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Finite Element Modelling of Car Seat with Hyperelastic and Viscoelastic Foam Material Properties to Assess Vertical Vibration in Terms of Acceleration

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Abstract

Primary objective of automobile seats is to offer adequate level of safety and comfort to the seated human occupant, primarily against vibration. Ideally, any sort of automotive seat is constructed by mechanical framework, cushion, backrest and headrest. The frame structures are made of metallic alloys, while the cushion, backrest and headrest are made of polyurethane foam material. During the design phase of automotive seat, the greatest challenge is to assign realistic material properties to foam material; as it is non-linear in nature and exhibit hysteresis at low level stress. In this research paper, a car seat has been modelled in finite element environment by implementing both hyperelastic and viscoelastic material properties to polyurethane foam. The car seat has been excited with the loads due to car acceleration and human object and the effects of vibration in terms of vertical acceleration at different locations have been measured. The aims of this simulation study are to establish a car seat with the foam material properties as accurately as possible and provide a finite element set up of car seat to monitor the vertical acceleration responses in a reasonable way. The RMS acceleration values for headrest, backrest and cushion have been found to be 0.91 mm/sec^2, 0.54 mm/sec^2 and 0.47 mm/sec^2, respectively, which showed that the car seat foam can effectively be modelled through combined hyperelastic and viscoelastic material formulations. The simulation outputs have been validated through real life testing data, which clearly indicates that this computerized simulation technique is capable of anticipating the acceleration responses at different car seat segments in a justified way.

Keywords

Car Seat, Hyperelastic Material, Viscoelastic Material, Finite Element, Vertical Acceleration, Vertical Vibration

1. Introduction

The car seat foam can be made of nylon, alcantara, vinyl, faux leather or polyester material, though the most common industrially used material for car seat foam is polyurethane. Over the last many years, numerous research studies had been carried out on car seat based on the shape, orientation, material to optimize the human safety and comfort standard, though seat material properties were always accounted as the mandatory factor regardless of the field of research.

Mechanical behaviour of polyurethane material is highly complex in nature. For a small quantity of strain effect, it continues to behave like elastic material, though further increment in strain amount causes gradual increment of stress generated inside it. At the end of compression stage, it exhibits sharp rise in stress level. Non-linearity with hysteresis and strain rate dependent energy dissipative nature of polyurethane foam material were shown in the finite element analysis of car seat [1] and load deflection measurement of foam material [2]. Simulation using LS DYNA for obtaining the force-deflection curve for the seat cushion had been performed [3] to show the static and dynamic characteristics of the cushion foam material. The seat base plate, the seat cushion and a circular disc had been taken into account to carry out the entire analysis and later the results were compared to experimental data. The seat cushion material properties had been simplified by assigning only density and Young's modulus. The influence of the seat foam material properties had been shown during the assessment of sitting comfort of the automobile seats [4] for contact interference and acceleration transmission between human body and seat. Various physical parameters including seat material properties had been explored [5] during the pressure distribution study between seat and sitting object. Driver's seat comfort was virtually simulated in finite element [6] to observe the pressure distribution inside seat with respect to inclination of the seat. Simplified seat model had been constructed, made of backrest and cushion with assigned density, Poisson's ratio and Young's modulus. Human health and safety had been investigated during the course of collision [7] and found that seat material would be responsible for the amount of movement of human occupant in the side and rear directions. Experimental and finite element studies had been conducted on polyurethane foam [8] to show the compression characteristics under the effect of random vibration. Researchers established a series of feasible models for foam material including hyperelastic or hyper-foam constitutive model. Co-relations between the stress, strain and volume of the foam material had been formulated while studying foam properties in depth [9]. Many research works in the past attempted to establish the properties of the polyurethane foam by relating the stress-strain behaviour as function of strain rate. Finite element investigation on car seat [1] stated that the stress-strain curve for foam material was directly related to strain rate, while study on foam material under the effect of dynamic impact load [10] graphically represented the stress-strain curve with respect to various uniaxial compressions with variable strain rates. Seat for heavy vehicle had been numerically simulated using lumped network system modelling [11] to monitor the riding comfort. The seat foam material had been modelled using both the hyper-elastic and viscoelastic material parameters to take into account the strain rate dependency and strain energy dissipation. Vibration transmission from seat leg to passenger body had been observed [12] and vibration damping in passenger seat had been assessed. Open-porous aluminum foam material had been considered and modal damping state followed by frequency response function and acceleration graph had been received. Seat cushion simulation under the effects of uniaxial compression and indentation forces [13] found that modelling the foam material with hyper-foam formulation was capable of anticipating the stress-strain curve in an accurate way. Finite element modelling of the human soft tissue and seat foam [14] used the hypothetical concept of strain energy absorption capacity along with hyperelastic material properties as described in the Ogden model equation. The same study extended the research work further by incorporating viscoelastic material properties to the seat cushion using Prony series formulation.

