PROBLEMS CONCERNING MOUNTING OF PICKUPS FOR VIBRATION LEVEL METER

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A vibration level meter with weighting network corresponding to human vibration sensation has recently been planned by the Acoustic Society of Japan to assess vibration pollution. However, weight, size and position of a sensing element of a vibration pickup of the vibration level meter have not been standardized. To determine optimum values for them, the contact resonance was examined on combinations of eleven mounting materials and seven vibration pickups on a vibration table of electrodynamic type in vertical and horizontal directions.

It was found that the vibration pickup which had weight of 300 g was desirable for vertical and horizontal vibrations under almost all mounting conditions except in the case of some special materials. The contact resonance frequency between the pickup and the mounting material was able to be elevated to a considerably high frequency for vertical vibration, but for horizontal vibration it was lowered until near half the value in vertical vibration. Therefore, vibration occurring in human environment is desirable to be measured by a VL range of the vibration level meter, in which the weighting circuit of the amplifier has the same frequency characteristics as those of human vibration sensation below 90 Hz and above it the cut-off frequency nature is -18 dB/oct. Vibration pickup of the vibration level meter was able to be calibrated without bolting on the vibration table below 90 dB (0 dB = 10^{-3} cm/sec²).

Residents who live near construction work sites, highways, railways and factories frequently complain of vibration pollution. In such cases, it is needed to measure a certain vibration value corresponding to grades of human vibration sensation, not a pure physical value such as displacement, velocity or acceleration. Specification of an apparatus for measurement of this vibration value called "Vibration Level Meter"¹⁾ has been proposed by Subcommittee for Vibration Measurement in the Acoustic Society of Japan (Chairman, Dr. J. Igarashi, Professor of the University of Tokyo), in which a network corresponding to the human vibration sensation proposed by International Organization for Standardization (ISO/TC 108/WG 7)²⁾ has been prepared for weighting input voltages of the vibration acceleration pickup defined as a VL range. In this specification, however, weighting circuit for the horizontal vibration was decided to be the same as the vertical vibration sensation for convenience. On the vibration pickup, size, weight and the setting position of a sensing element have not yet been standardized, because of

lack of the basic data for mounting conditions. The vibration level meters commercially available now in Japan have not been unified in these points. Therefore, result of vibration measurement may considerably be influenced by characteristics of the mounting conditions of vibration pickups.

Eleven kinds of the mounting samples encountered practically were vibrated on a vibration table of dynamic type in vertical and horizontal directions and seven kinds of the vibration pickups were placed on these samples to observe their frequency characteristics from 10 to 300 Hz.

Mounting problems of the vibration pickups studied by us in the present paper are those in the surface vibration among several kinds of vibrations.

EXPERIMENTAL PROCEDURES

Eleven kinds of mounting materials were examined as shown in Table 1. These samples are classified in three categories.

Table 1. Eleven kinds of mounting samples.

	Samples	Weight (kg)	Size (mm)	Bolts number for fixing on vibration table
Hard samples	Aluminum disc	4	17×340φ	6
	Concrets block	7.7	350×40×250	2
	Light weight block	7	390×150×190	2
	Fire brick (ISOLITE, N-5)	1	230×63×113	2
	Vinyl-tile	0.48	305×305×2	Adhesive
Wooden samples	Plywood plate	1.4	25×370φ	6
	Lauan plate	2.5	480×265×43	4
	Wooden-fiber cemented-plate	1.8	25×360φ	6
	Cypress rectangular lumber	3	480×116×116	2
Soft samples	Soil in aluminum box	35 (Total weight)	Inside sizes of 450×450×200 and thickness of 20	One sheet of paper without bolts
	Aluminum box	21		
	Tatami (Japanese mat)	1.4	300×300×65	2

i) *Hard samples*; Aluminum plate, concrete-block, light-weight block, fire blick and vinyl-tile.

ii) *Wooden samples*; Plywood plate, cypress rectangular lumber, lauan plate and wooden-fiber cemented plate.

iii) *Soft samples*; Soil and Japanese mat (Tatami).

These samples are frequently encountered for the vibration measurement either inside or outside of the house in Japan. The vibration on soil must frequently be measured for assessment of the vibration pollution, because local governments in Japan have stipulated regulations in which the vibration pollution shall be evaluated

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by the value on the ground of the borderline between the house of distressed residents and the vibration sources. As general Japanese houses use Japanese mat on the floor, vibration measurement on it is required, especially for assessment of vibration pollution. These samples except the soil in the box were fixed on the vibration table by bolts of which numbers were shown in Table 1. Soil in the garden of our institute was put in the aluminum box as also described in Table 1 and was trodden hard enough. To avoid the resonance caused from the vibration table and this aluminum box, a sheet of paper was placed between the table and the box.

