TECHNICAL PAPER

Vibration analysis of human body under seating posture: an automobile application

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Abstract

Vibrations are generated in the vehicles due to the uneven texture of the road and transferred to the occupants via tires, chassis, seats, bodies, and different parts of the vehicles. This kind of vibration is also known as Whole-Body Vibration (WBV) because the whole body of an occupant inside the vehicle experiences a force due to vibration. The comfort, performance, and long-term health of the occupant are impacted by the WBV transmission. This research study deals with the measurement and assessment of discomfort due to the WBV experienced by a passenger under seating posture inside the OMNI-E vehicle, with and without the use of polyurethane (PU) foam padding. Vibration at the seat, lower back, and floor of the car were recorded at four different speeds, i.e., 30, 40, 50 and 60 km/hr. The vehicle's seat effective amplitude transmissibility (SEAT) was assessed for both scenarios with and without padding. The reduction in the SEAT and acceleration values were computed to check the effectiveness and accuracy of the padding used in the investigation. Modal and harmonic (frequency response) analysis is performed on a 3D ellipsoidal human body model based on anthropometric data of the 50th percentile Indian male of 54 kg mass under damped vibration condition to examine the influence of vibration experienced by the passenger in the seating posture. The ellipsoidal human body model was modeled and assembled in SOLIDWORKS®2021 and the modal analysis on ellipsoidal human body model was performed to determine its natural frequencies since the human body is sensitive to low-frequency vibration. By utilizing the experimental acceleration values with and without padding, frequency response analysis was carried out throughout the frequency range of 0–9 Hz, and the maximal equivalent stresses corresponding to 9 Hz frequency were estimated by ANSYS®2022 Workbench. The obtained results showed that the amplitude of stresses was minimized with padding as compared to without padding. Thus, vibration has a low adverse impact on human muscles and occupants are less venerable to suffer from back injuries, muscle pain, disorders, etc. It leads to improvement in the overall comfort of the occupants.

Keywords Whole body vibration · Seat effective amplitude transmissibility · Padding · Ellipsoidal human body model · Modal analysis · Harmonic analysis

1 Introduction

Vibration travel's in the form of waves through structural components, vehicles, human body and transfers energy in the form of motion rather than mass. The whole body vibration or recurrent motion caused by the vibration leads to discomfort and pain for occupants inside the vehicle [1–3]. The

automobile is one of the most widely used machinery today. In the ground vehicle, the human body is subjected to two types of vibration, i.e., WBV and Hand-transmitted vibration (HTV). The WBV is conveyed from the vehicle to the human body and HTV is transferred from the steering wheel to the driver's hands through adjacent parts. WBV is the most frequent source of vibration transferred to human occupants and prolonged exposure will endanger the health [4–7]. As of 2019, there were 1.4 billion commercial and passenger motor vehicles operating globally, according to US publisher Ward's. Thus the design of these vehicles evolved over time to investigate vibration transmission and provide better comfortability to the occupants so it can become safer and more efficient. Nowadays car manufacturers are constantly

exploring new ways to reduce vibration and increase the passengers' comfort. Many factors affect the transmissibility of vibration: frequency, the direction of the input motion, quality of the seat material, seat design, suspension system and transmission associated with the dynamic system [8–11].

Many researchers assessed and measured discomfort experienced by the passenger under seating posture due to whole body vibrations. An experimental examination on the WBV of passengers in three various vehicles traveling at four different constant speeds was undertaken by Kumaresh and Aladdin [12]. They have recorded vibration along the x-, y- and z-axis at the seat, backrest, and near the feet of the driver and computed SEAT, root mean square (rms), and vibration dose values (VDV) as per the standards of ISO 2631-1 and BS 6841. They noticed that at medium to high speeds, vibration rises with speed, whereas at low to medium speeds, it reduces. Nahvi et al. [13] utilized VDV, kurtosis, frequency response functions (FRF), and power spectral densities (PSD) to access the vibration transmission to the occupants. Further, they have computed SEAT values based on VDV outputs datasets used for the design of seat suspension and vibration isolators. The most frequent position in automobiles are the seated position. To provide better comfortability to the passengers, the design of seat suspension and cushioning has a significant impact. Kumbhar et al. [14] assessed the human body's reaction to vibration at three distinct seats. In their study, they found that if the proper cushioning and suspension at the seats are maintained, that will minimize the substantial amount of vibration transferred to the occupants. Wang and Rahmatalla [15] used spring-damper components to model the surfaces in contact between the supine human and the transport mechanism. Singh et.al. [16] investigated the backrest inclination and its effect on human comfort under WBV. They found that the vibratory effect decreases as the backrest angle increases. One of the main risk factors for disorders of the spine has been identified as WBV. Amiri et al. [5] studied stresses in the spinal disk due to WBV and the seating position of the occupants. They discovered that at 6 Hz frequency and 70 degrees of setback direction, occupants suffered the maximum compressive stress and highest von-mises stress, respectively. Nevertheless, the ISO/CD 2631-5 standard states that the maximum risk of harm to the passengers is at a 7 Hz frequency and a 75-degree setback angle. My et al. [17] used rapid upper limb assessment and quick response check to assess the musculoskeletal disorders, i.e., lower back and shoulder pain among elderly Malaysian taxi drivers.

In recent years, numerical approaches and computer-based modeling processes have been established on various automobile structural components and human occupants to evaluate, measure, track, and describe the vibration level and its impact on human beings. The numerical simulation can save time and costs as compared to the experimental investigation. Mondal et al. [3] used finite element simulation to measure the acceleration at different human segments inside the moving car. They also validated finite element results with real-time testing and they found that there is good compliance between experimental and numerical results. Many researchers used 50th percentile anthropometric data for a seated 54 kg Indian male to model a semi-supine posture [18–22] and performed modal and harmonic response analysis to find the natural frequency, mode shape, and effect of vibration on the occupants. They observed that maximum deformation and stresses occurred when the model vibrated in the lateral direction. Kim et al. [23] discovered that estimating discomfort using experimental approaches takes a long time and requires a lot of effort. Biomechanical modeling in a vibrating condition can accurately anticipate the mechanical response of the human body. Simulation of these models might be a superior approach for the assessment of the aspects of the human that are dynamic. Desai et al. [4] modeled a 2D multibody with 20 degrees of freedom for seated humans and applied a genetic algorithm to optimize the model parameters for vertical vibration. Savara et al. [24] carried out an undamped modal and frequency response analysis for a seating male subject without backrest support under the different magnitudes of acceleration. It is inferred that ultimate stresses are observed between the neck and head, and joints of the central torso and lower torso.

The majority of research work so far completed has concentrated on improving the comfortability of occupants subjected to WBV, free and undamped vibration conditions, FEM analysis with the pre-defined value of acceleration. There is very insignificant research on vibration analysis with damped, experimentally investigated acceleration values used as input to simulate the FE model, WBV in automobile application and implementation of padding to seat passengers. In this research work, a vibration analysis is conducted in OMNI-E vehicles with and without padding under seating posture conditions. The vibration parameters such as SEAT and accelerations are computed at four different speeds of the vehicles. Further, a 3D modeling of the ellipsoidal human body model using the anthropometric data of the 50th percentile of 54 kg Indian male is modeled in SOLIDWORKS®2021, further, modal and harmonic analysis is carried out in ANSYS®2022 Workbench. The research article is arranged in the following order: Sect. 2 deals with the theoretical background, the experimental methodology is explained in Sect. 3. Section 4 briefly discusses numerical simulation, results and discussion is presented in Sect. 5, and the conclusion is precisely explained in Sect. 6.