Exploring the past research works on the automotive seat foam material, it is undoubtedly clear that the polyurethane material can be modelled using the formulations of stress-strain behaviour, hyper-elastic foam properties or combination of hyper-elastic and visco-elastic parameters, though the selection of the formulation in analysis study exclusively depends on the nature of the investigation. Majority of the past research works considered only the hyper-elastic properties for foam materials studies, visco-elastic properties for the assessment of foam material under shear loading or stress-strain curve for monitoring the cushion behaviour. Moreover, those researches considered only certain portion of entire automotive seat or very specific interaction between seat and human body. Very few studies had been found to have considerations for combination of different formulations to model the entire seat, however those studies were conducted using multi-degree of freedom system, lumped mass parameters method or some non-finite element tool. None of the previous case studies had shown the simulation modelling of whole car seat in finite element environment implementing the combined material formulations. Hence, there is a research gap in developing the finite element simulation of entire car seat using polyurethane foam with combined material formulations and therefore, demand arises for a comprehensive simulation based solution to judge the vibration level at any point of entire car seat. Various combinations are possible by taking into account the potential formulations, though careful judgment is necessary to choose the appropriate mathematical model for running flawless computerized simulation. This research paper aims to fill up the gap in existing literatures by outlining a distinct finite element based simulation set up for entire car seat with the most suitable combination of mathematical formulations for seat foam material.

During this research study, a non-robust car seat has been constructed. The dimensions of the seat are based on the recommended optimized seat parameters and industrial guidelines. During this span of simulation work, combination of hyperelastic and viscoelastic material properties have been taken into account. A comprehensive simulation technique including all the necessary input parameters has been described to establish a simulation model of the entire car seat to assess the vertical vibrations in terms of accelerations at headrest, backrest and cushion.

2. Methodology

2.1. Dimensions of Car Seat

Many research works had been conducted in the past to explore the ideal car seat dimensions to optimize comfort parameters for humans. Fit parameter analysis [15] advised that the least width of cushion to be 432 mm for a 95th percentile female occupant, though increment in the dimension would be beneficial taking into account the clothing. Similar sort of study [16] suggested the minimum width of cushion to be in the range of 480 mm to 500 mm. Based on the anthropometric dimensions, recommended length of seat had also been recorded in different case studies as 432 mm [17], 440 mm to 550 mm [16] and 330 mm to 470 mm [18]. The backrest width and height had been advised to be at least 360 mm and 550 mm above the H-point, respectively, during the survey of automotive seat design [19]. Database of "Ricaro", an industrial innovator in the sector of automobile seat designing, shows how the seat design had been changed over in the last 40 years.

Consulting with all the recommendations to optimize the seat parameters and assuming a 50th percentile male human body to occupy the seat, a CAD model has been established and the major overall dimensions are shown in **Figure 1**.

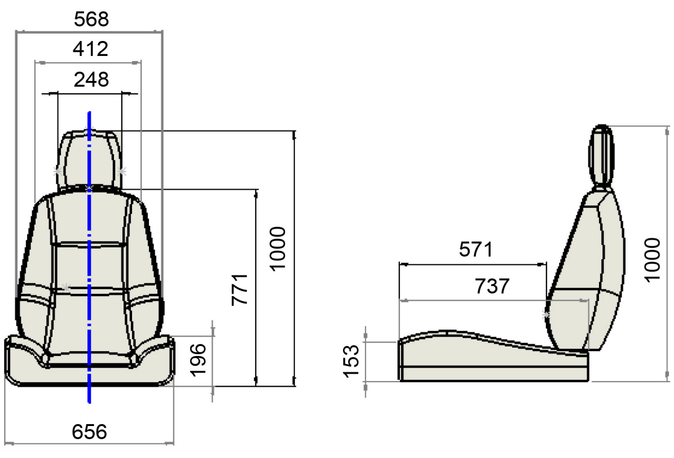


Figure 1. Overall major dimensions of car seat.

2.2. Hyperelastic and Viscoelastic Material Modelling for Seat Foam

Hyperelastic properties are suitable for defining the behaviour of foam material, while the viscoelastic properties are used to judge the effect of shear loading inside the deformable bodies. In this research work, both the hyperelastic and viscoelastic properties have been assigned to the car seat foam cushion to achieve the result as realistic as possible. To find out the best hypothetical formulation to be used, past relevant literatures have been consulted.

In conjunction with international standard ASTM D 3574-01 for testing procedure for flexible foam materials, a relationship between the stress and stress was evaluated [14] by applying second order strain-energy potential function under shear and compression loadings. The hyper-elastic material model was described using the Ogden model formulation [14] as shown in Equation (1).

$$[U]=\sum_{i=1}^{N}2\frac{\mu_i}{\alpha_i^2}\left[\tilde{\lambda}_1^{\alpha_i}+\tilde{\lambda}_2^{\alpha_i}+\tilde{\lambda}_3^{\alpha_i}-3+\frac{1}{\beta_i}\left(\left(J^{el}\right)^{-\alpha_i\beta_i}-1\right)\right] \tag{1}$$

N = Defining parameter for the approximation of the model.

$\tilde{\lambda}_j$ = Principal strength j.

J^{el} = Elastic volumetric ratio.

α_i,β_i,μ_i = Material dependent parameters.

