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Vibration Effect on Human Subject in Different Postures using 4-Layered CAD Model

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Abstract*: A human body gets exposed to vibration in their daily life due to multiple works like working on the machines, traveling, riding, escalators etc. Due to which people feels discomfort during working that causes bad impact on human body in various ways i.e. back pain, headache, hand sensation etc. In this study, harmonic analysis has been performed on the 3D CAD model of the 76 kg 4-layer (bone, organs, muscle and skin) of human subject in standing and sitting posture by considering 95th percentile anthropometric data of Indian male population. In standing posture, the human subject has been standing on the floor at excitation magnitude of 1 m/s^2 with damping ratio 0.337 between frequency ranges 0-20 Hz under vertical vibration. Feet to head transmissibility has been performed from feet to head in standing and seat to head transmissibility has been performed on the human subject in sitting posture in different inclination angle is 0˚, 12˚ and 21˚ on the automotive seat. The Polyurethane foam has been considered for the seat cushion as seat pan cushion and backrest cushion to increase the comfort level for human body during traveling. The biomechanical and physical properties of the human subject that include properties of bones, organs, muscles and skin along with other accessories i.e. seat and backrest cushion have been taken from existing literature. The maximum effect has been found at lower arm, head and organs of the human body between the frequency ranges 4-8 Hz and decreases continuously due to the biodynamic properties of the human solid model and seat cushion model. This study shows that results are approximately nearer to validated results and cushion material has good shock absorber property. There observed a less effect of vibration without seat suspension system and also, inclination of the backrest can improve the comfort level during riding by the vehicles.

***Keywords* : Sitting posture, Standing posture, CAD model, Human body, FEM, Harmonic response, Frequency, Damping, Stiffness, Vertical direction, Polyurethane foam, Transmissibility**

I. INTRODUCTION

These days, humans introduced new things in their life for their comfort and also, in every sector of work people want to do their work easily without losing their time. They have always desire to do something new in their life, therefore Humans on a daily basis used to walk, run, exercise etc. to avoid the health issues that can be due to many reasons that are gaining weight by eating unhygienic food products, working stress, long hours sitting etc. Each of these activities has introduced exposure of vibration that can also be a reason for various types of health issues like headache, spinal cord pain, heart problems etc. In this era, the human does their work with their compatibility and avoid losing their time for making their works early and easily, humans travel from one place to another place by various types of vehicles that exposed to vibration. In India, there is too much rush in every transportation system i.e. Buses, trains, ships etc. due to which people travel with trains, buses and any other vehicles in standing and as well as sitting posture. During traveling in standing and sitting posture, the excitation acceleration to the feet of the human subject causes discomfort in both the postures. The various properties of seat and seat cushion material play a very important role in exposure of vibration in sitting posture.

The discomfort causes by the vibration show the whole body vibration (WBV) has been found to be harmful for the human body and becomes an important area to study about in relation to automotive. In this study, finite element method (FEM) has been performed on the human subject in sitting posture sitting on automotive seat during traveling and also on human subject standing on the floor.

Related to increasing the comfort and reducing the vibration effect on human subjects, a lot of research work has been performed in this domain using different methods and biodynamic models of human subjects with different anthropometric data of variant countries in different types of postures and conditions. Singh et al. [1] performed the experimental analysis on 12 males in sitting posture with different acceleration, frequency and inclination angle of the backrest to analyze the vibration effect. Singh et al. [2] conducted a modal analysis on the 3D CAD model of Indian subjects in sitting posture without backrest using the FEM approach and evaluated the maximum deformation.

Alshabi et al. [3] introduced mathematical models of the seated human body in the Simulink/MATLAB environment to perform modal analysis and state-space methods to check and validate the results obtained from the simulation. Matsumoto and Griffin [4] conducted an experimental analysis to analyze the effect of vibration on the apparent mass of standing the human subject in the vertical direction. Harazin and Grzesik [5] conducted experimental analysis on 10 male subjects exposed to floor vibration stood in ten posture to analyze the effect of whole-body vibration of body posture in a standing position that the excitation acceleration has been applied on six body segments in z-axis direction to random vibration.

