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Development of frequency weighting function for Asian (Korean) people in vertical whole-body vibration; in comparison with ISO 2631-1 †

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Abstract

In the field of 'human vibration', until now most frequency weighting functions have been derived from particular experiments whose subjects were only Western people. However, because of inherent differences (e.g., characteristic and shape of body parts, muscular and cellular tissue) between Western people and Asian people, frequency weighting function based on Asian people is required. An experiment was carried out to develop a frequency weighting function for the Korean people in vertical whole-body vibration, and to verify whether this weighting is acceptable in practical applications in comparison with ISO 2631-1. Ten male subjects of mean weight and height were tested for a posture similar to sitting in a passenger seat (footrest, upright and placement of the palms of hands on thighs, etc.) of a car. This experiment was performed using sinusoidal excitation in the range from 2 to 250 Hz, which was a combination of one-half and one-third octave bands at eight determined amplitudes. To guarantee the reliability and accuracy of the test, non-parametric statistics was adopted to resolve the fact that there was not enough of the sample. Furthermore, two methods were considered to make the frequency weighting function and equal sensation curves. The first method changes the amplitude at every fixed frequency, and the other assigns weighting values. Korean people showed the most sensitivity to vertical whole-body vibration at 6.3 Hz excitation, so much higher weighting factors than weighting factors of other frequencies must be assigned near that frequency.

Keywords: Equal sensation curves; Frequency weighting function; Non-parametric statistics; Asian people; Vertical hole-body vibration

1. Introduction

Passengers in a vehicle are affected by many vibration stimuli from various sources because of the characteristics and shape of the vehicle and the roughness of the road surface. These stimuli can increase fatigue, cause discomfort and unpleasant feelings and decrease driving ability. It is important to identify the various factors which influence negative effects. It has been considered that most factors are affected by direction, frequency, amplitude and duration time of a vibration and the subject's posture, etc [1]. Griffin measured the effect of vertical vibration for a seated subject [2], and Parson investigated the influence of rotational vibration [3]. Paddan and Griffin evaluated the multi-axis vibration for many kinds of vehicles [4]. And Mansfield and Maeda considered the similarities and differences between single-axis and multi-axis vibration through a transfer function (apparent mass). They reported that the region from 4 to 6 Hz presented the resonance frequency of seated vertical whole-body vibration for the bank-on posture and region from 1 to 3 Hz of the seated x-axis and y-axis whole-body vibration for the same posture [5]. In

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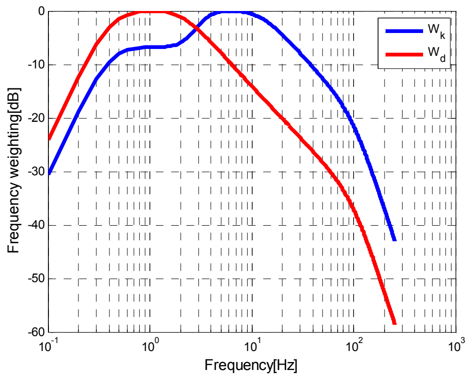

Fig. 1. Frequency weighting functions for seated whole-body vibration in ISO 2631-1.

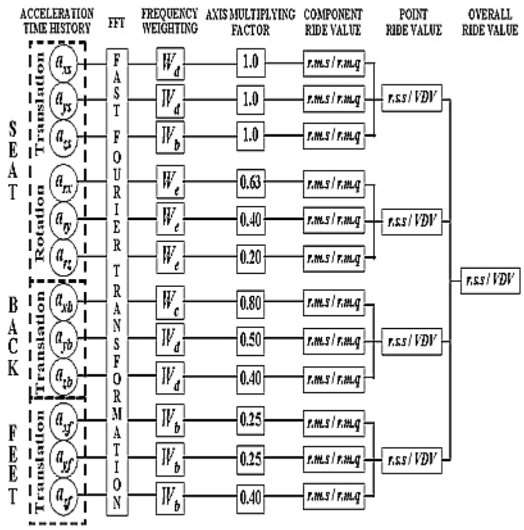

Fig. 2. Procedure for calculating component ride values, point ride values and overall ride values.

general, the discomfort of a seated subject has been mainly evaluated with single-axis vibration in laboratory and field experiments because of the importance of vertical whole-body vibration.

