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Modelling of the Human Body Under the Exposure to Recumbent Whole-body Vibration

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Abstract. Human is exposed to whole-body vibration either in sitting, standing or recumbent position. Many studies had been carried out to study the vibration responses and develop the mathematical modelling in sitting and standing vertical position. According to previous studies, the resonant frequencies of the human body were identified to be in the range of 4-6 Hz and 8-12 Hz in the vertical position. Recumbent whole-body vibration also plays an important role as many situations in our everyday life are related to recumbent whole-body vibrations such as riding a train, ambulance transporting a patient or even sleeping. However, the studies of recumbent whole-body vibration are very lacking. Therefore, the main objective of this study is to develop a mathematical model to identify the response when a human body is subjected to recumbent whole-body vibrations. In this study, a nine degree of freedom mathematical model was developed, and the responses of the body were analyzed using Matlab Simulink. The overall resonant frequency of the body was found to be 1.4 Hz. Meanwhile, the head and neck had two resonant frequencies, which were 1.3 and 3.28 Hz for the head, and 1.4 and 3.4 Hz for the neck. This newly developed mathematical model can be used as a fundamental model to predict the response of any recumbent whole-body vibration.

1. Background

Nowadays, human exposure to vibration is quite common whether in their occupational life or even at home. This is especially the case for jobs like construction workers, drivers for heavy vehicles such as trucks and busses. From previous works, human workers exposed to hand-transmitted vibrations (HTV) have risks of reduction in grip strength, manual dexterity and sensory perception. [1]

Based on previous works, it was concluded that whole-body vibrations (WBV) can be very complicated when it comes to human responses. It is also clear that prolong period of WBV exposure may cause several unwanted effects such as damaging health or cause discomfort which disrupts daily activities. [2] When exposed to vibrations, the body endures stresses which have a mechanical effect on it depending on the dynamic properties of the body. By understanding all these effects and harm vibrations can cause to the human body, it is clear that human body vibrations should be further studied and look into to provide an economical method to deal with these issues.

1.1. Whole-Body Vibration in Recumbent Position

The human body can be exposed to vibrations in three main different postures which are sitting, standing and the recumbent position. Vibrations can cause discomfort or can even threaten human health. For the recumbent position, discomfort from WBV is relevant when it comes to transportation where the passenger is lying down, such as ambulances and trains, or even houses where it is near to railway tracks



and airports. Despite the many cases of recumbent WBV, the number of studies of this area is relatively small compared to those of in sitting and standing posture. [3]

However, the effects of vibration could also be made to good use. A study showed that vibration can also be used to induce sleep with the right parameters. Previous studies had concluded that babies sleep well when being rocked gently as this rhythmic motion reassembles the movement and feeling while in the mother's womb. With deeper understanding of the human response under WBV, it would be possible to reproduce this motion using machines to put a person, such as an insomnia patient or infant to sleep without harm. [4]

1.2. Research Objectives

The main objective of this research is to construct a mathematical model of the human body in the recumbent position, as to simulate and study the response of recumbent whole-body vibration. The results from the simulation are also analyzed to obtain the resonant frequency of the different body parts.

1.3. Problem Statement

In this study, WBV is studied in three different postures, which are sitting, standing and supine. Previous studies were mainly on vertical vibrations in sitting positions. The number of studies of recumbent WBV is extremely low compared to the other two postures mentioned above. This was because WBV started as a study to solve problems such as vehicle comfort and pilot ejection injuries. Since recumbent WBV can now occur in many situations such as sleeping in rocking motion or in the trains, inter-hospital ground transports, infant incubators, the study has become more relevant to the society's current problems.

2. Methodology

For this study, a lumped-parameter study of the recumbent WBV is conducted. A mathematical model of the recumbent human body is developed and simulated under WBV using Matlab Simulink.

2.1. Development of Mathematical Model

The model for the human body is adapted from [5]. The original model was developed to simulate vertical and horizontal vibrations on the seated human body. Hence, this model consists of vertical and horizontal stiffness data which will be adapted in our simulation. The mathematical model is modified accordingly to suit the study of recumbent WBV. The modified model consists of 9 masses, similar to the adapted model, excluding the lower and upper arms. The arms are excluded from the model as they play a less significant role in terms of safety and comfort. Additional parameters were added to the model to match the recumbent body. The head, pelvis and thoracic spine is connected to the vibrating platform which simulates the real-life recumbent situation.

