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# Analysis Of Seated Human Body Under Low Frequency Vibrations Using Transmissibility And Driving Point Mechanical Impedance.

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## Abstract:

*Humans are more sensitive to whole Body Vibration under low frequency range. Under this frequency range human feels more discomfort. Due to this reason more research is going on from more number of years in low frequency range.As a part of research biodynamic models are prepared to number of degrees of freedom and these results are compared with the experimental data.In the present study the authors prepared a 5 DOF biodynamic model of the human body in a sitting posture without backrest under sinusoidal excitation to determine the.dynamic response characteristics such as Driving point mechanical impedance (DPMI)which describes the "to-the–body "force-motion relationship at the seat to human interference and Transmissibility function describes the "through–the-body " vibration transmission properties. As a part of this study analytical transmissibility data is validated with the experimental data. The resonant frequencies of the human subjects computed on the basis of Transmissibility function are found to be within close to that of the expected for the human body.*

## 1. Introduction:

There are many factors that affect comfort in a driving vehicle, such as pressure at seat interface, sittingposture, vibration, noise, visualeffects, humidity etc.Among them whole body vibration causes many problems in human health comfort and performance. Depending on the type and design of highway and off-highway vehicles, the drivers can be exposed to considerable levels of low-frequency vibration orienting primarily from the vehicle terrain interactions. Appropriate design and proper tuning of vehicle and seat suspension systems are often analyzed assuming negligible interactions of the human body, the body is known to have some influence on their vibration transmission performance.[1].During sinusoidal vertical oscillation at frequencies below about 2 Hz. most parts of the body moves up and down together. If the motion has a frequency below about 0.5 Hz it may eventually cause symptoms of motion sickness such as sweating or vomiting. Vertical oscillation of seated person at some frequencies above about 2Hz. Causes amplification of the vibration within the body. The resonance frequency varies for different parts of the body. It is commonly suggested that the first major resonance occurs at about 5 Hz. The transmissibility of vertical vibrations to the head is sometimes maximum at about 4Hz. The driving force per unit acceleration is a maximum at about 5 Hz.[2].The human feelings like discomfort and the levels of injury can be estimated with relationship and measured 12 axis whole body vibration. This discomfort estimation can be used in experimental method in vibrating environment such as vehicle. But this experimental method is time consuming and need much effort. So, analytical approach of the mechanical human models would be better to estimate dynamic characteristics of human body under sinusoidal vibration. Biodynamic models can be divided as lumped parameter and distributed models. The lumped parameter models consider the human body as several rigid bodies and spring-dampers. The distributed model treats the spine as layered structure of rigid elements, representing the vertebral bodies, and deformable elements representing the intervertebral discs by the finite element method. Kitazaki and Griffin (1997) developed a model using the finite element method and executed model analysis to verify the natural frequency of each segment. They showed the mode of the principle resonance at about 8 Hz. They also showed that a change of posture from erect to slouchdecreased the natural frequency of human body.Wei and Griffin (1998) determined the biodynamic model parameters using the apparent mass of the hip. Mansfield and Lundstrom (1999) developed models with parallel 3DOF systems to represent apparent mass of the seated body exposed to horizontal vibration. Boileau et.,al [3]investigated the relationships between driving point mechanical impedance and seat to head transmissibility functions based upon 11 reported one dimensional lumped parameter models. Wu et.al, [4] investigated a relationship between the APMI/DPMI and seat to head transmissibility functions based upon four biodynamic models ranging from single to 3 DOF models. It was shown that both the normalized apparent mass and seat to head transmissibility functions provide very similar fundamental resonance frequency, while the frequencies of higher modes of the higher order models differed. The objective of this study is to develop a 5 DOF biodynamic model to investigate and analyze the DPMI and transmissibility values obtained from analytical method in comparison with the experimental results.

## 2. Biodynamic response of the human body

The biodynamic response of a seated human body posture to whole body vibrationcan be broadly categorized into two types. The first category “To–the-body “ force motion interrelation as a function of frequency at the human seat interface ,expressed as driving point mechanical impedance or apparent mass. The second category “Through the body “responsefunction, generally termed as seat to head transmissibility for the seated occupant.

The DPMI relates the driving force and resulting velocity response as the driving point (the seat –buttock interface), and is given by [4]:

$$\mathbf{Z\ (jw)} = \frac{F(jw)}{V(jw)} = \frac{F(jw)}{\dot{x}(jw)} \qquad (1)$$

Where, Z (jw) is the complex DPMI.F (jw) and V (jw) or $\dot{x}(jw)$ and the driving force and response velocity at the driving point, respectively. W is the angular frequency in rad/sec, and j=$\sqrt{-1}$ is the complex phasor.

The apparent mass response relates the driving force to the resulting acceleration response, and is given by [5]

$$\mathbf{APMS\ (jw)} = \frac{F(jw)}{a(jw)} \quad \mathbf{(2)}$$

Where, a (jw) is the acceleration response at the driving point .The magnitude of APMS offers a simple interpretation as it equals to the static mass of the human body response supported by the seat at very low frequencies, when the human body resembles that of a rigid mass,the DPMI and APMS are related as

$$\text{APMS (jw)} = \frac{\text{DPMI(jw)}}{\text{jw}} (3)$$

Unlike the force – motion relationship at the driving-point the STHT describes the transmission of vibration through the seated body. The STHT response function is expressed as:

$$\text{H(jw)} = \frac{a_H\text{(jw)}}{\text{a(jw)}} \ (4)$$

Where,H (jw) is the complex STHT, aH (jw) is the response acceleration measured at the head of seated occupant, and a (jw) is acceleration response at the driving point.

### *2.1 Basic Assumptions on the Experimental data:*

The following requirements are selected for the biodynamic characteristics of the seated human subjects [6-8]

- A human subject is considered to be sitting without backrest support, irrespective of the hands position.
- Body masses will be limited within 49 – 94 Kg.
- Feet are supported and vibrated.
- Analysis constrained to vertical direction.
- Vibration excitation amplitude is below 5m/s$^2$ with the nature of excitation specified as being sinusoidal wave.Excitation frequency range is limited to 0.5 – 20 Hz.