Until now, the International Standard 2631-1, as shown Fig.1, and the British Standard 6841 have been widely used to evaluate vehicle ride comfort with respect to various axes for a seated subject [6,7]. These weighting curves are used to evaluate the ride comfort value with vehicle acceleration, shown in Fig.2. The difference between these two standards was examined by limiting the daily exposure durations, which were estimated by comparing the frequency weighted root mean square accelerations with the vibration dose values [8]. Nevertheless, most fre-

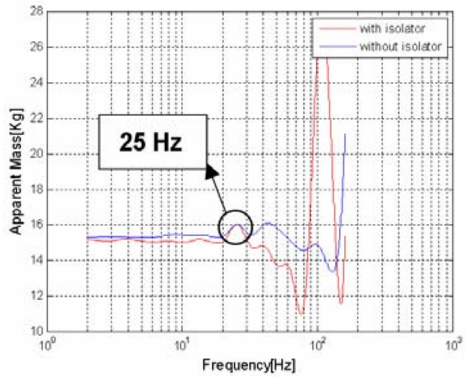

Fig. 3. Apparent mass of force platform.

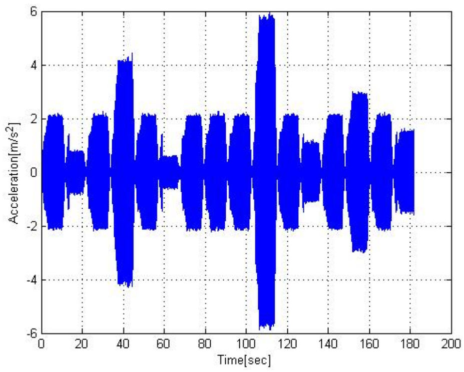

Fig. 4. Reference and test signals at 16 Hz.

quency weighting functions have been derived only for Western people. There are definite differences between Western people and Asian people with respect to characteristics and shape of body parts, muscular and cellular tissue. Therefore, these weightings may not be appropriate for evaluating the vehicle ride comfort of Asian people. Thus, a frequency weighting function to evaluate the vehicle ride comport for Asian people is required.

In this paper, a frequency weighting function of Korean people along the vertical direction, which is the most dominant axis of vehicle vibration, was derived by the following procedures. First, a subjective evaluation was conducted by using sinusoidal excitation, which was uniformly produced by a single-axis vibrator. Second, the obtained data were verified by non-parametric statistics methods to determine the reliability of the data. Third, once the data had been verified, equal sensation curves were plotted in eight grades of subjective evaluation scores from 40 to 320. Finally, the frequency weighting function was determined and compared with ISO 2631-1.

2. Experiments

2.1 Test signal

In this experiment, sinusoidal waveforms of various fundamental frequencies and magnitudes were used. The frequency ranges were divided into the low frequency region and the high frequency region because of phase differences and resonances of the excitation frequencies, as shown Fig. 3, which presents apparent mass of the force platform. To obtain the characteristics of the shaker with or without isolators, the shaker was vibrated at 1.00 m/s^2, and the apparent mass of the force platform was detected. This result indicated that the low frequency region ranged from 2 to 20 Hz and the high frequency region from 25 to 250 Hz. Signals with nineteen fundamental frequencies at one-third octave center frequencies from 4 to 63 Hz and at one-half octave center frequencies from 2 to 4 Hz and from 63 to 250 Hz were produced. At each fundamental frequency, signals having eight magnitudes of root mean squared values were generated from 0.35 to 4.00 m/s^2 (i.e. 0.35, 0.50, 0.71, 1.00, 1.41, 2.00, 2.80 and 4.00 m/s^2), which are usually applied to a passenger in a vehicle.

One example of a test signal is shown in Fig. 4. The reference signal was taken for 8 seconds to reduce the learning effect before the relative scores for the test signal were measured. Each test signal always had a reference signal prior to the reference signal.

2.2 Apparatus and subjects

The signals were produced by an electric shaker (IMV-i220) installed in the CAE Laboratory of Pusan National University. An accelerometer (Kistler 8310-B10) was mounted at the plate to measure the vertical acceleration applied in the region of the subject's ischial tuberosities. Also, the signals from the accelerometer were sent to the feedback control system (IMV K2Sprint) at 2000 samples per second. For signal processing, the acceleration signals were improved with the Butterworth 9th order low-pass filter. In some experiment related to steering wheel, a steering torque feedback simulator which has brushless DC servomotor is used [9].

Ten Korean male subjects participated in the experiment. Their characteristics are presented in Table 1. They were asked to sit at the center of a flat plate of 630.0 × 630.0 mm dimensions, without a backrest in a comfortable upright posture, with their feet on a foot rest, as shown in Fig. 5.

