THE APPARENT MASS OF THE SEATED HUMAN BODY IN RESPONSE TO LATERAL AND ROLL VIBRATION

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Abstract

The objective of this study was to compare the lateral apparent mass of the seated human body measured in response to lateral and roll motions. The lateral apparent mass was measured at the seat surface using a rigid flat seat with no backrest. The axis of rotation of the roll motions was also at the seat surface. Tests were conducted using pseudo-random motions band-limited at 0.2 and 2 Hz reproduced with three magnitudes of seat surface lateral acceleration. The lateral apparent mass, normalised with respect to the subject sitting weight, was found to be greater in response to roll vibration than in response to lateral vibration over the frequency range investigated.

1. Introduction

Current standards require that measurements of human exposure to whole-body vibration are made at the interfaces between the seat and the human body in the vertical and horizontal directions (e.g. ISO 2631-1, 1997; BS 6841, 1987). Separate guidance is given for the evaluation of rotational oscillation. However, roll and pitch oscillation of horizontally orientated accelerometers result in measurements of horizontal acceleration influenced by gravitational components.

Studies of human responses to vibration have been conducted separately for translational and rotational motion. The mechanical impedance, or apparent mass, of the body influences the transmission of vibration through seats. The accelerations measured in the horizontal directions in vehicles, which are partly due to horizontal motion and partly due to roll or pitch, will be evaluated as though they were horizontal motion. It is not known whether the human body responds in the same way if the 'horizontal' forces are similar, whether they arise from translation or rotation. For example, when considering the lateral motion of a seat in a vehicle it is necessary to consider separately the impedance of the body in roll and the lateral direction, or whether it is sufficient to consider the lateral acceleration measured by a horizontally oriented accelerometer whose signals are due to a combination of lateral motion and rotation thought the gravitational field of the earth.

Using random lateral oscillation, Fairley and Griffin (1989) measured the apparent mass of eight subjects between 0.25 Hz and 20 Hz with vibration magnitudes of 0.5, 1.0 and 2.0 ms^{-2} r.m.s. Resonances in the apparent mass were observed at approximately 0.7 Hz and around 2 Hz. With the addition of a backrest there was a single resonance at approximately 1.3 Hz in all subjects. With the

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backrest removed, increasing the vibration magnitude reduced the frequency of the 2 Hz resonance but had a negligible effect on the 0.7 Hz resonance.

With sinusoidal lateral oscillation, Holmlund and Lundström (1998) tested 15 male and 15 female subjects between 1.13 Hz and 80 Hz at acceleration magnitudes from 0.25 to 1.4 ms^{-2} r.m.s. No backrest was used. Resonances in the mechanical impedance of the body were observed at around 2 to 4 Hz and around 5 to 7 Hz. Male and female subjects showed these resonances, but the first resonance was more distinct for the males and the second resonance was of greater magnitude for the females.

The discomfort produced by lateral acceleration of the seated human body on a rigid seat with no backrest decreases with increasing frequency above about 2 Hz (Griffin et al., 1982; Howarth and Griffin, 1988) and is approximately constant with lateral seat acceleration at frequencies from 2 Hz down to around 0.5 Hz (Corbridge and Griffin, 1986). The cause of discomfort due to horizontal vibration is likely to be complex but may be in part related to the need to consciously stabilise the body. Robertson and Griffin (1989) measured myoelectric muscle activity in the right and left erectores spinae muscles while exposing subjects to lateral vibration and observed 180° phase difference between the muscles on either side of the back. This muscle activity appeared to be voluntary below approximately 1 Hz and involuntary at higher frequencies.

The lateral apparent mass may be defined as:

$$M_y = \frac{F_y}{\ddot{y}} \qquad \text{Equation 1}$$

where the apparent mass $My(\omega)$ is calculated from F_y, the y-axis force measured at the seat surface, and $\ddot{y}$, the acceleration in the y-axis.

The forces acting on a seated human body rotated in roll about a seat surface may not be as simply defined as for motion in a single translational axis. To a first approximation it is possible to consider the forces acting on the body in terms of three components.