## 2. Experimentalsetup:

The study was conducted on the vibration simulator in natural laboratory environment, developed as a mockup of a railway vehicle, in Vehicle Dynamics Laboratory, IIT Roorkee, and India. It consists of a platform of 2 m × 2 m size made up of stainless steel corrugated sheets, on which a table and two rigid chairs have been securely fixed. The backrest of the chair was rigid, flat, and vertical. Neither the seat, nor the backrest, nor the table had any resonances within the frequency range studied (up to 20 Hz) in any of the three axes. Three Electro-Dynamic Vibration shakers are used to provide vibration stimuli simultaneously to the platform in three axes; longitudinal (X-axis), lateral (Y-axis) and vertical (Z-axis). Each vibration exciter has a force capacity of 1000 N with a stroke length of 25 mm (peak-to-peak). For simplicity and safety reasons the internal positioning accelerometers of the shakers were continuously used for motion feedback. In this study the subjects were exposed to sinusoidal vertical whole-body vibration by vertical electro-dynamics exciter. The tri-axial accelerometers (KISTLER 8393B10) are placed on the seat, bite bar used at head positions in order to measure the acceleration at the respective points.We get the output signal from the SVANTEC vibration meter and the graphs are analyzed using SVANTEK software and transmissibility is calculated. The test subjects were seated on the chairs rigidly mounted on the platform of Vibration Simulator such that these are excited with the same frequency as the platform, up to 100 Hz.

### *2.1Experimental Design*:

The experiment was performed to measure the transmissibility of seated human erect posture under vibratory environment under low frequency vibration. Six male subjects with average age 25, average height174cm and average weight of 68Kg. take part in the experiment. In this study frequency ranges from 2-12 HZ and vibration amplitude is taken from 0.4 -0.8 m/sec$^2$.

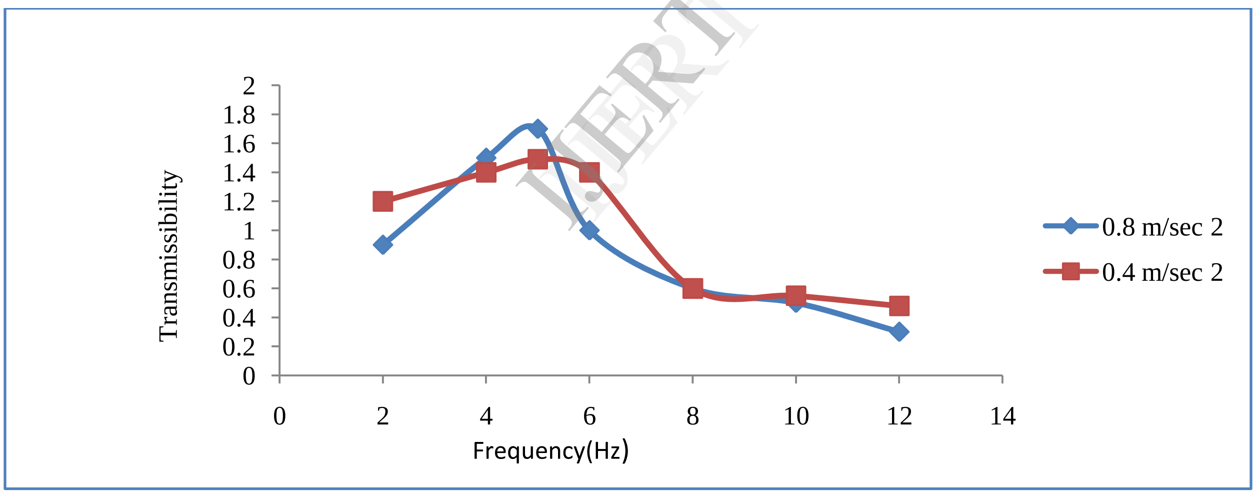
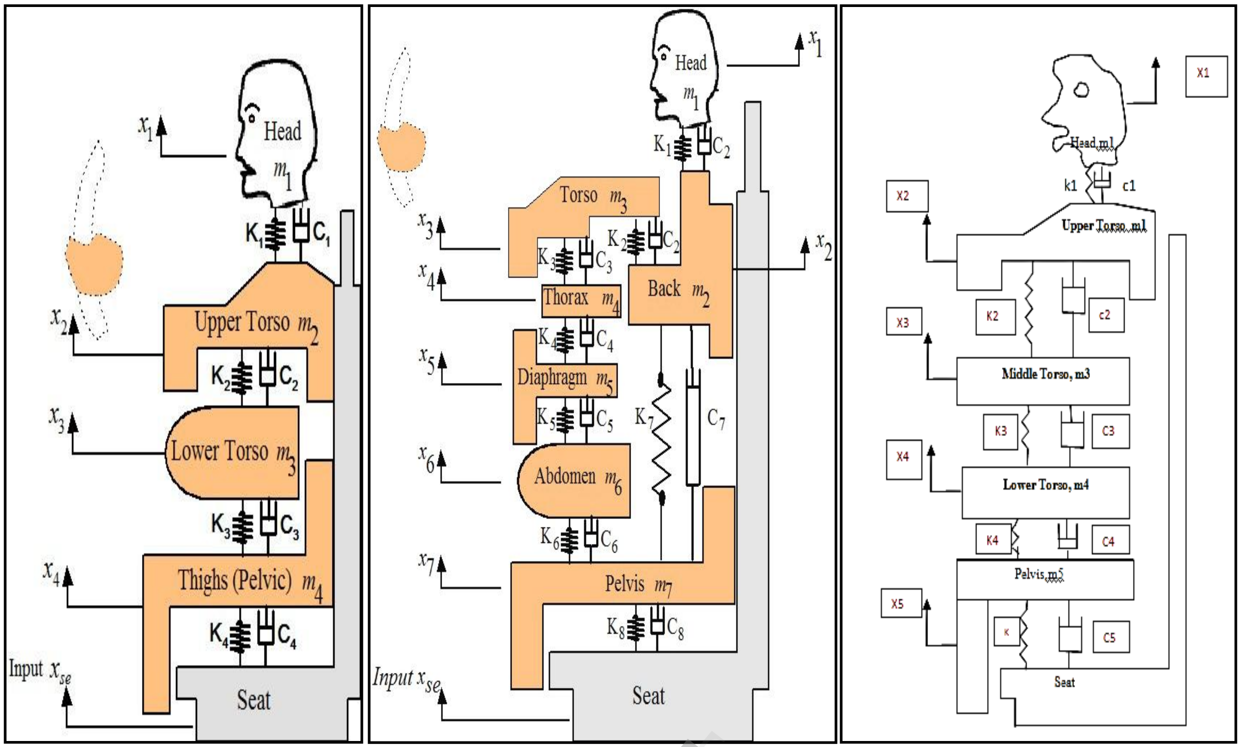