2 Theoretical background

2.1 Whole-body vibration (WBV)

WBV is described as a vibration communicated to the human body while operating machinery, driving, or traveling in vehicles such as trucks, army tanks, automobiles, and vans. When people are subjected to vibration for a lengthy amount of time, it causes discomfort, damage to any body part, back pain, headaches, and other issues. The passage of vibration in humans is influenced by both intrinsic and extrinsic factors. Extrinsic variables are those that indicate the state under dynamic conditions, such as the magnitude of acceleration applied, frequency, and direction of motion whereas intrinsic variables are those that describe the condition of human subjects, such as age, lying posture, gender, and weight. Intrinsic factors are further divided into two groups: intra-subject variability shows how the same individual respond to vibration changes when exposed to vibration in different postures, orientations, and positions. Inter-subject variability shows how different human bodies respond to vibration when exposed to the same vibration conditions. There are two benchmarks frequently assessed in automobiles to determine WBV. According to European Directive 2002/44/EC(2002) [25] and ISO2631-1(1997) [26], the exposure action value (EAV) is 0.5m/s^2 A(8), and necessary action is performed to limit WBV exposure anytime it exceeds the EAV value by 0.5 [27]. According to the control of vibration at work regulations 2005 states that the daily exposure limit value (ELV) to WBV is 0.5m/s^2 A(8) and it should not exceed by 1.15m/s^2 A(8), where A(8) represents WBV exposure limit values [28].

2.2 Effects of whole-body vibration

Vibrations frequencies up to 12 Hz have a great influence on human body parts and organs; however, greater than 12 Hz has a local impact. Low-frequency (less than 6 Hz) cyclic vibrations such as vehicle travel over uneven terrain can cause the body to resonate. After just an hour of vibration exposure under seating posture, the user may experience muscular fatigue and become more prone to back pain or back strain [13, 29]. It is crucial to understand how the human body reacts to WBV because it has a variety of impacts including decreased health, decreased comfort, motion sickness, interference with activities, and the feeling of low-magnitude vibration. The discomfort felt by the human body rises with the amplitude of the vibration, and their reaction is also affected by the frequency of the vibration. Lower back pain, ligament loosening, motion

sickness, bone damage, disorders of the spine, fatigue, irritability, headache and stomach digestive conditions are some of the health issues caused by WBV.

2.3 Seat effective amplitude transmissibility (SEAT)

SEAT values represent the vibration transmissibility from floor to seat of the vehicle. SEAT is a parameter for calculating the percentage of vibration experienced on the seat compared to the vibration generated on the floor [30].

$$\text{SEAT} = \frac{a_{\text{rmsz·seat}}}{a_{\text{rmsz·floor}}} \tag{1}$$

A SEAT value is said to be good when it is less than 100 percent and indicating that the seat dampens the vibration, thus lowering the vibration experienced by the occupants of the vehicle. Better vibration absorption can be experienced, as the SEAT value decreases. SEAT values can be used as a parameter to determine the comfortability of a vehicle seat. In order to compute the SEAT of the seat, the input parameter was the vibration recorded on the floor in the Z-direction. The output parameter was the vibration recorded at the seat pad in the Z-direction. There are two reasons for consideration of vibration in the Z-direction for calculating the SEAT values. Condition-1: The earlier research shows that cross-transmissibility between perpendicular axes does not occur and condition-2: Among all the axes on the seat, the Z- direction of the seat pad has the worst vibration, and only the worst direction shall be examined, according to European Directive 2002/44/EC (2002) [25] and ISO 2631-1:1997 [26].

2.4 Quantified discomfort scale

The extent of discomfort can be evaluated by the comparison between the acceleration (RMS) with the discomfort rating given in Table 1. It quantifies the discomfort experienced by the passenger ranging from comfortable to extremely

Table 1 Passengers' discomfort levels as per ISO 2631-1:1997 for various values of acceleration

RMS value of acceleration	Discomfort rating
< 0.315	Comfortable
0.315 – 0.630	A little uncomfortable
0.630 – 1.150	Fairly uncomfortable
1.15 – 1.60	Uncomfortable
1.60 – 2.50	Very uncomfortable
> 2.50	Extremely uncomfortable

uncomfortable with respect to RMS values of the accelera-tion [31, 32].

3 Experimental methodology

WBV is often transferred from the vehicle's seat, floor, and backrest to the human body via the occupants' or passen-gers' seats and feet. Thus, these experiments aim to measure the amplitude of vibrations at the seat, floor, and backrest at four different speeds, i.e., 30, 40, 50 and 60 km/hr of OMNI-E vehicle. Furthermore, compute the SEAT values corresponding to the four different speeds of the vehicle.

The experiment was carried out with and without using the Polyurethane (PU) foam to check the reduction in the SEAT values and vibration amplitudes experienced by the human body. The investigation was conducted at the prem-ises of "National Institute of Technology, Tiruchirappalli, Tamil Nadu, India-620015", on the suburban road using an OMNI-E Van. PU foam was utilized as the padding mate-rial as it is widely used for the fabrication of automotive seats due to its excellent performance and freedom of geo-metric design. It has suitable ball rebound properties, good vibration damping characteristics, and also durable and lightweight. The dimension of the PU foam padding used in the experiment was 16" ×16" × 1.75" in inches (406.4 × 406.4 × 44.45 in mm), as shown in Fig. 1a. The equipments used for recording the acceleration data in this study are as shown in Fig. 1b. The Larson Davis HVM200 is a compact, long-lasting vibration meter with built-in Wi-Fi. It measures hand-arm, whole-body, and general vibration. SEN027 Seat pad with triaxial accelerometer captures the acceleration signal in x, y, and z directions. CBL217-01 cable is used for connecting the SEN027 sensor and LD ATLAS mobile

application allows communication with the HVM200 by connecting the phone to the HVM200 hotspot.

The triaxial accelerometer sensor SEN027 was installed with compliance on the seat pad as per ISO 10361-1:2016 [12, 33]. The installed setup is placed over the seat, lower back and floor of van consecutively and occupant was allowed to seat on the setup. Furthermore, the amplitude of vibration transferred to occupant back and feet from the van is recorded and monitored for the investigation. Here, the experimental investigation is performed without and with PU foam padding consecutively. Figure. 2a shows without PU foam padding in this case the installed setup is placed over the seat, lower back and floor and occupant was allowed to seat on it and corresponding acceleration is measured for each trial. Similarly, Fig. 2b represents with PU foam with padding, in this case the installed setup is placed over the padding, lower back and floor and corresponding accelera-tion is recorded for each trial individually. These data were recorded for both the cases at 30, 40, 50, and 60 km/hr, respectively. The experiment is carried out three times for each cases. The average values of acceleration in z-direction is considered for computation of the SEAT values.

