contamination by the vibration inherent in the human body.

Finally, the equal-acceleration level contours estimated at the 5 measuring positions were expressed as

$$\begin{aligned}\mathrm{SPL} &= -50\log_{10}(f) + (\mathrm{AL}_{\mathrm{chest(R)}} + 109), \\ \mathrm{SPL} &= -50\log_{10}(f) + (\mathrm{AL}_{\mathrm{chest(L)}} + 110), \\ \mathrm{SPL} &= -23\log_{10}(f) + (\mathrm{AL}_{\mathrm{abdomen(R)}} + 71), \\ \mathrm{SPL} &= -34\log_{10}(f) + (\mathrm{AL}_{\mathrm{abdomen(L)}} + 87)\end{aligned}$$

and

$$\begin{aligned}\mathrm{SPL} = {} & -40\log_{10}(f) + 10\log_{10}[(50^2 - f^2)^2 + (11f)^2] \\ & + (\mathrm{AL}_{\mathrm{forehead}} + 44),\end{aligned}$$

respectively. In these formulae, ‘R’ denotes the right half of the body and ‘L’ denotes the left. These contours are depicted in Fig. 2. In spite of the right-left differences between the regression coefficients (Table 1), two contours estimated on both sides of the body corresponded well in the 25–50 Hz range.

The gradients with frequency in the estimated equal-acceleration level contours are regarded as frequency-weighting gradients when their signs are reversed. The frequency-weighting gradients are about 15 dB/oct. on the chest, about 10 dB/oct. on the abdomen, and about 20 dB/oct. on the forehead, respectively. These gradients, except for one obtained on the abdomen, are equal to or steeper than the gradient in the existing weighting curves: about 15 dB/oct. (25–50 Hz) in the A-weighting curve, about 13.5 dB/oct. (20–50 Hz) in the LF-weighting curve[8)], and about 12 dB/oct. (1–20 Hz) in the G-weighting curve[9)]. This simple comparison seems to show that noise in the lower frequency range is more severely assessed with the LF-weighting curve and the G-weighting curve than with the equal-acceleration level contours.

Nevertheless, the equal-acceleration level contours have one important advantage: with the contours we can predict