Fig 1.Mean Transmissibility Characteristic of the 6 male subjects maintaining a seated posture erect posture under 0.4, 0.8 m/sec $^2$ sinusoidal excitation.

From the Graph we observed that maximum frequency observed at a frequency of 5 Hz. results reveal a certain discrepancy of whole body resonant frequency on the subject mass.

## 3.Biodynamic modeling:

The human body in a sitting posture modeled as a mechanicalsystem that is interconnected by springs and dampers, [1]) the model is shown in the fig 1(a) consists of four sets of springs and dampers. The four mass segments interconnected by four sets of springs and dampers. The four masses represent the following four body segments: the head and neck (m1), the chest and upper torso (m2), the lower torso (m3), and the thighs and pelvis in contactwith the seat (m4). Thestiffness and damping properties of thighs and pelvis are (k4) and (c4), the lower torso are (k3) and (c3), upper torso is (K2) and (c2), and head are (k1) and (c1).



(a) (b) (c)

Fig 2.BioDynamic Models. (a) Boileau and Rakheja 4-DOF model [8] and (b) Patil and Palanichamy 7-DOF model [8]. (c) Present 5 DOF model.

The equation of motion of the Boileau and Rakheja human body can be obtained as follows:

$$\left.\begin{aligned}
&m_1\ddot{x}_1 + k_1(x_1 - x_2) + c_1(\dot{x}_1 - \dot{x}_2) = 0\\
&m_2\ddot{x}_2 + k_1(x_2 - x_1) + c_1(\dot{x}_2 - \dot{x}_1) + k_2(x_2 - x_3) + c_2(\dot{x}_2 - \dot{x}_3) = 0\\
&m_3\ddot{x}_3 + k_2(x_3 - x_2) + c_2(\dot{x}_3 - \dot{x}_2) + k_3(x_3 - x_4) + c_3(\dot{x}_3 - \dot{x}_4) = 0\\
&m_4\ddot{x}_4 + k_3(x_4 - x_2) + c_3(\dot{x}_4 - \dot{x}_3) + k_4(x_4 - x_{se}) + c_4(\dot{x}_4 - \dot{x}_{se}) = 0
\end{aligned}\right\} \tag{5}$$

Another 7-DOF nonlinear model was developed by Patil and Palanichamy [1]. In this model, the human body consists of seven mass segments inter connected by eight sets of springs and dampers, with total mass of 80 kg. The seven masses represent the following body segments: head and neck ($m1$), back ($m2$), upper torso ($m3$), thorax ($m4$), diaphragm ($m5$), abdomen ($m6$) and thighs and pelvis ($m7$). The arms and legs are combined with the upper torso and thigh, respectively. The stiffness and damping properties of thighs and pelvis are (k8) and (c8), abdomen are (k6) and (c6), the diaphragm are (k5) and (c5), the thorax are (k4) and (c4), the torso are (k2, k3) and (c2, c3), back are (k7) and (c7), and head are (k1) and (c1). The schematic of the

Model is shown in **Figure 2(b)**, and biomechanical parameters of the model are listed in **Table 2**.

The governing equation for the Patil and Palanichamy 7-DOF model is.

$$\left.\begin{aligned}
&m_1\ddot{x}_1 + k_1(x_1 - x_2) + c_1(\dot{x}_1 - \dot{x}_2) = 0\\
&m_2\ddot{x}_2 = k_1(x_1 - x_2) + c_1(\dot{x}_1 - \dot{x}_2) + k_2(x_3 - x_2) + c_2(\dot{x}_3 - \dot{x}_2) - k_2(x_2 - x_7) - c_7(\dot{x}_2 - \dot{x}_7)\\
&m_3\ddot{x}_3 = -k_2(x_3 - x_2) - c_2(\dot{x}_3 - \dot{x}_2) - k_3(x_3 - x_4) - c_3(\dot{x}_3 - \dot{x}_4)\\
&m_4\ddot{x}_4 = k_3(x_3 - x_4) + c_3(\dot{x}_3 - \dot{x}_4) - k_4(x_4 - x_5) - c_4(\dot{x}_4 - \dot{x}_5)
\end{aligned}\right\}$$

$$\left.\begin{aligned}
&m_5\ddot{x}_5 = k_4(x_4 - x_5) + c_4(\dot{x}_4 - \dot{x}_5) - k_5(x_5 - x_6) - c_5(\dot{x}_5 - \dot{x}_6) \qquad (6)\\
&m_6\ddot{x}_6 = k_5(x_5 - x_6) + c_5(\dot{x}_5 - \dot{x}_6) - k_6(x_6 - x_7) - c_6(\dot{x}_6 - \dot{x}_7)\\
&m_7\ddot{x}_7 = k_6(x_6 - x_7) + c_6(\dot{x}_6 - \dot{x}_7) + k_7(x_2 - x_7) + c_7(\dot{x}_2 - \dot{x}_7) - k_8(x_7 - x_{se}) - c_8(\dot{x}_7 - \dot{x}_{se})\\
&m_{se}\ddot{x}_{se} = -k_{se}(x_{se} - x_b) + c_{se}(\dot{x}_{se} - \dot{x}_b) + k_8(x_7 - x_{se}) + c_8(\dot{x}_7 - \dot{x}_{se})
\end{aligned}\right\}$$