Table 2. Seven kinds of vibration pickups for vibration level meter.

Vibration pickup	Type	Length of legs (mm)	Weight (kg)	Size (mm)	Amplifier
A	Ceramic	without	1.5	60×60×108	−2 dB/oct, above 90 Hz
B	Electro-dynamic	3	1.9	60×60×108	−5 dB/oct, above 90 Hz
C	Ceramic	25	2.5	93×106×73	−9 dB/oct, above 90 Hz
D	Ceramic	3	0.8	50×50×54	Flat, below 1 kHz
I	Ceramic	4	0.3	Outside dia, 50φ	d°
II	Ceramic	4	0.6	Outside dia, 65φ	d°
III	Ceramic	4	1.2	Outside dia, 86φ	d°

The inside diameter and the height of pickups I, II and III were the same as 35 mmφ and 30 mm respectively, and the usual vibration accelerometer of ceramic type (weight of 36 gr. and size of 30 mm×15 mmφ) was commonly used as the sensing element, provided that a small aluminum block (weight of 18 gr.) was used for setting when this accelerometer was employed in the vertical direction.

Seven vibration pickups were examined as shown in Table 2. Among them four pickups, A, B, C and D were commercially available and the other three pickups, I, II and III were tentatively made. It must be noticed that amplifiers of the former three pickups (A, B and C) made by their makers were used, while an amplifier produced by us was employed for the other pickups. Their cut-off frequency characteristics are shown in Table 2. The frequency characteristics outside the measuring frequency of these amplifiers had not yet been standardized at that time, though the frequency nature has now been determined as −12 dB/oct. above 90 Hz. Weight of the pickup I was adopted as the minimum value for field use. A sheet of paper was used between the pickup A and the mounting material to evade rattling because the pickup A did not have the legs, although the contact resonance frequency and its peak value might be affected by insertion of this paper.

The vibration tables of electro-dynamic type in the vertical and the horizontal directions were driven by an apparatus connected with a sinusoidal signal oscillator, a calibrated attenuator with 0.1 dB step and a power amplifier in series. The vibration acceleration level (VAL) given to these pickups for the examination was

selected as 90 dB, in which the reference level of the dB value (0 dB) was 10^{-3} cm/sec². The vibration frequency was watched by a frequency counter. The output voltage of the vibration pickup mounted on the sample was measured by a vacuum-tube-voltmeter and its wave form was scrutinized by an oscilloscope. The motion of the vibration table itself and of the surface of sample was observed by the reference accelerometers as shown in Fig. 1, namely, the one is the vibration accelerometer (25 g in weight and 30 mm×20 mm ϕ in size) and the other is the smallest accelerometer (4 g in weight and 12×5×5 mm³ in size) which was stuck with a both-surface adhesive cellophane tape or with an adhesive on the sample or was fixed on a small aluminum wedge (8 g) buried in the soil in the aluminum box.

Fig. 1. Photograph of the seven examined vibration pickups. The accelerometer set on the pickup I was used not only as the sensing element of the pickup I, II and III but also as the reference pickup on the vibration table. The accelerometer described as "REF" was employed as the reference on the mounting materials.

At first, the vibration level of the table was adjusted by the attenuator at 90 dB using reference accelerometer and the attenuator reading was recorded. Then, the output voltage of the vibration pickup mounted on the sample was controlled by the attenuator until 90 dB and its reading was also recorded. The difference of these two attenuator readings was defined as the frequency response. The frequency was varied between 10 and 300 Hz, because below 10 Hz, there occurs no contact resonance and the range above 300 Hz was not necessary for measurement of vibration pollution.

RESULTS AND DISCUSSIONS

The representative results are shown in Figs. 2–10, in which the ordinate denotes the difference of output voltage (dB) between the reference accelerometer set on the vibration table and the accelerometer mounted on the sample and the

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abscissa the vibration frequency (Hz). The contact resonance frequency (Hz) observed by the pickup mounted on the sample and its peak value (dB) are tabulated in Tables 3 and 4 for both vibrations. In these tables, lateral lines indicate contact resonance does not occur below 300 Hz. Vibration on the soil was measured by the reference pickup below 250 Hz for vertical vibration or below 100 Hz for horizontal vibration because of nonlinearity of the output signal of the pickup. So, the values of the soil in the column of "REF" are not the contact resonance frequency, but the end frequency and its level difference.

