Fundamental Study on the Effect of High Frequency Vibration on Ride Comfort*

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Abstract
To develop a more suitable method of evaluating ride comfort of high speed trains, a fundamental study was conducted on sensitivity of passengers to various frequencies of vibration with respect to ride comfort. Experiments were performed on 55 subjects using an electrodynamic vibration system that can generate vibrations in the frequency range of 1 to 80 Hz in the vertical direction. Results of experiments indicated that the subjects tend to experience greater discomfort when exposed to high frequency vibrations than that presumed by the conventional Japanese ride comfort assessment method, the "Ride Comfort Level."

Key words: Ride Comfort, Ergonomics, High Speed Trains, Evaluating Method

1. Introduction
The recent increase in magnitude of the components of high frequency vibrations at around 30 Hz, influencing on passenger ride comfort, has become a subject of discussion on high speed trains. The conventional Japanese ride comfort assessment method, known as the "Ride Comfort Level (RCL)," is growingly considered to be insufficient because the method involves frequency dependent weighting factors that are extremely small for such high frequencies.

To develop a more suitable method of evaluating ride comfort of high speed trains, a fundamental study was conducted on sensitivity of passengers to various frequencies of vibration with respect to ride comfort. In the study of ride comfort, it is necessary to examine both vertical and horizontal vibration. However, this paper reports the results of the experiments for vertical vibration because the high frequency vibrations in the vertical direction are remarkable.

2. Ride Comfort Level (RCL)
RCL is a method which evaluates ride comfort by calculating evaluation values using a frequency weighting curve (FWC) based on ‘equivalent sensitivity contours (ESC) (Fig. 1).’ ESC was modified by the former Japanese National Railways (JNR) on the basis of ISO 2631 (proposed in 1974, revised in 1985). The important point of focus is that ESC does not express changes in comfort/discomfort. The value of ESC at each frequency corresponds to the same magnitude of vibration perceived by subjects as that of 20 Hz, which is the reference frequency used for comparison.
Figure 2 shows the FWC based on ESC, $W_k$ (ISO 2631-1 proposed in 1997) and $W_b$ (ISO2631-4 proposed in 2000) for the vertical direction. ISO 2631-1 is a revised edition of ISO 2631 proposed in 1974 and presents the guidelines for general requirements. ISO 2631-4 presents the guidelines for the evaluation of effects of vibration and rotational motion on passenger and crew comfort in fixed-guideway transport systems.

The relationship between ESC and FWC used in the RCL method is shown by the next equation.

$$\text{Value of FWC} = -20 \log_{10}(A/A_0) \ [\text{dB}] \quad (1)$$

$A$: value of ESC

$A_0$: 0.315

3. Method of Experiments

3.1 Subjects

The subjects, 46 males and nine females, all indicated that they were in good mental and physical health. All subjects were members of the railway industry. The ages of the subjects ranged from 22 to 59 years, with a mean age of 38.9 years. The height of the subjects ranged from 154.5 to 184 cm, with a mean height of 169.4 cm.
3.2 Electrodynamic vibration system

Experiments were performed using the three-axis simultaneous electrodynamic vibration system (TS-600-20x10L produced by IMV Inc., Fig. 3) that generates vibrations in the frequency range of 1 to 80 Hz.

![Fig. 3 Electrodynamic vibration system and a subject sitting on a double seat](image)

3.3 Procedure

The subject sat on the left side of a double seat used in a “Shinkansen” high-speed express train, which was installed on the platform of the vibration system. The vibration input of the platform used as stimuli consisted of 16 types of vertical sine waves with frequencies of 1, 2, 4, 5, 6.3, 8, 10.1, 12.7, 16, 20.2, 25.4, 32, 40.3, 51, 64 and 81 Hz respectively. The magnitude of vibration acceleration was set such that the root-mean-squared (rms) value was the same in each stimulus. The acceleration amplitude was increased gradually from 0.04 m/s² to 1.7 m/s², then held at the maximum for two seconds, then decreased gradually and stopped (Fig. 4). The length of one stimulus was about one minute. The subjects pushed a button when they judged the magnitude of the vibration to be too large for them to permit from the perspective of ride comfort, on the assumption that they were riding on the Shinkansen train.

The vibration of the platform was measured by an accelerometer for three directions: forward-backward (X), lateral (Y), and vertical (Z) directions. The seat vibration was measured by the same type of accelerometers at two points, on the seat-surface and seat-back. The accelerometers for the seat were attached to seat cloth and covered by urethane sheets, 8 mm thick.

The subjects answered a ride comfort questionnaire after each vibration test carried out using one of the 16 types of vertical sine waves with the respective frequencies mentioned.

![Fig. 4 Example of the change of vertical vibration as stimulus (10.1 Hz)](image)
above. The subjects selected the most suitable evaluation classifications to describe their impressions of the vibration from the eight evaluation classifications, for example, “swaying,” “machine-like vibration,” “chatter vibration,” “awkwardness” and “sickness,” in the first question, and scored the degree of discomfort in the second question of the questionnaire.