The outcomes of the testing were exported into finite element set up and Ogden hyperelastic coefficients had been estimated by implementing numerical curve fitting technique. The hyperelastic coefficients were obtained as $\mu_1=164.861\text{ kPa}$, $\alpha_1=8.88413$, $\beta_1=0$, $\mu_2=0.023017\text{ kPa}$, $\alpha_2=4.81798$, $\beta_2=0$. The same investigation further explored the viscoelastic properties of foam and the viscoelastic coefficient values were obtained as $G_1=0.3003$, $\tau_1=0.010014\text{ s}$, $G_2=0.1997$, $\tau_2=0.10020\text{ s}$. Very similar material models were proposed during the performance assessments of slightly compressible hyper-elastic foams [20] and highly compressible hyper-elastic foams [21]. Polynomials and stresses of three kinds of polyurethane foams had been listed [22] to formulate the hyperelastic and viscoelastic material models and later, a series of Ogden coefficients had been tabulated. Finite element analysis of hyperelastic materials also presented [23] a set of Ogden parameters for different scenarios with optimized parameters in numerical and finite element. Polyurethane foam had been modelled using hyper-elastic, visco-elastic, polynomial and stress formulations [24] and a set of data on hyperelastic and viscoelastic coefficients had been reported. Ogden parameter values had been optimized and tabulated as $\mu_1=4.81\text{ kPa}$, $\alpha_1=19.8$, $\beta_1=0.01450$, $\mu_2=3.60\text{ kPa}$, $\alpha_2=19.8$, $\beta_2=0.0065$ for hyper-elastic materials during the numerical and finite element study [23] of foam material for different case scenarios.

Based on the data gathered from the past works done on the relevant field, hyperelastic Ogden coefficients (N = 2) have been implemented to the seat foam. Viscoelastic parameters have been allocated based on the time dependent function of instantaneous shear modulus. The coefficient values used during this research task, are outlined in Table 1 and Table 2.

2.3. Density and Poisson's Ratio

Density of polyurethane foam had been inspected by National Bureau of Standards, USA [25] at low temperatures 295 K, 111 K, 76 K and 4 K and reported as 64 kg/m^3. Car seat cushion modelling using polyurethane foam [1] considered the density value as 67 kg/m^3, while assessment of polyurethane foam material with respect to different types and cell sizes [26] reported the densities in-between 57 kg/m^3 to 68 kg/m^3. While finding the Poisson's ratio for seat cushion foam materials [27], the density had been in the range of 32 kg/m^3 and 64 kg/m^3. Based on the past works carried out on the density values of the foam material, density value of the polyurethane foam for this current analysis task has been taken as 64 kg/m^3.

Latest trend in automotive seat foam design is to develop seat material which will bulge to inward direction and display negative Poisson's ratio. One of the cutting edge technique developed on car seat cushion [27] found the Poisson's ratio of −0.13 for polymers with density of 18 kg/m^3 and compression ratio of 2.2, while with density of 25 kg/m^3 and compression ratio of 3.4, the obtained Poisson's ratio was −0.26. The seat foam material usually under the effects of compression without any sidewise constraints, hence, there is no co-relation between the lateral and longitudinal strains. Taking into account this fact, computational analysis of car seat and human body [14], finite element modelling of the car seat [1] and the process of designing the car seat [13] ignored the Poisson's ratio by assuming its value to be zero. Considering the real fact as described in the revenant investigations, in this simulation project the value of Poisson's ratio has been ignored.

Table 1. Hyperelastic parameters used.

Hyperelastic parameter	Value
μ_1	0.00481 MPa
α_1	19.8
β_1	0.01450
μ_2	0.00360 MPa
α_2	19.8
β_2	0.00650

Table 2. Viscoelastic parameters used.

Viscoelastic parameter	Value
G_1	0.3003
τ_1	0.010014 s
G_2	0.1997
τ_2	0.10020 s

2.4. Simulation Set Up-Loading, Step, Boundary Condition and Meshing

Loading condition in this simulation work has been applied considering a non-racer type accelerating car achieving a speed of 30 miles/hour from standstill condition. The road terrain has been assumed to be smooth, hence, the load primarily has been accounted due to initial accelerating period. Databases of Jaguar XK coupe [28] showed the measured acceleration value as 4.5 m/sec^2. Initial acceleration for the non-racer type of car at 60 km/hour and 40 km/hour [29] reported the acceleration values as 1.083 m/sec^2 and 0.861 m/sec^2, respectively. Average and peak accelerations for a normal passenger vehicle operating in rural area had been formulated [30] through Equation (2) and Equation (3).

$$a_{av} = a\mathrm{e}^{bv} \tag{2}$$

$$a_{\max} = c + dv \tag{3}$$

a_{av} = Average acceleration in m/sec^2

$a_{\max}$ = Maximum acceleration in m/sec^2

v = Vehicle speed in m/sec

a,b,c,d = Constants

The car seat in this project work has been assumed to cope with a 50th percentile human male body of 77.3 kg mass. Considering the closest possible matching criteria for vehicle operating scenario, the force exerted on the seat due to acceleration has been calculated using the acceleration value of 0.861 m/sec^2. Contact interfaces between the seat and humans have been estimated and vertical load due to human object and horizontal load due to acceleration have been implemented on the estimated interaction areas, in vertical and horizontal directions, respectively.

The entire simulation set up has been carried out in ABAQUS CAE 6.13. The base condition of the seat has been assigned in "Initial" step, while the loading conditions have been implanted in "Static General" step.

The boundary conditions have been simplified based on the aspects of this project work and implemented as realistic as possible. Underneath the seat cushion has been made fixed, while the backsides of backrest and headrest are not permitted to move from initial state. Angular fore-aft movements of the backrest and headrest about the respective bottom connecting points are allowed.

The common elements used for deformable bodies in finite element are quadrahedral and hexahedral. During this simulation set up, the seat structure has been meshed with ten-node tetrahedral element—C3D10. **Figure 2** is visually representing the anticipated contact surfaces, loading, boundary conditions and meshing.