The ‘gravitational’ force component acting on the body is that due to the rotation of the body through the gravitational force vector. This may be evaluated in the same manner as the lateral apparent mass described in Equation 1 with the lateral acceleration at the seat surface depending on the angle of rotation of the seat from the horizontal:

$$\ddot{y} = g.\sin(\theta) \qquad \text{Equation 2}$$

where θ is the angle between the horizontal and the plane of the seat surface and g is the acceleration due to gravity.

There is a ‘centripetal’ force acting on the rotating body due to the circular motion of the body. This is nominally perpendicular to the plane of the seat surface and proportional to the square of the rotational velocity. To a first approximation this force acts orthogonally to the lateral axis at the seat surface.

An ‘inertial’ component may be considered to be the resistance of the body to an applied rotational acceleration. As the centre of mass of the part of the body supported on the seat is offset from the axis of rotation at the seat surface there is a lateral force generated at the seat surface due to the rotational acceleration of the body that will increase in proportion to the rotational acceleration of the seat.

Using the simple model described above, the lateral apparent mass associated with roll oscillation will tend to be dominated by the gravitational component, proportional to the roll angle, as the frequency tends towards zero. As the frequency increases, the lateral component of the 'inertial' force, proportional to the angular acceleration, will become increasingly important.

The objective of the present study was to compare the apparent mass measured in the lateral axis with that measured in roll. No previous study has measured the apparent mass of the human body in response to a rotational motion and few authors have measured the apparent mass in the lateral axis.

It was hypothesised that the lateral apparent mass measured in response to roll motion would be similar to that measured in response to lateral motion. It was expected that this would be the case at low frequencies but would be less accurate at higher frequencies where the inertial forces introduced by the roll motion would become more important.

It was further hypothesised than the response of the human body would be non-linear due to voluntary or involuntary muscle control, or other reasons, resulting in differences in the lateral apparent mass at different vibration magnitudes.

2. Method

2.1. Apparatus

Horizontal motions were reproduced on a 1-metre stroke electro-hydraulic vibrator capable of accelerations up to ±10 ms^{-2}. Roll motions about the seat surface were reproduced on a rotating table actuated by the horizontal vibrator. The flat rigid seat surface was fixed at a height of 490 mm above the vibrator platform. No backrest was used. The two test conditions are shown schematically in Figure 1 and Figure 2.

The lateral seat surface acceleration was measured using a Smiths Industries AV-L-692 ±12g inductive accelerometer fixed behind the centre of the seat on the plane of the seat surface. The lateral force at the seat surface was measured using a Kistler 12-channel force platform.

An *HVLab* v3.81 data acquisition and analysis system was used to generate the test motions and acquire the signals from the transducers. The lateral acceleration and lateral force signals were acquired at 100 samples per second via 33 Hz anti-aliasing filters.

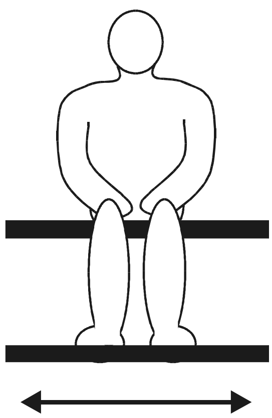

Figure 1 Seat lateral motion.

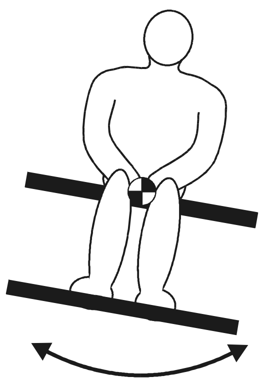

Figure 2 Seat roll motion about a centre of rotation at the seat surface.

2.2. Motions

The test motions used in this study consisted of flat constant bandwidth pseudo-random acceleration spectra band-limited at 0.2 and 2.0 Hz using six pole Butterworth filters. Each motion was of three minutes duration with a 1-second cosine taper applied to the beginning and end of each motion. The seat was actuated in the lateral or roll axis to reproduce the test motions at the seat surface with unweighted lateral accelerations of 0.05, 0.1 and 0.2 ms^{-2} r.m.s.