Table 3. Contact resonance frequencies between the vibration pickups and mounting materials (Hz, on the left side in the column) and their peak values (dB on the right side) for vertical vibration. Type of the vibration pickups are shown on the line as A, B, C, D, I, II, III and REF, and sorts of the mounting materials on the first column.

	A		B		C		D		I		II		III		REF	
Aluminum disc	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Concrete block	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Light weight block	—	—	—	—	—	—	—	—	—	—	—	—	270	14	—	—
Fire brick	—	—	290	13	200	5	—	—	—	—	—	—	—	—	—	—
Vinyl-tile	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Plywood plate	265	18	230	18	190	15	250	26	—	—	300	25	240	23	—	—
Lauan plate	300	18	230	18	215	8	280	30	—	—	—	—	280	22	—	—
Wooden-fiber cemented plate	215	21	190	20	170	14	230	31	—	—	280	30	235	24	—	—
Cypress rectangular lumber	245	15	210	16	180	11	270	23	—	—	—	—	280	26	—	—
Soil	145	16	138	15	112	17	155	20	213	23	196	22	169	19	250	10
Japanese mat	56	16	47	14	41	19	50	17	64	20	50	15	47	17	140	8

Table 4. Contact resonance frequencies between the vibration pickups and the mounting materials (Hz, on the left side in the column) and their peak values (dB, on the right side) for horizontal vibration.

	A		B		C		D		I		II		III		REF	
Aluminum disc	262	10	—	—	135	19	—	—	—	—	—	—	—	—	327	17
Concrete block	260	15	280	8	125	26	240	26	270	13	260	13	260	17	270	9
Light weight block	115	9	140	21	90	20	190	25	190	21	175	27	160	19	225	14
Fire brick	80	20	78	21	48	15	100	23	145	22	125	25	103	24	200	25
Vinyl-tile	—	—	—	—	120	14	—	—	—	—	—	—	—	—	329	15
Plywood plate	244	11	190	14	80	12	150	20	210	15	165	15	135	15	328	16
Lauan plate	255	12	215	15	100	18	160	22	210	19	170	21	170	21	330	11
Wooden-fiber cemented plate	165	12	180	18	70	15	200	17	250	22	205	23	190	14	325	10
Cypress rectangular lumber	170	21	155	16	90	22	150	26	190	23	160	19	155	17	310	21
Soil	70	13	62	12	50	15	60	15	100	20	80	18	70	16	100	8
Japanese mat	40	10	38	15	21	11	27	14	26	9	25	7	32	12	130	8

a) *Vertical sinusoidal vibration*

The resonance frequency of the vibration table itself in the vertical direction was high above 600 Hz, so it is easy to discriminate the resonance caused by the mounting sample.

On the group of hard samples, the results of the aluminum plate are shown in Figs. 2, a and b as the typical example of this group. Their frequency responses are flat below 90 Hz and different above 90 Hz depending upon the frequency characteristics of the amplifier of the pickups. On the other samples of this group, the results on the aluminum plate and the concrete block are in good agreement. However, the pickup III set on lightweight block and the pickups of B and C on the fire block have the resonance below 300 Hz, as indicated in Table 3, while these samples themselves did not have the resonance below 300 Hz. These resonances come from the vibration system consisting of elasticity of the contacted surface of the sample and mass of the pickup, which is called contact resonance. On the vinyl tile, all the pickups show similar response to the aluminum plate. Although

Figs. 2, a and b. Frequency responses of 7 vibration pickups on the aluminum plate for vertical vibration.

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Figs. 3, a and b. Frequency responses of 7 vibration pickups on the lauan plate for vertical vibration.

elasticity of the vinyl tile affects to some extent the result in higher frequency range, this deviation is less than that of the aluminum plate and in addition it is noticeable that contact resonance does not occur on the vinyl tile due to its viscosity.

Figs. 4, a and b. Frequency responses of 7 vibration pickups on the soil for vertical vibration.

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On the group of wooden materials, tendency of the response of the vibration pickups is almost the same except that the contact resonance frequency is somewhat different depending upon elasticity of the materials. The data observed on the lauan plate are shown as the typical example in Figs. 3, a and b. The lauan plate does not exhibit the peak response by the reference pickup below 300 Hz, but the pickups of A, B, C, D and III denote their peak between 200 and 300 Hz, although the frequency of the amplifiers of A, B and C had been cut above 90 Hz. The other samples of this group have almost similar tendency of the lauan plates as described in Table 3.

On the soil in the soft samples, the results are shown in Figs. 4, a and b. Their resonance peaks gather between 110 and 250 Hz and the contact resonance frequency between the soil and the pickup nearly decreases with increase of the mass of pickup. The soil itself shows resonance as plotted in Fig. 4, b, ($\times$), but the deviation between the soil itself and the contact resonance is considerably large.