3. Results

A 64 bit standard computer with Windows XP operating system, RAM of 6 GB and two dual-core 2.1 GHz Intel(R) Pentium(R) CPU B950 had been utilized to

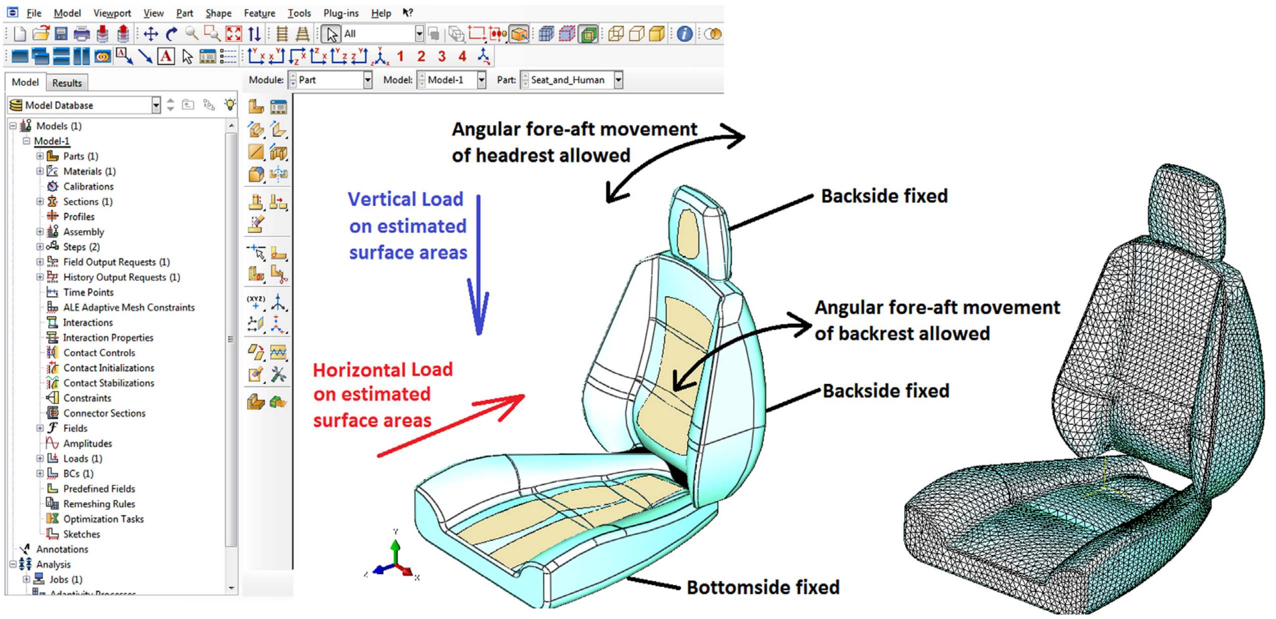


Figure 2. Estimated interfaces, directions of loads, boundary conditions and meshing.

carry out the simulation work. Because of the limitation in computer memory, the simulation running time had been set to 10 seconds. It took around 7 wall clock hours for ABAQUS solver to yield the results. The overall results obtained for acceleration responses, are visually represented in Figure 3.

From the ABAQUS post processor, the vertical accelerations at seat headrest, backrest and cushion had been extracted and shown in Figures 4-6.

The average and RMS acceleration magnitudes of car seat portions have been calculated and shown in Table 3.

4. Validation and Discussion

The vertical accelerations received from this analysis have been validated by comparing to real life test data gathered from identical operating condition to this simulation set up. An economic hatchback car with a male driver of 78 kg sitting on the driver seat had been accelerated from static condition to pick up the speed of 30 - 35 miles/hour and sensors had been mounted on the outer surfaces of headrest, backrest and cushion. There was no sign of irregularities on the road terrain and testing data were logged for 60 seconds. Vibration measuring unit NI 9234 USB module with Compact DAQ chassis and transducer Dytran 3055 were employed to read the acceleration vs time plots.

Transducer was mounted approximately at the central location of designated surface with the help of adhesive tapes and the cable from the transducer was linked to the vibration measuring module NI 9234. A standard laptop installed with signal processing tool "m + p Analyzer" was connected to other side of NI 9234. The test set up is shown in Figure 7.

The testing data were received in .SOT format and through the "m + p Analyzer", the graphs for acceleration with respect to time had been generated as

