Abstract

The objective of the work presented in this paper is to improve discomfort indicators for standing passengers in train specifications. Previous studies conducted by SNCF (Gallais et al., 2009) showed that the standardized estimators (Nvd, Nmv from ENV1229, 2009; and VDV for ISO2631, 1997) of standing passengers underestimated the discomfort perceived and especially when the discomfort felt is important. These estimators are currently calculated using frequency filters that have been established with seated subjects. It was hypothesised that the human response to vibration may differ between standing and seated postures requiring different frequency weightings. In this study, the effects of vibration frequency (narrowband random centred at 0.5 Hz, 1 Hz, 2 Hz, 4 Hz, 6 Hz and 8 Hz), magnitude (from 0.125 to 1.6 m.s^{-2} rms) and direction (fore-and-aft and lateral) on discomfort was evaluated with two groups of 15 subjects. On group was composed of “young subjects” (between 22 and 35 years old); the second group was composed of “elderly subjects” (between 50 and 70 years old). Frequency weightings were derived from comfort contours, which were measured using the magnitude estimation method. The frequency weightings obtained in this study show different behaviour than the one proposed by the standard (e.g. Wd from ISO 2631, 1997). Results also show an effect of age amplified by low frequency fore-and-aft vibrations. This paper presents results in agreements with recent studies (Thuong and Griffin, 2010) suggesting that the prediction of standardized estimator may be improved by using frequency weighting adapted to standing postures.

1. Introduction

One major source of discomfort in public transport is vibration transmitted to the body. Vibrations affects passengers’ practice of activities while seating like working on laptop, writing, sleeping but also in standing position when walking to restaurant coach or toilets or when ranking baggage. Improvement of standing comfort is also an important issue for suburban trains. Discomfort due to vibration can be estimated using standardized estimators such as VDV (ISO 2631, 1997), Nmv, Nva, Nvd (ENV 12299, 2009). The performance of these estimators was evaluated during a test campaign on board of a double-decker TGV train (Gautier et al., 2010). Results have shown that although the standardized dynamic estimators for seated subjects seemed to be correlated with the subjective measurement acquired, the estimators for standing subjects underestimated the discomfort experienced by the standing subjects (Gallais et al., 2009).

The standardized estimators all used filtered accelerations to estimate the level of dynamic discomfort. These filters, also called frequency weightings, were obtained with experimental studied performed on seated subjects. It is reasonable to suggest that the behaviour of seated subjects may differ from the standing subjects requiring different frequency weightings.

Since 2007, SNCF has launched two projects with the Human Factors Research Unit of the Institute of Sound and Vibration (Southampton, UK), and one study was performed in collaboration with the Ergonomic laboratory of the Railway Transport Research Institute (Tokyo, Japan), in order to better understand the mechanisms explaining discomfort and stability experienced by standing and walking subjects exposed to vibrations.

This paper is focused on an aspect of the study conducted in the Ride Comfort Simulator of the RTRI focusing on the frequency weightings of standing subjects exposed to horizontal vibrations. Most of the studies conducted with standing subjects have investigated response to vertical vibration. Figures 1 and 2 present results obtained by various studies reviewed by Thuong and Griffin (2008), showing perception threshold and comfort contour of standing subjects exposed to horizontal vibration.
These data show that perception threshold and discomfort of standing subjects tend to have the same behaviour: sensitivity to vibration acceleration decreases as the frequency increases. The perception threshold data seem to show that at a certain frequency standing subjects are less affected by the frequency of the acceleration. This behaviour does not correspond to the frequency weightings ‘Wd’ proposed by the standards.

The hypotheses investigated in this paper are:
- Discomfort of standing subjects exposed to horizontal vibration depends with vibration frequencies, showing two behaviours. For low frequencies, discomfort increases with frequencies; as the vibration frequency increases discomfort becomes less dependant on frequency.
- Discomfort at low frequencies is mainly due to stability issues.
- Age of the subjects have an effect of the frequency weightings, especially at low frequencies.
2. Method

2.1 Subjects

The study required the participation of 30 subjects. Among these 30 subjects, 15 subjects are between 22 and 35 years old, and the other fifteen subjects are in another age group, between 50 and 70 years old. Subjects are representative of the Japanese population in terms of size and weight and were all males. Each subject took part in one session of one hour and half (which includes also the walking study not presented in this paper). They all signed a consent form and the experimenter made sure they were fit to perform the tests.

