Dynamic Response of Human Foot in Vertical Body Position at Varied Frequencies

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Abstract— Human bodies are often exposed to vertical vibrations when they are in the workplace or on vehicles. Prolonged exposure may cause undue stress and discomfort in the human body. At the whole-body resonant frequency, there is maximum displacement between the organs and the skeletal structure, and which is the frequency of vibration that should be minimized in the workplace and elsewhere. By testing the response of the human body on a vibrating platform, many researchers found the human whole-body fundamental resonant frequency to be around 5 Hz. However, in recent years, an indirect method has been proposed which appears to increase the resonant frequency about 9 Hz. To explain this discrepancy, experimental work was carried out in KSU. The vertical whole-body resonant frequencies of fully clothed standing humans were measured using a vibrating plate method, which imposed a very low acceleration magnitude at the subjects' feet. The overall range of resonant frequencies was found to be from 9 to 19 Hz and independent of mass, height, and mass to height ratio.

Index Terms— Human; Resonance; Standing; Vertical; Vibration; Foot, Mass.

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1 INTRODUCTION

When exposed to vibration, the human body responds in a complex way. It has been identified that whole-body vibration is the cause of many forms of injury or industrial illness occurring in workplaces where workers are exposed for long periods of time to low-frequency vibration (Dupuis and Zerlett 1986). Those working with rotating and reciprocating machinery are most at risk from these, often suffering from back pain and other spinal disorders. Knowledge of the resonant frequency of the human body could aid the design of industrial buildings and transport systems so that exposure to vibration close to the body's resonant frequency may be minimized. At the resonant frequency, there is maximum displacement between the organ and the skeletal structure, placing biodynamic strain on the body tissue involved. Measurements of vibration transmissibility from the point of excitation (usually the seat) to the head (or other organs) reveal frequencies of maximum transmissibility that can be attributed to the resonance of the organ. However, such resonances are influenced by the response of other organs and the whole-body resonance. It is almost impossible to stimulate the natural frequency of one organ alone without exciting the whole-body resonances (Dupuis and Zerlett 1986).

Many measurements have been made of the whole-body resonance of seated persons as this is relevant to vibration during driving or traveling and much of this research has been used to assess and minimize the danger of vibration-related injury to the drivers of military vehicles. The whole-body resonant frequency of the seated person is typically 5 Hz (Griffin 1990), but this is influenced by many factors. Neither body posture (e.g. normal or erect) nor body weight has a large effect on the resonant frequency. Muscle tension can have a significant effect with most subjects showing a higher frequency when tense (Fairley and Griffin 1989). The height of a foot at rest changes the impedance at low frequencies but has little effect on the seated whole-body resonant frequency.

There has been relatively little work concerning the whole-body resonant frequencies of standing humans. Using the transmission response from the feet to the lumbar spine, the cervical spine and the forehead, Herterich, and Schnauber (1992) found resonances of 4, 8 and 16 Hz, but these can be attributed to spinal and head resonances rather than whole-body resonances. Again, using a transmission from the feet to the head, Paddam (1987) found resonances of vertical vibration at 2 to 5 Hz and a second smaller peak at 13 Hz for the three postures of legs locked at the knees, legs unlocked, and legs bent. Griffin (1990) quotes an unpublished study with eight subjects, which indicated a resonant frequency of about 5 Hz for the standing person with straight legs (locked at the knees) and about 3 Hz with knees bent. However, using an indirect technique, Ji et al. (1993) measured the resonant frequency of a standing person in the range of 8 to 10 Hz. Further work with this technique indicated a range of 10 to 12 Hz using four subjects and depending on the modal mass of the person (Ji 1995).

Measurements of the whole-body resonant frequency can be made by one of two methods. The first, the apparent mass method (Fairley and Griffin 1989) involves measurement of force and acceleration over a range of frequencies of a subject on an oscillating platform. The apparent mass for a given frequency is provided by the ratio of force to acceleration at that frequency. The resonant frequency appears as a peak in the frequency against an apparent mass curve. This method is unsuitable when working with animals as it requires a degree of co-operation on the part of the subject, or certain sensitive humans (e.g. pregnant women) as the magnitude of the r.m.s. acceleration might cause discomfort or distress.