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Matsumoto and Griffin [6] conducted experimental analysis on the eight male subjects exposed to vertical random whole-body vibration that analyzed and compared the dynamic responses (apparent mass and transmissibility) of the human body in standing and sitting posture. Chalotra et al. [7] evaluated the feet to head transmissibility and floor to knee transmissibility under acceleration $1m/s^2$ rms in the vertical and lateral direction under the frequency ranges from 3-15 Hz by constructed handrail to provide support for standing subjects in public state transport buses. Paddan and Griffin [8] studied the transmissibility effect on 12 male subjects at the head in two different standing posture i.e; holding handrail in front of them lightly and holding the handrail rigidly while they exposed to floor vibration in the three translational axis. The transmissibility found at the head in both posture at about 5Hz and transmissibility maximum in holding handrail rigidly in fore and aft direction. Kumar et al. [9] conducted experimental analysis on six healthy male subjects to analyze feet to head and floor to knee transmissibility effect by considering different excitation magnitude (0.5 m/s^2 and 1 m/s^2) and frequency range 1-20 Hz. The transmissibility effect analyzed 4 to 7 Hz frequency range for both transmissibility effects. Singh et al. [10] conducted FEM analysis on 76 kg male subject in standing posture holding a handrail while traveling in a passenger bus with excitation magnitude 1 m/s^2 between frequency range 1-20 Hz in the vertical direction to analyze the transmissibility effect on head and knee segments, where the maximum effect observed between 4-6 Hz frequency range. Thuong and Griffin [11] introduced the discomfort of 16 male subjects by exposing to lateral, vertical and fore and aft sinusoidal vibration at 0.5-16 Hz frequency. It has been analyzed that maximum discomfort observed at lower frequency less than 3.15 Hz of stability problem and higher frequency shaking sensation was found in leg and feet. Yang et al. [12] conducted experimental analysis on 16 subjects in a standing posture to analyze the transmissibility effect that the maximum effect was observed at pelvis in knee bent position at frequency range 9-11 Hz. Heikoop et al. [13] conducted a study to analyze the stress on the human heart during driving in real traffic by recorded heart rate, heart rate variability, respiratory rate and subjective responses of 9 subjects in the Tesla model with autopilot. Mizuno and Hiep [14] evaluated the effect of vibration by monitoring the heart rate of the driver by adopting seat fixed with piezoelectric sensors that measure the body vibration caused by the heartbeat and the signal that evaluate the vibration effects according to the road profile condition. Wang et al. [15] conducted experimental analysis on the 30 healthy subjects with different inclination angles and different vibration modes to investigated combining traction and vibration on back muscles, heart rate and blood pressure by analysis of power spectral frequency, median power frequency, pulse pressure and heart rate. Wang et al. [16] investigated seat to head transmissibility of seated human subject in the vertical and fore-and-aft directions by using 12 male subjects exposed to whole-body vertical random vibration in the 0.5-15 Hz frequency. Witkiewicz and Zielinski [17] investigated the mechanical properties for the compression test of PU foams by laboratory investigations by the considered a density of two foams of 16 kg/m^3 and 62 kg/m^3. Patel et al. [18] conducted a quasi-static compression test on PU foam cylinders by considering different lengths and different densities to determine the young's modulus, yield strength and energy observed to yield. Pywell [19] introduced the improvements in seat system design for comfort and safety where seat cushion suspension designs have a capacity of providing additional isolation at critical vehicle frequencies while giving support to buttock for long-duration driving and lap restrain to seat design may offer the reduced submarining potential for small occupants in frontal decelerations. Kumbhar et al. [20] conducted lumped parameter model with three different seat design (hard seat, seat with cushion but no suspension system and seat with both cushion and seat suspension) by considering different inclination angle and 71.32 kg human subject to analyze the human body response in a seated position. The analysis found that the seat with both cushion and seat suspension has good vibration isolation. It has been found from the currently available literature that there lot of work that has been done on human subjects in standing and sitting posture. Also, most of the work in standing posture has been performed in automotive by holding handrail or handle and in the sitting posture, most of the research work has been done on the seat cushion with suspension system by considering lumped parameter method and experimental method. In the current study, a simulation study has been performed to find out the transmissibility in a vertical direction by considering FEM analysis, while a human subject travels in standing posture on the floor under vertical excitation and in sitting posture, human seated on the automotive seat with a cushion at different inclination angle of the backrest support.

