EVALUATION METHODS FOR VIBRATION EFFECT

PART 9. RESPONSE TO SINUSOIDAL VIBRATION AT LYING POSTURE

Toshisuke MIWA and Yoshiharu YONEKAWA

National Institute of Industrial Health, Kizuki-Sumiyoshi, Kawasaki

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The sinusoidal vibration sensation at lying on the back was equalized into that at sitting by 10 male subjects in the frequency range between 0.5 and 300 Hz, in order to obtain equal sensation contours at lying posture. This experiment was carried out for the vertical and the horizontal vibrations.

As a result, the vertical vibration sensation of the lying subject receiving from 40 to 150 Hz was severer by about 12 dB in max. than that at sitting, because of the resonance of the skull. On the remainder frequency range, vibration perception was almost the same at both postures. On the other hand, the horizontal vibration sensation at both postures was nearly the same in all frequency range (0.5–300 Hz). From these results, the equal sensation contours at lying posture for both directional vibrations were determined.

The estimated equal sensation curves from above results agree with those obtained by direct measurement in which the vibration at a certain frequency from 0.5 to 300 Hz was equalized into the standard vibration at 20 Hz. Thus, the assessment method of the vibration at the sitting posture established previously can be applied to that at the lying provided that the equal sensation contour for the vertical vibration is revised near 80 Hz.

Evaluation methods of vibration effect on whole body at sitting and standing postures for various wave forms of vertical and horizontal vibrations were established in previous reports. The question what revision is needed in applying these evaluation methods to lying posture will be raised at the next step. The problems concerning the lying posture are important not only in public nuisance due to vibration generated in the night but also in surface transportations such as a sleeping car and a passenger boat.

There are few reliable data applicable to the assessment of the vibration at lying posture. The result observed by Reiher and Meister¹⁾ has been widely known. They classified the vibration emotion into 6 steps, as insensible, faintly sensible, enough sensible, strongly sensible, unpleasant and extremely unpleasant, and observed interrelation between these emotions and the vibration displacement. However, the observed frequency range was narrow and they did not search the relation between the lying and the other postures. Therefore, their result could

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not be directly used to our purpose. Thus, the experiments described in this paper were planned to establish the evaluation method of vibration at the lying posture.

EXPERIMENTAL PROCEDURES

Experimental Conditions

In experiments on the lying posture, what kind of vibration table is used for this purpose is the major problem. For supporting the human body lying on the vibration table, the square measure of about $200 \times 40 \text{ cm}^2$ may be needed. Besides, phase relations on all surface of this vibration table must be maintained to be the same in all frequency range (0.5–300 Hz), and its local surface resonance and rocking motion must be avoided even in the higher considered frequency range. The construction of this sort of vibration table satisfying the above requirements may not be easy from the technical and economical view points except the vibration table which is used only in the lower frequency range.

To carry out the lying experiment, we did not construct a new shaker with a large surface of the table. Experimental procedures were divided into two parts depending upon the frequency. In lower frequency range, the whole body at the lying posture was vibrated and in higher frequencies, some parts of the body at the lying posture were vibrated as the representative of the whole body.

To extend the table surface area of the shaker, one piece of plywood board of $178 \times 38 \times 2.5 \text{ cm}^3$ was bolted upon the vibration table of electro-dynamic type in the vertical and the horizontal directions used in the previous experiments. The

Fig. 1, a.

both corners of longer-size-side of this board were stiffened with bolted iron-angles. This supplemental table could be used below 5 Hz for the vertical vibration and below 60 Hz for the horizontal one without troubles concerning its rocking motion and its resonance even when loaded with the whole body. This improvised table when used in the horizontal direction showed the sharp resonance of the coupled vertical vibration induced by the horizontal one at near 16 Hz, but its frequency range was so narrow that there was no problem in the measurement for the horizontal vibration. At higher frequencies, the most sensible part of the body was selected as the representative instead of vibrating the whole body. Preliminary examinations were made on 5 male subjects concerning the perceptual threshold of various parts of the body, such as head, back, waist, buttock, femora, calves and heels. The results are shown in Fig. 1, a and b for the vertical and the horizontal vibrations. The sizes of our vibration tables are $\pi(20)^2 \text{ cm}^2$ for the vertical table and $60 \times 45 \text{ cm}^2$ for the horizontal one.

The ordinate in Fig. 1 is the vibration acceleration level (VAL), dB; $VAL = 20 \log_{10}(a/a_{\text{ref}})$, a = rms vibration acceleration value (g or cm/sec²) and $a_{\text{ref}} = 10^{-3} \text{ g}$ or 1 cm/sec^2 (rms), and the abscissa the vibration frequency (Hz). The observed values in this figure indicate the average on 5 subjects.

In Fig. 1, a, below 4 Hz, parts of the body (head, back and buttock) increase

Fig. 1, b.

