Vibration biodynamics studies at IAM – An overview

MK Vyawahare, B Aravindakshan

Department of Applied Physics and Biodynamics, Institute of Aerospace Medicine, Vimanapura Post, Bangalore, India

In aviation environment, low-frequency whole-body vibrations below 30 Hz acting in the longitudinal axis of the body are of great importance because of the body resonance phenomena. In this paper, an overview of whole-body vertical vibration studies conducted at IAM, viz. frequency-dependent transmission characteristics, and their validation through mechanical impedance studies of human body are presented.

Transmission studies for amplitudes in the range 0.5–2.0 m/s² indicated changes in the maximum transmissibility from 2.83–2.40 and in the resonance frequency from 4.35–3.73 Hz. From mechanical impedance studies, it was found that the frequency of maximum impedance decreased from 5.0–4.5 Hz whereas the magnitude of impedance increased from 3.47–5.30 kN s/m with increase in subjects' weight. The dynamic characteristics of the human body, viz. elasticity, damping constant and damping factor, were found to be 61.60 kN/m, 1.50 kN s/m and 0.69, respectively. Impedance matching is used in making human-like dummies for dynamic studies.

Keywords: Whole-body vibrations; Transmissibility; Mechanical impedance; Dynamic characteristics.

All types of transportation vehicles subject operators to some degree of vibration [1, 2], and aviation and space vehicles are no exception. Appreciable vibrations are nearly always present in the flight of an aircraft either from engines and auxiliary machinery or due to aerodynamic interaction [3]. In some areas of strategic flights and in helicopter flying, vibrations could be alarming, causing a host of aeromedical problems to fliers [4–6]. Vibrations generated in the vehicles are transmitted to the occupants through the supporting seat and floor or through the walls and equipment. This transmission results in motion of the whole body or some body parts. Although the vibrations reaching the operator or passenger of an aircraft usually have a multiaxial and multifrequency spectrum [7, 8], the concern is more often for vibrations occurring in the vertical direction, i.e. acting along the long axis of the human body in a seated posture. Also, the frequency range of interest in the vertical direction is usually confined to below 30 Hz, due to the specific biodynamic behaviour of the human body system [4].

The extent to which vibrations are transmitted through the body determine the degree to which they are comfortable, impair the performance and are likely to cause injury [9]. The human body, being a complex dynamic structure, has a mechanical response which is quite complicated and requires a large amount of experimental data to understand the behaviour. However, the whole body response, particularly the transmission at first resonance, is very important due to the large transmissibility factor and implication thereof on performance and interference to the operation in coordinated efforts.

Even though different body parts exhibit variable frequency response, it is possible to determine the whole-body transmissibility and mechanical impedance [10] to understand the vibratory energy transfer in the human body in a vibration environment. Thus, transmission and impedance studies are useful and convenient tools to estimate the effect of vibration on human comfort, performance and, in extreme cases, health. These studies are also necessary for a proper design of protective devices for isolation/reduction of vibratory energy through the body.

At IAM, therefore, efforts have been made over the years to study vibration transmission and mechanical impedance of human body in the seated posture in a low-frequency vibration environment.

Material and methods

An electrohydraulic uniaxial vibration simulator was employed in the studies. The simulator, with frequency and amplitude resolution of 0.1 Hz and $0.05 \times g$, respectively, was capable of generating vibrations in the frequency range of 2–25 Hz at amplitudes in excess of $1.0 \times g$ (rms) at high frequencies. The details of the vibrator are given elsewhere [11]. Vibration magnitude and frequency were measured using flat-frequency response accelerometers together with indicators and filters. The vibration simulator was checked for its consistency in frequency and amplitude with time.

Experimental series I

A helicopter cockpit was firmly installed on the vibrating platform to impart vertical vibrations to the subject. The seat was provided with a hard seat cushion and an adjustable and crushable hard backrest of 2″ thickness (condition I). A total of 15 subjects took part in the experiments. They were in the age range 22–41 yr with an average weight of 64.3 ± 8.7 kg and an average height of 166.7 ± 4.4 cm.

The subjects sat in the seat in an upright relaxed position and the vibration was administered at the seat level in the frequency range of 3–9 Hz in steps of 0.5 Hz. Four vibration amplitudes in the range of 0.5–2.0 m/s^2 in steps of 0.5 m/s^2 were used for each frequency. Vibration amplitudes were measured at the platform, seat and head levels. For the measurement of the intensity of vibration at the top of the head, thin fibre glass shells were used. Metallic plates were embedded on these fibreglass shells for proper fitment of the accelerometer.

The experiment was repeated by using a four-point harness system on the subject with cushion and backrest of condition I (condition II), a 3″ hard seat cushion with a 3″ soft backrest (condition III) and a 4″ soft seat cushion with a 3″ soft backrest (condition IV).

Experimental series II

In this series experiments were carried out by fixing a hard aluminium seat on the vibrating platform. Twenty-eight subjects in the age range of 22–46 yr with an average weight of 65.02 ± 9.70 kg and an average height of 168.7 ± 7.97 cm participated.

Force cells and velocity transducers were fixed on to the platform to measure the force exerted by the subject and the velocity produced under the vibrating condition. A phase meter was also used to determine the relative phase between the force and the velocity.

Vibrations, at three amplitudes in excess of $0.1 \times g$ rms, were used in the frequency range 3–21 Hz at each frequency setting. Frequency were varied in steps of 0.5 Hz in the range of 3–10 Hz and in steps of 1.0 Hz in the range of 10–21 Hz. Seat to head level transmissibility and mechanical impedance were determined in the frequency ranges 3–9 Hz and 3–21 Hz, respectively.