A second method (Ji et al. 1993, Randall and Peng 1995) makes use of a simple rectangular beam supported at the ends and made to vibrate in its fundamental mode by being gently struck near its center. The process is repeated with a subject standing at the center of the beam. In both cases, the resonant frequency of the beam is recorded, from which the resonant frequency of the subject may be deduced. In this situation, the magnitude of the vibration is negligible, and it is therefore safe when used with sensitive subjects. This method allows a quick and easy flow of subjects thus minimizing the time taken for measurements.

2 EXPERIMENTAL SET-UP AND MODE

The actual setup involved accelerometers attached to the top of the foot and to the top of a vibrating plate as shown below.

Figure 1: Actual setup of the accelerometer on volunteer's foot and on top of the vibrating plate

The model of the experiment is as follows:

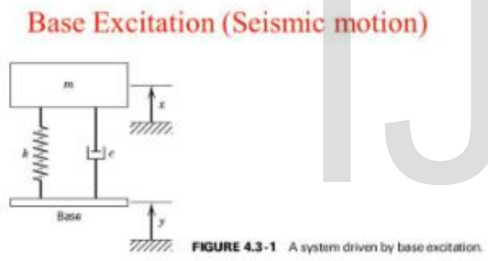

Figure 2: Spring, mass & damper system driven by base excitation

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3 METHODOLOGY

We start with the resonance frequency (in Hz) collected from the graphs; we also collect the acceleration magnitude reading (in Volts). The resonance frequency is multiplied by 2*π/60 to get the resonance frequency ω_n in rad/s.

We also know that: $\omega_n = \sqrt{\frac{k}{m}}$

And we can rewrite it to: $k = m * \omega_n^{2}$

Where m is the mass of the foot and k is the spring constant. Given the total mass of a person, we still need to find the mass of the foot to solve for the spring constant.

The mass of the foot is roughly 1.43% of the total mass of the body for males and 1.33% for females.

For a male for example, the spring constant is:

$$k = 0.0143 * m * \omega_n^{2}$$

The next step is to calculate the zeta value (ξ) Starting with the displacement transmissibility relation:

$$\frac{X}{Y} = \sqrt{\frac{4 * \xi^2 * r^2 + 1}{(1 - r^2)^2 + 4 * \xi^2 * r^2}}$$

Since we consider the forcing frequency to be the resonance frequency in this case, we know that r = 1

$$(r = \frac{\omega}{\omega_n})$$

The displacement transmissibility equation is simplified to:

$$\frac{X}{Y} = \sqrt{\frac{4 * \xi^2 + 1}{4 * \xi^2}}$$

We square both sides and solve for ξ:

$$\xi = \sqrt{\frac{Y^2}{4 * X^2 - 4 * Y^2}} \qquad (1)$$

Based off of the magnitude readings from the MatLab output, we can convert the voltage reading of the accelerometers into acceleration units. We need to divide the voltage reading by

100mV/g to get the acceleration in terms of g. We can multiply by 9.8 m/s^2 to get the acceleration in SI units. At this point, we need to still find the displacement of the accelerometers and of the vibration plate to find ξ.

We start the process with the steady-state response equation:
And then we differentiate both sides twice:

$$x(t) = X * \sin(\omega t) \quad \langle A \rangle$$

And then we differentiate both sides twice:

$$x''(t) = -X * \omega^2 * \sin(\omega t)$$

$$x''(t) = -\omega^2 * X * \sin(\omega t) \quad \langle B \rangle$$

Substitute A into B

$$x''(t) = -\omega^2 * x(t)$$

Solve for x(t)

$$x(t) = \frac{-1}{\omega^2} * x''(t)$$

Since we already have the acceleration, we can solve for the displacement x (t). The same process is used for finding y (t) as well. That is the displacement used in (1) to solve for ξ

Once ξ is found, we can use the relation:

$$\xi = \frac{c}{2*\sqrt{m*k}}$$

And solve for c

$$c = 2 * \xi * \sqrt{m * k}$$

And we can also solve for the force transmissibility using the relation: $F_t = k * X$

