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WHOLE-BODY SHOCK AND VIBRATION: FREQUENCY AND AMPLITUDE DEPENDENCE OF COMFORT

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1. INTRODUCTION

Whole-body vibration has long been implicated in causing adverse health effects and performance degradation of vehicle operators [1–3]. A variety of measures have been proposed and used to assess whole-body vibration dosage. The most commonly cited method is the ISO 2631 Standard [4]. ISO 2631 sets guidelines for how to take the measurements and calculate exposure statistics. ISO 2631 also recommends acceptable dosage levels. The primary ISO 2631 whole-body vibration statistics are derived from the power spectral densities of tri-axial acceleration measurements that are usually taken at the seat cushion interface. The power spectral density is a statistic that decomposes a vibration signal into frequency components. ISO 2631 then weights the frequency components based on empirically derived human sensitivities. The most sensitive frequency band for vertical motions of humans is 4–6 Hz.

A major shortcoming of the power spectral density approach is that it cannot distinguish between vibrations that contain mechanical shocks and those that do not. Two vibration signals, one that contains a few large isolated mechanical shocks and one that contains continual vibrations with minimal mechanical shocks, can have identical power spectral densities, if they contain the same average vibration power per frequency band. This is the situation that arises when one drives down a rough road with many small bumps versus driving on a relatively smooth road with occasional large potholes. Both roads can give rise to a ride with identical ISO 2631 statistics, but a dramatically different level of comfort, fatigue and even injury. This statistical shortcoming has been recognized by the ISO 2631. The ISO committee introduced a concept called the crest factor, which is the ratio of the maximum amplitude of vibration to that of the standard deviation of the vibration. The ISO 2631 dosage measures are not recommended for use in vibration environments with crest factors that exceed 6. To illustrate this point,

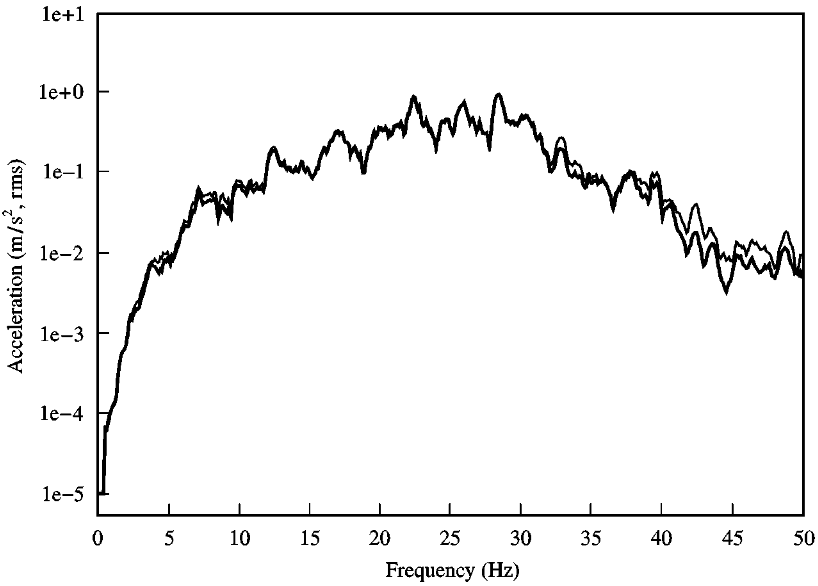

Figure 1. Power spectral density plots for white noise vibration with and without shocks: ———, white-noise vibration; ——, white noise & 8 Hz shocks.

acceleration data were collected at the seat pan of a electrohydraulic controlled truck seat with a simulated typical vibration input, with and without shocks. The white noise followed a Gaussian distribution and had an overall root mean square (r.m.s) vibration of 2·45 m/s^2. The shocks were single 8 Hz sine waves and occurred once every 30 s. The shocks had a peak-to-peak amplitude of 19.6 m/s^2, representing a crest factor of 8 compared to the background white-noise vibration. Power spectral density plots for both types of vibration are shown in Figure 1. These shocks are barely discernible in the plot using the power spectral density method.