Results

Tables 1 and 2 give the maximum transmissibility and resonance frequency under different conditions in the two series. Table 3 gives the maximum mechanical impedance and resonance frequency for different weight groups.

The average mechanical impedance (Z) and the dynamical characteristics of the subjects, viz. elasticity (k), damping factor (d) and damping constant (c), were calculated using the following formulae [17]: (The calculated values are given in Table 4.)

$$|Z| = \frac{F}{v} = \omega m \sqrt{\frac{n^2 s^2 + 1}{n^2 s^2 + (1 - n^2)}},$$

where F = the force required, v = the velocity required, $n = \omega/W$ = frequency ratio ω and W

Table 1. Maximum transmissibility and resonance frequency (experimental series I)

Experimental condition	Transmissibility and resonance frequency for vibration amplitude in m/s^2 (rms)			
	0.5	1.0	1.5	2.0
I	2.91 ± 0.31 (4.33 ± 0.33)	2.67 ± 0.42 (3.83 ± 0.35)	2.59 ± 0.34 (3.78 ± 0.34)	2.42 ± 0.29 (3.73 ± 0.19)
II	2.80 ± 0.114 (4.50 ± 0.25)	2.70 ± 0.19 (4.42 ± 0.18)	2.51 ± 0.17 (4.03 ± 0.32)	2.35 ± 0.19 (3.71 ± 0.17)
III	2.93 ± 0.26 (4.25 ± 0.31)	2.69 ± 0.27 (3.81 ± 0.24)	2.66 ± 0.15 (3.61 ± 0.22)	2.42 ± 0.27 (3.67 ± 0.27)
IV	3.15 ± 0.40 (3.94 ± 0.17)	2.91 ± 0.21 (3.72 ± 0.26)	2.80 ± 0.20 (3.67 ± 0.25)	2.59 ± 0.21 (3.65 ± 0.27)

Note. Bracketed values are resonance frequencies in Hz.

Table 2. Maximum transmissibility and resonance frequency (experimental series II)

Parameter	Vibration amplitude in m/s^2 (rms)	
	2.0	2.5
Maximum transmissibility	2.18 ± 0.31	2.01 ± 0.21
Resonance frequency (Hz)	4.61 ± 0.36	3.88 ± 0.32

Table 3. Mechanical impedance vs frequency

Weight group (kg)	Mechanical impedance (× kN s/m)	Resonance frequency (Hz)
50–59 (M)	3.47	5.0
50–59 (F)	3.34	5.0
60–69	3.51	5.0
70–79	5.03	4.5
80–86	5.30	4.5
Average	3.84	4.5

Table 4. Dynamic characteristics

Mechanical impedance (MI)	3.84 kN s/m
Frequency of MI maximum	4.5 Hz
Elastic constant	61.60 kN/m
Damping constant	1.50 kN s/m
Damping factor	0.69

being the forcing frequency and the natural frequency of the system) and $s = 2c/\omega$ (c being the damping constant),

$$k = m\omega^2 = \frac{Z(n = \sqrt{2})}{\sqrt{2}} \cdot \omega,$$

$$d = \frac{1}{\sqrt{\dfrac{Z(n = 1) \cdot \sqrt{2}}{Z(n = \sqrt{2})} - 1}},$$

$$c = m\omega d = \frac{Z(n = \sqrt{2})}{\sqrt{2}} \cdot d.$$

Discussion

The whole body vertical vibration transmission increases with frequency, reaching a peak around 3.5–5.0 Hz, and decreases thereafter with increase in the vibration frequency up to 10 Hz [9, 12]. There is a variability in transmissibility, leaner subjects having smaller values compared to higher-weight subjects. However, the average transmissibility magnitude at first resonance is limited to an amplification of <3. Cushions and backpads increase the transmission; however, they lower the resonance frequency (Tables 1 and 2). Increase in the magnitude of the input vibration reduces the transmissibility as well as the frequency of resonance [13, 14]. In one of our earlier studies [11], it was observed that seat to shoulder transmissibility approached near unity at vibration amplitudes of 4.0–6.0 m/s^2. Thus, in a low-frequency vibration environment body stiffness appears to increase with increasing vibration magnitude [15], as if to tolerate intense vibrations. Transmissibility is least if the subjects are in direct contact with the vibrating source, source, such as sitting directly on the vibrating seat. Similarly, strapping of the subject helps in reducing the head level transmissibility by increasing the stiffness. It has also been reported that under sustained acceleration, resonance frequency increases with increase in acceleration whilst the resonance magnitude decreases [16]. Thus, it is clear that body stiffness increases with vibration magnitude and so does the natural frequency and damping.

Mechanical impedance studies corroborate the finding regarding the first resonance frequency. For seated subjects in relaxed posture, the average is around 5 Hz although individual variations do exist [17].

Thus, in a vibration environment even if vibration exists in small magnitude in the low-frequency range, magnification of vibratory energy is likely to lead to possible large-scale interference in operators' tasks and may even be injurious if it turns chronic [18]. There exists a good relationship between transmissibility and mechanical impedance insofar as determining the resonance frequency for seated posture is concerned, and as such a similarity of natural frequency and impedance values around 5 Hz can be taken as a good match between the human body and a human-like dummy [9].

However, studies need to be continued at larger-magnitude, short-duration vibration to determine the impedance as well as transmission in human subjects. This will help in determining the dynamic characteristics and for developing appropriate dummies for shock and impact situations.

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