Table 1.Biodynamical parameters of the Rakheja and Boileau model

| Mass(Kg) | Damping Coeff. (N-Sec /m) | Stiffness Coeff.(KN/m) |
|---|---|---|
| m1=5.31 | c1=460 | k1=356.37 |
| m2 =28.49 | c2=5400 | k2=208.57 |
| m3 =12.78 | c3=5190 | k3=187.11 |
| m4=10.00 | c4=2370 | k4=103.48 |

Table 2.Biodynamical parameters of the Patil and Palanichamy model

| Mass(Kg) | Damping Coeff.(N-Sec /m) | Stiffness Coeff.(KN/m) |
|---|---|---|
| $m_1$=5.55 | $c_1$=3542 | $k_1$=3542 |
| $m_2$ = 6.94 | $c_2$=2685 | $k_2$=3542 |
| $m_3$ = 33.33 | $c_3$=351 | k3=351 |
| $m_4$=1.389 | $c_4$=237 | k4=237 |
| $m_5$=0.4629 | $c_5$=354 | k5=354 |
| $m_6$ =6.02 | $c_6$=225 | k6=225 |
| $m_7$ = 27.7 | $c_7$=2929 | k7=2929 |
|  | $c_8$=463 | k8=463 |

Here in our present model prepared a 5 DOF model consist of the human body consists of five mass segments inter connected by five sets of springs and dampers, with total mass of 74.46 kg. The five masses represent the following body segments: head (*m*1), upper torso including hands (*m*2), thorax and Back (*m*3), diaphragm and abdomen (*m*4) and two legs and pelvis (*m*5). The stiffness and damping properties of two legsand pelvis are (k5) and (c5), abdomen and diaphram are (k4) and (c4),the thorax and back are (k3) and (c3), upper torso including two hands (k4) and (c4), and head are (k1) and (c1). The schematic of themodel is shown in **Figure 2(c)**, and biomechanical parameters of the model are listed in **Table 3**.In this model we assumed that mass of the seat neglected and the displacement which occurs at the seat same as at the pelvis.
The governing equationsfor thepresent 5 DOF model are as follows.

$$\left.\begin{aligned}
&m_1\ddot{x}_1 + k_1(x_1 - x_2) + c_1(\dot{x}_1 - \dot{x}_2) = 0\\
&m_1\ddot{x}_1 + k_1(x_2 - x_1) + c_1(\dot{x}_2 - \dot{x}_1) + k_1(x_2 - x_3) + c_2(\dot{x}_2 - \dot{x}_3) = 0\\
&m_3\ddot{x}_3 + k_2(x_3 - x_2) + c_1(\dot{x}_3 - \dot{x}_2) + k_3(x_3 - x_4) + c_2(\dot{x}_3 - \dot{x}_4) = 0 \qquad (7)\\
&m_4\ddot{x}_4 + k_3(x_4 - x_3) + c_3(\dot{x}_4 - \dot{x}_3) + k_4(x_4 - x_5) + c_4(\dot{x}_4 - \dot{x}_5) = 0\\
&m_5\ddot{x}_5 + k_4(x_5 - x_4) + c_5(\dot{x}_5 - \dot{x}_4) = k_5x_5 + c_5\dot{x}_5
\end{aligned}\right\}$$

Table 3.Biodynamical parameters of the present 5DOF model

| Mass(Kg) | Damping Coeff.(N-Sec /m) | Stiffness Coeff.(KN/m) |
|---|---|---|
| m1=5.31 | c1=1400 | k1=310 |
| m2=28.69 | c2=2850 | k2=183 |
| m3 = 8.62 | c3=3585 | k3=250 |
| m4=10.00 | c4=3585 | k4=250 |
| m5=21.84 | c5=1700 | k5=10 |

Theequations of motion, (7), for the model can be expressed in matrix form asfollows: $[\boldsymbol{M}]\{\ddot{\boldsymbol{x}}\} + [\boldsymbol{C}]\{\dot{\boldsymbol{x}}\} + [\boldsymbol{K}]\{\boldsymbol{x}\} = [\boldsymbol{f}]$ **(8)**
Where [m], [c] and [k] are nxn mass, damping, and stiffness matrices, respectively; and [f]are the force vector due to external excitation.

$$[M] = \begin{bmatrix} m1 & 0 & 0 & 0 & 0 \\ 0 & m2 & 0 & 0 & 0 \\ 0 & 0 & m3 & 0 & 0 \\ 0 & 0 & 0 & m4 & 0 \\ 0 & 0 & 0 & 0 & m5 \end{bmatrix} \qquad [C] = \begin{bmatrix} c1 & -c1 & 0 & 0 & 0 \\ -c1 & c1+c2 & -c2 & 0 & 0 \\ 0 & -c2 & c2+c3 & -c3 & 0 \\ 0 & 0 & -c3 & c3+c4 & -c4 \\ 0 & 0 & 0 & -c4 & c4+c5 \end{bmatrix}$$

$$[K] = \begin{bmatrix} k1 & -k1 & 0 & 0 & 0 \\ -k1 & k1+k2 & -k2 & 0 & 0 \\ 0 & -k2 & k2+k3 & -k3 & 0 \\ 0 & 0 & -k3 & k3+k4 & -k4 \\ 0 & 0 & 0 & -k4 & k4+k5 \end{bmatrix} \qquad [f] = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ k5\, x_{se}+c5\, x_{se} \end{bmatrix}$$

By taking the Fourier transform of equation (3), the following matrix form of equation can be obtained:
**$[X(jw)] = \{[K]-w^2[M]+jw[C]\}^{-1}\{F(jw)\}$ (9)**
Where [X (jw)] and {F (jw)} are the complex Fourier transformation vectors of {x} and {f} respectively. 'w' is the excitation frequency. Vector {X(jw)} contains complex displacement responses of n mass segments as a function of 'w'($\{X_1(jw), X_2(jw), X_3(jw) \ldots X_n(jw)\}$).{F(jw)} consists of complex excitation forces on the mass segments as a function of 'w' as well.