The resonance of Japanese mat itself occurs at near 140 Hz. When some pickup is loaded on it, the contact resonance is seen at very low frequency even though its weight is not so large as shown in Figs. 5, a and b. The resonance frequencies of the pickups are concentrated in 50 Hz within ± 10 Hz and their peak values are similar by about 18 dB regardless of their weight.

Figs. 5, a and b. Frequency responses of 7 vibration pickups on the Japanese mat (Tatami) for vertical vibration.

b) *Horizontal sinusoidal vibration*

Our horizontal vibration table has the resonance frequency at about 330 Hz, so attention has to be paid for data analysis.

On the group of hard samples, the results of aluminum plate are shown in Figs. 6, a and b. In these figures, the pickups of B, D, I, II and III show the similar patterns to the reference pickup ($\times$), provided that concave curve of the pickup B above 100 Hz comes from the nature of its amplifier. On the other hand, the pickup C shows the different response, that is, the resonance occurs at 135 Hz, which is lower than the table resonance of 330 Hz. This resonance stems from long legs of this pickup of 25 mm, because this resonance frequency can be shifted

Figs. 6, a and b. Frequency responses of 7 vibration pickups on the aluminum plate for horizontal vibration.

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to higher frequency of about 270 Hz replacing these legs of 5 mm in length. The contact resonance of this pickup without the above improvement can be seen on the other samples at low frequencies for the horizontal vibration. The pickup A indicates the resonance at about 262 Hz, which comes from its rattling owing to not having their legs and rough bottom surface of the pickup. A sheet of paper was not used in this case.

On the vinyl tile, the pickups except C show almost similar response curve, barring the resonance occurs rather at lower frequency than that on the aluminum plate due to visco-elasticity of the vinyl tile, although this difference is negligible as described in Table 4.

On the other materials of the hard samples, the resonance frequency of the vibration system composed of the mounting material and the horizontal vibration table is considerably lowered on account of the mass of the material or its fixed condition with bolts on the table. The resonance frequency on the light-weight block observed by the reference pickup takes place at about 225 Hz as shown in Fig. 7, b and Table 4. The pickups of D, I and II in Figs. 7, a and b show nearly similar response pattern of the reference pickup, while the other pickups indicate rather lower resonance frequency. The lower resonance frequency of the pickups of B and III comes from their weight.

The resonance of the concrete block itself occurs at about 270 Hz. The pickups except C may follow the input vibration as shown in Table 4. As the fire block has light weight but high compliance, its resonance occurs at 200 Hz, which was observed by the reference pickup. All pickups on the fire block denote lower contact resonance frequencies below 150 Hz as tabulated in Table 4, especially, the pickups which show the resonance above 100 Hz are D, I, II and III.

On the group of wooden samples, the resonance frequency between the vibration table and the wooden material bolted on it is the same as that of the table itself checked by the reference pickup as shown in Table 4. On the other hand, the contact resonance between wooden samples and the pickups, however, is observed below 300 Hz in all cases. This contact resonance frequency is easily varied within ± 20 Hz as compared with the vertical vibration by the setting position of the sample or use of both-side adhesive cellophane tape or preliminary treatment that the legs of the pickup are rubbed on the material. Besides, contact resonance frequency is lowered in proportion as increase of weight of the pickup, while its peak value is kept at some constant level. The result of lauan plate is shown in Figs. 8, a and b as the typical example. Lauan plate has so higher stiffness that the contact resonance frequencies fall between 150 and 260 Hz except the pickup C and their peak values are about 20 dB on the pickups D, I, II and III.

Though plywood plate is softer than lauan plate, the result on plywood plate agrees well with that on lauan plate except that the contact resonance on plywood plate occurs at rather lower frequency.

(a)

(b)

Figs. 7, a and b. Frequency responses of 7 vibration pickups on the light-weight block for horizontal vibration.

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(a)

(b)

Figs. 8, a and b. Frequency responses of 7 vibration pickups on the lauan plate for horizontal vibration.

Wooden-fiber cemented plate shows similar response of the other wooden materials as denoted in Table 4. The resonance frequency on cypress square lumber itself is the same as the other plate and the contact resonance of the pickups except C occurs between 150 and 190 Hz as shown in Table 4.

On the group of soft samples, the results of soil are shown in Figs. 9, a and

Figs. 9, a and b. Frequency responses of vibration pickups on the soil for horizontal vibration.

Figs. 10, a and b. Frequency responses of 7 vibration pickups on the Japanese mat (Tatami) for horizontal vibration.