The values of the thoracic spine connection were justified and adapted from [6]. Meanwhile, the head and pelvis parameters were adapted from [5], with the assumption of the head is supported by a pillow which the mechanical parameters were equal to the buttocks tissue. The complete data of mass and mechanical parameters of the model are shown in Table 1 and 2 respectively. The mathematical model was developed as shown in Figure 1.

Table 1. Values for Mass

Mass No.	Body Segments	Mass (kg)
M ₀	Platform	-
M ₁	Head	5.445
M ₂	Cervical Spine	1.084
M ₃	Thoracic Spine	4.806
M ₄	Lumbar Spine	2.002
M ₅	Torso	32.697
M ₆	Thorax	13.626
M ₇	Diaphragm	0.454
M ₈	Abdomen	5.906
M ₉	Pelvis	27.174

Table 2. Values for Mechanical Properties

Mass No.	Parameter Description	Stiffness (N/m)	Damping Coefficient (kg/s)
12	Head-Neck	5364	365.1
23	Neck-Thoracic	5364	365.1
34	Thoracic-Lumbar	5364	365.1
35	Thoracic-Torso	5364	365.1
36	Thoracic-Thorax	5364	365.1
49	Lumbar-Pelvis	5364	365.1
55	Torso-Thorax	5364	365.1
67	Thorax-Diaphragm	89.41	29.8
78	Diaphragm-Abdomen	89.41	29.8
89	Abdomen-Pelvis	89.41	29.8
90	Pelvis-Platform	2550	37.8
30	Thoracic-Platform	2300	154
10	Head-Platform	2550	37.8

The item numbering in Table 2 indicates the 2 segments involved in the parameter. For example, k_{12} indicates the stiffness connecting the head and the neck.

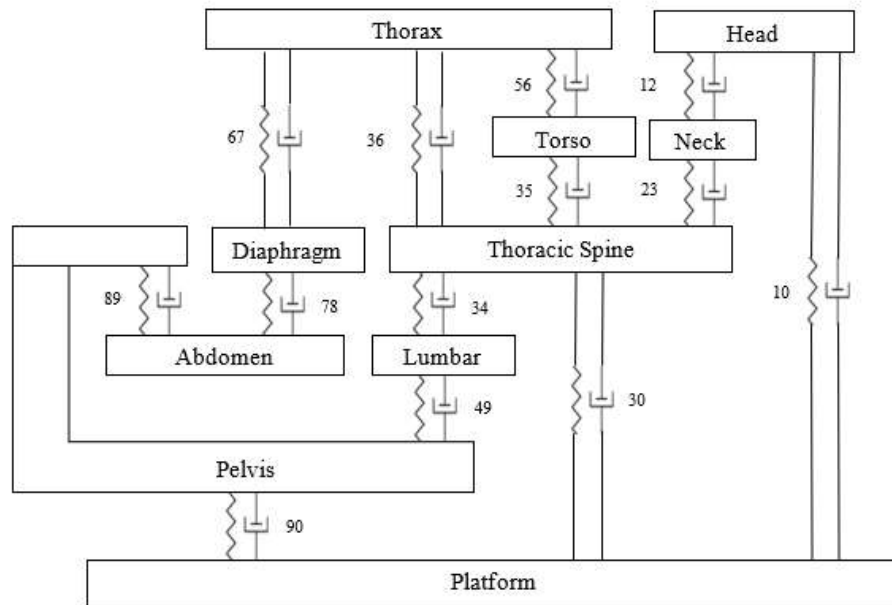


Figure 1. Mathematical model of recumbent whole-body vibratory system.