4 Numerical simulation

The physical model of an Indian male human subject weigh-ing 54 kg was used in the current investigation. Because the human body is made up of numerous layers of tissues, bones, material complexity, and so on, it was difficult to convert the actual physical model of the human subject into a 3D model. As a result, in this work, an ellipsoidal model was used to build a geometric model of an Indian male human subject in a seating posture. The anthropometric data were collected and the dimensions for the ellipsoidal model were calculated

Fig. 1 a Polyurethane (PU) Foam, **b** Connection between HVM200 and SEN027 through CBL217-01 along with LD ATLAS mobile application
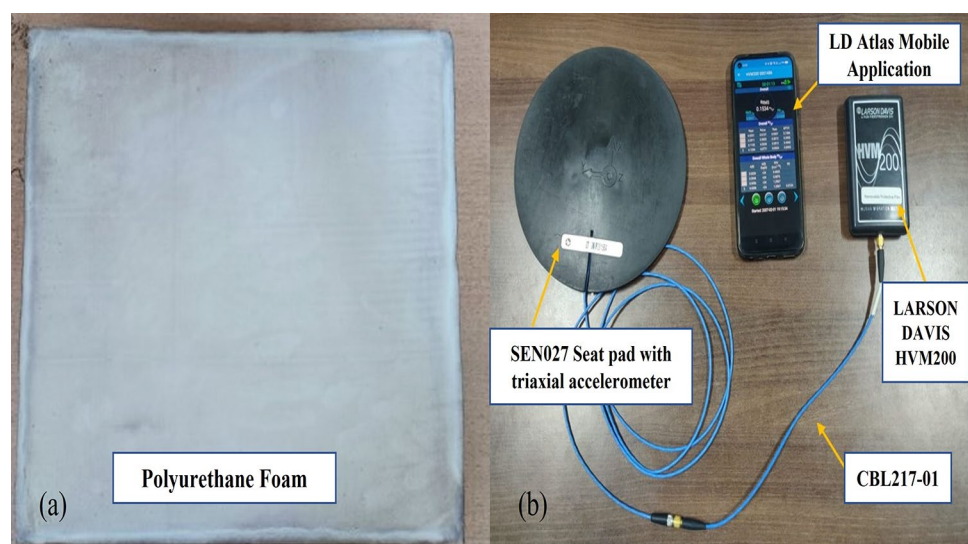
Fig. 2 **a** A triaxial accelerometer sensor installed on the seat without padding, **b** A triaxial accelerometer sensor installed on the seat with padding

using the formulas mentioned in the existing literature [34]. The 3D modeling and the modal and harmonic analysis were carried out in the SOLIDWORKS®2021 and ANSYS®2022 Workbench, respectively.

4.1 Anthropometric data

The anthropometric data for Indian male subjects [19, 34–36] used for 3D modeling are shown in Table 2.

4.2 Assumptions made in the modeling of human body model

The following presumptions have been made in the current study: (i) the subject is assumed to be seating upright without a backrest, (ii) each body segment has an ellipsoidal shape, (iii) both hands, upper arms, and lower arms are perpendicular to the ground, (iv) average body segment densities are assumed to be roughly equal and (v) the subject's material is assumed to be homogeneous and isotropic in nature.
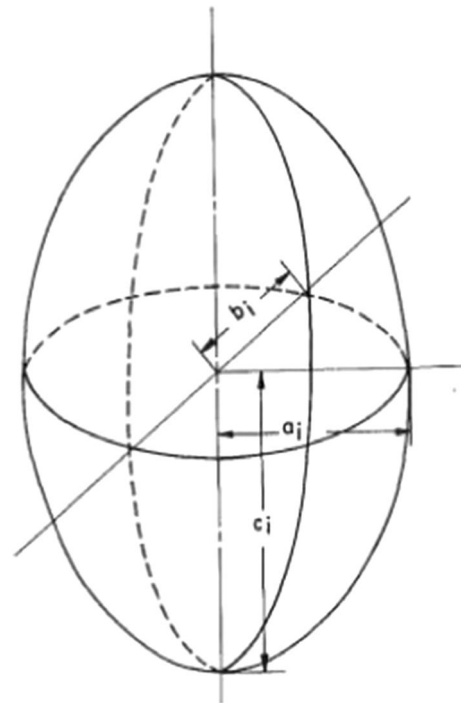
4.3 Ellipsoidal model

In this method, a physical human subject was taken into account and divided into five mass parts, comprising the head and neck, upper torso, middle torso, lower torso and upper legs, lower legs and feet. It was thought that the human subject's individual mass segments would have an elliptical form, as shown in Fig. 3. a_i, b_i, and c_i are the physical dimensions, which denote dimensions of the fore and aft axis, lateral axis, and vertical axis, respectively. These axes help to model each segment of the human subjects. The values of a_i, b_i, c_i, i.e., the physical dimensions of each part of the model were calculated using formulae present in the existing literature [34] as shown in Table 3. The formulae used the anthropometric data of 50th percentile Indian male subject of 54 kg mass [35].

Figure 4 a–e shows the modeled segment of head and neck, upper torso and both the arms (including upper and lower arms), central torso, lower torso and upper legs, lower legs and feet in SOLIDWORKS®2021. The modeled segments are assembled and displayed in Fig 5 a. The assembled model of the human body is imported to ANSYS Workbench to carry out modal and harmonic analyses. During analysis, the fixed-fixed contact is assigned between the respective joints. Further, the meshing of the ellipsoidal human body model as shown in Fig. 5b is done using the patch conforming method. This method produces tetrahedral elements (SOLID187, CONTAC174, TARGE170). Here, we have chosen an element size of 20 mm for the computation and obtained 67,221 elements and 1,02,941 nodes after meshing. Further, the appropriate boundary conditions such as the lower torso and feet are kept fixed and the simulation

Table 2 Anthropometric data of 50th percentile Indian male of 54 kg mass:

S.No.	Dimensional data (Li)	Abbreviations	Measurement (mm)
1	L1	Standing height	1648
2	L2	Shoulder distance from seat	576
3	L3	Armpit height	417
4	L4	Waist height	213
5	L5	Seated distance from seat	837
6	L6	Head depth	187
7	L7	Head breadth	147
8	L8	Head to chin height	243
9	L9	Neck breadth	112
10	L10	Shoulder breadth	380
11	L11	Chest depth	209
12	L12	Chest breadth	298
13	L13	Waist depth	192
14	L14	Waist breadth	259
15	L15	Buttock circumference	957
16	L16	Hip breadth (seating)	331
17	L17	Shoulder to elbow length	312
18	L18	Forearm length	243
19	L19	Biceps circumference	244
20	L20	Elbow circumference	273
21	L21	Forearm circumference	243
22	L22	Wrist circumference	156
23	L23	Knee height seated	519
24	L24	Thigh breadth	129
25	L25	Upper leg length	127
26	L26	Knee circumference	351
27	L27	Calf circumference	319
28	L28	Ankle circumference	239
29	L29	Ankle height outside	61
30	L30	Foot breadth	94
31	L31	Foot depth	248
32	L32	Neck height	43
33	L33	Upper leg length (buttock to knee length)	558
34	L34	Neck length	860
35	L35	Lower lumbar length	1010
36	L36	Abdomen depth	217
37	L37	Elbow to elbow (closed)	409
38	L38	Abdomen breadth	260
39	L39	Elbow rest	188
40	L40	Lower leg height	425
41	L41	Foot depth	248
42	L42	Foot height	61
43	L43	Head circumference	544
44	L44	Head height	213
45	L45	Hand length	180

Fig. 3 Schematic representation of an ellipsoidal segment [24, 37]

is performed to compute natural frequencies and stresses developed at a different section of the human bodies model.