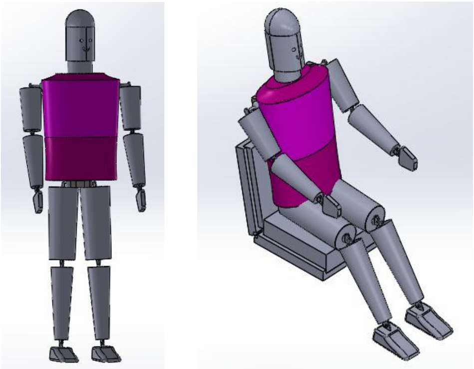
II. METHODOLOGY

The 4-layer 3D CAD model that includes skeleton, organs, muscles and skin of human subject in two different postures standing and sitting posture has been developed in solid work 2018 by considering 95th percentile Indian anthropometric data [21]. The FEM has been performed on the human subject in sitting and standing posture to find out the seat to head transmissibility and feet to head transmissibility.

A. 3D CAD model of human subject in standing and sitting posture

In standing posture, the human subject has been considered as standing on the floor for transmissibility analysis at excitation magnitude of 1 m/s^2 [22] with damping ratio 0.377 [23] between frequency range 0-20 Hz. In this 3D CAD model, 4-Layers have been introduced that includes different layers i.e. bones, organs, muscle and skin have been modeled using Solid Works 2018. All the layers have been designed by considering 95th percentile Indian anthropometric data [21] and the help of the dimensions that have been considered from the existing literature [24], [25]. In this model the 1st layer assumed as bones of the human body that included humerus and femur bone whose dimension has been considered from existing literature [21] and diameter of the bone has been considered between 14-26mm for humerus bone and 29.4-37mm for femur bone [26].

The organ layer has been defined as the 2nd layer of solid model that consist the effective organs (heart, lungs, liver and stomach) during exposure to vibration. During the vibration exposure, when human body connects with the vibrating surfaces then these organs are mostly affected due to the increasing of excitation acceleration that cause health issues like headache, stomach pain, hand sensation etc. in both standing and sitting posture. The 3rd layer has been considered as the muscles of the human subject whose dimensions (length and height) similar as layer 1and the thickness of the muscles has been varies from 13.85 to 67.7mm [26]. The thickness of the muscle depends upon the body weight, height and age also. The last and 4th layer has been introduced as the skin layer that is the outer layer of the human subject. The dimensions of the skin layer has been similar as the muscle and bone layer but the thickness of the skin has been considered as 1mm [27]. The solid model of the human subject in standing and sitting posture have been designed by consideration of all the assumptions as discussed above as shown in Fig. 1.



