EVALUATION METHODS FOR VIBRATION EFFECT

PART 8. THE VIBRATION GREATNESS OF RANDOM WAVES

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Perceptual threshold and equal sensation characteristics for random vibrations of 1 or 1/3-octave band were determined on the whole body in the vertical and the horizontal directions and on the hand in the vertical direction in the frequency range 2—250 Hz. Difference of sensation between the vertical and the horizontal whole body random vibrations with 1-octave band was examined and it was found out that the sensation of the vertical vibration was equalized to that of the horizontal vibration with the level of 10 dB larger than that of the vertical vibration above 16 Hz.

Then, the vibration greatness value of the random vibration having continuous wide frequency spectrum was measured by subjective experiment and compared with the value estimated from each VG value of its frequency component resulting from analysis by an 1 or 1/3 octave band filter as,

$$VG_T = VG_{M,1} + 0.3(\sum_i VG_{i,1}) - VG_{M,1} \quad (1)$$

$$VG_T = VG_{M,1/3} + 0.13(\sum_i VG_{i,1/3}) - VG_{M,1/3} \quad (2)$$

where VG_T is the vibration greatness value (in VG) of the random vibration, VG_M is the largest VG value in all of the VG_i values, and $\sum VG_i$ is the sum of the VG_i values of all bands. The suffix of 1 or 1/3 indicates the data analyzed by the 1 or 1/3 octave band filter. The estimated VG_T values of the random vibrations are in good agreement with the observed ones in both filter bands.

INTRODUCTION

Recently, the vibration problems concerning public nuisances and industrial labor environments have given rise to discussions on the measurements and assessments of the vibrations. In order to cope with this situation, psychological experiments were carried out for finding assessment methods on sinusoidal, compound sinusoidal and pulsed vibrations. Namely, psychological scales called vibration greatness level (VGL) and vibration greatness (VG) corresponding to loudness level (phon) and loudness (sone) in psychoacoustics were determined. Then, the emotional response (unpleasant or intolerable) was observed experimentally to clarify its relation to the vibration acceleration level through the parameter of exposure time. Thus, the evaluation methods for these vibrations were made up.

However, that on the random vibration has been left as the future problem.

There are a few research works¹⁾ for the evaluation on the random vibration. On the other hand, in the field of psychoacoustics, many reports²⁾ have been published on the assessment methods for the noise. Among them, the method proposed by S. S. Stevens³⁾ is considered to be convenient and easily applicable to the evaluation of the random vibrations with wide and continuous frequency spectra.

(a) Center frequency of octave band, 8 Hz

(b) Center frequencies of octave bands, 4 and 63 Hz

(c) Center frequencies of octave bands, 4, 31.5 and 63 Hz.

(d) Center frequencies of octave bands, 8, 16, 31.5 and 63 Hz

Fig. 1. Typical autocorrelograms of random signals.

a, b, c & d; for random signals of 1-octave band or combinations of band.

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In this paper, the evaluation method for the random vibrations not only of the 1 or 1/3-octave bands, but also of continuous wide spectra will be mentioned.

MEASURING METHODS

(i) *Random signal*

The random voltage from a zener diode⁴⁾ was impressed to a Flip-Flop circuit to produce the wave with random interval. The 1 or 1/3-octave band random signal was made by passing this square wave through the 1 or 1/3 octave band-pass filter (universal filter, SA 336, Rion). Moreover, in order to make the random signal with the wide band spectrum, this square wave was fed into a band pass filter with variable band width or a multichannel band-pass filter which consisted of contiguous octave bands, in which each octave band signal was combined at an arbitrary mixing ratio. These random signals were recorded in the data recorder (R-351 F; TEAC) (4 min long per each entry) and used for the subjective experiments.

The autocorrelation functions on these random sources were obtained by an autocorrelator of analogue type (CCA 32 W; Sony) and besides the instantaneous amplitude distributions were calculated from the patterns on the electro-magnetic oscillograph (EMO-121, Yokokawa). The typical results of the autocorrelation functions are shown in Fig. 1 and the amplitude distribution of each signal shows a normal distribution as expected.

(ii) *Generation of random vibration*

The next problem is to reproduce the recorded signal on the vibration table with high fidelity. The assembly composed of the electrical part of a driver coil

Fig. 2. General frequency characteristics of the acceleration of the vibration table for constant input voltage to the driver coil as a function of frequency for the electro-dynamic vibration machine without test load. The same characteristics are seen in the vertical and the horizontal vibration tables.

and the mechanical part of the vibration table generally indicates the specific frequency characteristics⁵⁾ as shown in Fig. 2.

Moreover, the effect of the load on the table should also be taken into consideration. The synthesized characteristics have to be compensated in order to generate random vibrations with wide spectra. For this purpose, an electric analogue method was used, in which differentiating and integrating amplifiers and summing and subtracting circuits were employed. The block diagram of the equalizer is shown in Fig. 3.

This equalizer (ASE 4 L 160; Akashi) is composed of four parts such as (1)

Fig. 3. Block diagram of the equalizer of analogue type.

Fig. 4. Frequency characteristics of acceleration of the vibration table in this institute; a and b; before and after equalizing under the condition loaded with and without human body.

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Low frequency equalizer which aims to reverse the characteristic of the vibration table at low frequency, (2) Peak-notch equalizer to reverse the peak or notch characteristics of the load, (3) Band-pass filter, and (4) Clipper amplifier to clip the excess input signals. The equalization can be achieved within ± 1 dB as shown in Fig. 4, in which vibration acceleration level (VAL) means $20 \log_{10} a/a_{\text{ref}}$ a; rms acceleration value (g or cm/sec²) and a_{ref} ; 10⁻³g or 1 cm/sec².

The examined acceleration spectra for the whole body and the hand vibrations which were generated on the vibration table and analyzed by the 1 or 1/3 octave band pass filter are tabulated in Table 1 and 2 respectively.

(iii) Measurement of perceptual threshold and vibration greatness for 1 or 1/3

Table 1. Frequency components of random vibration analyzed by 1-octave band pass filter.

VAL values of frequency components of 7 kinds of random vibrations with wide frequency band analyzed by the 1-octave band pass filter are shown in the case of the vertical or the horizontal whole body vibration or the vertical hand vibration. The observed VG_r values averaged on ten male subjects and their standard deviations on the 7 entries of random vibrations are also shown on the right end column.