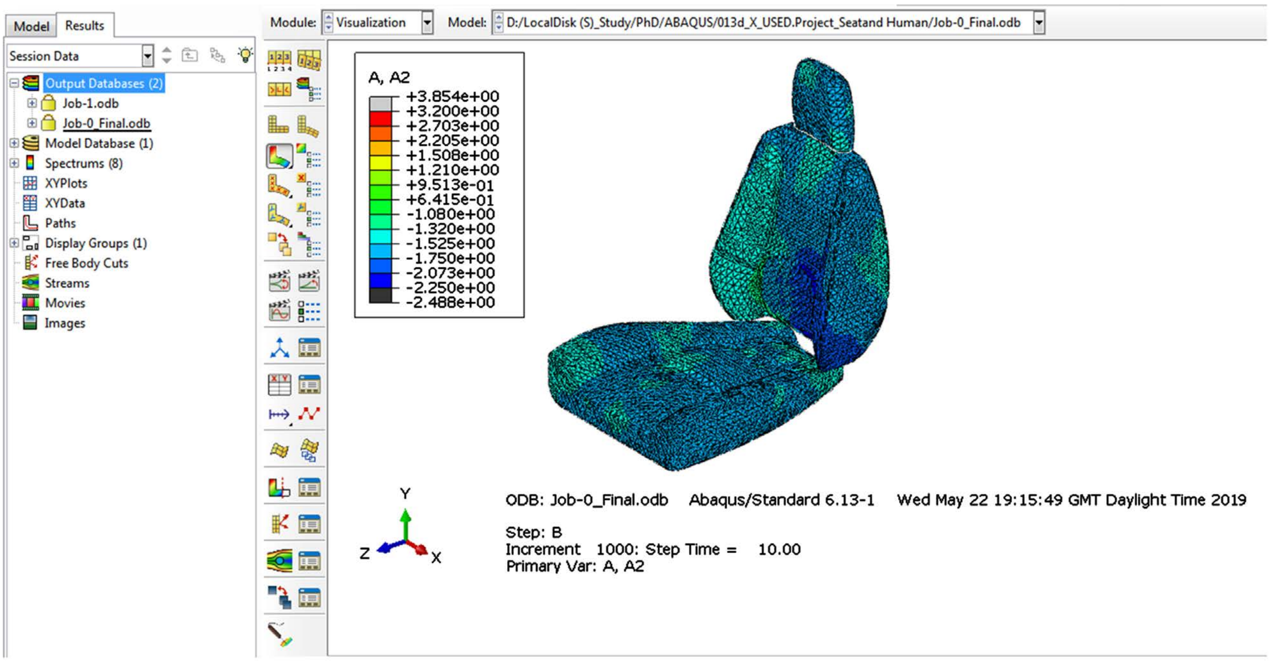


Figure 3. Overall vertical acceleration.

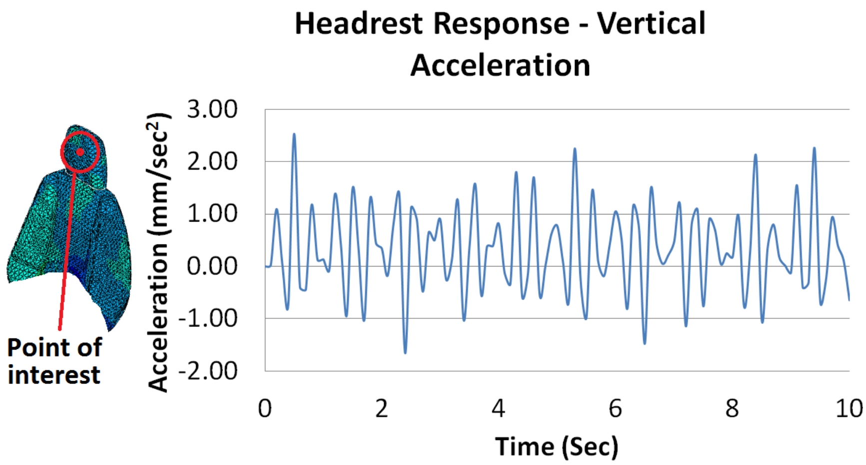


Figure 4. Vertical acceleration at headrest.

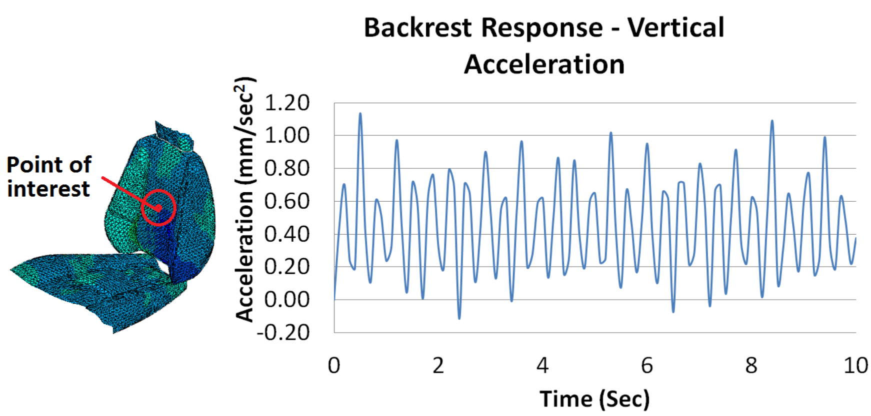


Figure 5. Vertical acceleration at backrest.

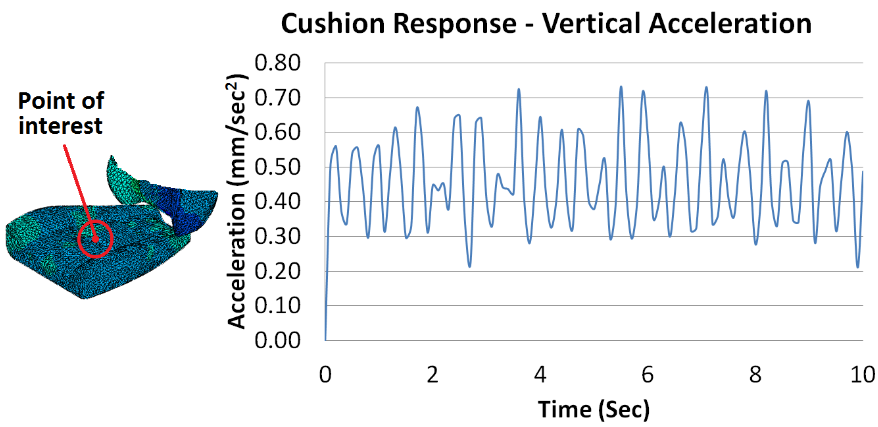


Figure 6. Vertical acceleration at cushion.