(a) **(b)**

Fig. 1. 3D CAD model of human subject: (a) Standing posture (b) Sitting posture

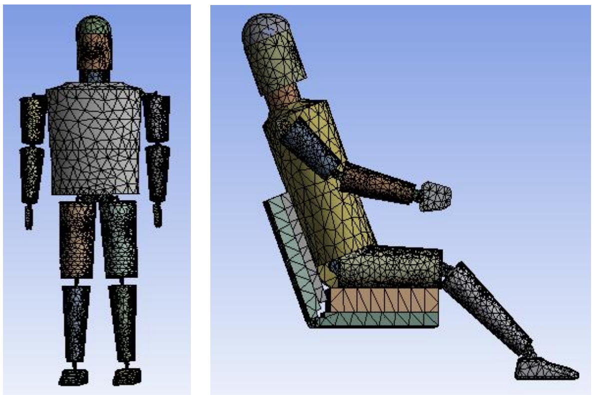
Fig. 1 introduced the solid model of human subject in standing and sitting posture that considered for the vibration analysis. In the sitting posture the human subject seated on the automotive seat that mostly used in the vehicle. Various types of health issues have to face to human body during traveling in vehicle due to vibration that generated by the vehicles and road profile. This study has been performed by the reverse engineering on the automotive seat. Now a day, there is suspension system has been used in the automotive sector to minimize the vibration effect and increases of comfort during traveling. But in this study vibration has been analyzed on the human subject by consideration of seat cushion only with backrest support. The seat to head transmissibility (STHT) has been evaluated with excitation acceleration 1 m/s^2 in vertical direction at different inclination angle i.e. 0˚, 12˚ and 21˚. The coir rubber and synthetic rubber polyurethane (PU) foam have been taken for the seat cushion material that help to reduce the effect of vibration reason of different biomechanical property and thickness of cushion material. The effect of vibration also depends on the dimensions of the seat cushion. The dimension of the seat cushion assumed as 400mm X 400mm as length and width that used in automotive seat [28]. Generally, the PU foam has been used for reduce the effect of vibration and give better support to the back and hip muscles [28]. 60-70% body mass depends upon the shape, size and posture of the body on the seat due to which seat cushion has been compressed forcefully by the body mass and backrest cushion has less compressed due to vertical vibration as compared to fore-and-aft and lateral vibration [19]. So, the thickness of the seat pan cushion has been considered greater that backrest cushion thickness. The thickness of the seat cushion and backrest cushion has been considered as 101mm and 54mm used for the 0˚, 12˚ and 21˚ inclination angle with synthetic rubber PU foam. The coir rubber PU foam has been used with 0˚ inclination angle only whose thickness is 90mm for seat cushion and 60 mm for backrest cushion. There are different biodynamic properties of seat and backrest cushion that help to reduce the transmissibility effect and depend on the thickness of the cushion. There are different biomechanical properties of the parts of the human CAD model in standing and sitting posture i.e. bone layer, organ layer, muscle layer, skin layer, seat cushion and seat frame as mentioned in Table 1, that make the 3D CAD model as the realistic model.

Table 1 shows the biomechanical properties of the 3D CAD model that help to evaluation of the vibration effect. There are different mechanical properties of the cushion material that help to make the cushion good shock absorber property. The damper and stiffness is the physical property that also depends upon the thickness of the cushion. By consideration of damper and stiffness, the cushion material behave like spring system due to which cushion materials introduced good shock absorber property and reduce the effect of vibration during traveling in the automotive. The damper and stiffness of the coir rubber PU foam (thickness 90mm X 60mm) used in the seat pan cushion and backrest cushion is 800 Ns/m and 20000 N/m for seat pan cushion and 1000 Ns/m and 10000 N/m for backrest cushion [34].

Table I: Biodynamic properties of 3D CAD model [17], [27], [29], [30], [31], [32], [33]

Type	Density (kg/m^3)	Young's modulus (MPa)	Poisson ratio
Seat frame	7850	20700	0.3
Seat cushion (Synthetic rubber PU foam with thickness 101mm)	69.72	25	0.3
Seat cushion (Coir rubber PU foam with thickness 90mm)	62.25	25	0.3
Backrest cushion (Synthetic rubber PU foam with thickness 54 mm)	68.70	25	0.3
Seat cushion (Coir rubber PU foam with thickness 60mm)	58.23	25	0.3
Bone	1700	12000	0.3
Organ	1065	0.06	0.3
Muscles	1062	13	0.3
Skin	1100	0.15	0.46

The other seat cushion is synthetic rubber PU foam used for thickness 101mm X 54mm, the damper and stiffness of the both seat pan cushion and backrest cushion is 109 Ns/m and 21000 N/m [34]. The medium carbon steel material has been considered as the frame of the seat that has generally used in vehicle seat frame [35]. In the FEM analysis, meshing play an important role for accurate results. When meshing is good in the solid model then the analysis has been performed on the model that response like realistic human body. Fig. 2, shows the meshing image of the solid models. Fig. 2 shows the meshing image of the solid model in standing posture and sitting posture. The tetrahedral mesh has been considered for the both standing and sitting posture. Due to multiple segments of the solid models, there is errors have been found in the other meshing property. But tetrahedral mesh has found comfortable, flexible and smooth during meshing. So the tetrahedral mesh has been taken by considering automatic mesh size. Due to tetrahedral mesh type, results become approximate accurate and closer to validated results.