Table 1. Characteristics of subjects.

	Height (cm)	Weight (kg)	Seated Height (cm)	Seated Weight (kg)	Age (yr)
Mean	176.26	73.99	94.19	60.38	26.71
S.D.	3.94	5.96	2.35	4.45	1.80

Fig. 5. Vibration shaker and posture of subject. (upright, footrest and the palms slightly resting on the knees)

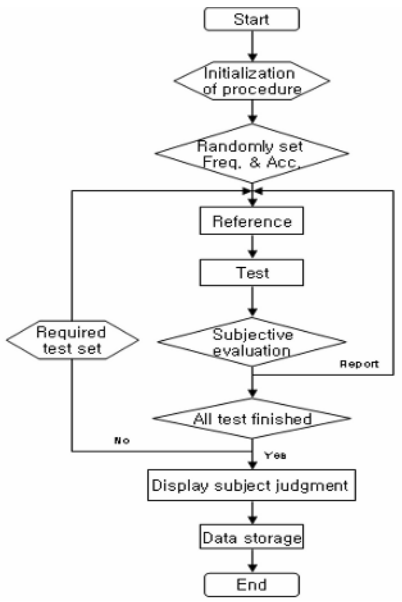

Fig. 6. Flow diagram showing experimental method.

In this experiment, the magnitude estimation method was used for subjective evaluation. All of the reference signals were assigned the score of 200. If a test signal reduced the subject's discomfort by half, then the score was assigned 100. A score of 400 is assigned to the test signal when it doubles the discomfort level. Subjective evaluation was done by two methods. First, it was to evaluate discomfort according to the change of vibration magnitude at any fixed frequency, and the other evaluated discomfort according to the change vibration frequency at any fixed magnitude. In the second method, 0.71 m/s^2 at 16 Hz was set to the first reference signal and 2.00 m/s^2 at 16 Hz to the second reference signal. The rest values were filled with weighting factors obtained by the calculation method of the octave band after evaluating the test signals against the two reference signals. The experiment lasted two hours for each subject.

The procedure of this experiment is presented, as shown Fig. 6, in which all signals were applied randomly and subject's judgment was reported every time.

2.3 Non-parametric statistics

To verify the weighting factors evaluated with the two reference signals, a non-parametric test was carried out because fewer samples were involved. This test is also used when the relationships of ordinal data are considered more important than those of absolute values. The null hypothesis, which says there is no difference between the measured data for the two reference signals, must be defined [10]. The null hypothesis for this research is as follows: there is no difference between the two types of data corresponding to the reference signals of 0.71 m/s^2 and 2.00 m/s^2 at 16 Hz, respectively; and although the reference accelerations were different, they have the same proportion at every frequency. Therefore, the null hypothesis was not rejected for this research. After verifying this hypothesis, a weighting factor matrix was formed. First, the Spearman correlation analysis was performed with relative values about the two reference signals acquired by subjects [10]. If the correlation coefficient between one subject and all the other subjects was less than seventy percent, the subject's data were not used. Second, after calculating the median value for the two reference signals, the Mann-Whitney test was used to verify the null hypothesis, which states that there is no difference between two independent groups [10]. Then, weighting factor matrix could be made by the calculation method of one octave band.

2.4 Psychophysical law

Stevens made psychophysical laws based on the results of various experiments. Stevens' power law is expressed as

$$\psi = \kappa \phi^n \tag{1}$$

where ψ is the sensation magnitude and ϕ is stimulus magnitude [11]. Also, in log-log coordinates, κ is constant, which is the value of the y-intercept, and n is a constant expressing a slope. With this law, we can make equal sensation curves and frequency weighting function. Ebe and Griffin predicted overall seat discomfort by using Stevens' psychophysical power law [12]. Also Hacaambwa and Giacomin used the law and extracted frequency weighting function for fore-and-aft direction whole-body vibration [13]. Jang and Hong plotted equal sensation curves using the magnitude estimation method, and compared the curves were compared to the frequency weighting function for a vertical vibration of a steering wheel [14].