From the system model driven by base excitation:

$$m * x'' + c * x' + kx = c * y' + k * y$$

Velocity difference:

$$x' - y' = \frac{k * (x - y) - m * x''}{c}$$

So that impedance, using the following relation:

$$Z = \frac{F}{v} \quad \text{or} \quad Z = \frac{F_t}{x' - y'}$$

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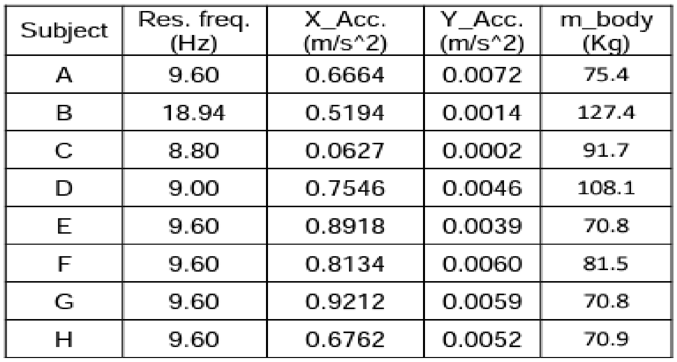
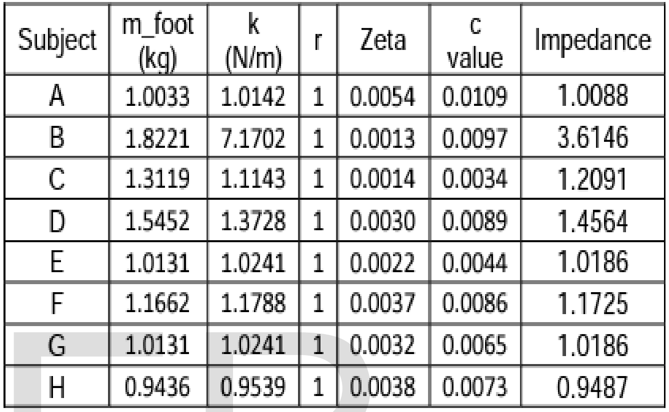
4 RESULTS



Subject	Res. freq. (Hz)	X_Acc. (m/s^2)	Y_Acc. (m/s^2)	m_body (Kg)
A	9.60	0.6664	0.0072	75.4
B	18.94	0.5194	0.0014	127.4
C	8.80	0.0627	0.0002	91.7
D	9.00	0.7546	0.0046	108.1
E	9.60	0.8918	0.0039	70.8
F	9.60	0.8134	0.0060	81.5
G	9.60	0.9212	0.0059	70.8
H	9.60	0.6762	0.0052	70.9

Table 1: Data collected on all 8 subjects using MatLab



Subject	m_foot (kg)	k (N/m)	r	Zeta	c value	Impedance
A	1.0033	1.0142	1	0.0054	0.0109	1.0088
B	1.8221	7.1702	1	0.0013	0.0097	3.6146
C	1.3119	1.1143	1	0.0014	0.0034	1.2091
D	1.5452	1.3728	1	0.0030	0.0089	1.4564
E	1.0131	1.0241	1	0.0022	0.0044	1.0186
F	1.1662	1.1788	1	0.0037	0.0086	1.1725
G	1.0131	1.0241	1	0.0032	0.0065	1.0186
H	0.9436	0.9539	1	0.0038	0.0073	0.9487

Table 2: Data calculated on all 8 subjects based on previous table data.
section.

5 CONCLUSION

There appears to be a possible correlation between heavier individuals having lower resonance frequencies, but there might be some error involved there. The outlier is subject B who is heaviest, but the data appears to be inconsistent there. I believe that was the first subject to conduct the experiment, so maybe we should simply overlook that one. It can also be noticed that five out of 8 subjects have the same resonance frequency. This could possibly be due to error on the signal processing SIDE, or it could possibly be that all individuals have the same resonance frequency on their feet.

Since the vibrating board is constantly moving, there is also a chance of the person inadvertently moving their feet to keep their balance, but the data appears to be consistent. The acceleration readings, however, do appear to be entirely different based on the individual's weight and the frequency of the vibrating board. The weight of each individual and the displacement of the accelerometers play a role in calculating all the other variables.

As far as the impedance is concerned, the data shows that the mass of the individual and the resonance frequency is directly related to the impedance of an individual. The higher the weight, the higher the impedance. This is highlighted by comparing the lightest and heaviest individuals (D & H). We are also ignoring subject B due to the unusually high resonance frequency which caused an unusually high impedance to result. According to research conducted, the leaner individuals are, the lower the impedance is due to the water content they hold. There was no focus on the body type of the individuals, but the heavier ones were not lean whereas the lighter individuals were. This appears to be consistent with other studies conducted on the whole body. Even if the focus here is only on the foot, the results should be consistent.

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