(a) (b)

Fig. 2. Meshing of solid model (a) Standing posture (b) Sitting posture

To perform harmonic response on the human subject the boundary condition has been considered for the human subject. In the standing posture, the human subject has considered to analyze the feet to head transmissibility (FTHT), where the human subject has to be stand in erect position on the floor without any external support where feet become fixed with the floor. The hands have been considered as the straight perpendicular to the floor without touching any part of the body. In the sitting posture, seat to head transmissibility (STHT) has been considered to analyze, where the human subject has considered as seated on the seat cushion with backrest support in different inclination angle. The inclination angle of backrest support assumed for the analysis is 0˚, 12˚ and 21˚ that help to analyze the maximum and minimum effect of vibration on the human subject. The feet have to fixed with floor and hip has to be connected with seat pan cushion and seat have to also be fixed. The transmissibility effect has been evaluated in sitting and standing posture in vertical direction with excitation acceleration (1 m/s^2) taken from existing literature [22] in the frequency range 0-20 Hz. The damping ratio of 0.377 [23] has been considered for the standing posture that human subject stand on the floor. The frequency range has been considered from 0-20Hz due to the maximum effect of vibration has been analyzed at low frequency range, these low frequency has been found to be dangerous for human health introduced by ISO-2631 [36].

III. RESULTS AND DISCUSSION

The FTHT and STHT have been analyzed in the current study at excitation acceleration (1 m/s^2) in the fixed frequency range (0-20 Hz) in standing and sitting posture by considering 95th percentile anthropometric data of Indian male subject. The transmissibility analysis has been analyzed by FEM technique.

A. Feet to head transmissibility in standing posture

The FTHT has been performed in the standing posture that the outcomes of the current study and validation result have been shown in the Fig. 3.

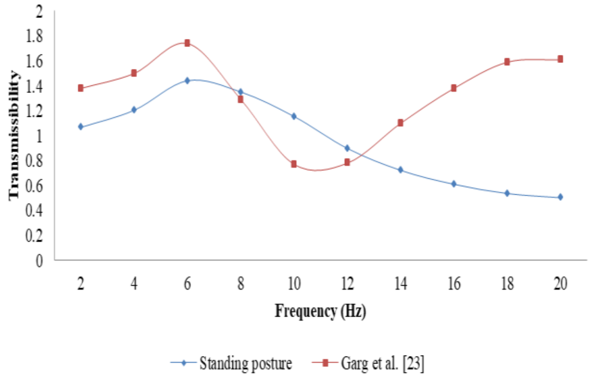


Fig. 3. Comparison of results in standing Posture

In Fig. 3, transmissibility effect has been analyzed on the head of the human subject that the excitation acceleration (1 m/s^2) applied to the feet due to that vibration transmit from feet to head. In this study, solid model includes the bones, sensitive organs like heart, liver, abdomen and lungs, muscles and skin layer. The outcomes of the current study is the maximum transmissibility effect has been occurred at frequency 6 Hz to be 1.4416 and then the transmissibility effect decreases continuously up to 20 Hz. It may be due to the damping ratio that has been considered and due to the soft tissues of human body have damping property that rise the damping value. So, human body can damped the vibration after the first excitation of transmissibility.For validation of the this study, the study of Garg et al. [23] has been considered that performed harmonic analysis on a LPM model in the frequency range 1-50 Hz with two different damping condition. The first peak point of the study of Garg et al. [23] is 1.74 at frequency 6 Hz that may be due to the upper body mass lies on the stiffness of the spine. And the 2nd highest peak or transmissibility found at 19.4 Hz as 1.63 that may be reason of body mass lies on the stiffness of the legs. The two different peak has been found due to two different damping condition of 0.377 for frequency range 0-10 Hz and for 10-20 Hz frequency range damping ratio is 0.422 [23].

By comparison of current study with the study of Garg et al. [23] it has been found that there is variation in the results. It may be due to the biomechanical and physical properties of the human subject. In this study, it has been found that the current result has been approximately nearer to the validated result up to 0-10 Hz frequency and after there is a difference in the result. This variation is due to the damping ratio considered in the current result and validated result.

The damping ratio is 0.377 in the current study for 0-20 Hz frequency range and same damping ratio for 0-10 Hz and for11-20 Hz a different damping ratio is 0.422 used in the validated result.

