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COMPARISON OF THE DRIVING-POINT IMPEDANCE AND TRANSMISSIBILITY TECHNIQUES IN DESCRIBING HUMAN RESPONSE TO WHOLE-BODY VIBRATION

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ABSTRACT

The driving-point impedance and transmissibility techniques were applied and compared to further evaluate the contribution of specific anatomical structures or regions in producing resonance behavior and nonlinear response characteristics. Five human subjects were exposed to sinusoidal and quasi-random vibrations which included frequencies from 3-21 Hz at two rms acceleration levels. Three quasi-random signals were generated using the sum-of-sines technique. While the results strongly supported the chest or upper torso as being the primary influence in generating the first impedance resonance peak, the data strongly suggested that the legs contributed to the nonlinear behavior observed for the second impedance peak under the test conditions used in this laboratory. The results also strongly supported the existence of coupling between the spine, upper torso or chest and head but will require further analytical and experimental evaluation. The data did suggest that the transmission of vibration to the head is dampened by the cervical spine above about 10 Hz.

1. INTRODUCTION

Driving-point mechanical impedance and transmissibility are two common measurement techniques used to evaluate the biodynamic response of humans exposed to seated, vertical whole-body vibration. In human experimentation, the driving-point mechanical impedance is defined as the ratio between the transmitted force and input velocity measured at the seat. The measurement is dependent on the combined motions of both coupled and uncoupled anatomical structures. (A related quantity, the apparent mass, is defined as the ratio between the transmitted force and input acceleration at the seat). Both the impedance and apparent mass techniques provide a totally non-invasive procedure for evaluating frequency response

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characteristics and resonance behavior, however, associating these characteristics with specific anatomical structures can be difficult. Certain structures, such as those located some distance from the point of load application, may not generate enough force to significantly influence the response measurement at the seat. Using the driving-point impedance or apparent mass techniques, Coermann (1966), Mertens (1978), ISO Standard 5982 (1981), Donati and Bonthoux (1983), Hinz and Seidel (1987), Fairley and Griffin (1989) and Smith (1992) (to name a few) have all observed a primary resonance peak located between 4 and 7 Hz. Several investigators have specifically associated the resonance with the thoraco-abdominal viscera (Guignard and King, 1960) or torso (ISO 5982, 1981). While secondary peaks have been observed, their occurrence has not been consistent.

Transmissibility is defined as the ratio between responses at two specific locations on the body and requires the attaching of transducers to the body. In the human studies, acceleration transmissibility has primarily been measured between the acceleration response at the head, shoulder or thorax and the input acceleration at the seat. For the human, investigators such as Mertens (1978), Donati and Bonthoux (1983), Hinz and Seidel (1987), ISO Standard 7962 (1987) and Wilder et al. (1982) have observed the primary resonance peak in the vicinity of 5 Hz regardless of which transmissibility was measured. In transmissibility measurements between the seat and head, Guignard and King (1960) associated the observed transmissibility peak with resonance in the upper torso and shoulder girdle. Two secondary resonance peaks have been observed at higher frequencies below 25 Hz. These peaks have been primarily associated with spine and head resonances. As with impedance, the secondary peaks have not been consistently observed and may be dependent on the driving conditions.

Nonlinearities in the impedance and transmissibility responses have been observed by Bastek et al. (1977), Cohen et al. (1977), Hinz and Seidel (1987), Manninen (1987), Fairley and Griffin (1989) and Smith (1992). These findings further complicate the assessment of resonance behavior and the mechanical characterization of the coupling between the anatomical structures.

The main objective of this study was to use both the impedance and transmissibility techniques to examine the effects of the type of vibration (sinusoidal vs quasi-random), frequency bandwidth, acceleration level and crest factor on nonlinear response behavior. This paper compares the results of impedance and transmissibility measurements at selected anatomical sites to isolate the contribution of specific structures in generating resonance behavior and to evaluate the nonlinear response characteristics.