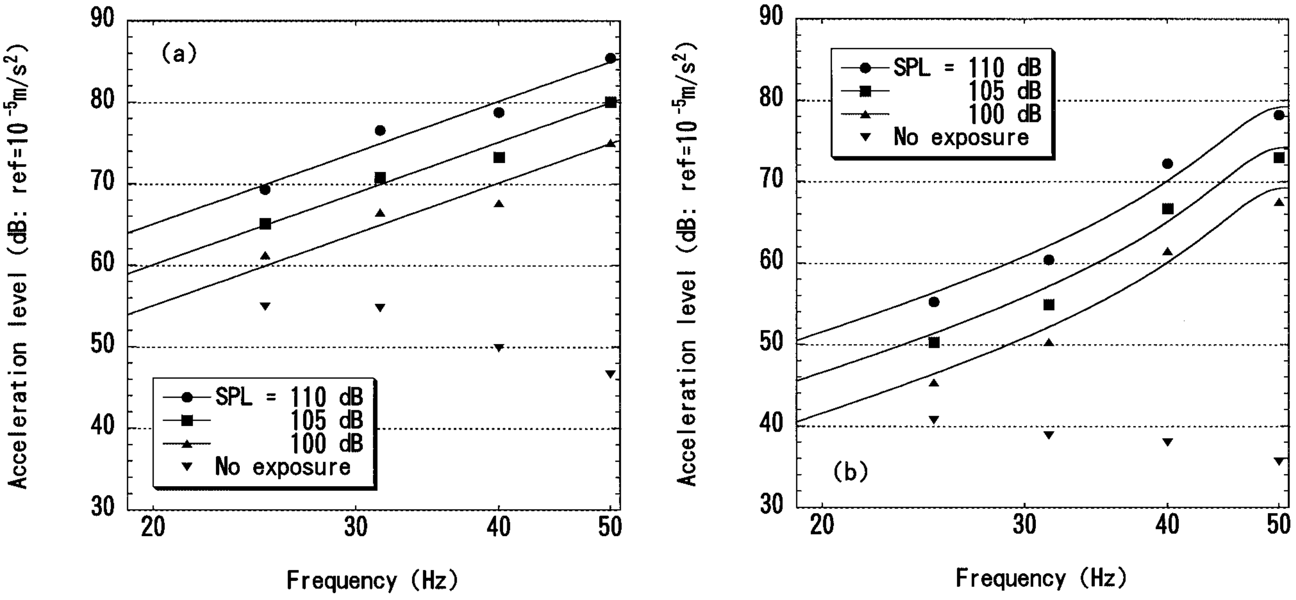

Fig. 1 The mean measured acceleration levels and the approximate curves. (a) On the left chest, and (b) on the forehead.

Table 1. The regression coefficients (C_1 and C_2) and the coefficients of determination (r^2) for the approximate curves obtained on the chest and abdomen.

Measuring positions		Sound pressure levels (dB(SPL))	C_1 (dB)	C_2 (dB)	r^2
Chest	Right	110	50	–109	0.956
		105			0.983
		100			0.952
	Left	110	50	–110	0.980
		105			0.982
		100			0.945
Abdomen	Right	110	23	–71	0.888
		105			0.868
		100			0.849
	Left	110	34	–87	0.853
		105			0.808
		100			0.772

Table 2. The regression coefficients (C_3 and C_4) and the coefficients of determination (r^2) for the approximate curves obtained on the forehead.

Measuring positions	Sound pressure levels (dB(SPL))	C_3 (dB)	C_4 (dB)	r^2
Forehead	110	11	–44	0.985
	105			0.984
	100			0.985