### 3.1Biodynamic Response of human body:

DPMI for the model can be represented as:

$$\text{DPMI}(jw) = \frac{F(jw)}{v(jw)} = \left|\left(c_5 + \frac{k_5}{jw}\right)\frac{x_{5(jw)}}{x_{1(w)}} - \left(c_5 + \frac{K_5}{jw}\right)\right| \quad \textbf{(10)}$$

Unlike the force – motion relationship at the transmission of vibration trough the seated body.The STHT response function is expressed as:

$$\text{STHT}(jw) = \frac{a_{H(jw)}}{a(jw)} = \frac{x_1(jw)}{x_{5(w)}} \quad \textbf{(11)}$$

## 4. Analytical results and discussions:

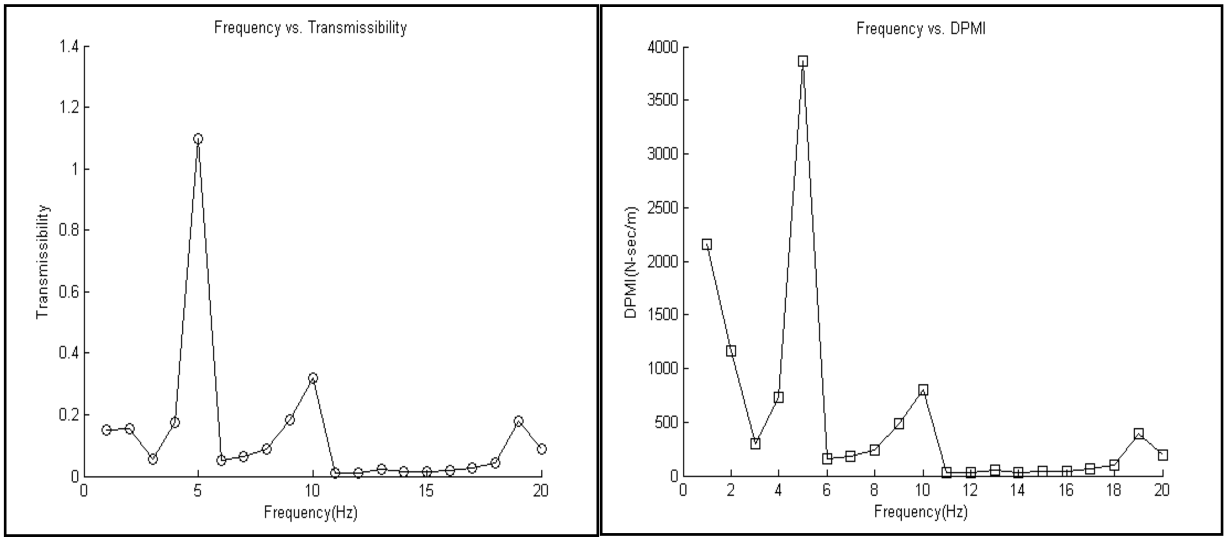


Fig 3.Transmissibility and DPMI of the S.Rakheja Model

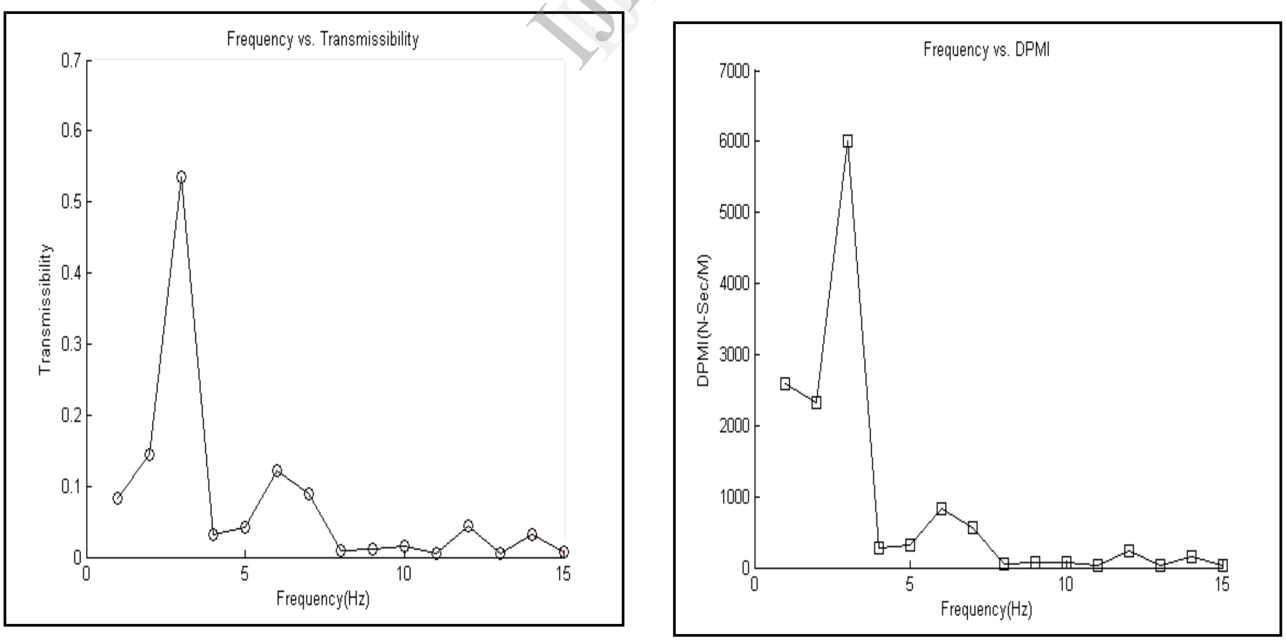


Fig 4.Transmissibility and DPMI of the Patil and Palanichamy Model.