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b. The surface of the soil itself has the resonance above 100 Hz. It can be said that weight of the pickup loaded on the soil lowers the contact resonance frequency which gathers in the narrow frequency range between 50 and 80 Hz except the pickup I. The pickup I somewhat elevates this resonance frequency, besides, in case the pickup I is attached with a square aluminum plate of $70 \times 70 \times 3 \text{ mm}^3$, the resonance can be shifted to higher frequency owing to widening of the contact surface.

The vibration on the Japanese mat was measured as shown in Figs. 10, a and b. The mat itself shows the resonance at 130 Hz. It is interesting that although the weight, the base area and the legs of the pickups are considerably different with each other, the contact resonance frequencies occur rather in quite narrow frequency range from 20 to 40 Hz and their peaks have the same height of about 10 dB. Even if the mass of the pickup is lessened, the resonance frequency is not varied so clearly.

Figs. 11, a and b. Peak values (dB) at contact resonance frequencies between the vibration pickups and the mounting materials for vertical vibration (a) and for horizontal vibration (b).

On Japanese mat for both vibrations and soil for horizontal vibration, the peak values are discriminated with the signs ($\times$ or $\triangle$ respectively) from the other materials ($\bullet$). The results observed by the reference pickup ("REF") are not included in the figures.

Finally, the peak values at contact resonance frequencies in Tables 3, and 4 are plotted in Figs. 11, a and b. From these results, the lighter the weight of the pickups, the better result, in which the contact resonance can be elevated to higher frequency range, was obtained for both vibrations. If the vibration acceleration (AL range) is wanted to measure by the pickup of vibration level meter, the cut-off frequencies of the amplifier are better to be selected at 80 or 60 Hz for both vibrations respectively and above it the cut-off characteristics have to be taken as -18 dB/oct. as shown in Figs. 11, a and b with dotted lines. It is also clarified that the Japanese mat for both vibrations and the soil for horizontal vibration must not be measured by AL range. Besides, if the VL range of vibration level meter is used, of which the weighting circuit is the same as equal sensation curves in the draft proposed by ISO/TC 108/WG 7 below 90 Hz and the frequencies above 90 Hz are cut by more than -18 dB/oct. , even Japanese mat's measurement seems to be allowed as shown in Fig. 11 with solid lines which are standard lines of 0 dB. On these lines, the frequency ranges between 4 and 8 Hz for vertical vibration, and 1 and 2 Hz for horizontal vibration are determined as the acceleration domain and above them as the velocity domain for human vibration sensation.

The contact resonance frequency for the vertical vibration can be easily elevated to the higher frequency above 300 Hz except the soft samples, while that for horizontal vibration is lowered until near half the value in vertical vibration. The mode of the contact resonance for horizontal vibration seems to stem from the pitching motion of the pickup.

CONCLUSION

i) It is desirable to make the contact resonance frequency elevate as high as possible, whatever the mounting materials may be. The pickup I which has weight (g), outside diameter, inside diameter, height and length of legs (mm) of 300, 50ϕ , 35ϕ , 30 and 4 respectively, and of which the sensing element is supported as low from the bottom as possible, is the best among all tested pickups in order to satisfy the above demand for all mounting samples except Japanese mat.

ii) The vibration measurement in the field of public nuisance shall mainly be made by the VL range of the vibration level meter standardized by the Acoustic Society of Japan. It seems to be required for the vibration level meter below 90 Hz that the frequency characteristics of the amplifier have to be the same as the equal sensation curves recommended by the ISO/TC 108/WG 7 for both vibrations respectively and above them to be cut as -18 dB/oct. , although the vibration level meter proposed now has the same weighting characteristics for both vibrations.

iii) The AL range of vibration level meter is desirable to make the frequency characteristics as flat below 80 or 60 Hz for respective vibrations and above it as -18 dB/oct. If vibration on the ground must be measured for AL range, vertical

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vibration alone is allowed to measure. At that time, the soil on the spot must be trodden hard enough before setting the vibration pickup. Horizontal vibration on the ground and both vibrations on the Japanese mat must not be measured by AL range of the vibration level meter. If it is required, vibration measuring method on the soft material obtained by us³⁾ shall be applied.

iv) The calibration of the pickup is possible without bolting it on the vibration table below the vibration level of 90 dB ($0 \text{ dB} = 10^{-3} \text{ cm/sec}^2$) in the frequency range between 1 and 300 Hz. It is also known that for the calibration the good results with little deviation is possible to obtain using the aluminum plate or the vinyl tile mounted on the vibration table.

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