Center freq. (Hz)		4	8	16	31.5	63	125	250	Observed average VG_r
Band (Hz)		2.8~5.6	5.6~11.2	11.2~22.4	22.4~45	45~90	90~180	180~250	
Entry	VAL								
Whole body vertical	1	30	35	36					1.20 ± 0.14
	2	26	31	34	36				1.10 ± 0.12
	3		32	35	39				1.07 ± 0.09
	4		27	31	36	38			0.98 ± 0.07
	5			32	37	38			0.91 ± 0.07
	6			28	34	37	40		0.81 ± 0.10
	7			28	33	36	39	41	0.74 ± 0.13
Whole body horizontal	1	30	34	37					1.65 ± 0.23
	2	27	32	33	36				1.52 ± 0.13
	3		32	35	36				1.34 ± 0.13
	4		27	32	33	36			1.20 ± 0.14
	5			31	34	36			1.02 ± 0.11
	6			29	32	34	36		0.88 ± 0.08
	7			27	29	32	34	37	0.80 ± 0.10
Hand vertical	1	32	36	38					1.40 ± 0.11
	2	28	33	35	37				1.30 ± 0.12
	3		33	35	37				1.30 ± 0.10
	4		29	32	34	36			1.09 ± 0.10
	5			32	35	37			1.03 ± 0.08
	6			30	32	34	37		0.86 ± 0.11
	7			28	31	32	35	36	0.80 ± 0.11

Table 2. Frequency component of random vibration analyzed by 1/3-octave band pass filter.

VAL values of frequency components of the same random vibration as in Table 1 analyzed by the third-octave band pass filter are shown. The estimated VG_T values obtained from these, Table 5 and Eq. 4, are also indicated on the right end column.

The total of three third octave band levels shows somewhat overestimated value in comparison with the octave band level. This fact may be explained by the error of reading out the fluctuated level of the random vibration on the recorded paper of the high speed level recorder, the error of equalization in the equalizer and the cut-off characteristics of the band pass filter.

Center freq (Hz)	3.15	4	5	6.3	8	10	12.5	16	20	25	31.5	40	50	63	80	100	125	160	200	250	315	Estimated VG_T
Band (Hz)	2.8~ 3.55	3.55~ 4.5	4.5~ 5.6	5.6~ 7.1	7.1~ 9.0	9.0~ 11.2	11.2~ 14	14~ 18	18~ 22.4	22.4~ 28	28~ 35.5	35.5~ 45	45~ 56	56~ 71	71~ 90	90~ 112	112~ 140	140~ 180	180~ 224	224~ 280	280~ 355	
VAL																						
Entry																						
1	26	27	27	28	32	33	33	33	33	33	34	35										1.39
2	25	25	23	25	28	30	30	30	30	33	35	36										1.33
3					28	29	30	31	32	34	35											1.06
4				20	23	24	24	26	27	30	31	33	33	34	34							0.98
5								28	28	30	32	33	33	35	35							0.86
6								27	28	28	29	31	32	33	33	34	35	36	36			0.82
7								23	24	26	28	30	31	32	32	33	35	36	36	36	37	0.85
1	24	25	27	29	30	31	32	33	32													1.63
2	22	23	24	24	28	28	29	29	29	31	32	32										1.58
3				26	28	29	30	31	31	32	32	32										1.36
4				21	23	25	25	27	27	29	29	30	30	31	31							1.10
5								26	28	29	30	30	31	32	32							0.87
6								25	25	27	27	28	29	30	30	30	31	32	32			0.86
7								22	23	25	26	25	26	28	28	28	29	32	32	33	34	0.75
1	26	29	30	31	32	33	34	35	34													1.44
2	23	23	23	26	28	29	29	31	31	33	34	35										1.32
3				26	27	28	30	31	32	34	34	35										1.17
4				23	24	25	27	28	28	30	31	32	32	33	34							1.06
5							25	27	28	31	32	33	33	34	34							0.92
6							27	28	29	27	29	31	30	32	32	32	34	34				0.89
7							23	24	24	26	28	28	28	29	29	31	32	33	33	33	33	0.81
Hand vertical																						

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octave band random vibrations

The perceptual threshold and vibration greatness for 1 or 1/3 octave band random vibrations were observed by the same method as for the sinusoidal vibration. The experiment was carried out by the method of paired comparisons, and the level of the random vibration was changed by blacketing method. The signal level was changed first lower, next higher than some assumed level. Then, the signal level gradually was made to converge zigzag to the matched level.

In the threshold measurement, the subjects were randomly given the random vibration and the rest interval with the same period (15 sec), in order to distinguish easily the random vibration from the feint vibration caused by the cardiac and respiratory motions.

In the vibration greatness measurement, the subjects compared the vibration greatness of the 1 or 1/3 octave band random vibration with that of the sinusoidal vibration having the standard frequency (20 Hz) and a certain fixed level. The level of the random vibration was changed by the tester according to the request of the subject so as to equalize its vibration greatness to that of the sinusoidal one. The presenting order was the sinusoidal vibration (15 sec) and the random vibration (15 sec). After 3 sec pause, this series was repeated until both vibrations could be matched.

(iv) Measurement of vibration greatness of random vibration with continuous and wide spectrum

The same procedure as for the compound sinusoidal vibration (in Part 5) was applied to this measurement. The subjects compared the vibration greatness of the random vibration with that of the sinusoidal vibration of 20 Hz, of which the level was changed by the tester in the blacketing method, while the level of the random vibration was maintained constant. The random vibration (15 sec), the sinusoidal one (15 sec) and the rest period (3 sec) were given to the subjects in this order.

(v) Experimental apparatus

The block diagram of the experimental apparatus is shown in Fig.5. The random signal from the data-recorder is impressed to the vibration table through the equalizer and the calibrated attenuator (0.1 dB step) and the power amplifier. The sinusoidal signal (20 Hz) is also impressed to the table through the other calibrated attenuator and the same power amplifier. Both signals are changed arbitrarily by the switch at the input of the power amplifier.

The acceleration wave form through the accelerometer set on the vibration table was watched by the cathode-ray oscilloscope.

(vi) Determination of rms value of random vibration

In vibration measurement, it is a very interesting problem which value (peak, arithmetical average or root mean square) has to be measured. To solve this

Fig. 5. Block diagram of the experimental apparatus.

matter, the effect of the phase between two different frequency sinusoidal vibrations on the human sensation was observed on three subjects by using a phase shifter as shown in Fig. 6. They did not detect the phase change even at the largest phase difference of 90° . This fact affirms that the rms indication is most suitable for the measurement of the random vibration because rms indication is not affected by the phase of the frequency component of the input signal. Therefore, the rms value has been measured in the case of the random vibration.