5 Results and discussion

### 5.1 Seat effective amplitude transmissibility (SEAT)

After the successful competition of experiment, the vibration amplitude is considered only in z-direction for the investigation, however, the vibration amplitudes in x- and y-direction are neglected because it has not much significant impact on occupants. The root mean square of acceleration in z-direction, according to Eq. (1) is used for computing SEAT values between the seat and floor with and without padding for the corresponding speed values at 30, 40, 50 and 60 km/hr as shown in Table 4 & 5. The total value of acceleration for WBV is derived using the following Eq.(2).

$$a_{rms} = \sqrt{(k_x \cdot a_{rmsx})^2 + (k_y \cdot a_{rmsy})^2 + (k_z \cdot a_{rmsz})^2} \qquad (2)$$

Where a_{rms} is the total acceleration value which is the product of root sum of squares of the weighting coefficients and three components of acceleration. a_{rmsx}, a_{rmsy}, & a_{rmsz} are measured root mean square of accelerations in x, y and z directions. Where k_x, k_y and k_z are measured weighting coefficients in x, y and z directions, respectively. Thus, the

Table 3 Formulae for physical dimensions of the ellipsoids representing body segments for 54 kg human subject [19, 34–36]

S.No.	Body segments	Mass elements (M_i)	Depth(x) a_i (mm)		Width(y) b_i (mm)		Height(z) c_i (mm)	
			Formula	Value	Formula	Value	Formula	Value
1	Head	M1	L6/2	93.5	L7/2	73.5	L44/2	106.500
2	Neck	M2	L9/2	93.5	L9/2	56	(L5-L2-L44)/2	24.000
3	Upper torso	M3	L11/2	56	L12/2	149	L17/2	156.000
4	Central torso	M8	L36/2	104.5	L38/2	130	(L17+L18+L45)/4	183.750
5	Lower torso	M9	$L15/2\pi$	108.5	$L16/2\pi$	165.5	$(L18+L45)/4$	105.750
6	Upper arm	M4, M5	$L19/2\pi$	152.3	$L19/2\pi$	38.83	$L17/2$	156.000
7	Lower arm	M6, M7	$L21/2\pi$	38.83	$L21/2\pi$	38.67	$(L18+L45)/2$	211.500
8	Upper leg	M10, M11	L33/2	38.67	L25/2	63.5	L25/2	63.500
9	Lower leg	M12, M13	$L27/2\pi$	279	$L27/2\pi$	50.77	L40/2	212.500
10	Feet	M14, M15	L31/2	50.77	L30/2	47	L42/2	30.500
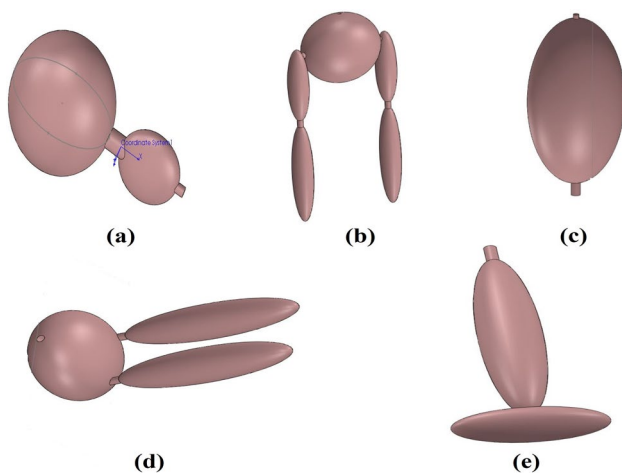
Fig. 4 Schematic representation of **a** Head and neck, **b** Upper torso and both arms, **c** Central torso, **d** Lower torso and upper legs, **e** Lower leg and foot

weighting coefficients are considered as 1.4 for x and y axes and value of 1 for the z-axis, respectively [38].

Table 6 shows the SEAT values for seats without and with padding. Basically, SEAT is an average amplitude of vibration at the seat and floor in the z-direction, i.e., vibration transferred from floor to seat. It is observed that SEAT values without padding are greater than 1, which shows that the maximum amount of vibration is transferred from floor to seat. Thus, the PU padding foam is provided above the seat to reduce the amplitude of vibration transferred to the occupants. The effect of padding is that it reduces the SEAT values below 1, which is desirable for the comfort of occupants. Figure 6 shows the graphical representation of the variation in SEAT values without padding and with padding with respect to the speed of vehicles. As the speed of the vehicle increases, the SEAT values decrease for both without padding and with padding cases. The maximum reduction in vibration amplitude is

observed corresponding to the lowest speed of the vehicles, i.e., 44.197%.

Table 7 shows the acceleration values at the seat without and with padding. Here, the total value of acceleration is the product of root sum of squares of the weighting coefficients and the components of accelerations which is given by Eq.(2). When the occupants' seats are unpadded, it is observed that the amplitude of vibration is larger and gets worse as the vehicle's speed rises. In another instance, the padding is used to quantify the vibration's amplitude. It is noted that the vibration's amplitude is lower than in the case without cushioning. The fluctuation of vibration amplitude with regard to vehicle speed is depicted in Fig. 7. It is indicated that when vehicle speed increases in both circumstances, the vibration amplitude increases. However, the implementation of padding causes a reduction in acceleration values as compared to normal conditions. The maximum reduction in acceleration is observed as 18.344% corresponding to 50 km/hr speed.

5.2 Quantified discomfort experienced by passengers at the seat

To evaluate the degree of discomfort experienced by the occupants, the RMS values of acceleration are investigated with and without padding conditions at different speeds on the seat. The level of discomfort for the passenger can be examined as per the ISO 2631-1:1997 for different values of acceleration by considering Tables 1, 4 and 5. From Table 8 we can observe that the comfort level of the passenger was increased with the use of padding from very uncomfortable to fairly uncomfortable.