B. Seat to head transmissibility in sitting posture

STHT transmissibility has been performed on the human subject in sitting posture with different inclination angle of backrest support. The results of the current study have been shown in Fig. 4.

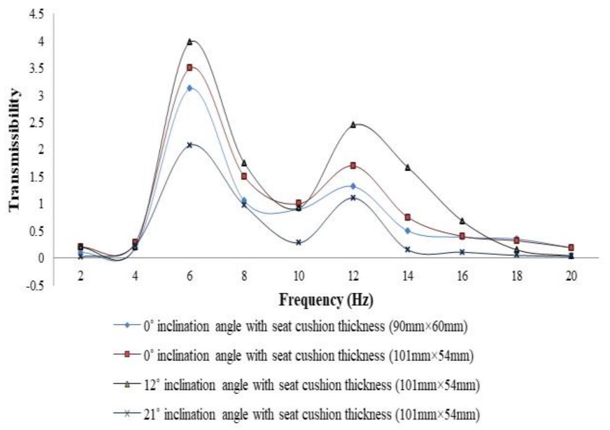


Fig. 4. Results of current study in sitting posture with different inclination angle

Transmissibility has been evaluated from seat to head with excitation acceleration in the frequency 0-20 Hz in different inclination angle of backrest. At first angle of backrest is 0˚ with cushion thickness (90mm×60mm), the first transmissibility effect has been found at 3.12 at 6 Hz frequency and transmissibility reduces up to 8 Hz frequency. After that the 2nd peak has been found at 12 Hz of 1.32 and again decreases continuously as shown in Fig. 4.

At inclination angle 0˚ with cushion thickness (101mm×54mm), the maximum peak of transmissibility occurs at frequency 6 Hz of 3.52 and another peak point is 1.7 at 12 Hz frequency. After the first peak it decreases up to 8 Hz and it increases, after second peak it decreases continuously.

The maximum effect of transmissibility occurs at 3.98 at 6 Hz and 2nd peak of transmissibility at 12 Hz of 2.45 in the 12˚ inclination angle with cushion thickness (101mm×54mm).

At 21˚ inclination angle with cushion thickness (101mm×54mm), 2.08 is the maximum transmissibility effect at 6 Hz frequency and the 2nd effect of transmissibility at 12 Hz of 1.11. During the result analysis, it has been found that the maximum effect of transmissibility of different inclination angle occurs between 4-6 Hz frequency range and it became decreases. The 2nd point of transmissibility found between 11-13 Hz frequency range and after 14 Hz it becomes decreases continuously. The whole body vibrations (WBV) were feels at chest, shoulder and stomach indicating the upper body segments have been affected more at higher value of excitation due to the source of excitation is close to the lower body segments [1].

By comparison of current results with each other it has been observed that change of inclination angle of backrest causes the most effect of transmissibility to be detected by the subjects at upper body parts and bit less at middle portion of the body [1]. No any movement is observed in this regard and seat cushion, backrest cushion, and seat properties reduce the resonance frequencies. The transmissibility effect may be decreased by increasing the seat cushion damping. So, when the floor excitation acceleration is applied to the human body, less transmissibility effect found at considered frequency range by selecting proper stiffness and damping coefficients of the seat cushion, backrest cushion and seat to minimize the vibration transmission to the human body and maximize the ride comfort [20]. By comparing the two results of this study i.e. inclination at 0˚ with cushion thickness (90mm×60mm) and inclination angle at 0˚ with cushion thickness (101mm×54mm), have been found that the outcome nearer to each other with some difference. It may be due to the physical and biomechanical properties (i.e. density, thickness of cushion, damping, stiffness etc.) of the seat cushion material considered for the harmonic analysis. And it is clear that after the comparison of the all four results that the inclination angle of backrest at 21˚ less effect of transmissibility has been found.

The results of sitting posture have been validated with the study of Wang et al [16] and Cho and Yoon [37] as shown in Fig. 5.