4. Results and Discussion

The black solid line including data points in Fig. 5 shows the average values of the vertical acceleration rms on the platform when the subjects pushed the judgment button, and can also be described as the “threshold vibration curve (TVC)” for the Shinkansen. The gray solid line indicates ESC in the RCL method. The minimum values of both curves are at around 5 Hz, but the slope of the threshold vibration curve is not as steep as that of the ESC above 16 Hz. Results of experiments indicate that the subjects tend to experience greater discomfort when exposed to high frequency vibrations than the discomfort assessed by RCL.

The black solid line in Fig. 6 shows the curve transformed by the equation (1) from TVC, and the gray line shows FWC. In addition, the red line shows the average values of the scores from the answers of the subjects with respect to the degree of discomfort (on a scale of hundred).

These results that vibrations over 30 Hz caused stronger discomfort in subjects than that estimated by RCL are extremely important. On the contrary, the values of the discomfort score and threshold vibration did not decrease at vibration frequencies over 30 Hz.

There might be several reasons for these results, but the most important reason is the difference between the methods by which ESC and TVC were derived. As described in Chapter 2, the value of ESC at each frequency corresponds to the same magnitude of vibration perceived by subjects as that of 20 Hz, which is the reference frequency used for comparison. However, the criterion of ride comfort should not be ‘magnitude,’ but ‘comfort/discomfort.’ In the past, there would have been no problem using RCL because the main frequency components of train vibrations were below 16 Hz, and there was little difference between the sensitivities to ‘magnitude’ and ‘comfort/discomfort’ in that range. However, recently the high frequency components over 16 Hz have increased to such a
large degree as to affect the ride comfort. Therefore, the problem of the divergence of ESC and TVC at high frequencies has become obvious.

Figure 7 shows the transfer ratio of acceleration of the seat-surface for the vertical direction (Z), and the seat-back for the Z direction and forward-backward direction (X) to the floor acceleration for the Z direction. The results showed that the resonant frequency of the seat-back (Z) was 50 Hz. This resonant vibration of the seat-back was considered to have influence on the slight decrease in the TVC at 50 Hz in Fig. 5. The peak ratio of the seat-surface (Z) and seat-back (X) might be caused by the resonant frequency of the subject’s body.

Figure 8 shows the selected ratio of subjects that chose the eight evaluation classifications and the discomfort score that described the subjects’ impression of vibration at the 16 different frequencies in the questionnaire. The results indicate that the three of four items of which the selected ratio peaked at frequencies below 16 Hz, “swaying,” “shaking” and “machine-like vibration,” are related to the magnitude of vibration. The fourth item that
peaked at a frequency below 16 Hz, “sickness,” suggests that low frequency vibration caused the subjects to feel discomfort, such as motion sickness. On the other hand, the three items of which the selected ratio peaked at frequencies over 16 Hz, “chatter vibration,” “numbness” and “awkwardness,” are the characteristic discomfort items at high frequencies. The existence of such characteristic discomfort items are the most probable cause of the divergence of ESC and TVC at high frequencies.

Figure 9 shows the selected ratio of subjects that answered freely in the questionnaire about the parts of their bodies that were particularly sensitive to vibrations at the 16 different frequencies. The results indicate that vibrations below 10 Hz tended to have effects on the head and abdomen, vibrations at around 10 Hz tended to have effects on the face and thigh, and vibrations above 10 Hz tended to have effects on the legs, hips and back.
5. Conclusion

This study investigated the influence of high frequency vibration on ride comfort. The result of the experiments showed that the sensitivity of passenger’s ride comfort to high frequency vertical vibration seems to be higher than that presumed by RCL. The results suggest that it is important to consider the influence of high frequency vibration on ride comfort. However, it is not clear why TVC does not increase at frequencies over 25 Hz. It is presumed that the audio sound of the same frequency as that of the vibration is one reason that influences the rise in sensitivity. Of course, the dynamic characteristics of the seat are important when examining the passenger sensitivity to vibration. The RCL was derived using rigid seats. However, the experiments used an actual seat with cushion in order to examine the vibration sensitivity of passengers in actual trains, because there are no rigid seats for passengers in high speed trains in Japan. The results of the experiments suggest that the momentary increase in sensitivity at 50 Hz might be caused by resonant vibration of the seat-back. However, the transfer ratio of the vibration on the seat-surface to the vibration on the floor tended to decrease above 10 Hz. In other words, subjects experienced discomfort even though the vibration of the seat-surface decreases above 10 Hz because of the cushion.

In the next phase of this study, it is necessary to research the influence of sound on the ride comfort and TVC for directions of vibration other than the vertical direction. This study is aiming for the development of a more suitable method of evaluating “Shinkansen” ride comfort.

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