Fig. 1 Averaged perceptual threshold at various parts of the body or the whole body for the vertical and the horizontal vibrations on 5 lying subjects. a; for the vertical vibration and b; for the horizontal one.

the sensitivity of vibration perception with the decrease of frequency. This fact can be explained that the body nearly detects relative velocity between these parts which are vibrated and their neighbouring ones which are not vibrated. Therefore, if the whole body is vibrated, the threshold becomes higher as seen in this figure. This fact can not be found in higher frequency, because the amplitudes of vibration become very small. In the frequency range from 4 to 30 Hz, various parts show somewhat the same tendency in the threshold, while between 40 and 300 Hz, the head shows clear threshold dip. This dip was already proved by the mechanical resonance measurement of the human skull²⁾. Except this resonance of the head, the observed values on the other parts of the body distributed nearly on the back's curve. As a result, it is reasonable that the head and back are chosen as the representative, because they show the lowest threshold values.

On the horizontal vibration, the situation is somewhat different from the vertical vibration. Namely, the threshold values on the head and back do not show lower level than those on the other parts. Besides, there is no typical notch in their curves, and the sensing part of the body moves gradually to the lower parts such as buttock, femora, calves and heels with the increase of the vibration frequency. From these data, the calves and heels are considered to be the representative for the horizontal vibration above 60 Hz. In addition to the calves and heels, the head and back was also chosen as the representative above 60 Hz for the horizontal vibration, because the results may be suspected of influence caused by shaking the head.

Equalizations of vibration sensation at lying posture to that at sitting

The vibration greatness of the sinusoidal vibration at the lying posture was compared by the subject with that at the sitting and the sensation at the both postures was equalized changing the level at the sitting by the tester in compliance with the subject's request, while the level at the lying was maintained constant.

First of all, the lying subject was given the vibration repeated two times for each about 15–10 sec. The impressing time was shortened with the increase of frequency. The sensation of this vibration was memorized. Then, the posture was varied to the sitting and the subject was begun to be vibrated from the lower level than that at the lying. The level was changed by the bracketing method to lower or higher level successively around the presumed equal sensation level.

As the VAL value of the vibration table varied by the change of postures (sitting or lying), it was maintained constant. Namely, the output voltage of an accelerometer set on the vibration table at the sitting was adjusted to the same voltage as at the lying by an attenuator which was inserted between the oscillator and the power amplifier of the exciter. This voltage was always read out by the VTVM. (vacuum tube volt meter). The posture was varied in arbitrary times until the subject would reach the equal sensation. The vibration frequency was changed from 0.5 to 300 Hz.

Fig. 2 Photographs of lying postures.

1. Whole body vertical vibration.
2. The head and the back were vibrated in the vertical direction.
3. Whole body horizontal vibration.
4. The calves and the heels were vibrated in the horizontal direction.
5. The head and the back were vibrated in the horizontal direction.

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It took about half an hour for the experiment of one directional vibration in the considered range of frequency. To check the dependency of the result upon the vibration level, the supplementary experiment was tried for the vertical vibration alone at 60, 80 and 100 Hz, in which the vibration levels were varied at 2 levels larger or less by 6 dB than those examined previously. The level-change experiment for the horizontal vibration was omitted, because no difference in the equal sensation at the both postures was found out.

Measurements of equal sensation at lying posture

The equal sensation contours at the lying can be estimated from the first experiment. That is to say, the equal sensation level at the lying may be calculated subtracting the sensational difference between the both postures from the equal sensation level at the sitting already shown in Fig. 13 (Part 1). To endorse the propriety of this assumption, it was measured experimentally by the method of paired comparisons. The experimental condition was the same as in the first experiment where the standard frequency was taken as 20 Hz, which had been commonly adopted in this series of report. However, as the considered frequency range was divided into two parts, the vibration at 4 Hz was selected as the standard in the measurement below 4 Hz for the vertical vibration, while the vibration at 60 Hz was chosen as the standard for the horizontal vibration above 60 Hz. In the other frequency ranges, 6–300 Hz for the vertical vibration and 0.5–60 Hz for the horizontal one, the standard frequency was chosen as 20 Hz.

The subject compared the standard frequency vibration (10–15 sec) with the other frequency vibration (10–15 sec) of which level was changed by the tester until he would reach the equal sensation. The standard vibration levels were taken as 35 and 50 VGL for the vertical and the horizontal vibrations respectively. The value of VGL has been already defined in Part 1, namely, the equally perceived level of the vibration with the frequency except 20 Hz in comparison with the standard vibration (20 Hz).

Subjects

The experiments were carried out on ten male subjects who had the normal vibration threshold level. Postures tested in this experiment were indicated by the photographs in Fig. 2. At that time, the non-shaking part of the body except the case vibrating the whole body was supported by the wooden table which was set on the same horizontal level as the vibration table.

RESULTS AND DISCUSSIONS

Equalization of vibration sensation between the lying and the sitting postures

The results for the vertical and the horizontal vibrations are shown in Fig. 3 a and b respectively. The ordinate is the difference of the standard vibration level (VAL) at the lying posture from the level (VAL) judged as equal sensation

Fig. 3, a.