2. METHODS AND MATERIALS

Three male and two female subjects weighing between 64 and 86 Kg were exposed to sinusoidal vibration and to three quasi-random signals. The frequency components for both types of vibration consisted of one-Hz increments between 3 and 21 Hz. Two overall acceleration levels were used; 1.0 and 2.0 ms^{-2} rms (0.102 and 0.204 g_{rms}). The three quasi-random signals were generated with crest factors (CF) of 2.7 (RAN1), 3.8 (RAN2) and 4.9 (RAN3). (The crest factor for sinusoidal vibration is always 1.4.) The crest factor is defined as the ratio between the peak acceleration and rms acceleration for a signal. The quasi-random signals were generated using the sum-of-sines technique according to the following equation for the acceleration time profiles:

$$A(t)=\sum\ [a_i\ SIN\ (\omega_i+\theta_i)] \tag{1}$$

where i equals the number of frequency components (19) and a_i equals 0.229 or 0.458 ms^{-2} rms depending on the overall acceleration level. The crest factor was varied by changing the phase profile, θ_i. Figure 1 illustrates two of the quasi-random signals (RAN1 and RAN3). An Unholtz-Dickie electrodynamic vertical motion simulator was used to produce the z-axis vibration. The human test seat, designed to respond as an inert mass over the frequency range of concern, was mounted on top of the table and included a seatback, lapbelt and double shoulder harness. For calculating the driving-point mechanical impedance, transmitted force was measured by three load cells located between the seat and the vibrator platform. Two accelerometers were attached to the seat. One was used to measure the magnitude of the input acceleration, while the second was used to measure phase. Miniature accelerometers were placed on the chest (at the level of the manubrium), the seventh cervical

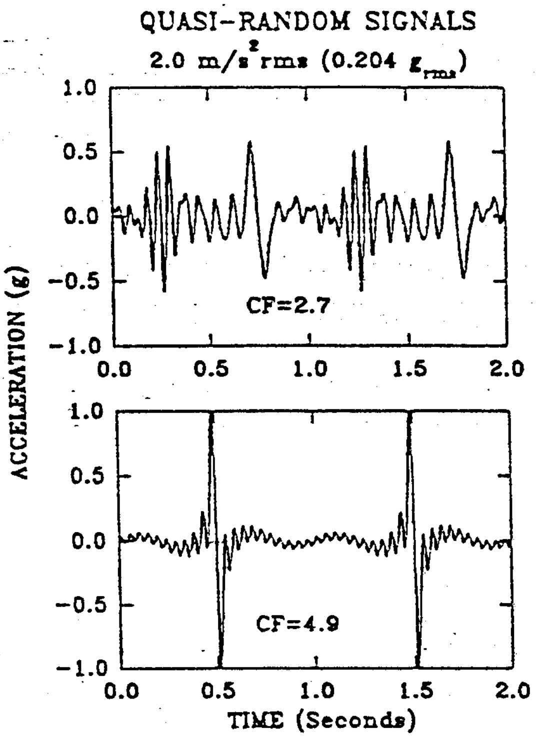

Figure 1 Quasi-Random Signals

vertebra (at the site of the spinous process), the thigh and the top of the knee (on the distal end of the femur). Vertical acceleration of the head was measured by attaching an accelerometer to a bite bar. A computer program was used to generate the selected frequencies or quasi-random profiles and to simultaneously collect all transducer data. The Fast Fourier Transform (FFT) was used to calculate the driving-point impedance magnitude and phase at each load cell site (ratio of transmitted force to input velocity calculated from the acceleration), as well as the acceleration magnitude and phase at each selected location for each frequency component. The impedance of the seat (collected previously) was subtracted from the calculated impedance at each site to obtain the subject impedance. The impedances at each site were summed to obtain the total complex impedance of the subject. The impedance magnitude was calculated as the absolute value of the respective complex ratio. The impedance phase was calculated as the arctangent of the ratio between the imaginary and real components of the respective complex values. The transmissibility magnitude was calculated directly from the frequency response data as the ratio between the accelerations measured at the anatomical site and seat for each specified frequency. Transmissibility phase was calculated by subtracting the measured phase at the seat from the phase measured at the anatomical site for each specified frequency. Two tests were conducted on each subject at each of the two acceleration rms levels. Both the sinusoidal and quasi-random exposures were included in a single seated session. Accelerations at the knee were not collected in the first test for Subject One (1.0 ms^{-2} rms).