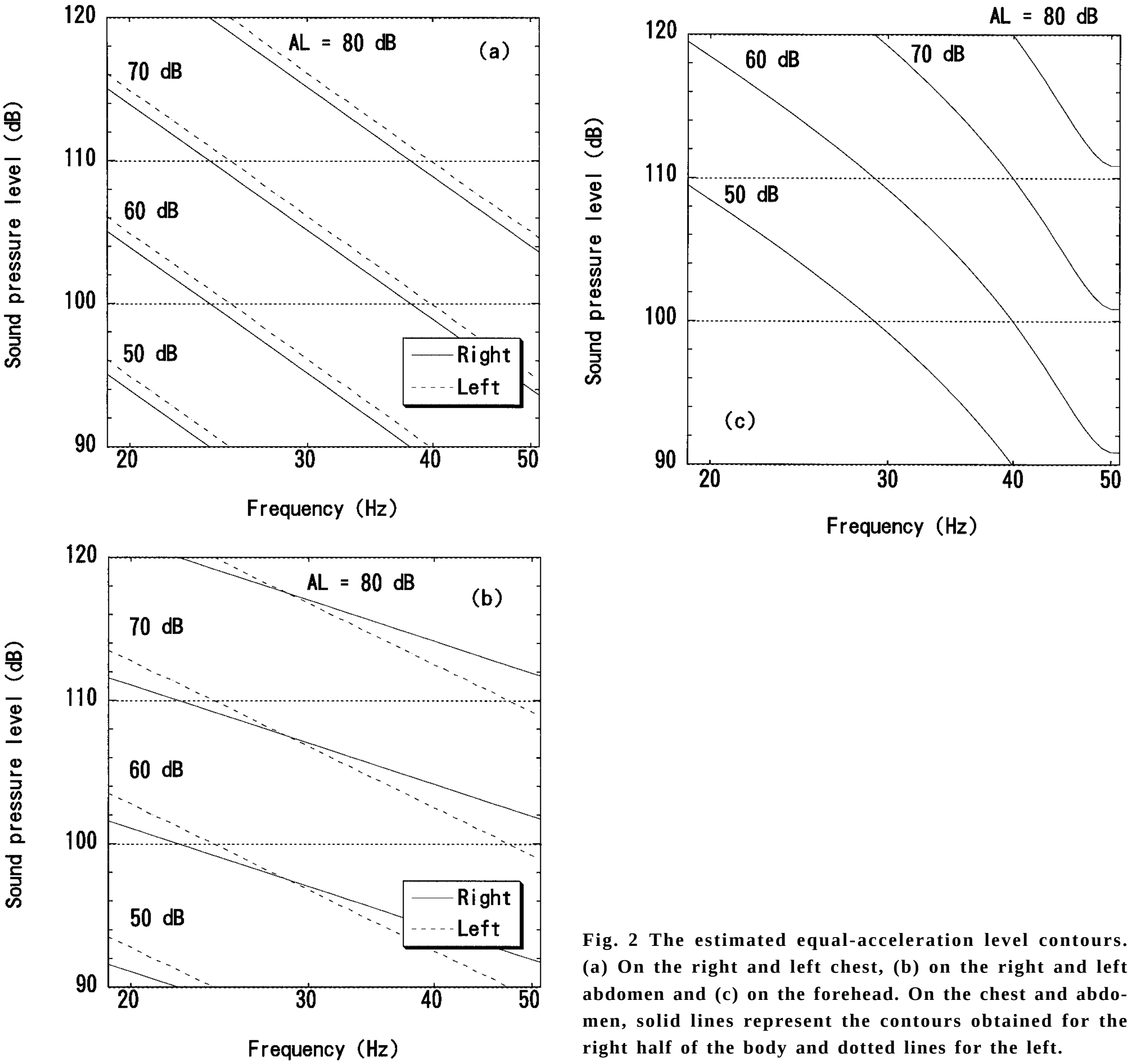

Fig. 2 The estimated equal-acceleration level contours. (a) On the right and left chest, (b) on the right and left abdomen and (c) on the forehead. On the chest and abdomen, solid lines represent the contours obtained for the right half of the body and dotted lines for the left.

the magnitude of noise-induced vibration at every measuring position on the body surface. In general, the physical effects caused by vibration are position-dependent, because robustness and susceptibility to vibration depend on the characteristics specific to each position. With respect to vibroacoustic disease, for example, many symptoms have been found in the chest[5–7)], which suggests that the chest has a higher risk of vibroacoustic disease than other parts of the human body. This is consistent with our results showing that the noise-induced vibration measured on the chest is higher than the vibration measured on other parts of the human body. The position-dependent predictability with the equal-acceleration level contours is expected to contribute to assessing high-level low frequency noise from the standpoint of predicting the position-dependent risk of adverse extra-aural effects.

Some important points in the estimated contours remain to be investigated and improved. First of all it is necessary to estimate the contours in the wider range of both frequency and the sound pressure level. With respect to frequency, it is desired for practical use that the contours are applicable in the frequency range up to 100 Hz. With respect to the applicable sound pressure level range, the lower boundary level does not need to be very low, because the extra-aural effect caused by low frequency noise is less important at lower sound pressure levels. But it is desirable for practical use that the contours be available in a range higher than about 80 dB (SPL). Secondly, it is desired to clarify the precise relationship between the vibrations induced on the body surface and in the inner body. This is essentially important for assessing adverse health effects such as vibroacoustic disease. When this relationship is clarified, we can predict the noise-induced vibration in the inner body with the equal-acceleration level contours. Finally, it is desired to establish the precise dose-response relationship between the noise-induced vibration and the degree of the extra-aural symptoms caused by low frequency noise. If this relationship is established, we can directly predict the risk of the adverse extra-aural effects such as vibroacoustic disease with the equal-acceleration level contours.

When these matters are clarified, the equal-acceleration level contours will be useful in assessing high-level low frequency noise in the working environment from the standpoint of predicting the adverse extra-aural effects. Together with the existing evaluating curves, low frequency noise will be measured and assessed from more different points of view.

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