5.3 Vibration experienced by the passenger at lower back

Table 9 shows the vibrations experienced by the passenger, with and without padding at the lower back with four
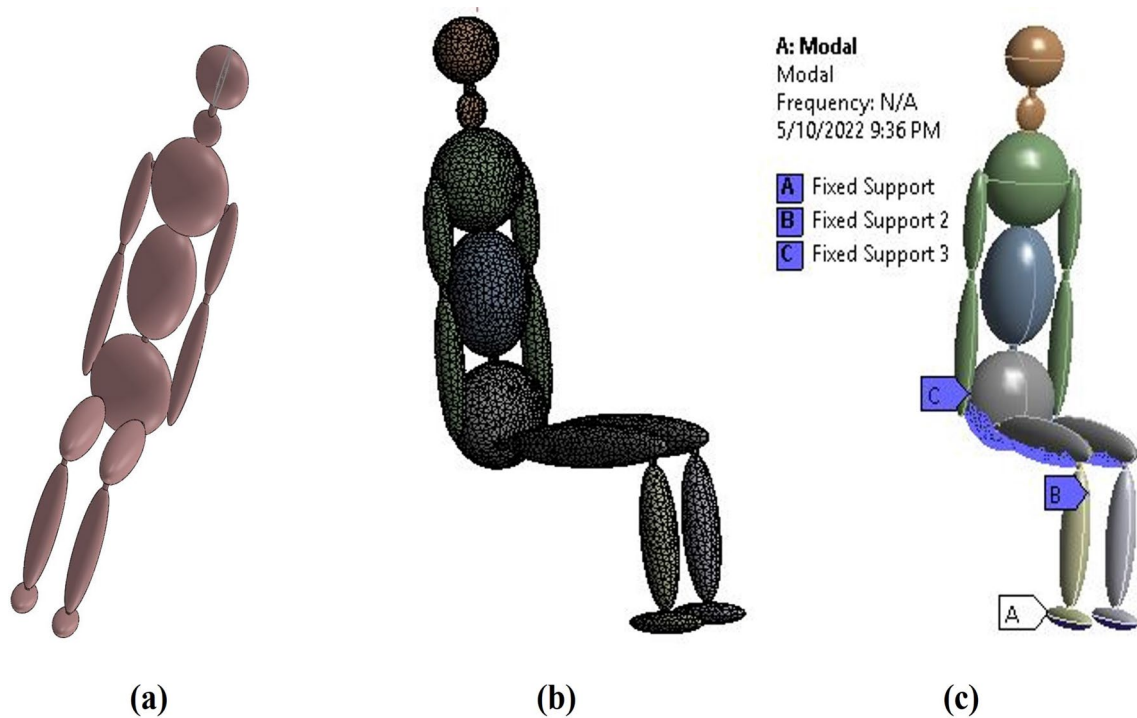
(a)   **(b)**   **(c)**

Fig. 5 **a** Assembly of human body, **b** Meshing of the human body model, **c** Boundary conditions

Table 4 Seat Effective Amplitude Transmissibility (SEAT) without padding at the seat pad

Speed(km/hr)	Seat pad without padding (m/s^2)				Floor (m/s^2)				SEAT
	$a_{rms.seat}$	$a_{rms.seat}$	$a_{rmsy.seat}$	$a_{rmsz.seat}$	$a_{rms.floor}$	$a_{rmsx.floor}$	$a_{rmsy.floor}$	$a_{rmsz.floor}$	$a_{rmsz.seat}/a_{rmsz.floor}$
30	0.729	0.089	0.290	0.593	0.493	0.202	0.122	0.366	1.620
40	0.919	0.105	0.285	0.815	0.854	0.240	0.297	0.667	1.221
50	1.232	0.168	0.310	1.129	1.202	0.298	0.396	0.982	1.149
60	1.448	0.175	0.502	1.243	1.241	0.190	0.233	1.168	1.064

Table 5 Seat Effective Amplitude Transmissibility (SEAT) with padding at the seat pad

Speed(km/hr)	Seat pad with padding (m/s^2)				Floor (m/s^2)				S.E.A.T
	$a_{rms.seat}$	$a_{rms.seat}$	$a_{rmsy.seat}$	$a_{rmsz.seat}$	$a_{rms.floor}$	$a_{rmsx.floor}$	$a_{rmsy.floor}$	$a_{rmsz.floor}$	$a_{rmsz.seat}/a_{rmsz.floor}$
30	0.627	0.285	0.189	0.406	0.487	0.075	0.112	0.449	0.904
40	0.874	0.383	0.232	0.609	0.867	0.216	0.220	0.753	0.809
50	1.006	0.436	0.264	0.710	1.231	0.512	0.271	0.927	0.766
60	1.307	0.644	0.324	0.799	1.268	0.189	0.252	1.189	0.672

different vehicle speeds in x-, y- and z-direction, respectively. The sensor is fixed on the seat pad using glue and the seat pad is placed on the seat. The z-direction of the sensor (local coordinates) is shown in Fig. 8 a. It is facing upward when it is placed at seat pad. When the seat pad is placed on the lower back the sensor is rotated by 90-degree about y-axis as shown in Fig. 8 b. Thus, the z-direction of sensor becomes parallel to the x-direction

of the global coordinates corresponding to the seat pad at seat conditions. Hence, in this case also, the acceleration in the z-direction of sensor (local coordinates) will be critical. The root sum of squares of acceleration values are computed as given in Table 9 and 10, to analyze the effect of vibration for without and with padding. It can be observed that with an increase in speed, there was an increase in vibration amplitudes in both cases, but there

Table 6 SEAT values at seat without and with padding

Speed (km/hr)	SEAT values without padding	SEAT values with padding	Reduction of SEAT values in %
30	1.620	0.904	44.197
40	1.221	0.808	33.824
50	1.149	0.766	33.333
60	1.064	0.672	36.842

was a substantial drop in the vibration experienced by the passenger when padding was used.

Figure 9 depicts the variation in the vibration amplitude with speed at the lower back. We observed that acceleration values are increasing with speed for both with padding and without padding cases. With padding cases, the amplitude of acceleration is reduced as compared to without padding cases. The maximum reduction in acceleration is observed corresponding to the higher speed of the vehicle, i.e., 36.994 %.

5.4 Quantified discomfort experienced by passengers at lower back

To evaluate the degree of discomfort experienced by the occupants, the root mean square value of acceleration is investigated with and without padding conditions at different speeds on the lower back by considering Tables 1 and 9. The level of discomfort for the passenger can be examined as per the ISO 2631-1:1997 for different values of acceleration. From Table 11, we can observe that the comfort level of the passenger was increased with the use of padding from a very uncomfortable to a fairly uncomfortable state.

5.5 Modal analysis

The modal analysis was performed in ANSYS®2022 workbench for six modes with boundary conditions mentioned in Sect. 4.3. The damping factor of 0.4 was taken from the previous research work [20]. The results of the modal analysis and the frequency range of 9.0611 Hz to 91.686 Hz are given in Table 12. Since all of the body's organs or parts are affected by vibrations up to a frequency of 12 Hz, and higher frequencies only have local effects, When a vehicle crosses an uneven surface, low-frequency cyclic vibrations happen and cause the body to resonate. Hence, the first modal frequency, i.e., 9.0611 Hz has the greatest importance for investigation.