3. RESULTS

For driving-point mechanical impedance, up to four regions of resonance were identified between 3-21 Hz from the magnitude profiles and were similar to the regions described by Smith (1992). For the results of this study, the regions were defined as follows: Region One, 5-7 Hz; Region Two, 7-9 Hz; Region Three, 10-14 Hz; and Region Four, 16-19 Hz. Figure 2 illustrates the means and standard deviations for the resonance frequencies associated with these regions for all exposures. The figure

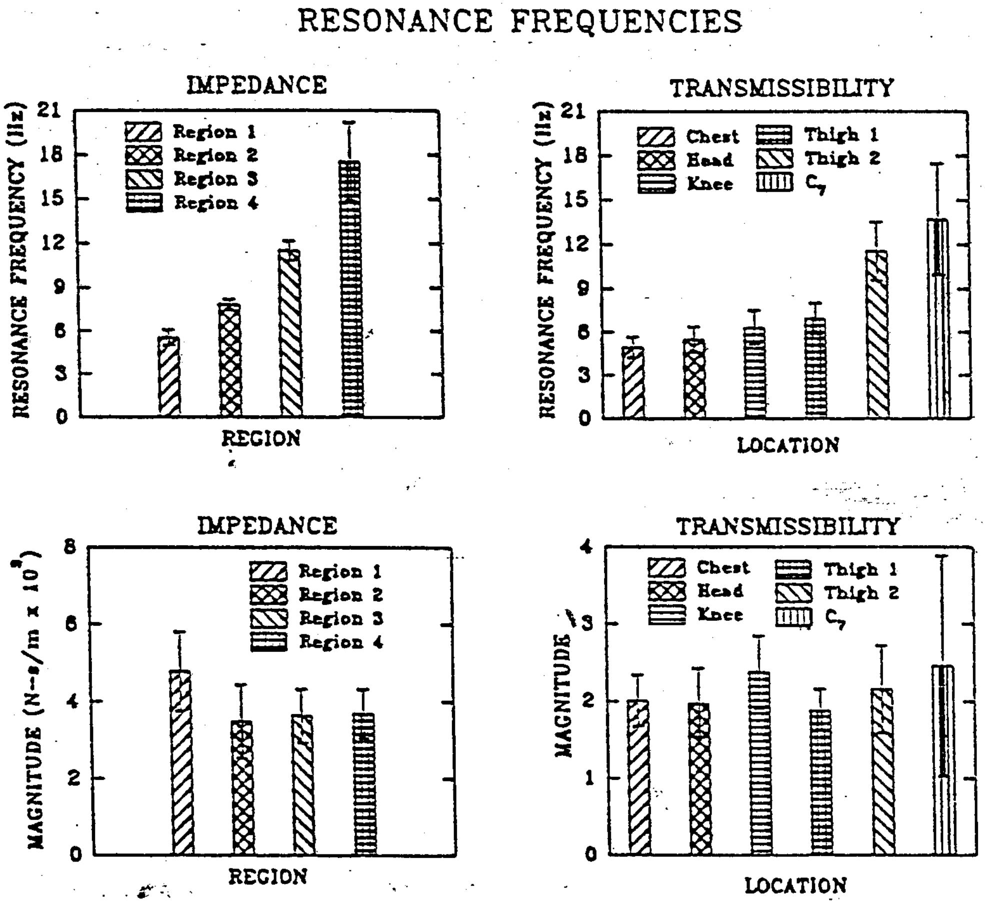

Figure 2 Impedance and Transmissibility Means and Standard Deviations

also shows the means and standard deviations of the impedance magnitudes associated with the peaks. The magnitude was the highest for the first resonance peak in the majority of the data. The phase response showed a rapid decline through the first region. While the phase tended to change direction in the vicinity of a resonance peak, some of these changes were difficult to identify. For impedance, the appearance of resonance peaks varied with the type of exposure. Resonance peaks were more easily identified for the quasi-random exposures. The most marked influence of the type of exposure was observed in the occurrence of the second impedance resonance peak between 7 and 9 Hz. The highest incidence of this peak occurred for RAN2 at the lowest acceleration level with the peak being clearly observed in 80% of the tests. For 60% of the tests, the resonance peak observed in the second region was higher in magnitude than the first resonance peak. The occurrence of the peak declined to 30% at the higher acceleration level. RAN1 showed a 30% occurrence of the second peak at the lower acceleration level and no occurrence at the higher acceleration level. The second resonance peak was observed in only one test for RAN3 at the lower acceleration level. Figure 3 depicts the impedance response of a subject for RAN2 and RAN3 and illustrates the generation of the second resonance peak for RAN2 and the elimination of the peak