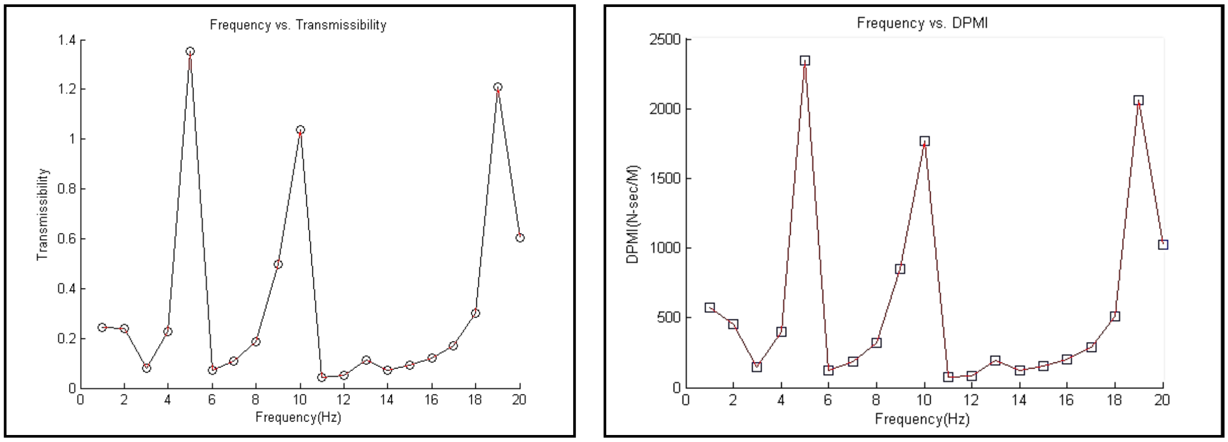
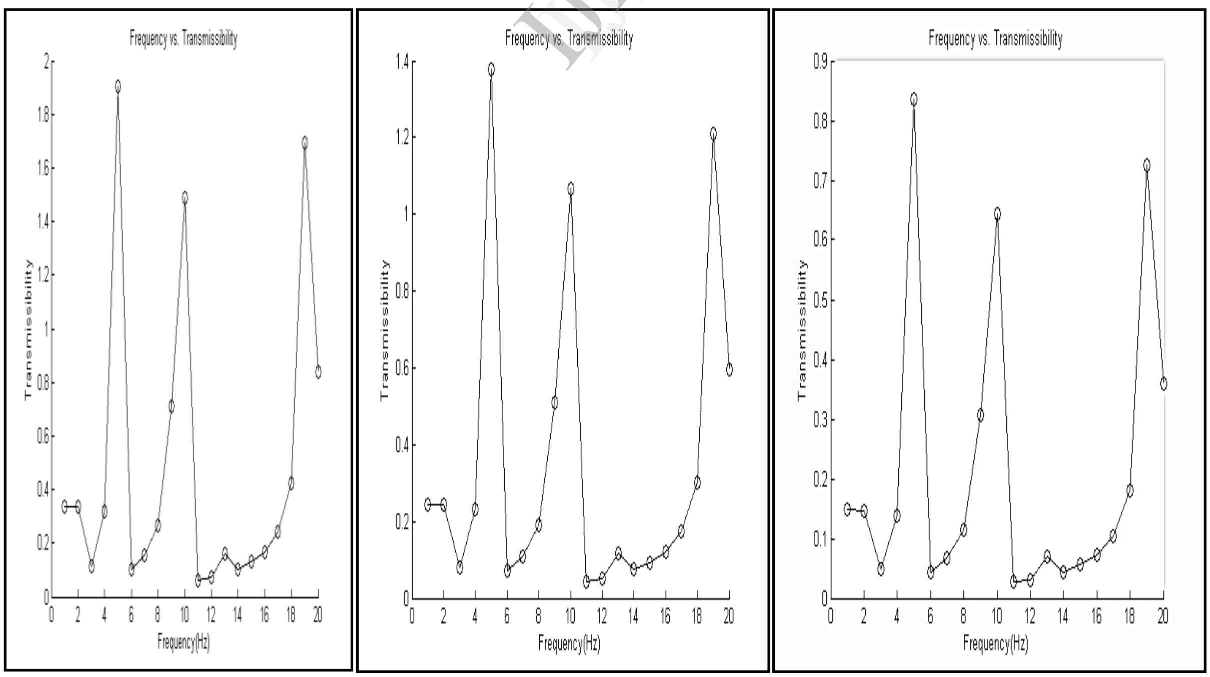


Fig 5.Transmissibility and DPMI of the 5DOF Model

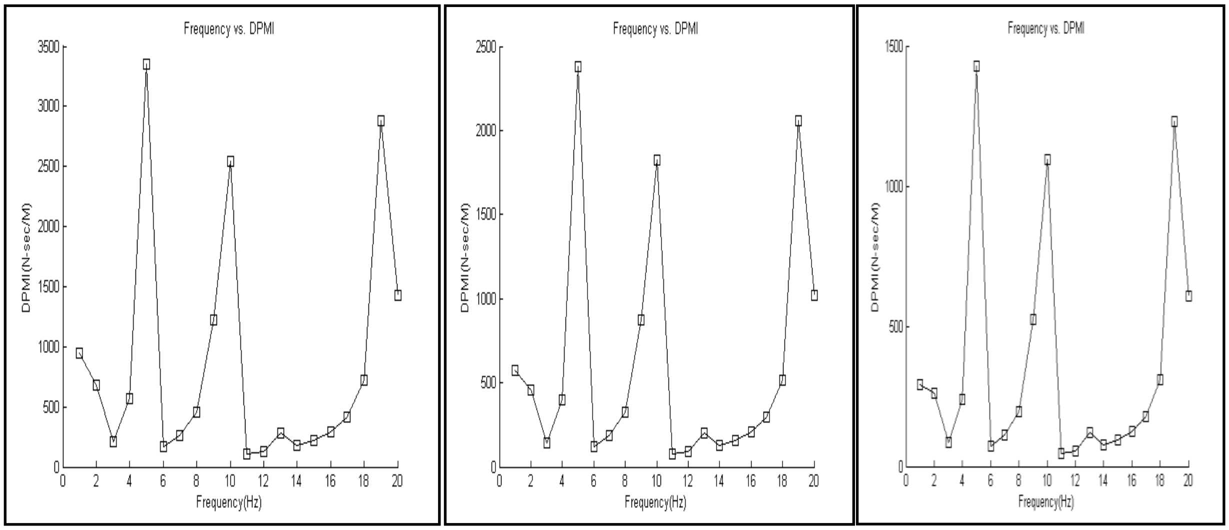
The above graphs represent the Transmissibility and DPMI of the S.Rakheja Model, Patil and Palanichamy Model and the present 5 DOF model. Fromthe 5 DOF model it is observed that Maximum frequency observed at a frequency of 5 Hz in the both Transmissibility and DPMI graphs. Similar results were observed in S, Rakheja 4 DOF model.. Hence,the observed frequency of 5 HZ is in the range of our human resonance frequency of 4-6 Hz. [1].