Fig. 3, b.

Fig. 3 Sensation difference of the lying posture from the sitting. a; for the vertical vibration and b; for the horizontal vibration.

Table 1, The effect of the vibration level on sensation difference between lying and sitting postures for the vertical vibration. The number in this table means the average value of the relation [(Level judged as equal sensation at sitting) - (Standard level at lying)] (dB) on ten subjects and $\pm$ numbers its standard deviation.

VGL	Hz	60	80	100
	dB			
29		10.4 ± 2.3 -3.1	12.5 ± 2.1 -2.6	8.0 ± 1.0 -1.2
35		9.0 ± 1.7 -2.1	12.0 ± 2.7 -3.3	7.3 ± 2.0 -2.8
41		10.0 ± 1.3 -1.6	12.0 ± 1.5 -1.9	

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by the sitting subjects. In this figure, + dB means that the vibration sensation at the lying is severer than that at the sitting and - dB that the vibration sensation at the lying is milder than that at the sitting. The abscissa shows the frequency (Hz). Among black circles connected with straight vertical line, their center means the average value and outsides of them the standard deviation observed on 10 male subjects.

The peak of 12 dB at 80 Hz appears clearly for the vertical vibration (Fig. 3, a), while there is no clear difference between both postures for the horizontal vibration (Fig. 3, b). This peak comes from the resonance of the skull as explained in Fig. 1, a. Moreover, the data obtained from changing the test level for the vertical vibration are shown in Table 1. It can be seen that the level change does not influence their results. Therefore, the result in Fig. 3, a may hold good under the level range in which we do not feel pain by the impressed vibration.

For the horizontal vibration above 60 Hz, the result shown in Fig. 3, b was observed on the calves and heels. On the head and back, there was no articulate difference from the calves and heels. In addition to the experiments in which the horizontal vibration was impressed along the lying body axis, the other case impressing the vibration at right angles to the body axis was tried. However, there was no difference between the both impressing angles to the body axis in all frequency range (0.5-300 Hz).

Thus, the quantitative interrelation of the vibration sensation between the lying and the sitting was gained. Therefore, the evaluation method for the vibration at the sitting posture established in the previous reports can entirely be applied to the lying, provided that the equal sensation contour at the lying for the vertical vibration must be corrected.

The equal sensation contours at the lying for the vertical and the horizontal vibrations are drawn referring to the result at the sitting in Fig. 13 (Part 1) as shown in Fig. 4. The ordinate shows the VAL value (dB) and the abscissa the frequency (Hz). The upper dashed curve is drawn without correction from the equal sensation contour for the horizontal vibration at the sitting at 50 VGL. The lower dashed curve is obtained from the calculation subtracting the value of the equal sensation relation between the both postures (Fig. 3, a) from that of the equal sensation for the vertical vibration at the sitting at 35 VGL. On the other hand, the values observed experimentally are shown with the black circles. The center of three signs connected with straight vertical line means the average value and outsides of them the standard deviation on ten male observers.

For the horizontal vibration, the curve and the observed value are in good agreement in considered frequency range except the result at 0.5 Hz. In the case of the vertical vibration, the concord between the estimated and the observed values is considerably good except above 150 Hz. At 0.5 Hz for the horizontal vibration and above 150 Hz for the vertical one, these disagreements may be attributed to

Fig. 4 Comparison of the equal sensation levels between the estimated values obtained from the sensational differences at the both postures (dashed curves) and the observed values by the method of paired comparisons (black circles). Clear circles and stars on these dashed curves show the standard level in the equal sensation experiment.

the fact that the equal sensation curve in Fig. 13 (Part 1) is drawn by averaging on the two different postures (sitting and standing).

In this experiment, the standard level was lowered at 200 and 0.5 Hz for the horizontal vibration and at 0.5 Hz for the vertical vibration because of restriction of the power in the power amplifier or limit of the amplitude in the vibration table. The observed data were relatively heightened by calculation to the level with the same VGL value as at the other frequencies. This operation may not influence the result.

The average and the standard deviation values of the lying threshold on the ten subjects are plotted in Fig. 5 under the same experimental conditions as before and the asymptotic curves are also drawn. The tendency is the same as already presumed in Fig. 1, a and b.

CONCLUSIONS

It can be proved that the equal sensation curve at the lying posture for the

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both vibrations can be estimated from the sensation difference between the both lying and sitting postures. As a result, the contours in Fig. 6 are recommended as the threshold and the equal sensation curves at the lying posture. The same evaluation procedure for the sinusoidal, the compound and the random vibrations at the sitting posture established previously can be applied to the lying without any revision, provided that Fig. 6 is used as the equal sensation contours.

It was found out in Part 2 that the vertical vibration was equalized in sensation to the horizontal vibration with larger level by 10 dB than that of the vertical one above 10 Hz. From this fact, the sensation difference of the both vibration at the lying becomes 22 dB at 80 Hz. This difference was confirmed experimentally on 3 subjects.

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