Other statistical measures have been recommended for assessing the amount of mechanical shock in a vibration signal. These include the root mean quadrature, higher-power root mean statistics, kurtosis and cumulants [5,6]. The key feature is whether or not the random vibrations are Gaussian.

To date the studies that compare different mechanical shock-containing vibration, signals on humans have been somewhat limited. A large mechanical hammer was used to impact the seat under an elastically suspended test subject [7]. The impact test data were used to determine linear mechanical response properties of a seated subject. Dupuis *et al.* [8] tested subjects with a seat acceleration that consisted of mechanical shocks superposed on stationary random vibrations. Symmetric and asymmetric shock profiles were used. The results indicated that increasing mechanical shock levels increased the mechanical and muscular response of the test subjects (as indicated by electromyography). The subjective response of the subject was evaluated with a mechanical steering wheel tracking device. The subjects performance on the steering test degraded when subjected to the symmetric shocks, but not the asymmetric shocks. Spang [9] used a series of 50 single-event mechanical shocks, with acceleration amplitudes of up to 3 g on 92 subjects to test for a subjective rating of 1 (least intense) to 10 (most intense).

2. METHODS

The objective of this study is to examine how the shape, frequency and amplitude of the mechanical shocks affect the comfort response of the seated human. The specific hypothesis is that reported levels of comfort or discomfort in response to these mechanical shocks will be significantly different for mechanical shocks with different shape, frequency and amplitude. Those mechanical shocks with frequencies near to the first natural frequency of a seated human, i.e. between 4 and 6 Hz, will cause the most discomfort.

After obtaining local IRB approval, 10 healthy subjects with no history of back pain were recruited (7 males, 3 females). After explaining the experiment to the subjects, including safety measures and test abort procedures, consent was obtained. Height and weight were then recorded. Although the data are not reported here, bilateral electromyographic transducers were placed on the lower back and an accelerometer was placed on the torso. The subjects were then seated on a electrohydraulic controlled truck seat while it was stationary. Adjustments to the seat, backrest, and foot-support were made to allow the subject to sit comfortably in an erect, upright position. The subjects were instructed not to use the seat backrest. In order to obtain quantitative information concerning subjective levels of comfort, a modified Borg scale rating system was used [10]. The modified Borg scale has the subjects rate the quality of ride on a scale of 1 to 10. Verbal descriptors are associated with the numbers where 1 is "comfortable" and 10 is "painful" (Table 1). The subjects were handed a card printed with the modified Borg scale verbal descriptors. They were then asked to rate the various rides with different shock levels and profiles.

A set of input signals was used to drive the seat. These signals were designed to be representative of different types of bumps that are encountered while riding in a vehicle. The test protocol was configured to test for the effects of different

Table 1

Modified Borg scale

1	Comfortable
2	
3	Slightly uncomfortable
4	
5	Mildly uncomfortable
6	
7	Very uncomfortable
8	
9	Extremely uncomfortable
10	Painful

mechanical shock shape, different mechanical shock amplitude and different mechanical shock frequency. The shock shapes created were single sine wave and a single half-sine wave. For the single sine wave the seat first rose, then dropped below center, finally returning to the center. For the single half-sine wave shock, the seat rose and simply returned to the center. The two shock shapes, sine wave and half-sine, are shown inserted into the white noise signal in Figures 2 and 3 respectively.