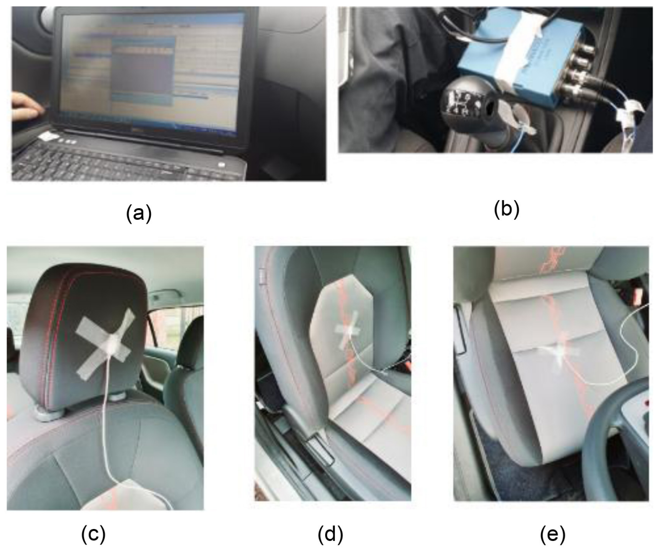


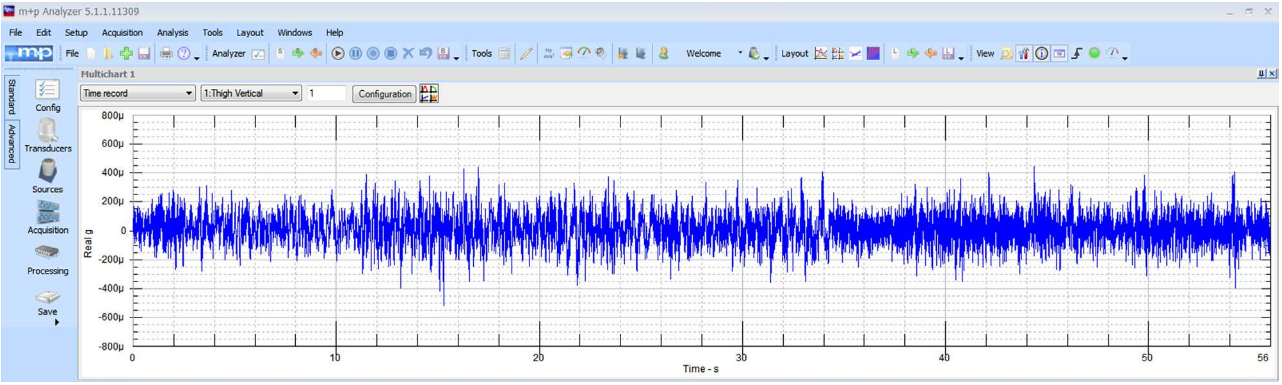
Figure 7. Test set up (a) Laptop with the signal processing tool "m + p Analyzer"; (b) NI 9234 module; (c) Dytran 3055 sensor mounted on headrest; (d) Dytran 3055 sensor mounted on backrest; (e) Dytran 3055 sensor mounted on cushion.

Table 3. Average and RMS accelerations of car seat segments from simulation.

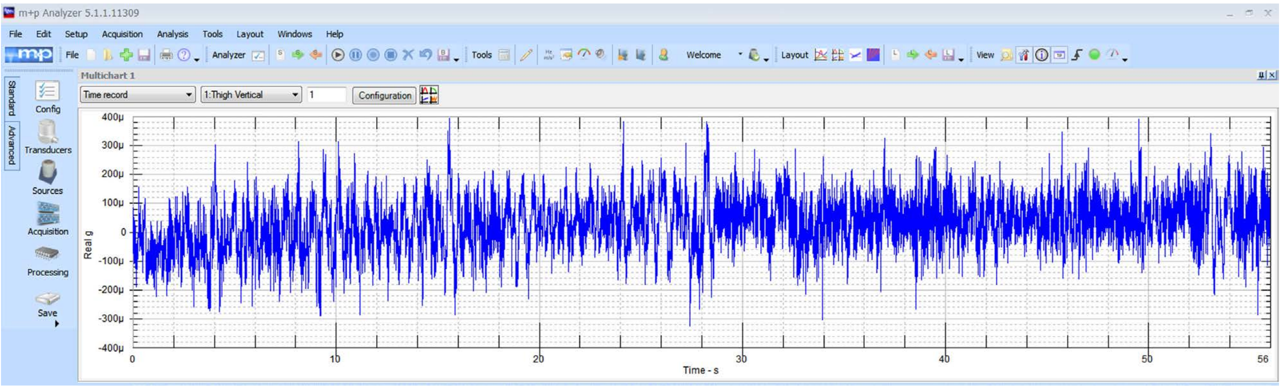
Seat segment	Average acceleration (mm/sec^2)	RMS acceleration (mm/sec^2)
Headrest	0.32	0.91
Backrest	0.45	0.54
Cushion	0.46	0.47

shown in Figure 8.