### *4.1 Effect of the Stiffness Coefficient:*

Three different values of pelvic stiffness k5 is used in the present model and the value ± 40 % are used to investigate the effect of pelvis stiffness on the response behaviours of human body.(STHT ,DPMI) as shown in the fig.(6).It is observed that the pelvic stiffness ,the biodynamic response characteristics of the seated human body (STHT and DPMI ) are increased.



(a) (b) (c)



(d) (e) (f)

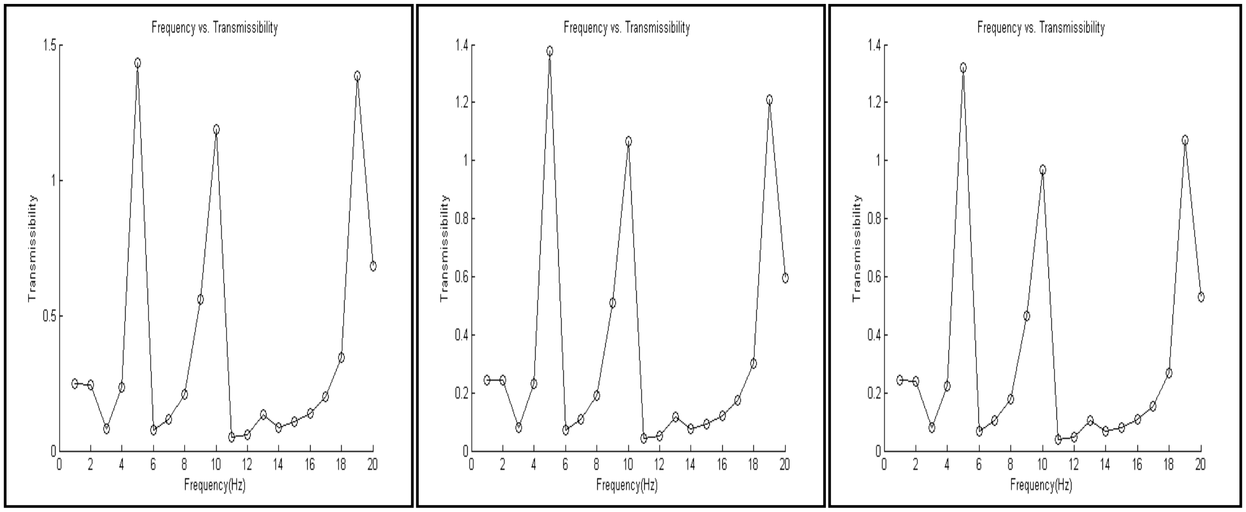
Fig 6.Effect of the stiffness between the pelvis and the seat on the Transmissibility and DPMI

(i) a, d represents K5 at14000N/m(+40%) (ii)b,e represents K5 at 10000 N/m

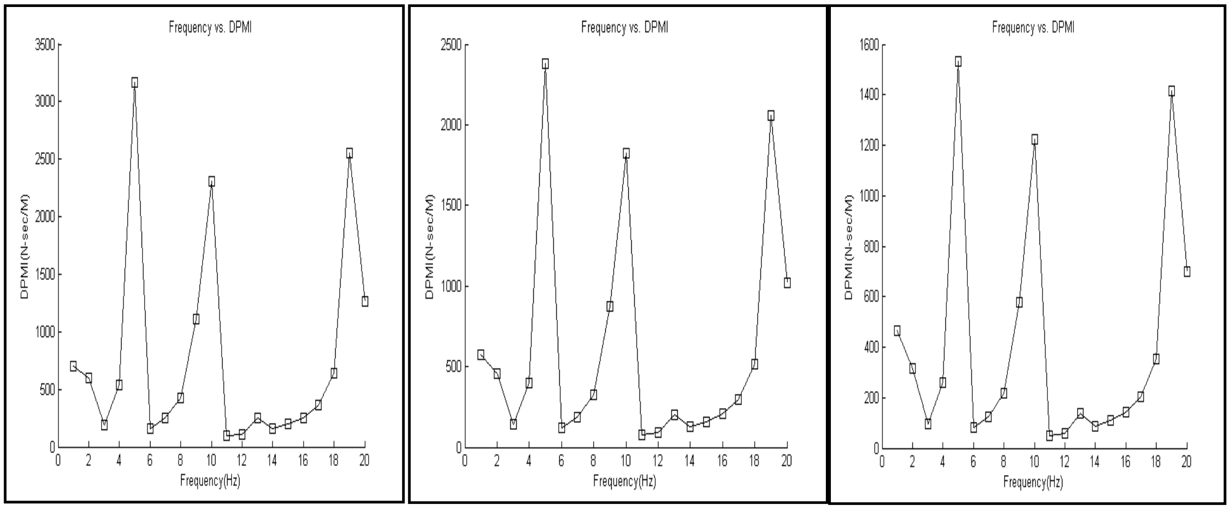
(iii) c,f represents K5 at 6000N/m(-40%)

### *4.2 Effect of the Damping constant:*

Three different values of pelvic damping c5 is used in the present model , and value ± 40 % are used to investigate the effect of pelvis damping constant on the response behaviors of human body.(STHT ,DPMI) as shown in the fig.(7).It is observed that the pelvic constant, the biodynamic response characteristics of the seated human body (STHT and DPMI) are decreased which is observed at the 10 Hz. frequency.