2.2 Experimental set-up

The study was undertaken on the ride comfort simulator of the RTRI (see Figure 3). The simulator was in a configuration with a corridor and seats on each side, to be as close as possible as in a real train environment. Subjects were positioned as in Figure 3 so subjects can grab easily a backrest in case of loosing balance. The external stimuli were controlled (i.e. acoustic noise, visual field) so that the judgement of discomfort is only due to the vibration inputs and not on the noise or the external visual field, which can be used by the subjects to judge the intensity of the magnitude motions instead of the discomfort induced by these motions. To achieve this, subjects were wearing headphones playing a white noise at 74 dBA and the window of the cabin had a curtain.

2.3 Stimuli

The stimuli have two waveforms: narrowband random vibration and shocks. Narrowband random vibrations are centred at 0.5, 1, 2, 4, 6 and 8 Hz. The waveforms of the shocks were designed using measured acceleration data acquired on board of High Speed Trains. Narrowband random vibration and shocks are investigated in the lateral and fore-and-aft directions for standing subjects; lateral and roll shocks are investigated for walking subjects (results of walking subjects are not presented here). For each frequency, waveform and direction, seven magnitudes are used. The Table 1 is listing all the stimuli that were used in these studies. The direction is relative to the subjects. Figure 4 shows some examples of the stimuli used (one shock and one narrowband random vibration).
Table 1 List of stimuli (only results of the standing conditions are presented in this paper)

<table>
<thead>
<tr>
<th>Direction</th>
<th>Lateral</th>
<th>Fore-and-aft</th>
<th>Roll</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waveform</td>
<td>Shock</td>
<td>Shock</td>
<td>Shock</td>
</tr>
<tr>
<td>Frequency [Hz]</td>
<td>0.5 1 2 4 8</td>
<td>0.5 1 2 4 8</td>
<td>0.5 1 2 4 8</td>
</tr>
<tr>
<td>Duration [s]</td>
<td>6 6 6 6 6</td>
<td>6 6 6 6 6</td>
<td>1.5 1.5</td>
</tr>
<tr>
<td>Waveform</td>
<td>Narrowband random</td>
<td>Narrowband random</td>
<td>Shock</td>
</tr>
<tr>
<td>Acceleration [m.s(^{-2}) r.m.s.</td>
<td>0.125</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Frequency [Hz]</td>
<td>0.16</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Acceleration [m.s(^{-2}) r.m.s.</td>
<td>0.2</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Frequency [Hz]</td>
<td>0.25</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Acceleration [m.s(^{-2}) r.m.s.</td>
<td>0.315</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Frequency [Hz]</td>
<td>0.4</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Acceleration [m.s(^{-2}) r.m.s.</td>
<td>0.5</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Frequency [Hz]</td>
<td>0.63</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Acceleration [m.s(^{-2}) r.m.s.</td>
<td>0.8</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Frequency [Hz]</td>
<td>1</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Acceleration [m.s(^{-2}) r.m.s.</td>
<td>1.25</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Frequency [Hz]</td>
<td>1.6</td>
<td>*</td>
<td>*</td>
</tr>
</tbody>
</table>

Stimuli used in walking study only
Stimuli used in standing study only
Stimuli used in both standing and walking studies

Figure 4 Examples of stimuli used in the studies.
2.4 Procedure

The method used to obtain the comfort contours and the frequency weighting curves is the magnitude estimation method. In this method the subject is exposed to pairs of stimuli. The first stimulus is the reference stimulus and we assigned a value of discomfort of 100. The second stimulus is the test stimulus. For each pair presented, the subject has to determine the level of discomfort of the test stimulus relative to the reference stimulus. For example if the test stimulus is felt twice more uncomfortable than the reference stimulus, the subject will have to assign the mark 200 (see Figure 5).

Figure 5 Example of a pair of stimuli used in the magnitude estimation method.

For the standing session, all subjects were positioned at the same location in the cabin (see Figure 3). They were asked to use the backrest of the seat only if necessary (in case of loosing balance). The presentation of the stimuli is randomised.