2.5 Filters

The human body has characteristics of low-pass, high-pass and downward or upward step filter, etc. When we make a frequency weighting function, these filters are required to express the characteristics of the human body. These filters can be expressed as

$$|H_h(p)| = \left| \frac{1}{1+\sqrt{2}\omega_1 / p + (\omega_1 / p)^2} \right| \tag{2}$$

$$|H_l(p)| = \left| \frac{1}{1+\sqrt{2}p / \omega_2 + (p / \omega_2)^2} \right| \tag{3}$$

$$|H_s(p)| = \left| \frac{1+p/(Q_3\omega_3)+(p/\omega_3)^2}{1+p/(Q_4\omega_4)+(p/\omega_4)^2} \cdot \left(\frac{\omega_3}{\omega_4} \right)^2 \right| \tag{4}$$

Eqs. (2) and (3) represent the Butterworth 2nd order low-pass filter and the Butterworth 2nd order high-pass filter, respectively. Eq. (4) is a downward step filter having steepness of approximately 6 dB per octave ($\omega_1 \sim \omega_4$ are determined corner frequencies and Q_3 and Q_4 are resonant frequency factors). The frequency weighting function of the Korean people was made by using these three equations.

3. Experimental results

3.1 Verification of subjective evaluation

The relationships among subjects were verified by Spearman correlation analysis. The results are given in Table 2. If the correlation was less than 70 percent, the data were removed for calculating median values, which were used for the Mann-Whitney test. As shown in Table 2, the correlation of subject B had only 33.3 (3/9) percent and that of subject A had only 55.7 (5/9) percent correlation with the other subjects.

Therefore, the data of the two subjects were excluded in constructing the weighting factor matrix because these data were considered to contain errors, which probably occurred during the experiments on the subject's judgment.

Next, median values were extracted from the two kinds of data of the remaining subjects, and the Mann-Whitney test was carried out for two independent groups. The result is shown in Table 3. The Mann-Whitney U is 147.00 and the level of significance of reliability was higher than 95 percent, so these data were considered useable.

Table 2. Relationships among subjects for reference signal of 0.71 m/s^2 at 16 Hz.

	A	B	C	D	E	F	G	H	I	J
A	1		**	*			**	*	**	
B		1		**	*					*
C			1		*	*	**	**	**	**
D				1	*	**	**	**	**	**
E					1	**	*	**	*	**
F						1	*	**	*	**
G							1	**	**	**
H								1	**	**
I									1	**
J										1

Table 3. Mann-Whitney U test for two independent groups (16 Hz, 0.71 m/s^2 and 16 Hz, 2.00 m/s^2).

	Test of difference between two acceleration references
Mann-Whitney U	147.000
Exact Sig. [2* (1-tailed Sig.)]	0.339

3.2 Equal sensation curves and frequency weighting function

Subjective evaluation data obtained by nonparametric statistics were matched with objective data measured by the accelerometer. Here, objective data were verified by checking the difference between the input and output acceleration signals. This result is shown in Table 4, in which the input is the required acceleration, the output is measured acceleration and O_S.D. is the standard deviation of the output.

To make the equal sensation curves, the values of κ and n were found by using the psychophysical power law. In other words, the error of the regression analysis obtained by using the median values of the subjective evaluation points in all the level of acceleration at a fixed frequency had to be minimized. Then, coefficients κ and n in Table 5 were obtained at one octave center frequencies. Determination coefficients were close to 1; therefore, equal sensation curves could be plotted, as shown in Fig. 7. The lowest curve represents a subjective evaluation score of 40. When the score is 200, the fifth contour from the

Table 4. Input and output signals and standard deviation about signals.

Input (m/s^2)	0.35	0.50	0.71	1.00
Output (m/s^2)	0.33	0.49	0.70	0.99
O_S.D. (m/s^2)	0.01	0.01	0.01	0.01
Input (m/s^2)	1.41	2.00	2.80	4.00
Output (m/s^2)	1.42	1.98	2.84	3.97
O_S.D. (m/s^2)	0.02	0.02	0.03	0.05

Table 5. Parameters of regression analysis.

	2.0 Hz	4.0 Hz	8.0 Hz	16.0 Hz
κ	148.5	232.5	257.1	203.4
n	0.830	0.940	1.290	0.897
R^2	0.969	0.982	0.992	0.981
	31.5 Hz	63.0 Hz	125.0 Hz	250.0 Hz
κ	168.5	90.2	81.9	29.8
n	1.190	0.879	0.846	1.106
R^2	0.980	0.941	0.837	0.959

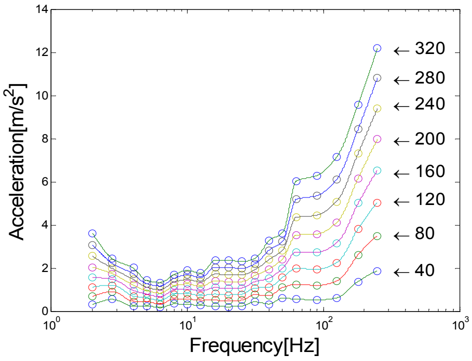

Fig. 7. Equal sensation curves about various sensation magnitudes.