(a) (b) (c)

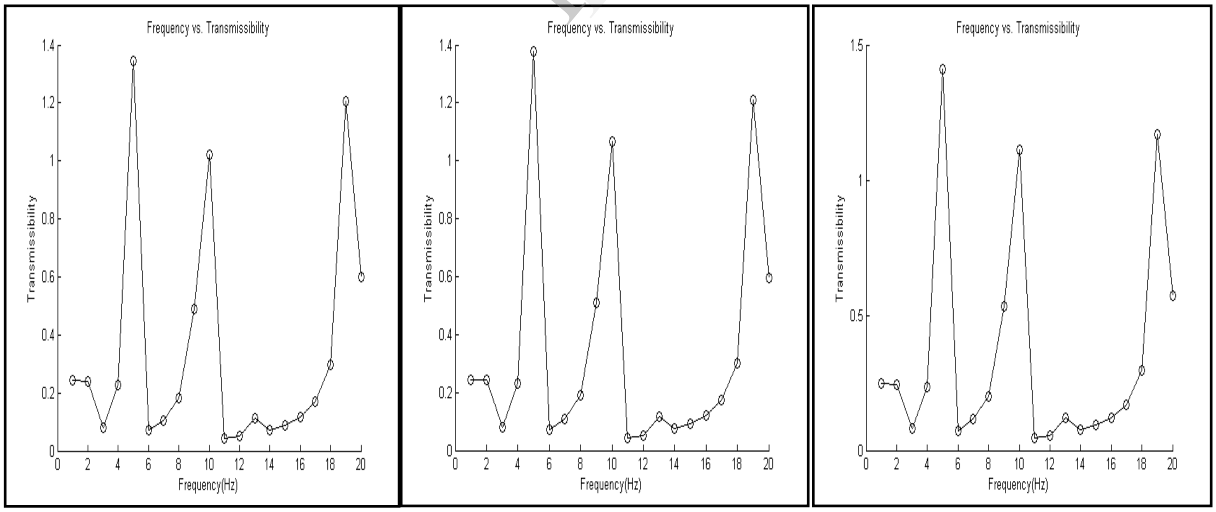


(d) (e) (f)

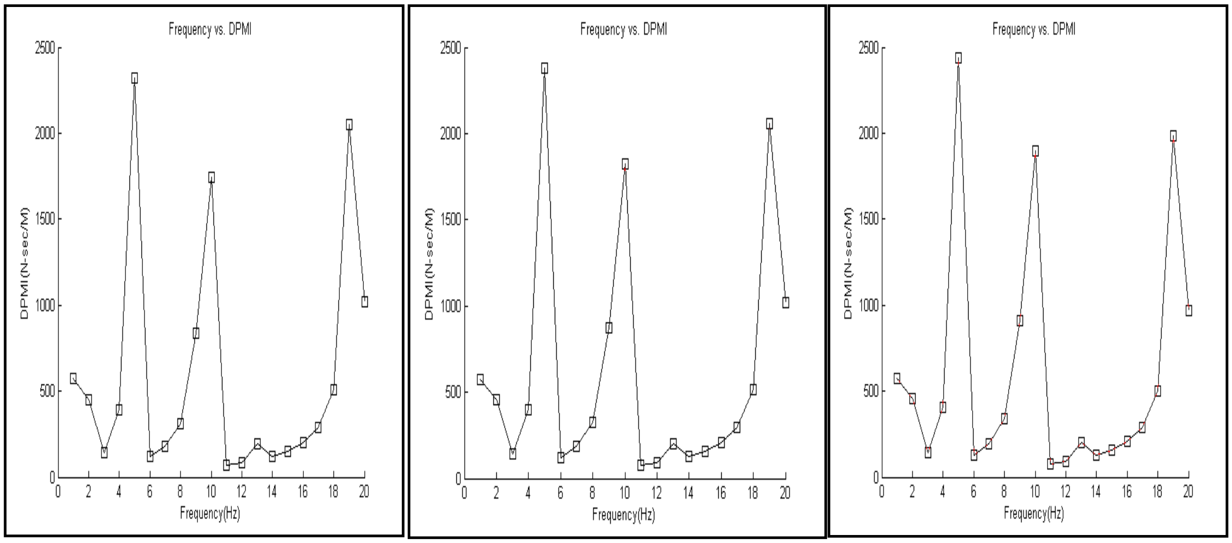
Fig 7.Effect of the Damping Constant between the pelvis and the seat on the Transmissibility and DPMI (i) a, d represents c5 at1020N-sec /m(-40%) (ii) b,e represents c5 at 1700 N-sec/m (iii) c,f represents c5 at 2380N-sec/m(+40%)

### *4.3 Effect of Human Body mass:*

The different total body mass (65.32, 74.46 and 83.2kg.) are used to investigate the effect of mass on the behavior of human body(STHT,DPMI)As shown in the figure ( 8) It is observed that increasing the mass of the human body the biodynamic response characteristics of the seated human body (STHT and DPMI ) slight increased has been observed..



(a) (b) (c)



d) (e) (f)

Fig 8.Effect of the mass on the Transmissibility and DPMI

(i)a, d represents Human mass of 65.72 Kg(ii)b,e represents Human mass of 74.46Kg.

(iii) c, f represents Human mass of 83.20 Kg**.**

## 5 Conclusions:

- Based on the experimental and analytical investigation of the 5 DOF model the resonance frequency observed at 5 Hz in transmissibility and DPMI of the 5 DOF model.
- From the current model it is concluded that the change in the human body mass, pelvic stiffness and pelvic damping coefficient givea remarkable change in the biodynamic response behaviors of the seated human body. Directly proportional to seated human body‘s mass and pelvic stiffness coefficient and inversely proportional to the seat to pelvic interface damping coefficient.

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