The rms level of the random vibration from the accelerometer was recorded on the paper of the high speed level recorder of which the rectifier response switch was set on "rms" indication (Type 2305; Brüel & Kjaer). The available frequency range of this recorder was 2–200,000 Hz. The writing speed of the pen was

Fig. 6. Phase shifter made by an integrated circuit of operational amplifier.

If R is varied, the phase of the input sine voltage above 3 Hz can be changed from 0° to 180° without changing its amplitude.

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changed to adjust the fluctuation of the recorded signal within about 3 dB as far as possible and its mean value was read out as the rms value. When the level of the random signal indicates large variance on the paper of the level recorder, especially at low frequency, the average of the rms value was obtained by a statistical distribution analyser (Type 4420; Brüel & Kjaer). The same signal was reproduced with higher speed than the original one by the data-recorder to make its frequency increase above 20 Hz and was recorded on the paper of the level recorder as the rms value. The rms values in both cases were discerned to be in good agreement with each other. It was checked in advance that the characteristics of amplitude and phase of the signals recorded in the data-recorder were not varied at the speed change in the reproduction.

(vii) *Subjects and their postures*

The experiments were carried out on 10 male subjects who were the same member as in the previous experiments. On the whole body, the horizontal (from chest to back) or the vertical vibration was impressed to the subjects on the sitting erect posture. On the hand, only the vertical vibration was tested, because the horizontal hand vibration has the same sensation as the vertical one at the same vibration acceleration level. The force pressing the vibration table was maintained constant as far as possible by the subjects who watched a strain meter of which a strain gage was applied on the curved leaf spring of the vibration table.

RESULTS AND DISCUSSIONS

(i) *Perceptual threshold*

The threshold curves for the random vibration of octave band on the whole body and the hand are shown in Fig. 7 a, b and c. The observed values can be approximated by the broken lines as drawn in these figures. The slopes of these broken lines and their intersections are tabulated in Table 3. The slopes of these curves in Table 3 have the following features defined as the physical meaning, -6 dB/octave is jerk, 0 dB/octave acceleration, +6 dB/octave velocity and +12 dB/octave displacement. The standard deviations are within ± 4 dB.

On the whole body, the threshold curves for the random vibration in both directions are superposed as shown in Fig. 8. It is found that they have almost similar inclination. It is worth noticing that the threshold of the horizontal vibration is higher by about 5 dB in maximum than that of the vertical vibration within 8—50 Hz. On the contrary, below 5 Hz, the threshold level of the vertical vibration is higher by about 4 dB in maximum than that of the horizontal one. These two curves coincide with each other above 80 Hz.

As compared with the threshold for the sinusoidal vibration (Fig. 13 in Part 1), in the horizontal direction, the threshold for the random vibration is lower by about 10 dB in maximum than that for the sinusoidal one between 16 and 125 Hz.

In the vertical direction, below 8 Hz, the threshold of the random vibration is

Fig. 7. a

Fig. 7. b

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Fig. 7. c

Fig. 7. Contours of threshold and equal sensation for the random vibration with 1-octave band; a, for the vertical whole body vibration, b, for the horizontal whole body vibration and c, for the hand vertical vibration.

The ordinate denotes the vibration acceleration level (VAL) ($VAL = 20 \log_{10} a/a_{ref}$; a , rms acceleration value (g), a_{ref} , 10^{-3} g) and the abscissa the center frequency of 1-octave band (Hz). The numbers on the curves indicate the VGL values. The middle signs of three circles with dots show the average values on ten male subjects and the others the standard deviations. The solid lines are the asymptotes which are approximated from the observed values.

Table 3. Frequency characteristics of threshold

Whole body, Vertical						
Slope of asymptote		Acceleration, Velocity, Acceleration, Velocity, Displacement				
(dB/octave)		(-3 dB)	(0)	(6 dB)	(0)	(6 dB)
Intersection (Hz)		4	9	16	45	125
Whole body, Horizontal						
Slope of asymptote		Acceleration, Velocity, Acceleration, Velocity, Displacement				
Intersection (Hz)		4 16 83 125				
Hand, Vertical						
Slope of asymptote		Velocity, Acceleration, Jerk, Velocity				
Intersection (Hz)		4.5 20 63				

higher by about 6 dB in maximum than that of the sinusoidal one. Between 20 and 70 Hz, the threshold of the random vibration is lower by about 6 dB in maximum than that. The threshold difference between the random and the sinusoidal vibration comes only from easiness or difficulty of the subjective judgment.

On the hand vibration, the distinguishable nature is the appearance of plateau at 4–20 Hz. Except this frequency range, the threshold curve is similar to that of the sinusoidal vibration (Fig. 5 in Part 3).

(ii) *Equal sensation of 1-octave band random vibration*

The results on the whole body and the hand for the random vibration of 1-octave band are also shown in Fig. 7, a, b and c. The observed values can almost

Fig. 8. Synthesized contours of threshold and equal sensation for the random vibration of 1-octave band on the whole body.

The results for the whole body vertical vibration are denoted by the solid lines and those for the horizontal one by the dotted lines. When the observed VAL value falls in the interspace between the described contours, the corresponding VGL value can be estimated by drawing the same slope curve along them. The same VGL values in either directional vibration give rise to identical sensation, though the frequency is different. However, it must be noticed that the different directional vibration (vertical or horizontal) does not cause the same sensation, even if their VGL value is the same.

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be approximated by the broken lines with different slopes which are tabulated in Table 4. The standard deviations of these observed values are within ± 5 dB.

On the whole body, the curves of the equal sensation for the vertical and the horizontal vibrations are superposed (Fig. 8). Above 15 Hz, their curves are sufficiently in good agreement with each other, but below 15 Hz they are extremely different. Moreover, for each directional vibration in Fig. 7, a and b, the two curves of the vibration greatness at different *VGL* level denote the good accordance with each other. Thus, the same curves were extrapolated in the interspace between the observed curves as shown in Fig. 8.

These equal sensation curves are compared with those for the sinusoidal vibration (Fig. 13 in Part 1). The curves for the 1-octave bands are the same above 15 Hz as those for the sine wave independent of the vibration direction, except that the intersection between the velocity and the displacement asymptotes for the random vibration moves to higher frequency (125 Hz) than that for the sinusoidal one (60 Hz). This fact means that the random vibration may be felt to be severer at high frequency. This phenomenon is explained as follows. The octave band width varies as 2^n and the bandwidth between the center frequency of the 1-octave band and its corner frequency increases with the increase of frequency. The vibration at the lowest corner frequency gives severer sensation by 3 or 6 dB than that at the center frequency, because the contours of the equal sensation show the slope 6 or 12 dB/octave in the higher frequency range.