Table 7 Vibration amplitude (rms acceleration) without and with padding

Speed (km/hr)	Acceleration without padding (m/s^2)	Acceleration with padding (m/s^2)	Reduction of acceleration in %
30	0.729	0.627	13.991
40	0.919	0.874	4.896
50	1.232	1.006	18.344
60	1.448	1.307	9.737

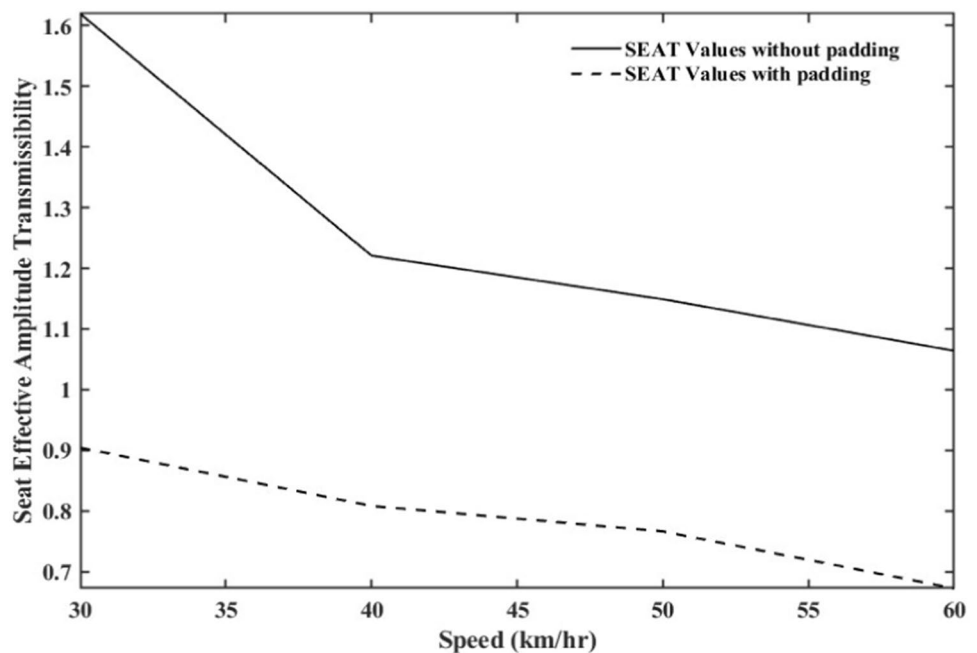**Fig. 6** Variation in SEAT values with speed of vehicle at seat

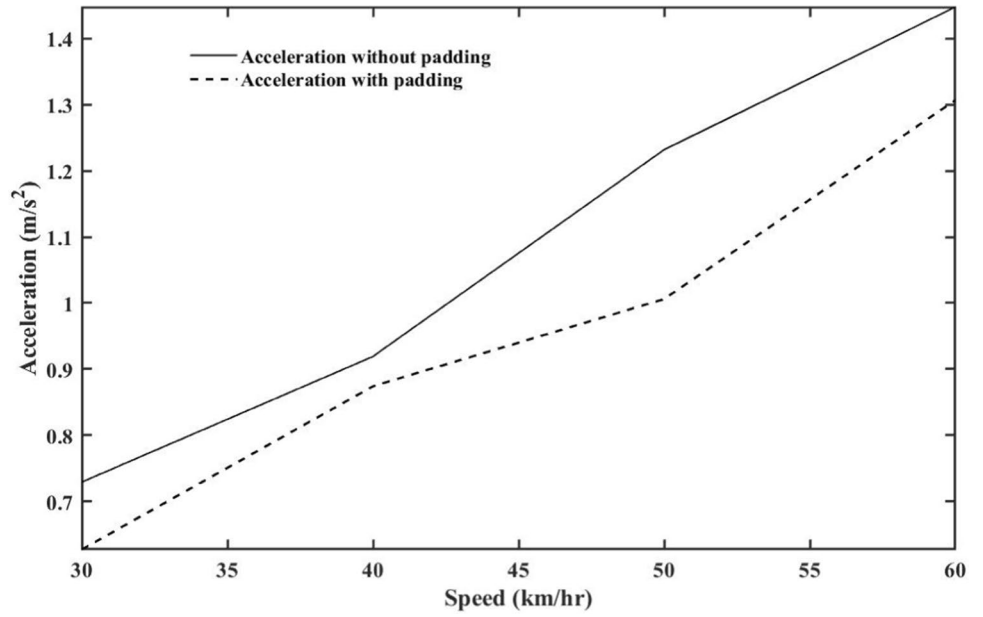**Fig. 7** Variation in vibration amplitude (acceleration) with speed of vehicle

Table 8 Passenger's discomfort levels as per ISO 2631-1:1997 for various values of acceleration, at the seat:

Discomfort scale	Without padding				With padding			
	30	40	50	60	30	40	50	60
Comfortable								
A little uncomfortable					*			
Fairly uncomfortable	*	*				*	*	*
Uncomfortable			*					
Very uncomfortable				*				

Fig. 8 **a** Sensor position at seat pad, **b** Sensor position at back seat pad

Table 9 Acceleration values at the back with and without padding

Speed(km/hr)	Back without padding (m/s^2)				Back with padding (m/s^2)			
	$a_{rms.back}$	$a_{rmsx.back}$	$a_{rmsy.back}$	$a_{rmsz.back}$	$a_{rms.back}$	$a_{rmsx.back}$	$a_{rmsy.back}$	$a_{rmsz.back}$
30	0.707	0.340	0.248	0.392	0.525	0.261	0.185	0.275
40	1.108	0.568	0.328	0.621	0.997	0.528	0.265	0.558
50	1.567	0.788	0.551	0.821	1.134	0.500	0.264	0.813
60	2.003	0.958	0.718	1.097	1.262	0.475	0.475	0.842

Table 10 Reduction in Acceleration Magnitudes (%) at Lower Back

Speed (km/hr)	Acceleration without padding (m/s^2)	Acceleration with padding (m/s^2)	Reduction in acceleration (%)
30	0.707	0.525	25.742
40	1.108	0.997	10.018
50	1.567	1.134	27.632
60	2.003	1.262	36.994

5.6 Frequency response analysis

Harmonic analysis was carried out in ANSYS®2022, at various acceleration magnitudes with the frequency ranges of 0-9 Hz, to examine the impact of vibration. The acceleration values that were given as input for the simulation were experimental values that the passenger experience in the lower back as given in Table 9. The maximum equivalent stress values at a frequency of 9 Hz were obtained for each speed of the vehicle without and with padding, as shown in Table 13.

The FE simulation results are depicts in Figs. 10 a–d and 11 a–d for the harmonic response of vibration at the lower

Fig. 9 Variation in the vibration amplitude with speed at lower back
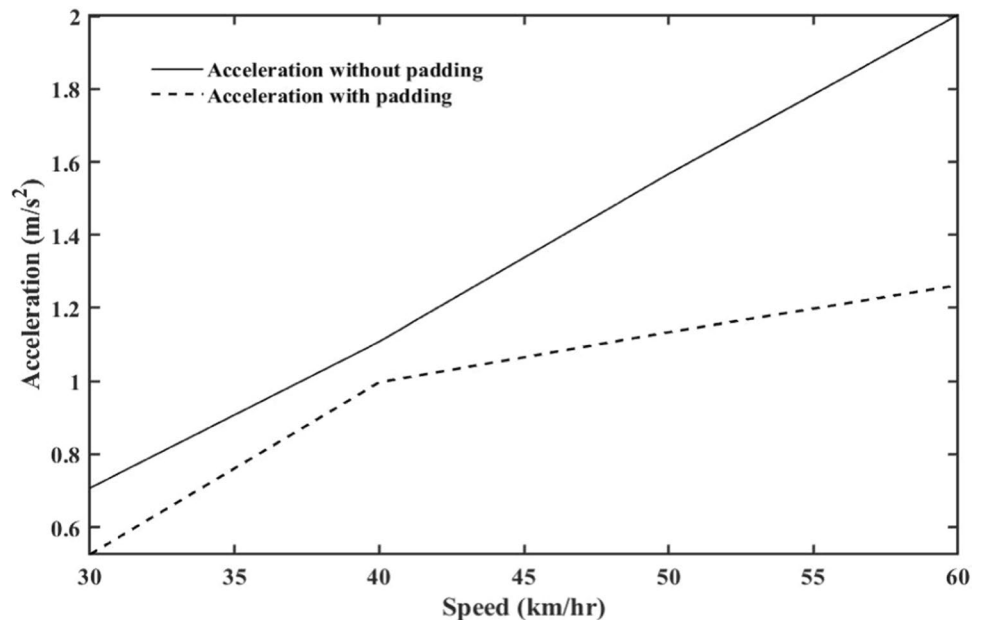