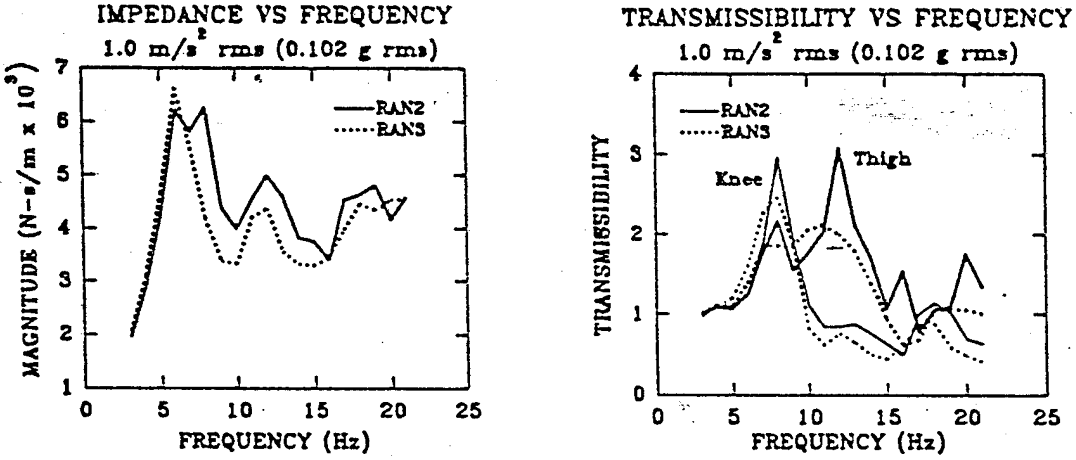

Figure 3 Impedance and Transmissibility Results for RAN2 and RAN3

at the higher crest factor (RAN3). Reductions in the impedance resonance frequency of 1-3 Hz were also observed at the higher acceleration level for several of the exposures. The most significant of these reductions included the fourth resonance peak in 90% of the tests at RAN2, and the third resonance peak in 90% of the tests at RAN3.

Multiple resonance peaks were observed in the transmissibility for several of the anatomical sites. Due to maximum error between accelerometers of about 10%, a transmissibility of 1.2 (20% change) was considered the minimum value for evaluating significant vibration transmission. Values less than 1.2 were associated with unity transmission or with dampened transmission. Frequency regions were determined for each anatomical site which showed the most consistent resonance behavior. As with impedance, the phase tended to change in the vicinity of a resonance peak. These changes were used to clarify the occurrence of resonance but were difficult to associate with specific frequencies in some cases. Figure 2 illustrates the means and standard deviations for the primary resonance frequencies and associated magnitudes observed in the transmissibility profiles. For the chest, the primary resonance peak occurred between 4 and 6 Hz which coincided with the first region of resonance identified in the impedance response results. Most of the profiles showed a transmissibility of less than unity following the initial peak, indicating dampened vibration transmission from the seat to the chest above 7 Hz. Two regions of resonance were consistently observed for the thighs and are illustrated in Figure 2. The first resonance peak observed for the thighs was located between 6 and 9 Hz. Subjects Two and Three did show resonance frequencies at 5 Hz for the sinusoidal exposures at 1.0 ms^{-2} rms. The second region of resonance was observed primarily between 10 and 13 Hz. The first peak coincided with the location of the resonance peaks in both Regions One and Two for impedance, while the second transmissibility peak coincided with the third impedance resonance region. The transmissibility measured at the knee showed a primary peak located between 5 and 8 Hz and, similar to the first peak observed for the thighs, coincided with the resonance frequencies observed in Regions One and Two for impedance. The primary or highest resonance peak observed at the seventh cervical vertebra (C_7) occurred between 12 and 17 Hz. Over 90 percent of the profiles showed secondary peaks primarily located between 5 and 6 Hz. For ten profiles resonances were not observed or the transmissibility was lower than 1.2 for the primary region between 12 and 17 Hz. For these cases, however, a peak was usually observed below 9 Hz. The frequency region between 12 and 17 Hz coincided with both Regions Three and Four for impedance, while the secondary peaks between 5 and 6 Hz coincided with Region One for impedance. The highest peak observed for transmissibility to the head was observed between 4 and 8 Hz with one profile showing a primary peak at 3 Hz. The transmissibility peaks observed for the head were similar to the secondary peaks observed for C_7, coincident with Region One for impedance.