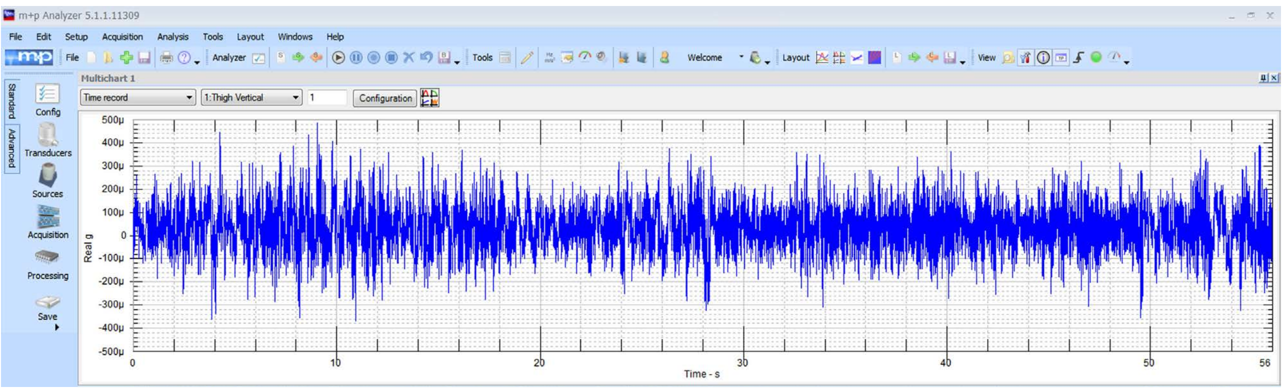
The raw testing data had collected for time period of initial 60 seconds had been curtailed to initial 10 seconds to match the simulation duration and filtered in .XLS format to get clear pictures of the testing data. The average and RMS acceleration magnitudes obtained from test data have been extracted from the graphs and shown in Table 4.



(a)



(b)



(c)

Figure 8. Testing data of vertical acceleration vs time at (a) headrest, (b) backrest, (c) cushion.

Table 4. Average and RMS accelerations of car seat segments from test data.

Seat segment	Average acceleration (mm/sec^2)	RMS acceleration (mm/sec^2)
Headrest	0.02	0.17
Backrest	−0.03	0.16
Cushion	0.04	0.22

Later both the simulation results and testing data were merged into single graphical plot areas for comparison purpose and represented in **Figures 9-11**.

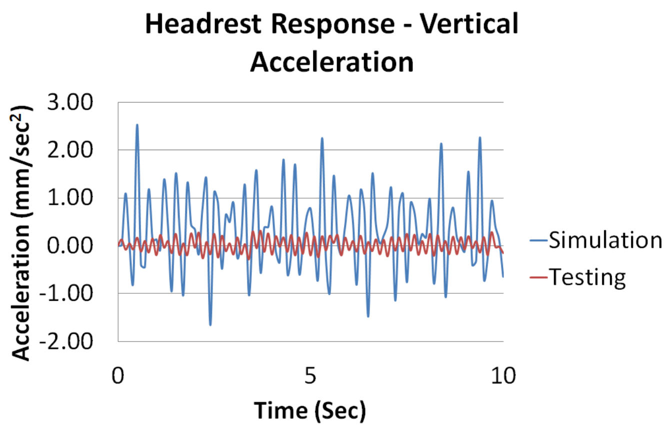


Figure 9. Vertical accelerations of headrest from simulation and testing.

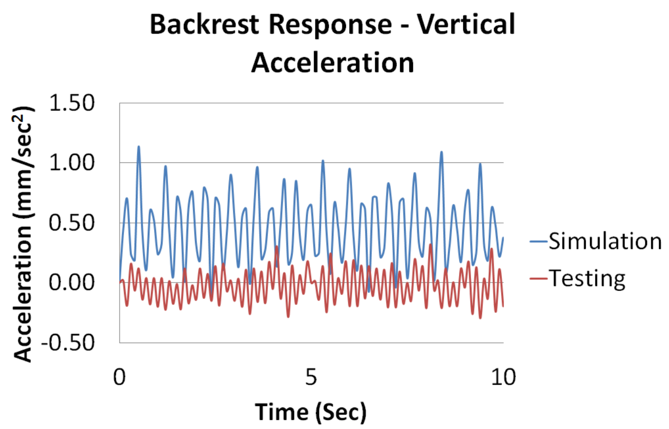


Figure 10. Vertical accelerations of backrest from simulation and testing.

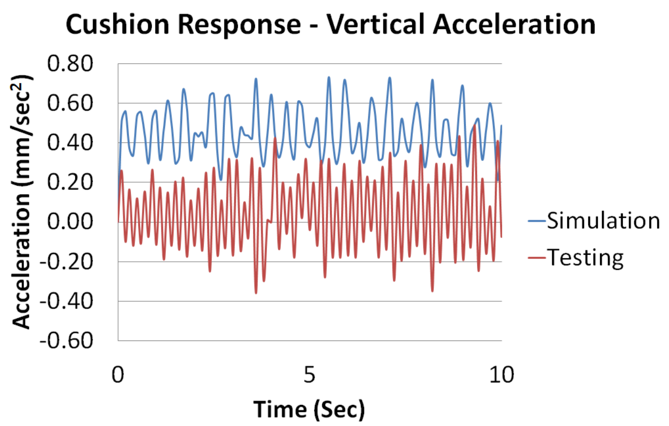


Figure 11. Vertical accelerations of cushion from simulation and testing.

