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Mechanical impedance studies and development of human like dummy

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The magnitude of mechanical impedance gives an idea of mechanical energy per se transferred per se from vibrating environment to the human body with respect to the frequency of vibratory motion and is computed as the ratio of force exerted by the body to the velocity produced at the site of excitation. 28 human volunteers with average age and weight of 31.2 ± 5.43 yr. and 65.0 ± 9.70 kg respectively were subjected to vertical vibration in the frequency range 3-21 Hz. Mechanical impedance was determined at three amplitudes (above 1.0 m/sec^2) at each frequency setting.

A human like dummy of 68 kg weight and 175 cm height having natural frequency and frequency of impedance maximum similar to that of human subject was fabricated. The dummy can be used in situations where the magnitude of acceleration, impact, shock etc., are above human tolerance.

Keywords: Transient acceleration, transmissibility, vertical vibration, mechanical impedance, dynamic characteristics, anthropomorphic dummy.

For purposes of transient acceleration inputs, human body can be taken as a mechanical system[1]. The response of a mechanical system to an accelerative force depends not only on the magnitude, direction and duration of the applied force but also on the rate at which the force builds up. In sustained acceleration, force builds up slowly and may be accommodated by the system. In the case of rapidly applied force, acceleration builds up too fast for the mechanical system to track it and a transient or impact response occurs which differs considerably from the steady state response that would have resulted if the same force was applied slowly [2]. The ability of a system to track accelerative forces of varying application rates is described by its frequency response[3]. Thus, determining the frequency response of the system reveals its tracking ability. A significant characteristic of some mechanical systems is their natural tendency to respond to a non-sinusoidal brief force application with a sinusoidal mechanical response at a fixed frequency. Human body is considered no exception to that and is regarded as a resilient system with a resonance in the vertical axis between 4-8 Hz with variable damping [4].

A simple method of studying the dynamic response of the human body is to measure its driving point impedance under steady state sinusoidal vibration excitation. Since no instrumentation is attached to the body, this technique is considered near ideal. Although, the data collected would be for a lumped parameter representation of the human body, it is also applicable for multifrequency environment. Also, it is the only method where one is able to probe into human body in order to find out its characteristics of compressibility and damping [5].

The mechanical impedance is a ratio of the force exerted at the rigid interface between the structure and the environment and the velocity produced. If an impedance head is used, the actual magnitude of the force applied is not required. A dummy fabricated with similar

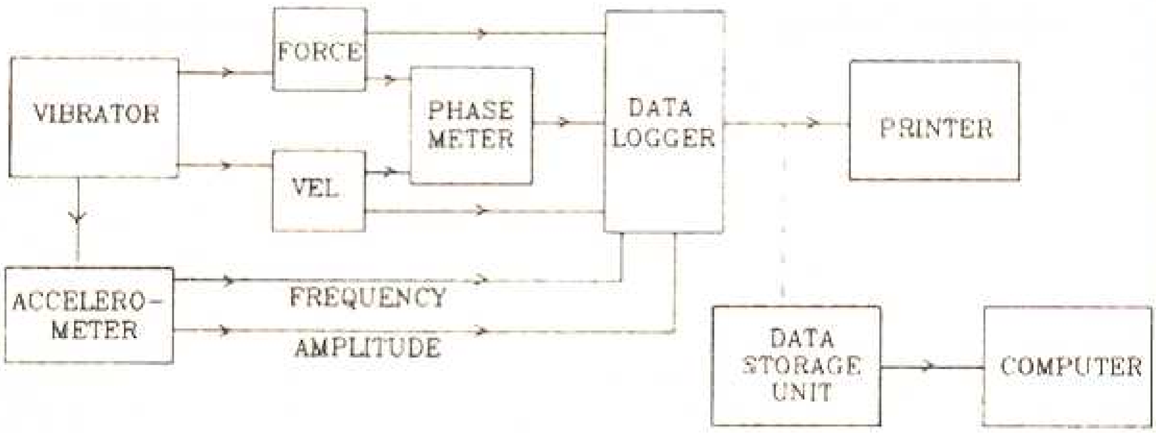

Figure 1. Mechanical impedance measurement set up.

frequency and mechanical impedance response can be employed to a great advantage in high magnitude acceleration environment where human beings cannot be used as subjects.

The present paper describes the studies carried out on mechanical impedance determination of human subjects and fabrication of human like dummy.

