Perception Thresholds for Sinusoidal and Impulsive Vibration on the Brake Pedal

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1 Introduction

Vibrations inside vehicles affect the subjective comfort feeling of the driver. ABS and ESP cause vibrations due to modulation of the brake pressure. These systems excite vibration mainly at the brake pedal. While many publications are concerned with human response to vertical whole-body vibration for seated subjects, very few data are available on foot-transmitted vibration [1]. Suggestions of existing standards on human exposure to whole-body vibration [2] need to be checked for their applicability on brake pedal vibration perception. In our investigation vibration perception thresholds for brake pedal vibration are measured with subjects sitting in a realistic vehicle simulator representing the particular posture and pedal forces during braking.

2 Experimental conditions

All tests are done in a simulator, consisting of a vehicle cabin with no doors, real vehicle seats and interior. Also the pedal unit is taken from a real vehicle. An electrodynamic shaker is used for brake pedal excitation. The excited pedal unit is de-coupled from the cabin. Background vibration at the floor pan, steering wheel and seat is less than 1 mms^{-2} in either case with and without excitation of the brake pedal. The background vibration is not perceivable. The environmental noise level is below 30 dB(A) for the whole hearing range. During the experiments the participants wear closed headphones, reducing the background noise by another 10 dB. The noise radiated by the shaker is inaudible. During each experiment the force applied to the brake pedal is continuously measured. The acceleration at the foot is measured directly at the plantar area inside the shoe using the "plantar pad" (see Figure 1).

2.2 Signals

The signal duration is 3 seconds in each case. The sinusoidal stimuli have fixed frequencies between 10 and 500 Hz. Two carrier signals at 63 and 125 are amplitude modulated with a sine (modulation index=1) and a square wave, respectively, at either 5 Hz or 10 Hz, leading to eight impulsive stimuli.

2.3 Procedure

Four experiments are conducted: brake pedal excitation with sinusoidal vibration at pedal forces F_P=40, 100 and 300 N, respectively, and excitation with impulsive vibrations at a pedal force of 100 N. A staircase procedure with an adaptive step size decreasing by 6 dB after each upper reversal is used to estimate the vibration perception thresholds (VT) at 50%-level for positive response [3]. All participants wear shoes and normal clothes. The pedal force is shown to the subjects on a monitor. During signal play back, the subjects are asked to push the brake pedal constantly with the requested F_P and to keep their heels on the floor pan. Signal play back starts only if the actual F_P is +/- 10% of the requested. If the mean F_P over one signal is not in the same range, this signal is excluded from further evaluation. During an experiment only one type of stimulus is presented and one pedal force is requested. Signals are presented randomly. All presented VT are determined as the medians of the individual VT.

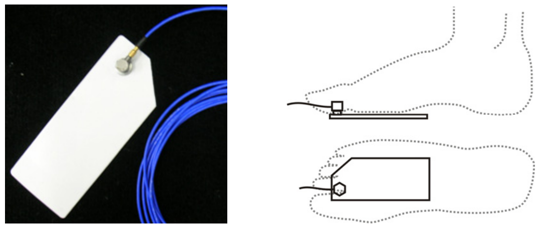

Figure 1: Measurement of acceleration transferred to the foot using the plantar pad. The plantar pad consists of a rigid metal plate with an accelerometer mounted at one corner. It is easily inserted into the shoe and not annoying. The first resonance of the plate is above 1 kHz.

3 Results

3.1 Sinusoidal stimuli and pedal force 40 N

The VT for F_P=40 N is shown in Figure 2. The data are taken from experiments with 12 male participants. The VT values at frequencies between 10 and 16 Hz differ significantly (Wilcoxon, $p<0.05$, [4]) from the VT at 25 Hz and the VT at 125 Hz differs significantly (Wilcoxon, $p<0.01$, [4]) from all other frequencies. This means the slope between 10 and 25 Hz as well as the U-shape between 25 and 500 Hz are significant. A significant correlation between the individual VT and personal data (age, height, weight, body mass index , length of right foot, lower limb and thigh) is found for the weight and the individual VT at 25 Hz.

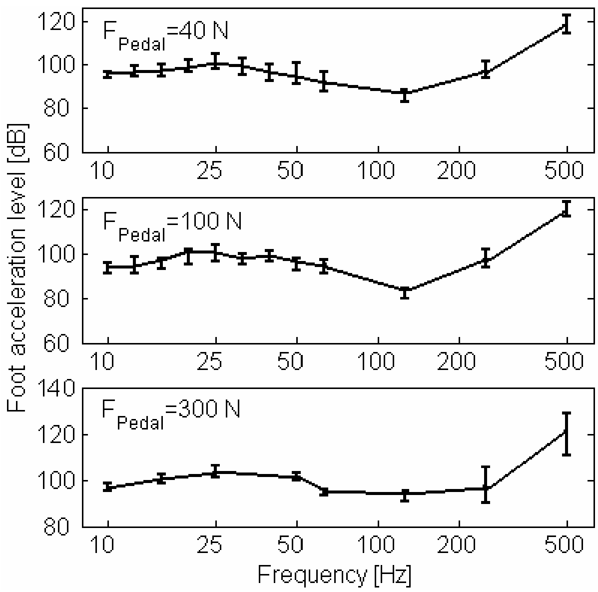

Figure 2: Median vibration perception thresholds for the three pedal forces 40, 100 and 300 N. Bars indicate the interquartile ranges.