Figure 9 is showing the accelerations of the seat cushion, where both the upper and lower peaks of testing data are well below the respective peaks of simulation results. Figure 10 and Figure 11 are showing the accelerations of headrest and backrest, respectively, where upper limits of simulation results are exceeding the respective limits of testing data and lower limits of simulation results are well below those of testing data. If the absolute accelerations are considered irrespective of the positive and negative magnitudes of the acceleration values, almost all the simulation results are higher than the testing data, hence, the outputs received from computerized simulation are more conservative in nature.

Deformation mechanism of polyurethane foam structure is a very complex phenomenon where numerous factors are associated and each one of these factors is capable of manipulating the behaviour of foam structure on its own. Type of seat, configuration of seating arrangement, car class, road terrain, time span of acceleration, foam material properties etc. all can be defining parameters for maneuvering the final output from simulation and testing. This fact confirms that the deviations between the simulation results and testing data are inevitable. Moreover, the testing data had been gathered from a car being driven by a real human, while this piece of simulation work considered the loadings coming from virtual human object.

The variations similar to this project task, had been observed in many past research works for automobile and seat related investigations. Vibration transmissions and accelerations were found to be varied with respect to different sitting postures [31] [32] [33] while studies on vibration transmission [34] [35] showed a small alteration in the posture could greatly amend the transfer function and frequency response of the car seated arrangement. Same human body had been used for a number of times in identical test set up [36] and each time the vibration related outputs were different.

The vertical acceleration in the simulation can further be lowered by applying potential remedies as outlined in past relevant literatures on vibration transmission [34] [35] [36] [37]. The vertical acceleration values received from the finite element simulation of this project work are of higher magnitudes than the test data, hence, this simulation set up is useful to optimize the health, comfort and safety levels in worst case scenario. The simulation using both the hyperelastic and viscoelastic materials is able to provide the flawless desired output.

5. Conclusions and Scopes of Further Development

In this research paper, a finite element simulation methodology has been offered to anticipate the final level of vibration by monitoring vertical accelerations at different locations of car seat. From the results of this analysis, the following conclusions can be drawn:

1) This finite element simulation method can be implemented efficiently to the car seat structure to predict the final levels of acceleration responses at different segments. In this simulation set up of car seat, load conditions due to acceleration and human mass along with hyperelastic and viscoelastic material properties have been incorporated. In contrast, in the real life measurement process numerous operating parameters are associated and gathered experimen-

tal data are hugely dependent on the instrument used and its signal processing systems. The basic philosophy behind the vibration measurement system is based on the signal transfer function defined by Laplace domain, where a small alteration in any of the input parameters can tune the final level of vibration to a great extent. So, the mismatches between the test data and simulation output are evident. As the simulation results are more conservative in nature, it can be stated that this simulation technique on car seat using hyperelastic and viscoelastic materials is successful to anticipate the vertical vibrational effect on car seat by means of monitoring acceleration, regardless of the reasonable amount of mismatches between the simulation outputs and testing data.

2) Car seat polyurethane foam can be formulated in computerized simulation by the combination of hyperelastic and viscoelastic materials to run an effective analysis. Assignment of Ogden coefficients for hyperelastic materials and time dependent shear modulus coefficients for viscoelastic materials can lead the simulation to yield necessary outputs.

3) This simulation process is able to predict the acceleration responses inside car seat portions in a sensible way. More advanced research works on the foam material properties are necessary to lower the peak values of accelerations. Numerous combinations of different parameters can be chosen to conduct the simulation and the accurateness of the output will be enhanced with the increment in the number of allocated input parameters.

Enormous potential for further improvement is there to take this emerging simulation methodology to advanced stage. Firstly, a longer finite element simulation running time will inevitably help to obtain enhanced acceleration and frequency plots. Cause of the limitation in computer capability, simulation running time was restricted to 10 seconds during this course of analysis work. Highly configured computer hardware will definitely be beneficial to perform analysis faster and for a longer period of time. Observation on the frequency response plots from this simulation work found that the frequency values are gradually getting stabilized and lowered over the time, hence, longer simulation operating time will eventually display lower ranges of frequencies for the driver human and car seat portions. In case of association of road terrain, non-racer type of automotive and accidental case scenario, it is highly recommended to run the simulation at least for 60 seconds. Secondly, stiffness data can be calculated in a more precise way by subdividing the human segments into smaller portions and viscoelastic coefficients for the time dependent shear modulus function can be introduced along with hyper-elastic material. The frequency response curves received from this simulation are getting steady over time, thus showing the effect of stiffness, damping and hyperelastic material parameters as anticipated. More convincing frequency curves with lower magnitudes can be achieved through improved stiffness data and associated viscoelastic material properties. Thirdly, in the present analysis scenario, only the vertical vibration has been assessed at different segments of the car-driver assembly. For the completeness in understanding of the vibration related effects, it will be beneficial to take account of the fore-aft vibration by means of acceleration and displacement along the direction of vehicle movement. Comprehensive solution based on cost effective simulation process for predicting accelerations and frequencies at different points of human-car system can omit the necessity of time consuming real life vibration testing procedure.

Based on all the discussions on simulation results and validation, it can be concluded that this unique biodynamic simulation methodology in finite element environment is presenting realistic output data regardless of the fact that the magnitudes of the peak responses are out of the permissible criteria.

Therefore, this simulation technique presented in this research paper is following the right path and recommended fine-tunings on different parameters can successfully lead this technology to anticipate accurate acceleration and frequency responses of full car seat and human system.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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