Principle

The equation of motion of lumped parameter linear system under forced vibration is

$$\ddot{x} + 2c\dot{x} + \omega^2 x = A \sin(\Omega t) \quad (1)$$

where,

x = Displacement

c = Damping constant

ω = Natural frequency of the system = $(k/m)^{1/2}$

k = Spring constant

m = Mass of the system

Ω = Forcing frequency

A Sin (Ωt) = Impact acceleration

Modulus of Mechanical Impedance,

$$|z| = \frac{F}{v} = \Omega m \sqrt{\frac{n^2 s^2 + 1}{n^2 s^2 + (1-n^2)^2}} \quad (2)$$

where,

F = Force exerted

v = Velocity generated

$n = \frac{\Omega}{\omega}$ = Frequency ratio

$s = \frac{2c}{\Omega}$

From the measured values the modulus of impedance at different frequencies and dynamic characteristics like apparent mass, elastic constant and damping constant can be calculated using [2].

Materials and methods

An electrohydraulic vibration simulator capable of simulating vertical vibrations in the frequency range 2-25 Hz with a frequency resolution of 0.1 Hz was used in the study. A light weight aluminium chair was fixed on to the moving piston through two aluminium platforms. Three force transducers were rigidly fixed at 120° apart between the two platforms. To measure vibration frequency, amplitude and velocity generated at the platform level, two linear response accelerometers were used in conjunction with appropriate indicators. A phase meter was used to determine the phase angle

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between force and velocity signals. Analog signals corresponding to force, velocity and phase angles were fed to a datalogger and print outs of these quantities were taken. The output of the datalogger could be connected to a data storage unit to store all the data on floppy disk. The details of the set up are given elsewhere[6].

The line diagram of the setup is given in Figure 1.

Methodology

The mechanical impedance measurement set up was tested for its linearity and proper functioning using rigid mass of seat plus platform of 25.5 kg, additional standard mass of 60 kg and a rigid dummy of 66 kg weight. Frequency in steps of 0.5 1 and 2 Hz were used in the range 3-10, 11-16 and 17-21 Hz respectively. At each frequency three amplitudes in excess of 0.1 g rms were employed and the ratio F/v calculated.

Study with human subjects

A total of 28 human volunteers, including three females, participated in the study. Subjects were in the weight group of 50-86 kg. Subject sat upright on the seat without any harnessing/restraining device. Frequency range of 3-21 Hz was administered in the same steps as in the case of rigid masses/dummy. In between each frequency setting, subject was allowed to come out of vibrating chair. For complete recording of one set of data comprising a single frequency and three amplitudes, approximately 10 min. were required. Therefore, appropriate tolerable vibration levels were used as per ISO guidelines[7]. Seat to head transmissibility was also measured using a triaxial seat accelerometer (B&K Type 4322) and a miniature unigain linear response accelerometer. Subject sat on the seat accelerometer while the other accelerometer was attached on to the subject's headgear. Since the first resonance occurs between 3-8 Hz, this frequency range was used to find the natural frequency of each subject. Mechanical

Figure 2. Anthropomorphic dummy.

impedance values were averaged for different weight groups of subjects as well as for the entire group at each frequency and mechanical impedance versus frequency graphs plotted.

Fabrication of anthropomorphic dummy

To make human like dummy, anthropometric data conforming to 50th percentile of Indian Air Force pilot population was used. The weight distribution of different body parts was matched exactly in fabricating the dummy.

The head of the dummy was made from seasoned teakwood pieces of 1.25 cm thickness glued together by synthetic glue and shaped like human head with full facial features. Neck was made from a steel rod which passes through the head. A steel plate attached at right angles to the neck rod made the collar bone. The rib cage was made from plastic rings shaped similar to human rib cage so as to hinge in the forward direction.

To give the visco-elastic characteristics, a vertebral column of 50 cm length and 5 cm diameter was made from fibre plastic. The column was embedded with 22 rings of hard rubber to simulate intervertebral discs. The vertebral column so made was treading through the rib cage and attached at the top to the neck rod and at the bottom to the pelvic joint. The pelvis, which was made of wood, conform to that of human body.

Legs and arms were made from steel rods and joint movements were provided at elbow as well as at knee so as to keep the dummy in sitting posture. Chemically treated raw rubber was attached to the skeleton, layer by layer, and proper shape was given to the torso as well as arms, thighs and calves. Feet were made from wood whereas, fingers were made of tin. On top of the raw rubber, layers of foam and crepe rubbers were attached. Each part of the dummy was weighed carefully at various stages to achieve a weight distribution of a 68 kg human of 175 cm height. Figure 2 shows the photograph of the dummy.

Experiments with dummy

The dummy was seated on the vibrating seat and secured with the help of shoulder and lap harnesses. Impedance experiment was carried out as with human subjects, in the frequency range 3-21 Hz, at three amplitudes for each frequency setting. Natural frequency was similar to that of human subjects in the weight group 60-69 kg.

Results

Table 1 gives the subject characteristics and natural frequency (w) for all the subjects grouped together and for subjects in the weight group 60-69 kg. The characteristics of the fabricated dummy are given in Table 2.

Discussion

The validity of mechanical impedance measuring set up is evident from Figure 3 where the impedance of the rigid mass of 25.5 kg of seat and platform as well as additional rigid mass of 60 kg (i.e., a total of 85.5 kg) were linear.