2.3. Subjects

Twelve male subjects, aged between 24 and 52 years with stature between 1.72 m and 1.91 m, participated in the study. The subject standing masses ranged from 67 kg to 101 kg with static masses supported on the seat ranging from 56 to 86 kg. The feet were flat on the vibrator platform at the shoulder width of each subject. The mass supported by the seat was measured by placing a set of scales on the seat surface and providing a flat footrest to correct for the increase in height of the seat surface. Subjects attended two sessions in which they were exposed to either roll or lateral motion. The order of presentation of the axis of motion was balanced across the twelve subjects and the order of presentation of the vibration magnitudes during each session was randomised. At the start of a session, subjects were instructed to maintain a comfortable upright posture with no backrest contact.

2.4. Analysis

The lateral force and acceleration measured with each subject in each axis of motion at each test magnitude were normalised and the apparent mass of the test subject calculated according to Equation 1. Welch's cross-spectral density method was used to estimate the transfer function between the seat surface lateral acceleration and the seat surface lateral force between 0.2 and 2.0 Hz with a frequency resolution of 0.098 Hz.

The mass of the force platform was accounted for by mass cancellation in the frequency domain. The magnitude of the measured apparent mass of the unloaded platform was subtracted from the magnitude of the apparent mass of each subject. The platform apparent mass measured with lateral acceleration without a subject was 14.6 kg at 0.2 Hz, with a coherence in excess of 0.95 across the 0.2 to 2 Hz frequency range and with a phase between force and acceleration less than 5°. The unloaded apparent mass was independent of frequency for lateral oscillation but showed a decrease of 23% with increasing frequency for the roll condition. This was attributed to the asymmetric mass distribution about the axis of rotation due to the force platform being rotated about the upper surface and not the geometrical centre.

The median normalised lateral apparent mass in response to both axes of motion was calculated from the apparent mass of each subject divided by the subject sitting weight.

3. Results

The non-normalised lateral apparent masses of the twelve test subjects in response to lateral and roll motions are shown in Figure 3 and Figure 4 respectively. The median and interquartile normalised apparent masses for all subjects in response to all test motions are shown in Figure 5.

The difference between the lateral apparent masses in response to lateral oscillation and rotational oscillation was investigated using the Wilcoxon matched-pairs signed ranks test at each frequency from 0.20 to 2.05 Hz at intervals of 0.098 Hz and at each magnitude. After correcting for the number of test performed, the lateral apparent mass with roll oscillation was found to be significantly greater than with lateral oscillation for all frequencies and all magnitudes (p<0.02) except for 0.05 ms^{-2} r.m.s. at 0.20 Hz (p>0.05).

The differences between the lateral apparent masses at the three magnitudes were investigated using Friedman's test at each frequency from 0.20 to 2.05 Hz at intervals of 0.098 Hz. After correcting for the number of tests performed, only lateral oscillations at 0.59 Hz and at 1.56 Hz were found to show a significant change in apparent mass with vibration magnitude (p<0.05). Significant differences (p<0.05) were also found at 0.20 Hz and 0.29 Hz but these were rejected due to the poor coherence of the apparent mass of most subjects at these frequencies (see Figure 3). No significant change in lateral apparent mass was found at any frequency in response to changes in the magnitude of roll oscillation.