Table 11 Passenger's Discomfort Levels as per ISO 2631–1:1997 for Various Values of Acceleration

Discomfort scale	Without padding				With padding			
	30	40	50	**60**	30	40	50	60
Comfortable								
A little uncomfortable	*				*			
Fairly uncomfortable		*				*	*	*
Uncomfortable			*					
Very uncomfortable				*				

Table 12 Natural frequencies of Human Body at Seating Posture

Mode	Natural frequency (Hz)
1	9.0611
2	23.325
3	32.864
4	34.864
5	52.966
6	91.686

back without and with padding, respectively. The maximum stresses are observed at the joint between the lower torso and central torso and also a substantial increase in stresses was observed at the joint between the neck and head and arm joints. The stress values observed without padding range from 29.514 MPa to 82.542 MPa, which is much higher than the average muscle strength of the human body. The amount of stress on the lower back could lead to muscular fatigue and make the passenger more vulnerable to back injury. It could also lead to severe back pain if the passenger has been
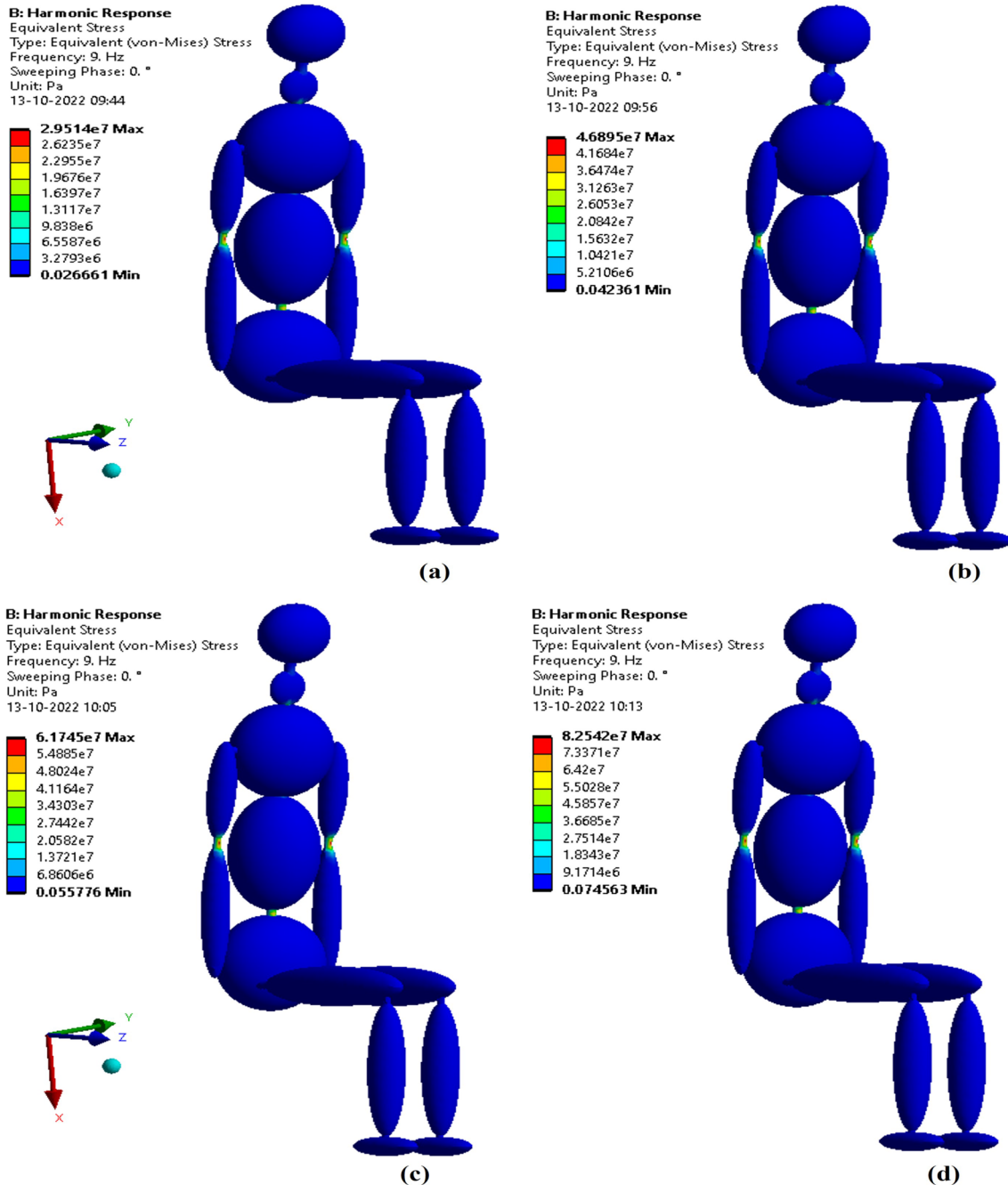