Table 1: Subject characteristics (m ± SD)

Weight Group (kg)	n	Age (Yr.)	Height (cm)	Weight (kg)	ω (Hz)
50–86	28	31.2 ±5.4	168.7 ±8.0	65.0 ±9.7	4.6 ±0.4
60–69	8	29.4 ±4.5	171.0 ±5.5	63.0 ±2.6	4.8 ±0.2

Table 2. Characteristics of anthropomorphic dummy

Height (cm)	Weight (kg)	Natural Frequency (Hz)
175.0	68.0	5.5

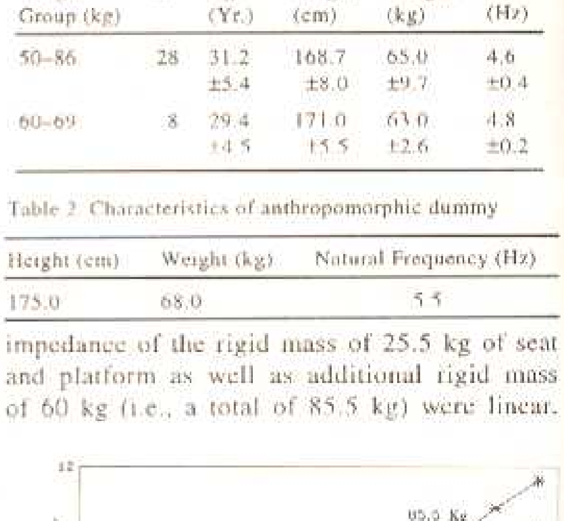

Figure 3. Mechanical impedance *Vs* frequency (standard masses and rigid dummy)

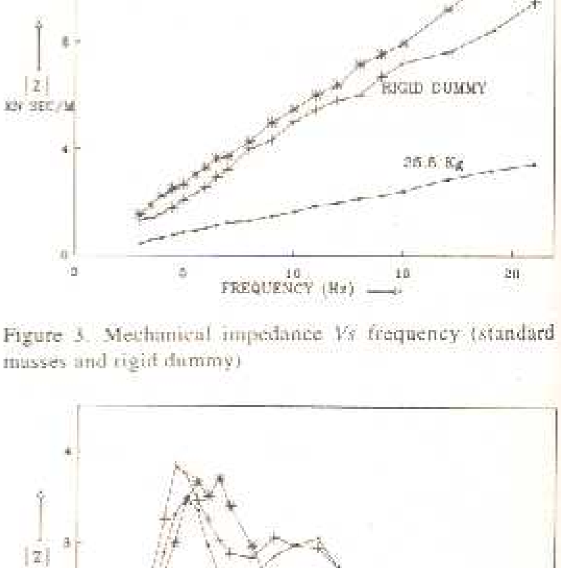

Figure 4. Mechanical impedance *Vs* frequency (human subjects and anthropomorphic dummy)

However, for the rigid dummy, the impedance values were somewhat higher between 8-21 Hz. The natural frequency for the 50-86 and 60-69 kg groups were 4.61 and 4.81 Hz whereas, the frequency and magnitude of impedance maximum for the respective groups were at 5.0 & 4.5 Hz and 3.51 & 3.84 KN sec/m. The natural frequency values and frequencies of impedance maximum are quite close to each other whereas, impedance response with frequency showed an increase with weight. The second peak shown in the impedance curve at 9.0 Hz for 50-86 kg and at 11 Hz for 60-69 kg weight groups were in the form of localised maxima rather than sharp peaks. This observation was similar to Coermann's findings[8].

Mechanical impedance is frequency dependent and for a pure mass without springiness and damping, the impedance increases linearly with frequency. This is the case with rigid masses and rigid dummy. For a seated human being, the mass can be treated as a pure mass upto about 2 Hz of excitation in the vertical axis and thereafter the maxima occurring between 4-5 Hz shows changes in the apparent mass. Above 7 Hz, apparent mass falls below that of pure mass indicating isolation of some body parts.

An anthropomorphic dummy of 68 kg, that was developed in the present study, had a weight distribution similar to a man of equivalent weight. That the dummy had dynamic properties similar to seated human being was obvious from the mechanical impedance as well as natural frequency values. The anthropomorphic dummy had a mechanical impedance value of 3.68 and 3.71 KN sec/m at 5.5 and 6.5 Hz respectively whereas, for human subjects the impedance maximum was found to be at 5 Hz. It has been reported, in vibration transmission studies, that increase in acceleration biasing increases the natural frequency of seated human subjects[9]. In our study, the slight increase in the frequency of impedance maximum as well as frequency at resonance can be taken to indicate the usage of dummy for higher magnitudes of vibration amplitude also. The use of transmission studies in conjunction with impedance determination can therefore be used to validate the similarities between human subjects and dummies.

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