On the contrary, the random vibration of the 1-octave band below 12 Hz is felt to be weaker about 7 dB in maximum than the sinusoidal vibration as judged from the comparison between Fig. 8 in this report and Fig. 13 (Part 1). The difficulty of the subjective judgment and the comprehension difference of the equal sensation between the random and the sinusoidal signals by the subjects may cause this difference.

Table 4. Frequency characteristics of vibration greatness

Whole body, Vertical			
Slope of asymptote	Acceleration	Velocity	Displacement
(dB/octave)	(-3 dB)	(0)	(6 dB)
Intersection (Hz)	3.5	14	125
Whole body, Horizontal			
Slope of asymptote	Acceleration	Velocity	Displacement
Intersection (Hz)		5	125
Hand, Vertical			
Slope of asymptote	Acceleration	Velocity	
Intersection (Hz)		15	

For the hand vibration, the observed curves are rather simple as compared with those for the sinusoidal vibration, because the asymptote with the displacement slope at high frequencies disappears. However, the similar phenomena for the severity and weakness to the random vibration in comparison with the equal sensation curve for sine waves at higher or lower frequencies are also observed in this case. Since a good similarity of two contours at the different vibration level in Fig. 7, c is held, the same curves with equal level interval are extrapolated in the interspace as shown in Fig. 9.

In order to prove these severity and weakness induced above, the random vibration of 1-octave band was compared with the sinusoidal vibration at the center frequency of each 1-octave band. The same *VGL* value as shown with the solid line in Fig. 10 was adopted as the reference level of the sinusoidal vibration. The *VGL* value was already determined in Fig. 13 (Part 1) or in Fig. 5 (Part 3). The frequencies of the sine waves were changed from 2 to 250 Hz. This experiment was carried out by the same method described before on 10 male subjects.

Fig. 9. Synthesized contours of threshold and equal sensation for the random vibrations of 1-octave band on the hand.

For the hand vibration, it was found that the horizontal and the vertical vibrations at the same *VGL* value gave the identical sensation as described in Part 3. Therefore, these curves can be used to the evaluation for both vibrations.

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The results are shown in Fig. 10, a, b and c.

The most remarkable fact found is that in these three graphs the observed values in 16—63 Hz and in 125—250 Hz are lower by about 1 dB and 3 dB than the *VGL* curve for the sinusoidal vibration respectively. Therefore, the fact concerned with the severity of the random vibration in comparison with the sine wave above 16 Hz is endorsed obviously.

Fig. 10. a

Fig. 10. b

Fig. 10. c

Fig. 10. Vibration greatness obtained by comparing the random vibration of 1-octave band with the sinusoidal one at the center frequency of each octave band. a, for the whole body vertical vibration, b, for the whole body horizontal vibration and c, for the hand vertical vibration.

The standard level of the sinusoidal vibration at each center frequency was chosen as the same *VGL* value of 35 or 45 as shown with solid lines in these figures. The equal *VGL* curve for the sinusoidal vibration was already determined in Fig. 13 (Part 1) and in Fig. 5 (Part 3) on the whole body or on the hand respectively. The middle signs of three circles with dots are the average values observed on ten male subjects and the others the standard deviations.

While, below 8 Hz, the observed value is somewhat higher about 3 dB than the level of the sinusoidal vibration except on the horizontal vibration. Although the weakness of the random vibration of about 7 dB in maximum mentioned above cannot be found out, the tendency of the weakness is proved.

The random vibration in 16–63 Hz is severer by 1 dB than the sinusoidal one, but this difference is so small as compared with the standard deviations in Fig. 7, a, b and c that this difference of 1 dB was neglected drawing the asymptotes of equal sensation curves in Fig. 7.

(iii) *Equal sensation of third octave band random vibration*

The following experiment was carried out, to answer the question how the band width of the random vibration affects the equal sensation. The random vibration with third octave band was compared with the sinusoidal vibration of 20 Hz. The standard level of the sinusoidal vibration was adopted at 30 VAL for the vertical whole body vibration and at 40 VAL for the horizontal whole body vibration and the hand vertical one. The measured center frequencies of 1/3-

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octave bands are 2, 4, 8, 16, 31.5, 63, 125 and 250 Hz.

The result is shown in Fig. 11. The solid lines are the equal sensation contours for the 1-octave random vibration shown in Fig. 8. and 9. The observed values are denoted with three circles with dots connected by the straight line which correspond to the average and the standard deviations on ten male subjects. The clear difference cannot be found out between the observed values and those of the solid line. Namely, the solid lines can commonly be used as the equal sensation curves in both cases of the random vibration with 1 or 1/3-octave band.

The equal sensation level for the third octave band vibration ought to be higher than that of the one octave band vibration, because the level of the latter vibration is physically larger by about 5 dB than that of the former. However, the present procedure of comparison between the sinusoidal (20 Hz) and the random vibration could not detect obviously the level difference between the one and the third octave band vibrations on the obtained equal sensation curves.

(iv) *VGL value for random vibration with wide frequency band*

In the author's reports in Part 5, the compound sinusoidal vibrations were treated by the same idea introduced by S. S. Stevens⁹⁾. It was found in part 5, that the inhibition effect of the two frequency components decreased with the increase of band interval and the value of $F=0.3$ for the compound sinusoidal vibration held good below the vibration level of 55 *VGL*.

$$F = (VG_T - VG_M) / ((\sum_i VG_i) - VG_M) \quad (1)$$

where VG_T ; observed *VG* value of the compound sinusoidal vibration, VG_i ; *VG* value of its frequency components and VG_M ; maximum *VG* value among them. This result may hold in the random vibrations. To affirm this assumption, the *F* value was measured on the random vibration with wide frequency band.

On 7 entries in Table 1, the observed *VGL* values of the random vibration obtained by the comparison with the sinusoidal vibration of 20 Hz are converted to the *VG* values by the calculation table (Table 5, d) which is made by Eq. 4 in Part 4. This observed *VG* value is called the observed VG_T . The results are tabulated in table 1 on the right column, in which the average and standard deviation on ten male subjects are indicated.