The results indicated that both the thigh and knee responses could have contributed to the generation of the second region of resonance between 7 and 9 Hz. It appeared, however, that the response measured at the knee, which included the dynamic motion of the lower legs, may have had the greatest influence in the majority of tests.

Figure 4 illustrates that the mean resonance frequency associated with the knee measurement was reduced at the higher acceleration level. While the results were variable between subjects, the paired t-statistic, which compares the results between acceleration levels for the same subject, indicated that the reduction was significant at the five percent confidence level. In addition, the paired t-statistic also indicated that, for a given subject, the resonance frequency associated with the knee was significantly higher for RAN2 which may have contributed to the generation of the distinct impedance peak consistently observed around 8 Hz for this exposure. Figure 3 includes the thigh and knee transmissibility magnitudes associated with the illustrated impedance responses at RAN2 and RAN3. For the particular test results shown, the location of the resonance peak associated with the knee was identical for the two acceleration levels yet the impedance response at RAN2 clearly shows the second resonance peak. The higher transmissibility observed at the knee for RAN2 may have had an influence on the appearance of the second impedance peak for this test. The distinct peak in the transmissibility of the thighs at 8 Hz for RAN2 suggests that the response of the thighs

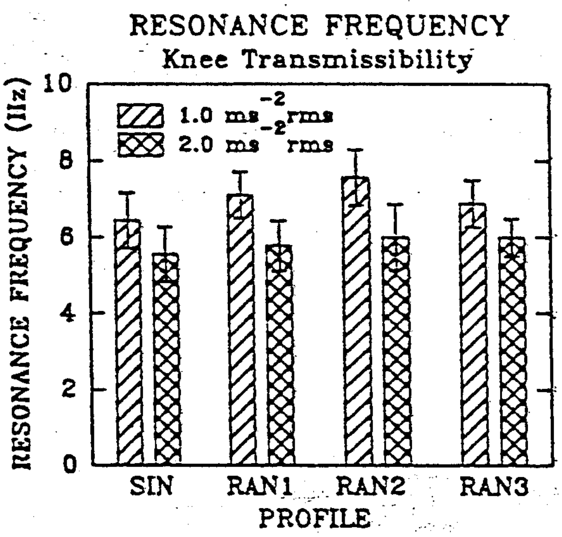

Figure 4 Mean Knee Resonance Frequencies

may have provided a substantial contribution to the impedance resonance peak.

The significant reductions in the resonance frequencies for RAN2 in the fourth region and RAN3 in the third region with increasing acceleration could be associated with changes in the transmissibility of specific anatomical sites. While several of the different types of exposures showed reductions in the resonance frequencies for specific tests, the reduction in the resonance frequency associated with Region Four for RAN2 was quite dramatic (1-4 Hz) and included significant reductions in the magnitude of the peaks. For RAN3, the reduction in the resonance frequency associated with Region Three at the higher acceleration level for impedance appeared to be associated with a significant reduction in the primary resonance frequency observed for the thighs and the elimination of this peak in several tests. The lack of an observable transmissibility peak did not necessarily preclude the observation of peaks in the impedance profiles which suggests that other anatomical structures may be contributing to the impedance peak in the third region.