The reference stimulus (taken from the stimuli used) was chosen so that half of the test stimuli are expected to produce more discomfort and the other half is expected to produce less discomfort than the chosen reference stimulus. The reference stimulus was a fore-and-aft narrowband random vibration at 2 Hz with a magnitude of 0.5 m.s$^{-2}$ rms (obtained from preliminary study performed with sine waves at ISVR – SNCF internal report Thuong and Griffin 2008). Only one reference was chosen for both direction of excitation. Because the simulator is 6-axis, it is possible to play the reference in the fore-and-aft direction and then a lateral test stimulus, without asking the subjects to change his position.

After the presentation of each test stimulus, in order to determine the probability of loosing balance depending on the frequency, magnitude and waveform of the stimulus, the subjects were asked:

"What is the probability that you would lose balance if the same exposure were repeated?"

At this question, subject are expected to give a percentage of chance of loosing balance (e.g. ‘If exposed to the same stimulus, I have 40% chance of losing balance’)

The analysis of the results gives a magnitude threshold to guaranty stability for various stimuli. It also allows the evaluation of the boundary between the judgement of discomfort unaffected by the stability and the judgement of discomfort affected by stability issues.

2.5 Data processing

The magnitude estimation test was analysed by Stevens’ power law, which is used to relate the subjective value given by a subject exposed to a stimulus, $\psi$, to the physical magnitude of the stimulus, $\phi$ (Stevens, 1975):

$$\psi = k \phi^n$$

or in the logarithmic form:

$$\log (\psi) = \log (k) + n \log (\phi)$$

Where $k$ (referred to as the ‘constant’ in Stevens’ power law) and $n$ (referred to as the ‘exponent’) are assumed to be constant for a given stimulus. In this study, $\phi$ is the magnitude of the measured acceleration of the vibration. By performing linear regressions between the experimental values of $\log (\psi)$ and $\log (\phi)$, estimates of the constant $k$ and the exponent $n$ were obtained for each subject. Equivalent-sensation contours were derived using the ‘inverted’ form of Stevens’ power law: For any
level of discomfort, $\psi$, this equation gives the acceleration, $\varphi$, needed at each frequency to achieve this level of discomfort.

3. Results

3.1 Equivalent sensation contours

Equivalent sensation contours curves are calculated from the data acquired during the magnitude estimation method. Figures 6 and 7 show discomfort contour curves at three levels of discomfort (70, 100: reference and 140) obtained for lateral, fore-and-aft stimuli and for young and elderly groups of subjects. These curves represent for each frequency, the acceleration magnitude required to produce the same level of discomfort. Frequency weighting curves are the inverse of these equivalent sensation contours. One of the objectives of these curves is to evaluate the non-linearity of the response of the subjects with the magnitude of the excitation. Frequency weighting curves are indeed the inverse of these equivalent sensation contours and if they are non-linear, complex frequency weightings curves should be built including dependence on the excitation magnitude.

![Comfort contours Fore&Aft direction](image)

![Comfort contours Lateral direction](image)

**Figure 6** Equivalent sensation contours with subjects of the young group

In most cases the discomfort contour curves show that to perceive equivalent discomfort, the magnitude of the vibration needs to increase with increasing frequency. Standing subjects of both groups (young and old) found that vibration is more uncomfortable at 0.5 Hz and then as the frequency increases the body seems to be less sensitive. Shocks may be less critical for discomfort than very low frequency vibrations, but that may vary on the way the vibration magnitudes is quantified (peak to peak or rms…). For most cases, the behaviour of the discomfort contour curves seems to be similar at different levels of discomfort.

*Effects of age and direction of excitation on equivalent sensation contours*
Figures 8 and 9 show the discomfort contour curves at the level of the reference stimulus (100). It allows comparison of the effects of age group and direction of excitation on discomfort.

**Figure 7** Equivalent sensation contours with subjects of the elderly group
Figure 8 Equivalent sensation contours (effect of direction of excitation)
Figure 9 Equivalent sensation contours (effect of age group)

For low frequencies, between 0.5 Hz and 2 Hz, fore-and-aft excitation seems to be felt more uncomfortable than lateral excitation. Then, at 6 Hz and 8 Hz, the sensitivity of the subject to lateral vibration increases and lateral vibrations become more uncomfortable than fore-and-aft excitations. Age seems to have an effect at low frequencies, between 0.5 Hz and 2 Hz, with older subjects being more sensitive to the vibration than younger subjects. Above 2 Hz, the comfort contour curves between the two age groups become very close.