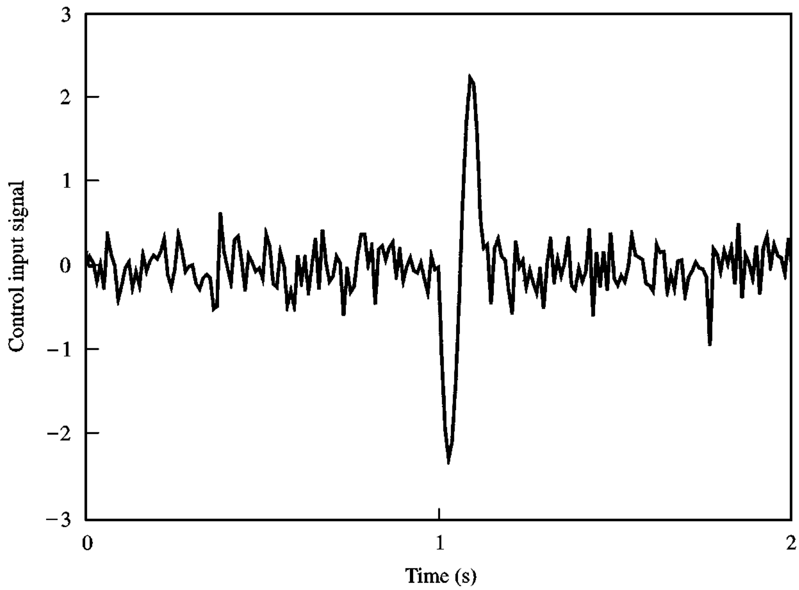

Figure 2. Two second time history of the control input signal showing the insertion of an 8 Hz sine wave shock.

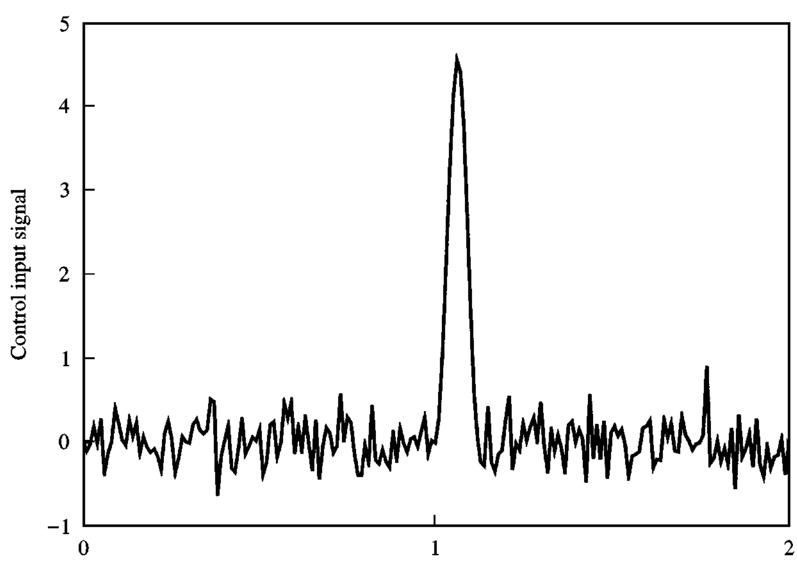

Figure 3. Two second time history of the control input signal showing the insertion of an 8 Hz half-sine shock.

The two levels of shock amplitude tested, high and low, corresponded to crest factors of 8 and 4, respectively. The five shock frequencies tested were 2, 4, 5, 6, and 8 Hz. These shocks were superposed onto a test file containing background vibration of 0·5–30 Hz bandpass filtered Gaussian white noise. Each test file thus created had a set of randomly occurring identical mechanical shocks, with a mean arrival time of once every 10 s. One additional test file contained the background white noise only and was used as a control.

The subject first performed a practice run containing all of the types of mechanical shocks to determine acceptance. This input signal was "turned up" slowly while the investigator monitored the subject. After approval from the subject the testing began.

The tests consisted of having the subject undergo a series of 21 tests with a duration of 60 s each. Between tests the seat was held stationary for a minimum 1-min rest period. At the completion of the first series of tests the subject was encouraged to rest, stretch, or walk around for at least 20 min. Then the series of tests was repeated. The test sequence was order-randomized for both series. During the test, the subjects were asked to rate each test ride on the scale of 1 to 10.