On the other hand, the random vibration is analyzed by the 1-octave band filter to obtain the *VAL* value of each frequency component and the *VAL* value is also transformed to the *VG* value by the calculation table (Table 5, a, b and c) which is made by Figs. 8 and 9 in this report and Eq. 4 in Part 4, which is named VG_i . The *F* value can be calculated by these VG_T and VG_i . These *F* values about three kinds of vibrations (whole body and hand) on ten male subjects are shown in Fig. 12. In this figure, the *F* values may be said to be nearly 0.3 on the horizontal whole body and the hand vibration except one over-estimation of the entry 5 on the horizontal whole body vibration. While, on the vertical whole body vibration, the observed *F* values are rather less than 0.3 in all the entries. Besides, when the frequency components below 5.6 Hz exist in the random vibra-

Fig. 11. a

Fig. 11. b

Fig. 11. c

Fig. 11. Equal sensation curve obtained by the comparison between the random vibration of the third-octave band and the sinusoidal vibration of 20 Hz. a; for the whole body vertical vibration, b; for the whole body horizontal vibration and c, for the hand vertical vibration.

On three circles with dots connected by the straight perpendicular line, their center shows the average value and their outsides the standard deviation observed on ten male subjects. The abscissa indicates the center frequency of the random vibration with the third octave band and the ordinate vibration acceleration value (VAL , dB).

tion, the F value is also less than 0.3 in all kinds of vibrations (entry 1 and 2). However, from consideration of an approximation, $F=0.3$ is reasonable value to the whole body vertical, the horizontal and the hand vibrations for the data of the random vibration analyzed by the 1-octave band filter.

(v) Analysis by third octave band pass filter

As we adopted the F value as 0.3, the F value for data obtained by the third octave band filter is fixed as 0.13 as explained by S. S. Stevens. Namely, when three of random vibration of 1/3-octave bands in the contiguous frequency range with the equal VG value ($VG_{1/3}$) are combined and total VG value of them (1-octave band) is assumed to be 1, the Eq. 2 is formulated from the definition of F .

$$1 = VG_{1/3} + 2F_{1/3}VG_{1/3} \quad (2)$$

Then, if six of the contiguous frequency components of 1/3-octave band ($VG_{1/3}$)

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Table 5. Relation between VAL and VG values.

The calculation tables are made using Figs. 8 and 9 in this report and Eq. 4 in Part 4. First of all, the VGL value is changed to the VG one by Eq. 4 in Part 4 as tabulated in Table 5, d. Then, the VAL value of the random vibration of 1-octave band is changed to the VGL value at its center frequency in Figs. 8 and 9, and this VGL value is changed to the VG value by Table 5, d as shown in Table 5, a, b, and c. If these calculation tables for the 1-octave band analysis are used to the data from the 1/3 octave band analysis, the correcting value (dB) described in the last row must be added to the VAL value of each 1/3-octave band. These correcting values are also determined by Figs. 8 and 9. The numbers in small letter in the VG values on the same upper right corners mean the VGL value at the center frequency of 1-octave band corresponding to the VAL.

Table 5, a. Calculation table for whole body vertical vibration of random signals

Center Freq. (Hz)	2	4 ; 8	16	31.5	63	125	250
VAL	VG	VG	VG	VG	VG	VG	VG
0							
1							
2		0.09					
3		0.10	0.09				
4	0.09	0.11	0.10				
5	0.10	0.11	0.11				
6	0.11	0.12	0.11				
7	0.11	0.13	0.12				
8	0.12	0.14	0.13				
9	0.13	0.15	0.14	0.09			
10	0.14 ¹¹	0.16 ¹³	0.15 ¹²	0.10			
1	0.15	0.17	0.16	0.11			
2	0.16	0.18	0.17	0.11			
3	0.17	0.20	0.18	0.12			
4	0.18	0.21	0.20	0.13			
15	0.20	0.23	0.21	0.14	0.09		
6	0.21	0.24	0.23	0.15	0.10		
7	0.23	0.25	0.24	0.16	0.11		
8	0.24	0.27	0.25	0.17	0.11		
9	0.25	0.29	0.27	0.18	0.12		
20	0.27 ²¹	0.31 ²³	0.29 ²²	0.20 ¹⁶	0.13 ¹⁰		
1	0.29	0.33	0.31	0.21	0.14	0.09	
2	0.31	0.35	0.33	0.23	0.15	0.10	
3	0.33	0.38	0.35	0.24	0.16	0.11	
4	0.35	0.41	0.38	0.25	0.17	0.11	
25	0.38	0.44	0.41	0.27	0.18	0.12	
6	0.41	0.47	0.44	0.29	0.20	0.13	
7	0.44	0.50	0.47	0.31	0.21	0.14	
8	0.47	0.54	0.50	0.33	0.23	0.15	
9	0.50	0.58	0.54	0.35	0.24	0.16	
30	0.54 ³¹	0.62 ³³	0.58 ³²	0.38 ²⁶	0.25 ²⁰	0.17 ¹⁴	
1	0.58	0.66	0.62	0.41	0.27	0.18	
2	0.62	0.71	0.66	0.44	0.29	0.20	
3	0.66	0.76	0.71	0.47	0.31	0.21	0.09
4	0.71	0.81	0.76	0.50	0.33	0.23	0.11
35	0.76	0.87	0.81	0.54	0.35	0.24	0.11
6	0.81	0.93	0.87	0.58	0.38	0.25	0.11
7	0.87	1.00	0.93	0.62	0.41	0.27	0.12
8	0.93	1.05	1.00	0.66	0.44	0.29	0.13
9	1.00	1.12	1.05	0.71	0.47	0.31	0.14
40	1.05 ⁴¹	1.17 ⁴³	1.12 ⁴²	0.76 ³⁶	0.50 ³⁰	0.33 ²⁴	0.15 ¹²
1	1.12	1.23	1.17	0.81	0.54	0.35	0.16
2	1.17	1.30	1.23	0.87	0.58	0.38	0.17
3	1.23	1.37	1.30	0.93	0.62	0.41	0.18
4	1.30	1.45	1.37	1.00	0.66	0.44	0.20