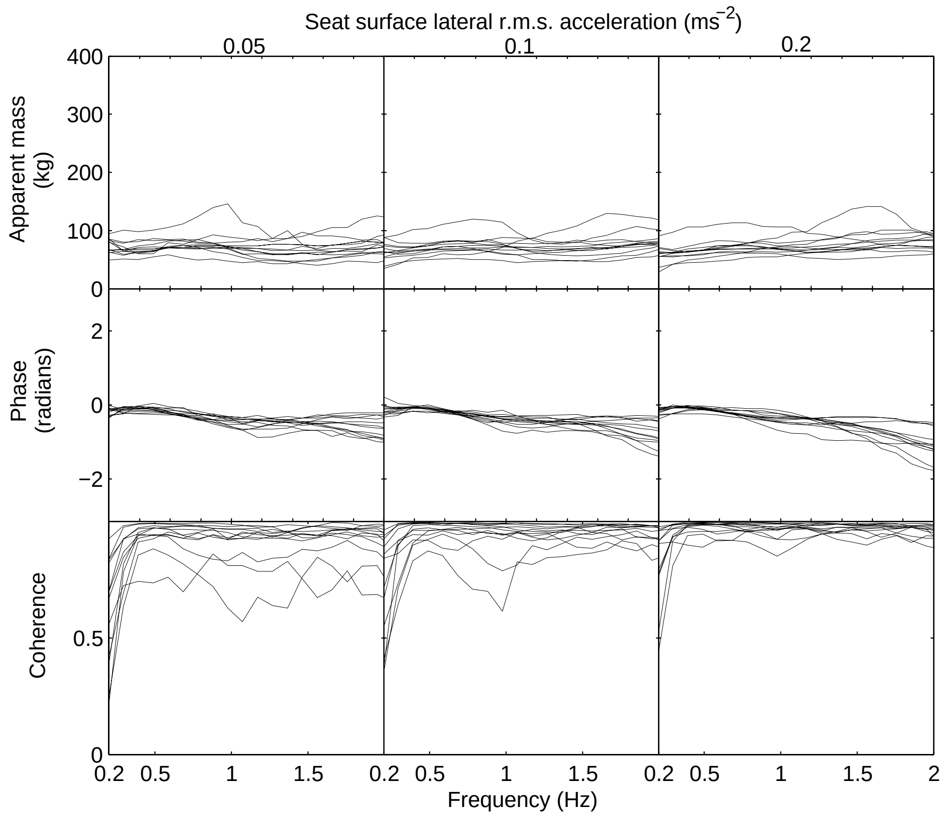

Figure 3 The lateral apparent masses of all subjects in response to lateral oscillation.

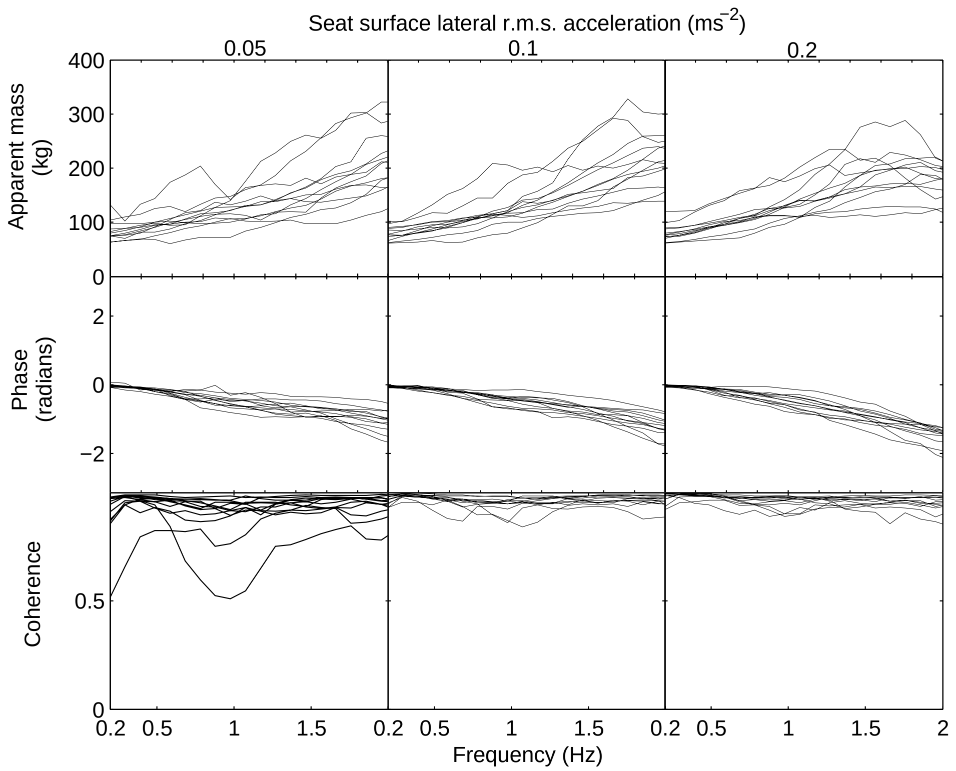

Figure 4 The lateral apparent masses of all subjects in response to roll oscillation.