2.2. Equations of Motion

Equations of motion are derived for each mass (Table 2.1). The harmonic force $F(t)$ exerted by the platform is represented by F in the equations. The derivations of the masses are as follows.

$$\ddot{x}_1 = \frac{1}{m_1} [-(k_{12} + k_{10})x_1 - (c_{12} + c_{10})\dot{x}_1 + k_{12}x_2 + c_{12}\dot{x}_2 + F] \quad (1)$$

$$\ddot{x}_2 = \frac{1}{m_2} [k_{12}x_1 - (k_{12} + k_{23})x_2 + c_{12}\dot{x}_1 - (c_{12} + c_{23})\dot{x}_2 + k_{23}x_3 + c_{23}\dot{x}_3] \quad (2)$$

$$\ddot{x}_3 = \frac{1}{m_3} \left[-(k_{36} + k_{30} + k_{35} + k_{23} + k_{34})x_3 - (c_{36} + c_{30} + c_{35} + c_{23} + c_{34})\dot{x}_3 \right. \\ \left. + k_{36}x_6 + c_{36}\dot{x}_6 + k_{35}x_5 + c_{35}\dot{x}_5 + k_{23}x_2 + c_{23}\dot{x}_2 + k_{34}x_4 + c_{34}\dot{x}_4 + F \right] \quad (3)$$

$$\ddot{x}_4 = \frac{1}{m_4} [k_{34}x_3 + c_{34}\dot{x}_3 - (k_{34} + k_{49})x_4 - (c_{34} + c_{49})\dot{x}_4 + k_{49}x_9 + c_{49}\dot{x}_9] \quad (4)$$

$$\ddot{x}_5 = \frac{1}{m_5} [k_{56}x_6 - (k_{56} + k_{35})x_5 + c_{56}\dot{x}_6 - (c_{56} + c_{35})\dot{x}_5 + k_{35}x_3 + c_{35}\dot{x}_3] \quad (5)$$

$$\ddot{x}_6 = \frac{1}{m_6} \left[-(k_{67} + k_{36} + k_{56})x_6 - (c_{67} + c_{36} + c_{56})\dot{x}_6 + k_{67}x_7 \right. \\ \left. + c_{67}\dot{x}_7 + k_{36}x_3 + c_{36}\dot{x}_3 + k_{56}x_5 + c_{56}\dot{x}_5 \right] \quad (6)$$

$$\ddot{x}_7 = \frac{1}{m_7} [k_{67}x_6 + c_{67}\dot{x}_6 - (k_{67} + k_{78})x_7 - (c_{67} + c_{78})\dot{x}_7 + k_{78}x_8 + c_{78}\dot{x}_8] \quad (7)$$

$$\ddot{x}_8 = \frac{1}{m_8} [k_{89}x_9 + c_{89}\dot{x}_9 - (k_{89} + k_{78})x_8 - (c_{89} + c_{78})\dot{x}_8 + k_{78}x_7 + c_{78}\dot{x}_7] \quad (8)$$

$$\ddot{x}_9 = \frac{1}{m_9} [-(k_{89} + k_{90})x_9 - (c_{89} + c_{90})\dot{x}_9 + k_{89}x_8 + c_{89}\dot{x}_8 + F] \quad (9)$$

2.3. Simulink Model

The Simulink model was constructed based on the EOM derived using equations 1 to 9. After the model has been constructed. The sinestream input was set to range from 0.1 to 20 Hz with 0.1 increment. This range was selected as this range of frequency was considered to be the everyday transport vibrational frequency. [3] Due to large overall Simulink model, only the model for the head (M1) is shown as follows.

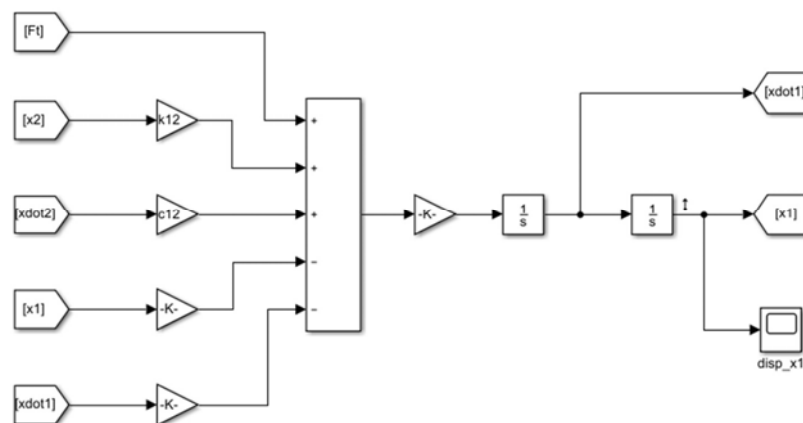


Figure 2. Simulink model for M1 (Head)

3. Results and discussion

Frequency Response Estimation and the bode plot for the simulation was obtained from the simulation. Due to large amount of data, only the Bode Plot for the head and neck are shown in Figure 3 and Figure 4. The results of the simulation are summarized in Table 3.