3.2 Probability of loosing balance

Figures 10 and 11 show the median percentage of probability of loosing balance at each frequency for stimuli at 0.5 m.s$^{-2}$ rms. This magnitude was chosen because it has been used at all frequencies. The Figures show that there are high issues of stability at 0.5 Hz and 1 Hz. At 0.5 Hz most subjects lost their balance. After 2 Hz and at this magnitude, stability is no longer an issue. Shocks at this magnitude are not critical for balance. It seems that there is an important effect of the direction of excitation: fore-and-aft stimuli generate more stability issues than lateral stimuli. It seems also that the elderly group had higher probability to loose balance than subjects from the young group.
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![Graph 10](image10.png)

**Figure 10** Probability of loosing balance for standing subjects exposed to stimuli at 0.5 m.s^{-2} rms (effect of direction of excitation).

![Graph 11](image11.png)

**Figure 11** Probability of loosing balance for standing subjects exposed to stimuli at 0.5 m.s^{-2} rms (effect of the age group).
With these results, it is already possible to see that for 0.5 Hz and even 1 Hz vibrations, a magnitude of 0.5 m.s\(^{-2}\) rms is already too high to guarantee the stability of standing passengers.

4. Discussion

4.1 Frequency weighting

Because frequency weightings are used to filter the accelerations measured to represent the human behaviour when exposed to whole-body vibrations, frequency weightings are the inverse of the equivalent sensation contours (frequency weightings = 1 / equivalent sensation contours). The frequency weightings have been normalised at the frequency where subjects were the most sensitive, which was for the frequencies studied 0.5 Hz. Figure 12 shows the frequency weightings for lateral and fore-and-aft stimuli obtained with the young group of subjects compared to the current standardised “Wd” frequency weighting and the frequency weightings obtained with sinusoidal stimuli at ISVR (Thuong and Griffin, 2010).

**Figure 12** Comparison of the frequency weightings with the equivalent sensation contours obtained with the young subjects with the standardized frequency weightings and the frequency weightings obtained by ISVR (Thuong and Griffin 2010)

The main result to observe is the difference between the current standardised frequency weighting “Wd” and the ones obtained by ISVR (Thuong and Griffin, 2010) and in this study. The “Wd” suggests that vibrations between 0.5 Hz and 2 Hz produce (at the same acceleration magnitude) similar level of discomfort, whereas the other frequency weightings suggest that discomfort decreases as the frequency increases until 2 Hz. After 2 Hz, “Wd” suggests that discomfort decreases continuously with increasing frequency, whereas, the other frequency weightings suggest either an increase of sensitivity or a stability. The frequency weighting from ISVR shows a greater sensitivity between 4 Hz and 6 Hz.

The other noticeable result is the difference between the lateral weighting proposed by ISVR and the lateral frequency weighting obtained in this study. They have generally the same tendencies. However, it seems that the frequency weightings obtained in the lateral direction by ISVR is closer to the fore-and-aft frequency weighting than the lateral frequency weightings obtained in this study. There are possible reasons explaining this:
- The frequency weightings are obtained by taking the inverse of the equivalent comfort contours and then there is a normalisation realised by dividing all the points of the curve by the acceleration of the frequency where the sensitivity is the greatest. Therefore the relation between the frequency weighting curves will depend greatly on the value of the data point used for normalisation.
- It should be reminded that the frequency weighting curve obtained by ISVR was built with sine waves whereas the frequency weightings obtained in this study were built with narrowband random vibrations.

4.2 Relationship between stability and equivalent sensation contours

From the various results presented a link between stability and discomfort can be suggested. Equivalent sensation contours showed that subjects are more sensitive at low frequencies, where high probability of loosing balance is observed. This is also reinforced by the fact that the elderly group, which had higher probability of loosing balance, perceived in general more discomfort than the group of young subjects.

5. Conclusion

This study has shown that the standardised frequency weightings “Wd” used in estimators of dynamic discomfort seems not adapted for standing subjects. The probability of loosing balance showed some relationships with the equivalent sensation contour curves, effects of the age group and direction of excitation. These relationships suggest that the frequency weighting at low frequencies may be affected by stability.

Standardized estimators used to estimate discomfort should be used carefully to specify dynamic discomfort of high speed trains. Their performance may be improved by using more adapted frequency weighting. Further work should be performed to suggest and validate improvement of these estimators.

6. References

O.Thuong and M.J.Griffin, 2008: Internal report for SNCF.
ENV 12299, 2010 Railway applications. Ride comfort for passengers.