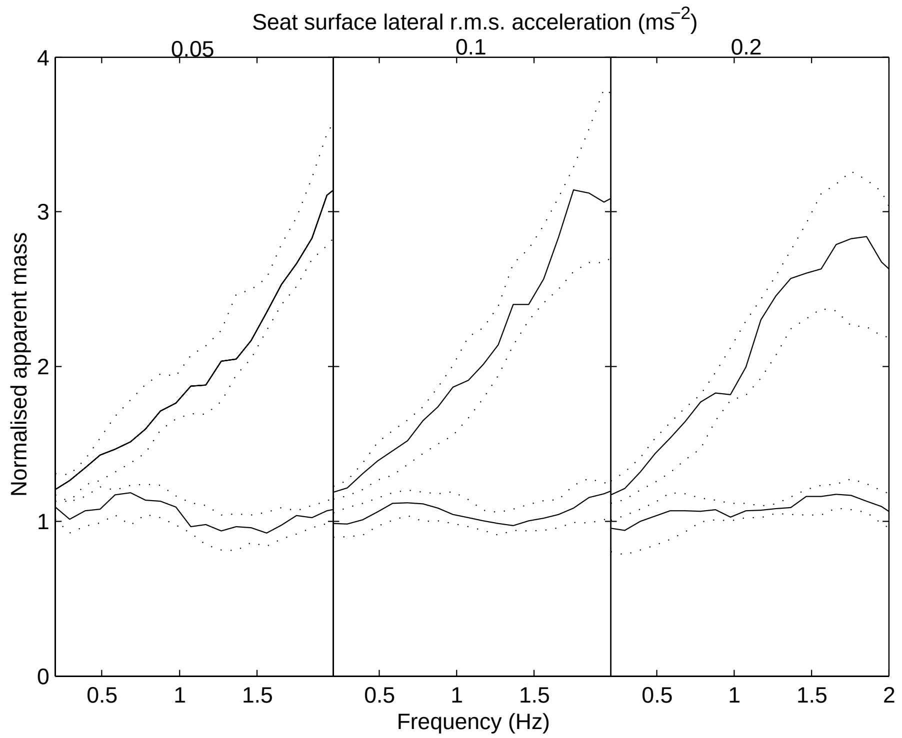

Figure 5 The lateral apparent mass of all 12 test subjects normalised by sitting mass showing the median and interquartile ranges for lateral oscillation (lower lines) and roll oscillation (upper lines) in response to each magnitude of seat surface lateral acceleration.

4. Discussion

The lateral apparent mass measured in response to lateral oscillation was significantly different from the lateral apparent mass in response to roll oscillation. The lateral apparent mass magnitudes over the frequency range investigated in this study were consistent with results obtained by Fairley and Griffin (1989). The normalised apparent mass in response to roll oscillation was greater than that in response to lateral oscillation and increased with increasing frequency. The hypothesis that at low frequencies the lateral apparent mass in response to roll oscillation will be similar to that obtained in response to lateral oscillation must be rejected for the frequency range investigated in this study. Changes in lateral apparent mass with magnitude over the frequency range investigated were small compared with the inter-subject variability and there was no clear statistical evidence to suggest non-linear behaviour. There was some suggestion of the 0.7 Hz resonance in response to lateral oscillation found previously by Fairley and Griffin (1989) but this could not be clearly identified for all subjects or all vibration magnitudes.

5. Conclusions

The lateral apparent masses in response to lateral and roll oscillation were found to be significantly different over the frequency range 0.2 to 2 Hz. The apparent mass with roll oscillation was greater than the apparent mass with lateral oscillation and increased with increasing frequency over the frequency range investigated.

6. Acknowledgments

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