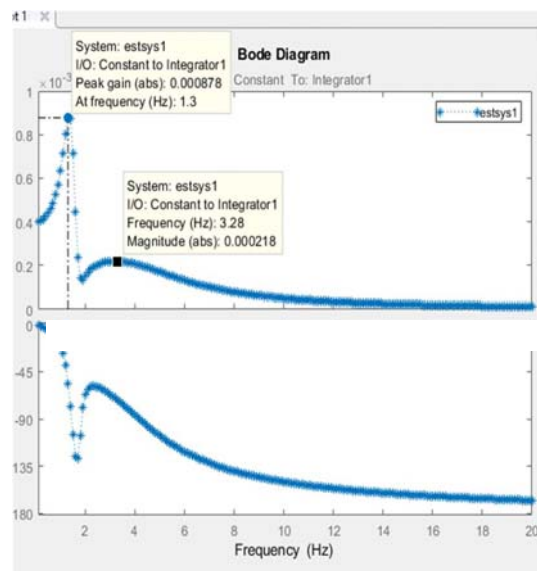


Figure 3. Bode Plot for M1 (Head)

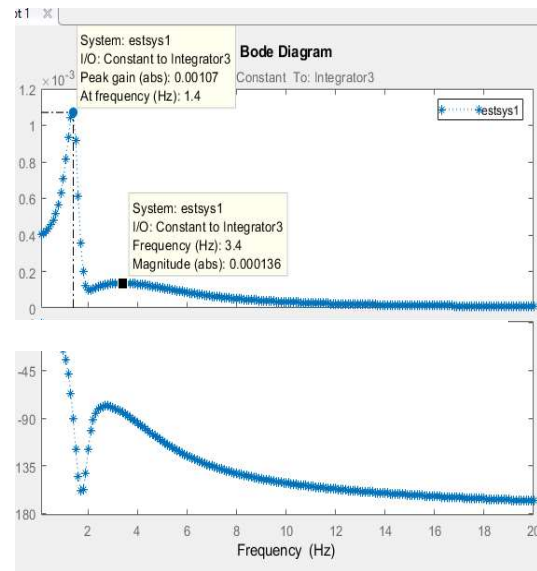


Figure 4. Bode Plot for M2 (Neck)

Table 3. Simulation results from Bode Plot

Mass	Description	Resonant Frequency (Hz)	Displacement Amplitude (m)
M1	Head ⁽¹⁾	1.30	0.000878
	Head ⁽²⁾	3.28	0.000218
M2	Neck ⁽¹⁾	1.40	0.001070
	Neck ⁽²⁾	3.40	0.000136
M3	Thoracic Spine	1.40	0.001280
M4	Lumbar Spine	1.40	0.001310
M5	Torso	1.40	0.001620
M6	Thorax	1.40	0.001620
M7	Diaphragm	1.40	0.001340
M8	Abdomen	1.40	0.001110
M9	Pelvis	1.40	0.001510

⁽¹⁾ Dominant Peak

⁽²⁾ Secondary Peak

After the simulation, two peaks appeared in the Bode Plot for both head and neck. The first peak for the head (1.3 Hz) was rather significant and much more distinguishable. As for the second peak (3.28 Hz), it was rather diminished but still distinguishable. Similarly, for the neck, two resonant

frequencies, 1.4 Hz and 3.4 Hz were found. The case was similar to the head where the first peak was more distinguishable than the second.

The second resonant frequency of the head (3.28 Hz) had a similar finding to [3], where the experiment conducted in his work showed the resonant frequency of the head to be 3 Hz. The slight difference may be due to the different constraints applied to the neck. In his experiment, the head was supported by a collar which further constrains the movement of the head. In this simulation, the head was assumed to be resting on a pillow. However, the results were logical as the values were quite close to the experiment.

The relation between the head and the neck is very close as they give almost similar responses from the simulation, showing a significant first peak and a distinguished second. The resonant frequencies of the head and the neck were also quite close for both peaks. A possible reason for this is that the head is directly connected to the neck in the body, which explains the similar responses. Another finding is that the second peak was only found in the head and the neck, but not the other body parts.