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Center Freq. (Hz)	2		4 ; 8		16		31.5		63		125		250						
VAL	VG		VG		VG		VG		VG		VG		VG						
45	1.37		1.51		1.45		1.05		0.71		0.47		0.21						
6	1.45		1.62		1.51		1.12		0.76		0.50		0.23						
7	1.51		1.70		1.62		1.17		0.81		0.54		0.24						
8	1.62		1.74		1.70		1.23		0.87		0.58		0.25						
9	1.70		1.78		1.74		1.30		0.93		0.62		0.27						
50	1.74 ⁵¹		2.00 ⁵³		1.78 ⁵²		1.37 ⁴⁶		1.00 ⁴⁰		0.66 ³⁴		0.29 ²²						
1	1.78		2.10		2.00		1.45		1.05		0.71		0.31						
2	2.00		2.20		2.10		1.51		1.12		0.76		0.33						
3	2.10		2.35		2.20		1.62		1.17		0.81		0.35						
4	2.20		2.45		2.35		1.70		1.23		0.87		0.38						
55	2.35		2.57		2.45		1.74		1.30		0.93		0.41						
6	2.45		2.70		2.57		1.78		1.37		1.00		0.44						
7	2.57		2.88		2.70		2.00		1.45		1.05		0.47						
8	2.70		3.05		2.88		2.10		1.51		1.12		0.50						
9	2.88		3.23		3.05		2.20		1.62		1.17		0.54						
60	3.05 ⁶¹		3.40 ⁶³		3.23 ⁶²		2.35 ⁵⁶		1.70 ⁵⁰		1.23 ⁴⁴		0.58 ³²						
1	3.23		3.58		3.40		2.45		1.74		1.30		0.62						
2	3.40		3.75		3.58		2.57		1.78		1.37		0.66						
3	3.58		3.94		3.75		2.70		2.00		1.45		0.71						
4	3.75		4.17		3.94		2.88		2.10		1.51		0.76						
5	3.94		4.40		4.17		3.05		2.20		1.62		0.81						
Center Freq. (Hz)	2	2.5	3.15, 4, 5, 6.3, 8, 10.0		12.5	16	20	25	31.5	40	50	63	80	100	125	160	200	250	315
Correc tion Values (dB)	0	+1	0		+1	0	-2	+2	0	-2	+2	0	-2	+2	0	-4	+4	0	-4

Table 5, b. Caluculation table for whole body horizontal vibration of random signals

Center Freq. (Hz)	2; 4	8	16	31.5	63	125	250
VAL	VG	VG	VG	VG	VG	VG	VG
0	0.15 ¹²	0.11					
1	0.16	0.12					
2	0.17	0.13					
3	0.18	0.14	0.09				
4	0.20	0.15	0.10				
5	0.21	0.16	0.11				
6	0.23	0.17	0.11				
7	0.24	0.18	0.12				
8	0.25	0.20	0.13				
9	0.27	0.21	0.14	0.09			
10	0.29 ²²	0.23 ¹⁸	0.15	0.10			
1	0.31	0.24	0.16	0.11			
2	0.33	0.25	0.17	0.11			
3	0.35	0.27	0.18	0.12			
4	0.38	0.29	0.20	0.13			
15	0.41	0.31	0.21	0.14	0.09		
6	0.44	0.33	0.23	0.15	0.10		
7	0.47	0.35	0.24	0.16	0.11		
8	0.50	0.38	0.25	0.17	0.11		
9	0.54	0.41	0.27	0.18	0.12		
20	0.58 ³²	0.44 ²⁸	0.29 ²²	0.20	0.13		
1	0.62	0.47	0.31	0.21	0.14	0.09	
2	0.66	0.50	0.33	0.23	0.15	0.10	
3	0.71	0.54	0.35	0.24	0.16	0.11	
4	0.76	0.58	0.38	0.25	0.17	0.11	
25	0.81	0.62	0.41	0.27	0.18	0.12	
6	0.87	0.66	0.44	0.29	0.20	0.13	
7	0.93	0.71	0.47	0.31	0.21	0.14	
8	1.00	0.76	0.50	0.33	0.23	0.15	
9	1.05	0.81	0.54	0.35	0.24	0.16	

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Center Freq. (Hz)	2; 4				8				16				31.5				63				125				250			
VAL	VG				VG				VG				VG				VG				VG				VG			
30	1.12 ⁴²				0.87 ³⁸				0.58 ³²				0.38 ²⁶				0.25 ²⁰				0.17 ¹⁴							
1	1.17				0.93				0.62				0.41				0.27				0.18							
2	1.23				1.00				0.66				0.44				0.29				0.20							
3	1.30				1.05				0.71				0.47				0.31				0.21				0.09			
4	1.37				1.12				0.76				0.50				0.33				0.23				0.10			
35	1.45				1.17				0.81				0.54				0.35				0.24				0.11			
6	1.51				1.23				0.87				0.58				0.38				0.25				0.11			
7	1.62				1.30				0.93				0.62				0.41				0.27				0.12			
8	1.70				1.37				1.00				0.66				0.44				0.29				0.13			
9	1.74				1.45				1.05				0.71				0.47				0.31				0.14			
40	1.78 ⁵²				1.51 ⁴⁸				1.12 ⁴²				0.76 ³⁶				0.50 ³⁰				0.33 ²⁴				0.15 ¹²			
1	2.00				1.62				1.17				0.81				0.54				0.35				0.16			
2	2.10				1.70				1.23				0.87				0.58				0.38				0.17			
3	2.20				1.74				1.30				0.93				0.62				0.41				0.18			
4	2.35				1.78				1.37				1.00				0.66				0.44				0.20			
45	2.45				2.00				1.45				1.05				0.71				0.47				0.21			
6	2.57				2.10				1.51				1.12				0.76				0.50				0.23			
7	2.70				2.20				1.62				1.17				0.81				0.54				0.24			
8	2.88				2.35				1.70				1.23				0.87				0.58				0.25			
9	3.05				2.45				1.74				1.30				0.93				0.62				0.27			
50	3.23 ⁶²				2.57 ⁵⁸				1.78 ⁵²				1.37 ⁴⁶				1.00 ⁴⁰				0.66 ³⁴				0.29 ²²			
1	3.40				2.70				2.00				1.45				1.05				0.71				0.31			
2	3.58				2.88				2.10				1.51				1.12				0.76				0.33			
3	3.75				3.05				2.20				1.62				1.17				0.81				0.35			
4	3.94				3.23				2.35				1.70				1.23				0.87				0.38			
55	4.17				3.40				2.45				1.74				1.30				0.93				0.41			
6	4.40				3.58				2.57				1.78				1.37				1.00				0.44			
7	4.59				3.75				2.70				2.00				1.45				1.05				0.47			
8	4.90				3.94				2.88				2.10				1.51				1.12				0.50			
9	5.14				4.17				3.05				2.20				1.62				1.17				0.54			
60	5.43 ⁷²				4.40 ⁶⁸				3.23 ⁶²				2.35 ⁵⁶				1.70 ⁵⁰				1.23 ⁴⁴				0.58 ³²			
1	5.73				4.59				3.40				2.45				1.74				1.30				0.62			
2	6.03				4.90				3.58				2.57				1.78				1.37				0.66			
3	6.37				5.14				3.75				2.70				2.00				1.45				0.71			
4	6.72				5.43				3.94				2.88				2.10				1.51				0.76			
5	7.08				5.73				4.17				3.05				2.20				1.62				0.81			
Center Freq. (Hz)	2.0, 2.5		3.15, 4		5	6.3	8	10	12.5	16	20	25	31.5	40	50	63	80	100	125	160	200	250	315					
Correc- tion Value (dB)	0		-1		+2	0	-2	+2	0	-2	+2	0	-2	+2	0	-2	+2	0	-4	+4	0	-4						