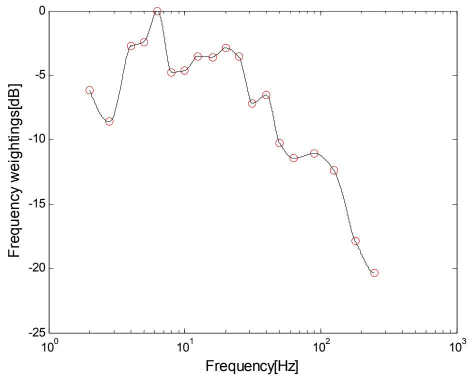

Fig. 8. Frequency weighting values for Korean about 80 score of subjective evaluation.

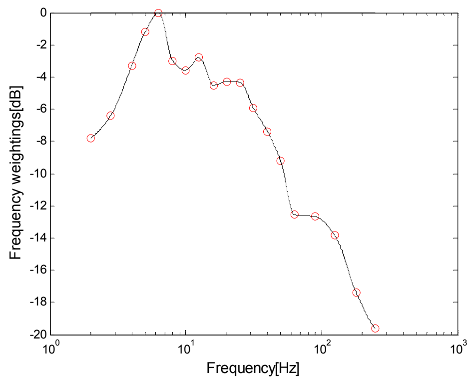

Fig. 9. Frequency weighting values for Korean about 200 score of subjective evaluation.

lowest curve is observed. The most sensitive region is from 4 to 8 Hz, and the sensitivity at higher frequencies, especially 180 and 250 Hz, falls rapidly.

Observing the effect of acceleration magnitude, almost the same phenomena occurred. But at a higher amplitude level, the effect near the resonant region is

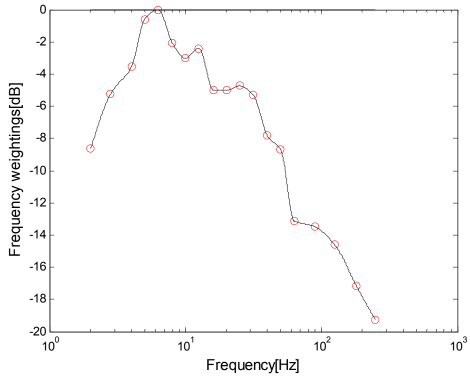

Fig. 10. Frequency weighting values for Korean about 320 score of subjective evaluation.

sharply increased. The frequency weighting function for Korean people is shown in Fig. 8-10. These figures show that the most important region in the seated posture of Korean people corresponds to the a frequency range from 4 to 8 Hz. In this region, most people felt extremely uncomfortable from the vertical whole-body vibration and experience a resonant frequency. Over 50 Hz, most people felt an uncomfortable level that was more than one-third compared with the maximum uncomfortable level.

3.3 Frequency weighting function

The measured data were used to make a frequency weighting function for the Korean people. A plot compared with ISO 2631-1 is shown in Fig. 11. The shapes of the two curves are a little different, but they have a similar tendency. In the frequency region of interest, the frequency weighting function for the Korean people has changed less than that of ISO 2631-1.

4. Discussion

4.1 Through the experiment

This experiment was performed with two kinds of methods. The first subjective evaluation data were obtained by changing the acceleration magnitudes. In this experiment, the score of the subjective evaluation was increased according to the increment of the acceleration magnitude. So, it is concluded that an increase of acceleration causes a decrease of comfort. And a nonparametric test was not needed because the distribution of the scores for all frequencies showed a similar tendency. Subjective evaluation of the second method is collected when the center frequencies are considered as independent variables. In this second experiment, subjects had some difficulty in deciding the scores about the reference signal, so they showed some differences in scoring. So, nonparametric tests such as the Spearman correlation analysis and the Mann-Whitney test were used for the second case. Consequently, the subjective evaluation data was proper for deriving the frequency weighting.