The results from the simulation would not be suitable to compare to the studies of vertical standing or sitting vibrations, as the position of the head, and other parts of the body, differs from the recumbent posture. This is because the weight of the body parts in the recumbent position are less likely to act on the connected parts, unlike in the vertical position, where the weight of the head rests on the neck and so on. Hence, the resonant frequencies found in this simulation differs greatly from vertical WBV.

3.1. Resonant Frequencies for M3 to M9

The resonant frequencies were similar for these masses, which was 1.4 Hz. This value is reasonably close to the findings of [5], which was 1.54 Hz for lower arms where the vibrational input was from the seat and injected horizontally to a seated human mathematical model. It was mentioned that when the vibrational input was from the seat, the vibrations will have to travel through the pelvis, abdomen, torso and thorax before reaching the lower arms. Although the lower arms were not investigated in the project's simulation, the similar resonant frequencies obtain show that the body parts may act as a single mass when subjected to recumbent vertical vibrations.

The value of 1.4 Hz was also found in the first peak of the neck (cervical spine). This similarity may be due to the rigid connection of the body parts (spine, torso, abdomen) when in recumbent state. The rigid connection may affect the response of these body parts to act as one single mass. This can be further observed from the displacement amplitude during resonance, where the displacement values differ slightly from one to another, especially in the case for torso and thorax.

The value of 1.4 Hz could be taken as the overall natural frequency of the body in the recumbent state as it correlates to 8 out of 9 parts of the body (excluding the head).

The results from the simulation are difficult to compare to previous studies of the vertical standing and sitting vibration as these are two completely different scenarios. However, the values of these resonant frequencies are logical as they do not differ much from the head and neck.

3.2. Amplitude Responses

Based on the 1.4 Hz peak, the lowest amplitude reading was taken from the neck (0.00107 m) while the highest amplitude was taken from the torso and thorax (0.00162 m), which differs only by 0.00055 m.

However, the neck allows more rotational movement compared to the other parts of the body. If the neck was excluded, the lowest amplitude reading would be taken from the abdomen (0.00111 m), which is considered to be a “softer” body part. Meanwhile, the head had the lowest displacement amplitude in the 1.3 Hz peak which was 0.000878 m. A possible explanation for this low amplitude reading may be the rotational effects of the neck and head.

Another possible reason for the similarity for the 1.4 Hz found in the neck was because the neck was part of the spine, which explains the similar vibrational characteristics to the thoracic and lumbar spine. The amplitude readings for the thoracic and lumbar spine are 0.00128 and 0.00131 m respectively, which only differed by 0.00003 m. The slightly greater difference found in the neck can once again be explained by the fact that it provides more rotational movement compared to other parts of the body.

For the second peak of the head and neck (3.28 and 3.4 Hz), the displacement amplitude diminished to 0.000218 and 0.000136 m respectively. The amplitude of the head was much greater than the neck (deviation of 0.000082 m), which showed an increase of 60% from the neck to the head. This can be explained by the fact that the head is allowed to rotate while pivoted to the neck. Hence, the vertical displacement of the head is greatly enhanced as it is not only affected by the lateral stiffness of the neck but also the free rotational movement provided from the neck. This scenario could be addressed in future studies by including rotational stiffness in the simulation as done by previous studies. [8]

4. Conclusion

A mathematical model for a recumbent WBV simulation was developed for this research. The model was adapted from [5] and was modified accordingly for recumbent WBV. Also, a Simulink model was constructed from the model for the project’s simulation. Resonant frequencies of the major body parts were obtained from the simulation and was recorded in Section 3. The data was captured in the form of Bode Plot where the resonant frequencies and amplitude responses were extracted.

The results from the simulation were more or less expected as they did not deviate greatly from previous works. Comparisons were made mainly based on the study of [3], as his research was on recumbent WBV. Comparisons were also made based on the findings of [5], where his simulation was on a seated model subjected to horizontal vibrations. The data obtained from the simulation differed slightly to previous studies due to unsimilar conditions. In the study of [3], the movement of the head was constrained by a neck collar. In the study of [5], the study was mainly to obtain the response of the lower arm. However, the resonant frequencies did not deviate much from the project’s findings.

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