Table 5, c. Calculation table for hand vibration of random signals.

Center Freq. (Hz)	2; 4; 8,	16	31.5	63	125	250
VAL	VG	VG	VG	VG	VG	VG
10	0.16	0.15	0.10			
1	0.17	0.16	0.11			
2	0.18	0.17	0.11			
3	0.20	0.18	0.12			
4	0.21	0.20	0.13			
15	0.23	0.21	0.14	0.09		
6	0.24	0.23	0.15	0.10		
7	0.25	0.24	0.16	0.11		
8	0.27	0.25	0.17	0.11		
9	0.29	0.27	0.18	0.12		
20	0.31	0.29	0.20	0.13		
1	0.33	0.31	0.21	0.14	0.09	
2	0.35	0.33	0.23	0.15	0.10	
3	0.38	0.35	0.24	0.16	0.11	
4	0.41	0.38	0.25	0.17	0.11	

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Center Freq. (Hz)	2; 4; 8,	16			31.5			63			125			250			
VAL	VG	VG			VG			VG			VG			VG			
25	0.44	0.41			0.27			0.18			0.12			0.09 0.10 0.11			
6	0.47	0.44			0.29			0.20			0.13						
7	0.50	0.47			0.31			0.21			0.14						
8	0.54	0.50			0.33			0.23			0.15						
9	0.58	0.54			0.35			0.24			0.16						
30	0.62 ³³	0.58 ³²			0.38 ²⁶			0.25 ²⁰			0.17 ¹⁴			0.11 ⁸			
1	0.66	0.62			0.41			0.27			0.18			0.12			
2	0.71	0.66			0.44			0.29			0.20			0.13			
3	0.76	0.71			0.47			0.31			0.21			0.14			
4	0.81	0.76			0.50			0.33			0.23			0.15			
35	0.87	0.81			0.54			0.35			0.24			0.16			
6	0.93	0.87			0.58			0.38			0.25			0.17			
7	1.00	0.93			0.62			0.41			0.27			0.18			
8	1.05	1.00			0.66			0.44			0.29			0.20			
9	1.12	1.05			0.71			0.47			0.31			0.21			
40	1.17 ⁴³	1.12 ⁴²			0.76 ³⁶			0.50 ³⁰			0.33 ²⁴			0.23 ¹⁸			
1	1.23	1.17			0.81			0.54			0.35			0.24			
2	1.30	1.23			0.87			0.58			0.38			0.25			
3	1.37	1.30			0.93			0.62			0.41			0.27			
4	1.45	1.37			1.00			0.66			0.44			0.29			
45	1.51	1.45			1.05			0.71			0.47			0.31			
6	1.62	1.51			1.12			0.76			0.50			0.33			
7	1.70	1.62			1.17			0.81			0.54			0.35			
8	1.74	1.70			1.23			0.87			0.58			0.38			
9	1.78	1.74			1.30			0.93			0.62			0.41			
50	2.00 ⁵³	1.78 ⁵²			1.37 ⁴⁶			1.00 ⁴⁰			0.66 ³⁴			0.44 ²⁸			
1	2.10	2.00			1.45			1.05			0.71			0.47			
2	2.20	2.10			1.51			1.12			0.76			0.50			
3	2.35	2.20			1.62			1.17			0.81			0.54			
4	2.45	2.35			1.70			1.23			0.87			0.58			
55	2.57	2.45			1.74			1.30			0.93			0.62			
6	2.70	2.57			1.78			1.37			1.00			0.66			
7	2.88	2.70			2.00			1.45			1.05			0.71			
8	3.05	2.88			2.10			1.51			1.12			0.76			
9	3.23	3.05			2.20			1.62			1.17			0.81			
60	3.40 ⁶³	3.23 ⁶²			2.35 ⁵⁶			1.70 ⁵⁰			1.23 ⁴⁴			0.87 ³⁸			
1	3.58	3.40			2.45			1.74			1.30			0.93			
2	3.75	3.58			2.57			1.78			1.37			1.00			
3	3.94	3.75			2.70			2.00			1.45			1.05			
4	4.17	3.94			2.88			2.10			1.51			1.12			
65	4.40	4.17			3.05			2.20			1.62			1.17			
6	4.59	4.40			3.23			2.35			1.70			1.23			
7	3.90	4.59			3.40			2.45			1.74			1.30			
8	5.14	4.90			3.58			2.57			1.78			1.37			
9	5.43	5.14			3.75			2.70			2.00			1.45			
70	5.73 ⁷³	5.43 ⁷²			3.94 ⁶⁶			2.88 ⁶⁰			2.10 ⁵⁴			1.51 ⁴⁸			
1	6.03	5.73			4.17			3.05			2.20			1.62			
2	6.37	6.03			4.40			3.23			2.35			1.70			
3	6.72	6.37			4.59			3.40			2.45			1.74			
4	7.08	6.72			4.90			3.58			2.57			1.78			
75	7.46	7.08			5.14			3.75			2.70			2.00			
Center Freq. (Hz)	2.0, 2.5, 3.15, 4.0, 5.0, 6.3, 8, 10		12.5	16	20	25	31.5	40	50	63	80	100	125	160	200	250	315
Correc- tion Value (dB)	0		+1	0	-2	+2	0	-2	+2	0	-2	+2	0	-2	+2	0	-2

Table 5, d. Calculation table for conversion between *VGL* and *VG* values.