Fig. 10 a-d Harmonic response for the vibrations experienced at the lower back without padding at different speeds
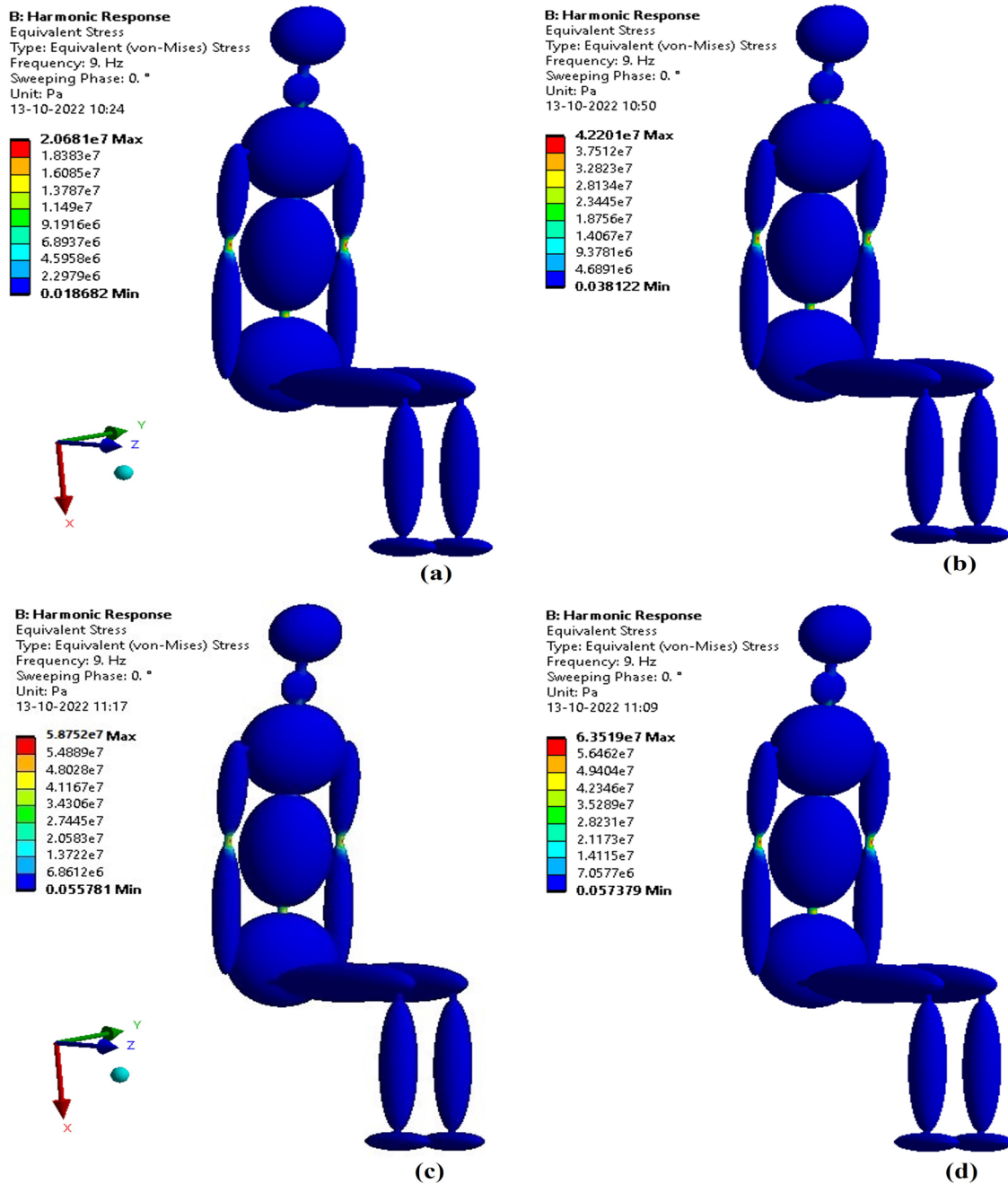
Fig. 11 a-d Harmonic response for the vibrations experienced at the lower back with padding at different speeds

exposed to these vibrations for a longer period of time. It is observed that the stress values are increasing with the increase of speed, for both with and without padding. But with the use of padding, the stress values have been substantially reduced between 4 to 29 percent, as shown in Table 13. For the lower speed, it can be seen that the reduction in stress values is higher, which means that the padding attenuates the vibrations in a reasonable manner such that there will be less ill effect of the vibrations on the human muscles. The passenger will be less susceptible to back-related injury or disorders. The graphical comparison of the reduction in the stress values is depicts in Fig. 12.

Fig. 12 Variation in the vibration amplitude with speed at lower back
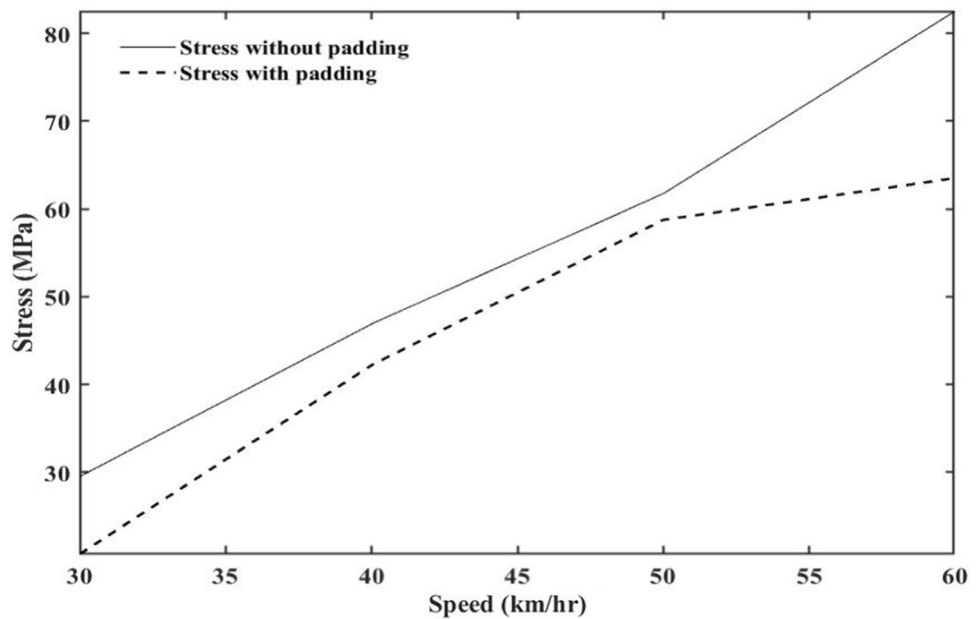
6 Conclusion

The experimental study of the whole-body vibrations was carried out in the OMNI-E van with and without padding conditions. The output parameters obtained from the experimental investigation were given as input to the Finite Element simulation (Modal and Frequency Response analysis). The WBV was measured inside the vehicle under seating posture at the seat, floor, and lower back at four different constant speeds of 30, 40, 50, and 60 km/hr. With the use of PU foam, the total acceleration and SEAT values become lower than 1.15 m/s^2 and 1, respectively, for all speeds. The maximum reduction in total acceleration and SEAT values with padding are attained at 26.057 and 44.197 percent, respectively. The overall discomfort experienced by the passenger was also improved from very uncomfortable to fairly uncomfortable. The frequency varies between 9.0611 Hz and 91.686 Hz for a 3D ellipsoidal model. As we know, low-frequency vibrations affect all organs of the human body; thus, 9.0611 Hz frequency is highly important as obtained from FE simulation. Therefore, a harmonic analysis was performed on the frequency of 9 Hz. The stress values observed without

padding ranges from 25.528 MPa to 71.813 MPa at different speeds, which are much higher than the average muscle strength of the human body. This could lead to muscular fatigue, making the passenger more vulnerable to back injury. With PU foam padding, stress from vibrations at the lower back has been reduced between 7 and 40 percent and ranges from 19.608 MPa to 43.052 MPa at different speeds. The reduction in stress values was higher for the high-speed vehicle. This leads to the common, ill effect of the vibrations on the human muscles, and the passenger will be less susceptible to back-related injury or disorders.

Declarations

Conflict of interest The authors state that they have no known conflicting financial or personal interests that may have seemed to affect the work presented in this study.

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Table 13 Stress Induced at the Lower Back due to Vibration

Speed (km/hr)	Stress without padding (MPa)	Stress with padding (MPa)	Reduction in Stress value (%)
30	29.514	20.681	29.928
40	46.895	42.201	10.000
50	61.745	58.752	4.847
60	82.542	63.519	23.046

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