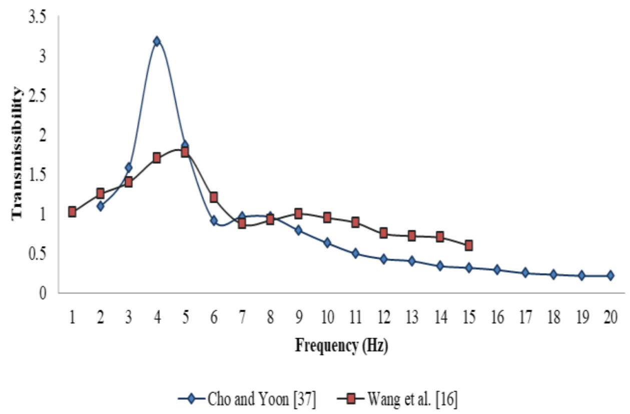


Fig. 5. Results for validation

The study of Wang et al. [16] has been performed on the 12 male subjects in multiple posture that is without backrest support, vertical backrest support and inclined backrest support in vertical and fore-and-aft direction at excitation of 0.25, 0.5, and 1.0 m/s^2 between 0-15 Hz frequency range. In this study [16] author mounted an accelerometer on the helmet to measure the vibration effect in the three translational axis. This study has been considered for the validation of 0˚ inclination angle of backrest with different seat cushion and thickness. The effect of vibration has been evaluated by considering excitation acceleration 1m/s^2 in vertical direction where the maximum effect of vibration occurs at 5 Hz of 1.78 and 2nd effect lies at 10 Hz is 1. Another paper has been used been for the validation of 12˚ and 21˚ inclination of backrest. Cho and Yoon [37] performed harmonic analysis (STHT) on the 1, 2, 3 and 9 DOF biomechanical model in sitting posture with backrest support in different inclination angle for analyzing of automotive ride quality.

The effect of vibration has been measured at hip, back and head of 10 subjects with the floor under vertical vibration that three transmissibility effects has been obtained for each subject. The author [37] compared their experimental results of 1, 2, 3 and 9 DOF model that shows, 9 DOF model has best description of the results. The results of 9 DOF model shows good matching for vibration effect, where the maximum effect has found at 4.2 Hz of 3.2223 and the 2nd effect of transmissibility is 1.00 at 7.7 Hz frequency.

By comparison and analysis of this study and the validated result in seating posture, it has been observed that there is an approximate value with the validated results. It is also found that by increasing of the inclination angle of the backrest than the transmissibility effect has decreased. The variation has been found in the results during the study and comparison with validated paper, it may be due to the different models, positions of the body parts, different dimension and structures of body and different biomechanical properties of the models.

It has been found from the current study in standing and sitting posture that the human subject exposed to the vibration in different posture then the organs of human body get more affected due to high acceleration in the frequency range 4-8 Hz. During the analysis, it has noticed that the head get mostly affected by the vibration and causes headache, motion sickness etc. Lower arm of the human subject has maximum effect found during the analysis in standing posture that caused hand pain, hand sensation. As per evaluation in current study, it has been observed that due to the maximum transmissibility effect the human body will feel discomfort at considered excitation magnitude at frequency 6 Hz.

IV. CONCLUSION

Harmonic analysis has been performed on 76 kg 4-layer (bone, organs, muscle and skin) of human subject in the sitting and standing posture by FEM technique. In standing posture, the human subject has been standing on the floor at excitation magnitude 1 m/s^2 with damping ratio 0.337 between frequency ranges 0-20 Hz under vertical vibration. Feet to head transmissibility has been calculated and find out that it occurs at 6 Hz frequency with value of 1.4416 and after 6 Hz transmissibility decreases continuously that may be due to the boundary conditions and properties considered in 4-layer CAD model. In the sitting posture, seat to head transmissibility has been performed at excitation magnitude of 1 m/s^2 between frequencies ranges 0-20 Hz in different inclination angle (0˚, 12˚ and 21˚) of backrest under vertical vibration without seat suspension to analyze the effect of vibration on the human subject with seat cushion only. The maximum effect has been found at lower arm, head and organs of the human body between the frequency ranges 4-8 Hz at considered different inclination angle of backrests. By comparing the current results with validated results, it has been found that results found to be approximately nearer to each other. The cushion material has good shock absorber property so there is less effect of vibration without seat suspension system and also, inclination of the backrest can improve the comfort level during riding on the vehicles.

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