<i>VGL</i>	<i>VG</i>	<i>VGL</i>	<i>VG</i>	<i>VGL</i>	<i>VG</i>
5	0.09	35	0.71	65	3.75
6	0.10	6	0.76	6	3.94
7	0.11	7	0.81	7	4.17
8	0.11	8	0.87	8	4.40
9	0.12	9	0.93	9	4.59
10	0.13	40	1.00	70	4.90
1	0.14	1	1.05	1	5.14
2	0.15	2	1.12	2	5.43
3	0.16	3	1.17	3	5.73
4	0.17	4	1.23	4	6.03
15	0.18	45	1.30	75	6.37
6	0.20	6	1.37	6	6.72
7	0.21	7	1.45	7	7.08
8	0.23	8	1.51	8	7.46
9	0.24	9	1.62	9	7.87
20	0.25	50	1.70	80	8.32
1	0.27	1	1.74		
2	0.29	2	1.78		
3	0.31	3	2.00		
4	0.33	4	2.10		
25	0.35	55	2.20		
6	0.38	6	2.35		
7	0.41	7	2.45		
8	0.44	8	2.57		
9	0.47	9	2.70		
30	0.50	60	2.88		
1	0.54	1	3.05		
2	0.58	2	3.23		
3	0.62	3	3.40		
4	0.66	4	3.58

Fig. 12. *F* values on the random vibration with continuous wide frequency band.

The abscissa shows numbers of the entry in Table 1 and the ordinate the *F* value. The middles of three signs indicate the average values of *F* on ten male subjects and the others the standard deviations.

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are combined to give 2-octave band. The total octave band can be calculated as

$$1.3 = VG_{1/3} + 5F_{1/3}VG_{1/3} \quad (3)$$

where 1.3 comes from the combination of two of the 1-octave bands ($1VG$) concerning the definition of F ($VG_T \doteq 1 + 0.3(2-1) = 1.3$). Eliminating $VG_{1/3}$ from Eqs. 2 and 3, F becomes $0.125 \doteq 0.13$.

Thus, the following equation ought to hold good for the analyzed data by the third octave band pass filter.

$$VG_T = VG_{M,1/3} + 0.13 \left(\sum_i VG_{i,1/3} \right) - VG_{M,1/3} \quad (4)$$

The definitions of $VG_{T,1/3}$, $VG_{M,1/3}$ and $VG_{i,1/3}$ are the same as in Eq. 1, except these values are obtained by the third octave band pass filter. The VG_T values of 7 entries which are described in Table 2 on the right end column are calculated from the VAL values of frequency components of each entry by using Eq. 4. The 7 entries in Table 2 are the same sources as in Table 1.

These estimated values are compared with the observed average values in Table 1 on the right end column. The both values considerably agree with each other and the maximum deviation from the observed value is about ± 3 dB in their VGL values. Therefore, Eq. 4 holds good for the data of the random vibration analyzed by the third octave band filter.

(vi) Comparison of sensation between vertical and horizontal whole body random vibration with 1-octave band

In Fig. 8, the curves for the vertical and the horizontal random vibrations coincide perfectly above 15 Hz. However, this perfect concord between in both directions does not mean that the both vibrations at the same VGL level are felt equally, because, as these curves for both vibrations are only superposed on the graph for the comparison, this graph does not indicate their mutual relation.

The subject compared the vertical whole body random vibration with the horizontal one to determine the mutual relation. The subject first sat the vertical vibration table of the dynamic type and the random vibration with 1-octave band was impressed 15 sec to him and each vibration was repeated two times with interval of 5 sec. He was asked to memorize the sensation of this vibration and then to sit on the horizontal vibration table of the dynamic type. The impressing procedure of the horizontal random vibration was the same as described above. He compared the sensation of the both vibrations. The tester adjusted the level of the horizontal vibration to equalize the subject's sensation into the vertical one in accordance with his requests. The hydraulic vertical vibration table was used in the measurement at 3.15 Hz and the 7 center frequencies of each 1-octave band were examined from 3.5 to 125 Hz.

The figures of these vibration tables were already shown in Part 1 and Part 2. The hydraulic vibration table was devised for purpose of physiological experiments 6 years ago.

The result is indicated in Fig. 13. The ordinate denotes the difference of

vertical vibration acceleration level (VAL_v) as the standard from the horizontal level (VAL_H) judged as the equal sensation and the abscissa the center frequencies of the random vibration of 1-octave band. The difference of +dB of ($VAL_H - VAL_v$) means that the sensation of the vertical vibration is severer than that of the horizontal one. It is found that above 16 Hz this difference is about 10 dB, but below 16 Hz this decreases with the decrease of the frequency. This tendency agrees with the equal sensation contours on both directional vibrations in Fig. 8. That is to say, the contour for the vertical vibration at 20 *VGL* ought to agree with that for the horizontal vibration at 30 *VGL*. The level difference of both contours is 10 dB above 15 Hz, but, below 15 Hz, this difference decreases with the decrease of frequency.

The same fact was already explained in the case of the equal sensation contours of both directional sinusoidal vibrations in Fig. 13 (Part 1). The experiment concerning this fact was carried out above 5 Hz in Part 2, but this thought has been left only an assumption below 5 Hz. Therefore, the experiment to prove this point was made in the overlapped frequency range of 8, 6.3 and 3.15 Hz and the data are also shown in Fig. 13 with the black circles. This result affirms the propriety of the assumption below 5 Hz.

APPLICATION

When the random vibration with wide band spectrum is observed by the accelerometer and analysed by the 1 or 1/3 octave band filter, the vibration acceleration level (VAL) of each band can be obtained. The VAL value of each

Fig. 13. Comparison of sensation between the vertical and the horizontal random vibrations with the 1-octave band.

In this figure, the result on the sinusoidal vibration sensation obtained by the comparison between the vertical and the horizontal vibrations is also shown.

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component is turned into the VG value by the calculation table (Table 5, a, b, and c) for the whole body vertical or the horizontal vibration or the hand vibration respectively. The VG_T value can be calculated by the following equations in association with the analyzed band width,

$$VG_T = VG_{M,1} + 0.3(\sum_i VG_{i,1}) - VG_{M,1}$$

$$VG_T = VG_{M,1/3} + 0.13(\sum_i VG_{i,1/3}) - VG_{M,1/3}$$

The VG_T value is again changed to the VGL value by the calculation table (Table 5, d). The emotional response (unpleasant or intolerable) caused by this random vibration can be estimated with this VGL value by Table 1 for short exposure or by Table 3 for long exposure in Part 6.

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