This experiment was done in the frequency range of 2~250 Hz and at acceleration levels of 0.35~4.00 m/s^2. One kind of signal is shown in Fig. 4 which is verifying that signals are very uniform, consistent and reliable. And as shown in Table 4, the objective data are similar to the input signals and have very small standard deviation. This means that the subjective evaluation of the subjects was carried out without external effects such as shock signals and inconsistent signals, etc. Therefore, it can be confirmed that this experiment was performed with reliable signals.

4.2 Equal sensation curves

In the equal sensation curves shown in Fig. 7, the points are densely populated at 4-8 Hz, especially at 5 and 6.3 Hz. In this region, the Korean people respond most sensitively. The lowest curve shows that it is 5 times more comfortable than the reference score (200). At this score, the degree of discomfort is very similar through the entire frequency region. In other words, much lower vibration amplitudes yield almost the same level of comfort through the frequency region. The fifth curve from the lowest level is the score of 200. The comparison of this curve with the other low curves shows that at very high vibration amplitude and frequencies, especially from 180 to 250 Hz, most Korean people feel the same level of discomfort. This also means that high frequencies can be affected by acceleration levels. At 16-31.5 Hz and 63-125 Hz, the curve for the Korean people is shown as almost flat; this means most Korean people feel almost the same sensation, regardless of frequency changes. From the equal sensation curves, it is possible to find the frequency weightings at every score of subjective evaluation by a reciprocal of the curves, as shown in Fig. 8-10.

4.3 Comparison with ISO 2631-1

The characteristics of Western people differ from that of Asian people, so it may be unreasonable to apply ISO 2631-1 to Asian people.

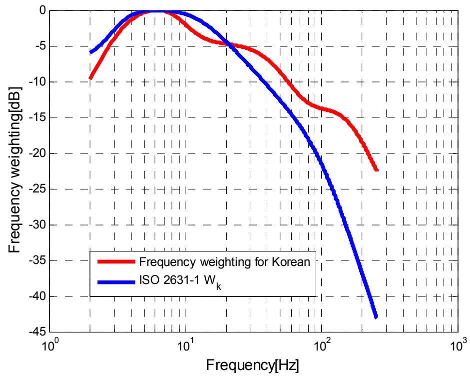

Fig. 11. Comparison between ISO 2631-1 (Wk) and frequency weighting function for Korean.

The frequency weighting function for the Korean people and that of ISO 2631-1 are shown in Fig. 11. The maximum frequency weighting function for the Korean people is located at 6.3 Hz, which means that the Korean people have the most sensitivity at this center frequency. This result is a little different from ISO 2631-1, which gives similar weightings from 4 to 8 Hz. In regions lower than 6.3 Hz, the slope of frequency weighting function for Korean decreases at about 10 dB/octave (6 dB/octave in ISO2631-1); this also indicates that the Korean people are more sensitive than Western people to acceleration levels in that region. In regions above 6.3 Hz, the frequency weightings cross each other at 11 Hz. At 5-11 Hz, ISO 2631-1 gives higher weightings, but above 11 Hz it gives lower weightings than that found for the Korean people. Change of frequency weighting function for the Korean people is generally smaller than that of ISO 2631-1. For that of the Korean people, flat regions appear at 10.5~12.0 Hz and 60~110 Hz. These regions do not appear in ISO 2631-1, and this result means that insensitivities are almost constant in those regions. At 250 Hz, the values are different. The insensitivity of ISO 2631-1 is about 10 times higher than that of the frequency weighting function for the Korean people. This is a numerically large difference, but with respect to vehicle ride comfort.

5. Conclusion

Subjective evaluation for the Korean people was carried out. This evaluation was divided into high frequency and low frequency ranges because of the ability of the vibration shaker. And two kinds of experiments about frequency and magnitude were performed. The subjective evaluation values were verified by non-parametric tests such as the Spearman correlation analysis and the Mann-Whitney test. Next, the verified data were used to combine with each other. To verify the objective data, signal processing was performed by acceleration signals. Parameters κ and n were obtained from a psychophysical law, and then equal sensation curves were plotted by using these values. Also the frequency weighting function for the Korean people normalized by the maximum weighting was shown as median values of the subjective evaluations. Finally, the frequency weighting functions for the Korean people and ISO 2631-1 were compared with each other.

A little irregularity was included in the shape of the frequency weighting function for the Korean people, but a gentle shape was presented in ISO 2631-1. It is possible that these different results are caused by the differences of the characteristics and shapes of bodies, errors included in the excitation signals, and a sampling error of the Korean people. Therefore, more subjects and various groups have to participate in future experiments.

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