3.1 Sinusoidal stimuli and pedal force 100 N

In this test 12 male subjects participated. Figure 2 shows the VT. There is no significant difference (Wilcoxon, $p<0.001$, [4]) between the VT for F_P=40 and F_P=100 N (cf. Figure 3). Significant correlations (Pearson, $p<0.05$, [4]) are found between foot length and individual VT at 12.5 Hz, length of lower leg and VT at 12.5 and 25 Hz, age and VT at 125 and 250 Hz as well as between BMI and VT at 20 and 40 Hz.

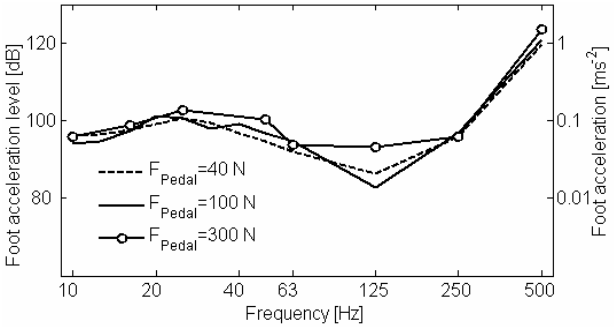

Figure 3: Comparison between the median perception thresholds for sinusoidal vibration stimuli and different pedal forces.

3.2 Sinusoidal stimuli and pedal force 300 N

Nine persons (8 male, 1 female) participated in the experiments for F_P=300 N. The VT is plotted in Figure 2. In this experiment the number of test frequencies is reduced compared to preceding series of tests due to the fact that more breaks are necessary between signals to recover the foot. A significant deviation from the other thresholds is observed only for 125 Hz, where the sensitivity is lower for F_P=300N (cf. Figure 3).

3.3 Impulsive stimuli at a pedal force of 100 N

Six male persons participated in the experiments for impulsive stimuli. The VT are expressed as the rms values of the acceleration signal measured at the plantar pad (cf. Figure 4). All VT for impulsive stimuli are higher than those of the corresponding VT for pure sinusoidal stimuli. Neither modulation frequency (the frequency of the impulses) nor the type of impulsive signal show a significant effect on the thresholds.

4 Discussion

There is a clear effect of frequency on the VT of sinusoidal brake pedal vibration for the investigated pedal forces 40, 100 and 300 N. For these stimuli the pedal force has no general effect on the perception threshold except for 125 Hz, where the thresholds for 40 as well as 100 N differ significantly from that at 300 N (Wilcoxon, $p<0.001$, [4]). A comparison with a study of Miwa [5] on the mechanical characteristics of the foot-leg system could not explain this phenomenon, but it indicates a minimum of the mechanical impedance around 150 Hz which could be a reason for the high sensitivity around this frequency.

A good agreement exists between a study of Morioka and Griffin [1] and our VT results measured for F_P=40 and F_P=100 N (cf. Figure 5).

The weighting curves proposed in ISO 2631-1 [2] are not appropriate for the evaluation of brake pedal vibration, as can be seen in Figure 5 from the exemplary comparison of the reciprocal of ISO-curve W_k and our results for F_P=100 N.

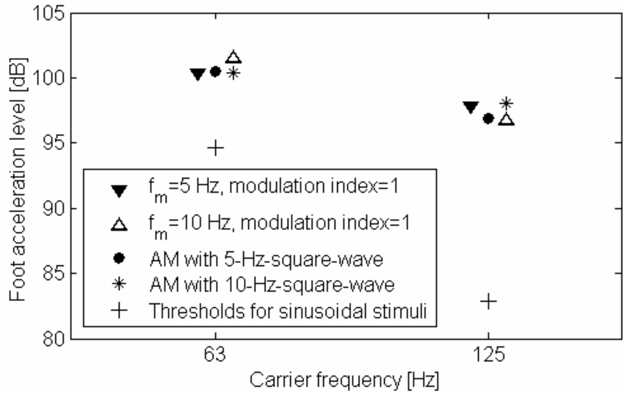

Figure 4: Thresholds for impulsive stimuli. Markers are slightly shifted in frequency for better view.

The vibration energy content of an impulsive signal is less than that of a corresponding continuous sinusoidal. With respect to temporal integration effects in human vibration perception (cf. [6]) and the fact, that the pulse durations in our stimuli are shorter than the rise time T_0, necessary to approach "full" perception (T_0>0.8 s, cf. [6]), this lower energy content explains the higher VT for impulsive stimuli.

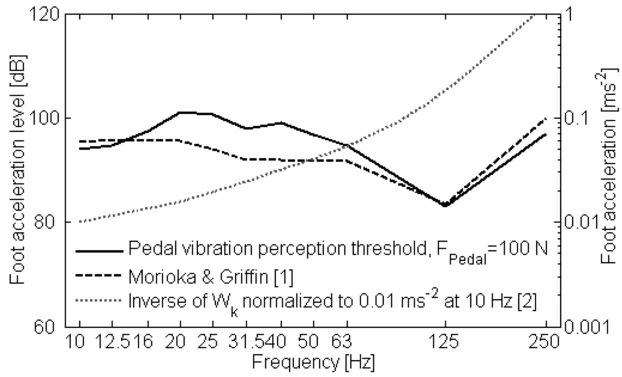

Figure 5: Comparison between own results for perception thresholds of brake pedal vibration an literature data.

5 Summary

We have measured perception thresholds for brake pedal vibration at different pedal forces. The frequency of sinusoidal stimuli has a significant effect on the perception threshold. The greatest sensitivity for such brake pedal vibration is found at 125 Hz with decreasing sensitivity towards lower and higher frequencies. The effect of pedal forces in the range 40-300 N is negligible, except for 125 Hz where the threshold for 300 N is about 10 dB higher. Thresholds for the investigated impulsive stimuli are higher than corresponding values for pure sinusoidal stimuli.

References

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