4. DISCUSSION

Comparison of the impedance and transmissibility results presented for this study strongly support the association of specific anatomical structures or groups of structures with human resonance behavior. For the first region of resonance located between 5 and 7 Hz, it appears that the chest structures have the primary influence in the generation and location of the impedance peak. This is supported by previous studies (Guignard and King, 1960), by visual observations and by the subjective response of subjects (Smith, 1992). The transmissibility results in this study also suggest that, depending on the acceleration level and type of exposure, the legs also contribute to the first region of resonance for impedance and are the primary contributor to the nonlinear response behavior observed in the second region of resonance. Nonlinearity in the generation of the second impedance peak was reported previously under similar testing conditions (Smith, 1992), however, the generation of the second peak occurred at a relatively low acceleration level (0.347 ms^{-2} rms) for sinusoidal vibration. The acceleration level used in this study for sinusoidal vibration was higher at 1.0 ms^{-2} rms and, as expected, the second peak was not observed in this data. While the overall acceleration level for the sum-of-sines signals were identical to that used for the sinusoidal exposures, the acceleration levels associated with each frequency component in the sum-of-sines were relatively low (0.229 and 0.458 ms^{-2}) and comparable to the levels previously associated with the generation of the second resonance peak. The high incidence of the second peak for RAN2, however, indicates that changes in the stiffness and damping characteristics associated with the leg response depend on both the rms and the peak acceleration levels of the exposure.

It was speculated that the generation of the second region of resonance, which has not been observed by other investigators, was primarily due to the lack of a footrest and the resultant increased loading of the legs against the seat. In the previous study, the legs were modeled as a single-degree-of-freedom subsystem and considered to be uncoupled from the other resonance structures. The generation of two distinct peaks in the transmissibility data for the thighs implies that the legs may be responding as a two degree-of-freedom system. The first peak observed for the thighs was coincident with the transmissibility peak observed at the knee and may represent the response of the lower leg. The second resonance peak observed for the thighs (between 10 and 13) may be primarily influenced by the response of the upper leg. Smith (1992) attributed the third resonance peak with the response of the abdominal structures, basing the assumption on visual observations and subjective response. It appears that the thighs may provide an additional contribution to the impedance measurement in the third frequency region as supported by the similarity in the nonlinear behavior observed for the third impedance peak and the second transmissibility peak observed for the thighs.

The impedance modeling results of Smith (1992) and the results of this study strongly suggested that the motions of the upper torso or chest and spinal column are coupled. The head transmissibility data collected in this study is in agreement with the results of previous investigations (Guignard and King, 1960; ISO 7962, 1987) and further suggests that the head is also coupled with the chest and spinal column. The results of this study do not clearly indicate the nature of this coupling which will require further analytical evaluations using both the impedance and transmissibility data. One consideration is that the motion of the spinal column may be represented as a two-degree-of-freedom system. Mertens (1978) assumed that there were different stiffness and damping characteristics associated with the upper (thoracic) and lower (lumbar) spinal regions. Hagena et al. (1986) measured accelerations at the first, fourth and fifth lumbar vertebrae (L_1, L_4 and L_5), the sixth thoracic vertebra (T_6), the seventh cervical vertebra (C_7) and the head. The results indicated that, for the lower lumbar spine, the highest peaks occurred at about 8 Hz with dampened transmission above 10 Hz. Transmissibility peaks were observed at about 8 and 19 Hz for C_7 and were of similar magnitude. The highest transmissibility for the spine was observed in the thoracic region (T_6) between 19 and 20 Hz. Hinz and Seidel (1987), however, observed the transmissibility peak between about 4 and 5 Hz at the level of T_5. While a few tests showed the highest transmission for C_7 between 4 and 9 Hz in the present study, the majority of data showed the highest transmissibility at higher frequencies between 12 and 17 Hz, similar to the trend observed by Hagena et al. (1986). These investigators also observed the peak transmissibility of the head at about 8 Hz which also coincides with the results of this study. The magnitudes of the transmissibilities observed by these investigators, however, were lower than those observed in this study. Additional measurements are necessary to delineate those structures and the characteristics of the motions contributing to the relatively high transmissibility and high resonance frequency observed at C_7 particularly since there are conflicting results from previous investigations. It is speculated that the measurements are reflective of the transmission characteristics of the upper or thoracic spine under the test conditions used in this study. The results, therefore, strongly suggest that the vertical transmission of vibration to the head above 10 Hz is dramatically dampened by the cervical spine, possibly with the redirection of motion to other translational and rotational axes. Head motion during whole-body vibration is being further investigated in this laboratory.

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