The subjective ranked data was analyzed in a repeated measures analysis of variance model using SPSS 9·0 statistical software (SPSS, Inc., Chicago, IL).

3. RESULTS AND DISCUSSION

The average ratings of the different shocks from 10 subjects are shown in Figure 4. The discomfort rating for the background white noise alone was 2·7. All

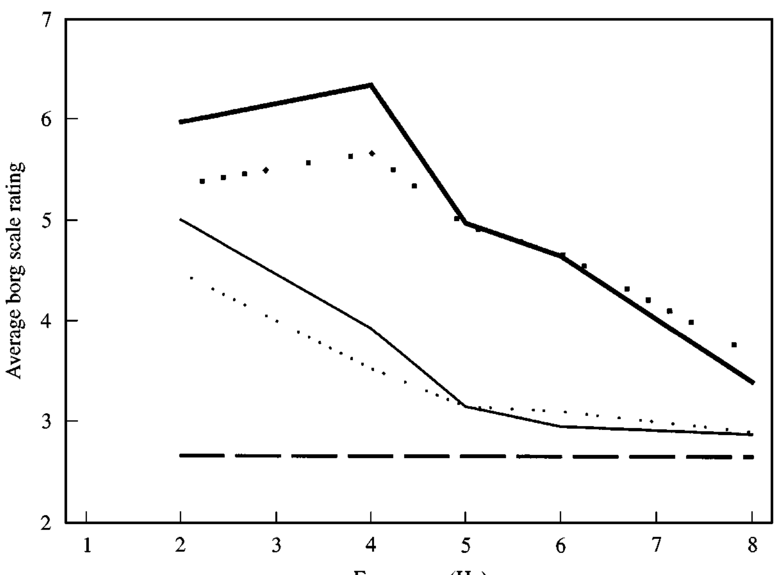

Figure 4. Average ratings of the different shocks from 10 subjects. The upper four plots show the ratings for the shocks at 2, 4, 5, 6, and 8 Hz; the lower dashed line shows the rating for the white noise alone, and is not frequency specific: ———, high CF sinewave; ■■■, high CF half-sine; ———, low CF sinewave; · · ·, low CF half-sine; — —, white noise only.

of the shocks at 2, 4, and 5 Hz were significantly more uncomfortable than the white noise alone ($p < 0{\cdot}05$). The most uncomfortable shock was the high crest factor (CF) sine wave at 4 Hz. The mean rating for this shock at 4 Hz was 6·4. It was also very uncomfortable at 2 Hz with an overall rating of 6·0. The differences between 2 and 4 Hz were not significant for any of the shock types. At 5 Hz and above there were no differences between the two shapes of the shocks, sine wave and half-sine. Similarly, for the low crest factor shocks, there was no difference between shock types above 5 Hz. At the lower frequencies, 2 and 4 Hz, the sine wave shocks were again significantly more uncomfortable than the half-sine shocks ($p < 0{\cdot}05$). At 2 Hz the sine waves were rated at an average of 5 and the half-sines received a score of 4·5. When looking at the frequency effects of the lower crest factor shocks, it is apparent that the lower the frequency, the more uncomfortable the shocks become.

It is not surprising that the worst shocks were felt at 4 Hz, which is very close to the vertical natural frequency of the human. What is surprising is the high discomfort ratings for the shocks at the low frequency of 2 Hz. Vibration at this frequency, for vertical vibration, is weighted quite low by the ISO 2631 standard. Data here show that shocks at this frequency are even more uncomfortable than at 4, or 6 Hz, frequencies which are weighted much higher in the standard. These findings suggest that current proposals to use the same weighting values for shocks that are currently used for background vibration need to be re-examined.

ACKNOWLEDGMENTS

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