Vibration in Car Seat- Occupant System: Overview and Proposal of a Novel Simulation Method

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Abstract. In the modern automotive industries, vibration levels inside the human body and the car seat are mainly validated using the on-road vehicle testing or laboratory experiment. This paper aims to propose a novel bio-dynamic simulation technique which will provide the level of vibration in term of acceleration, displacement or velocity inside the car seated human body and the car seat itself. There are many existing simulation technologies in the market to provide vibration related solution for a specific portion or sub-portion of the human-car seat system, but this proposed novel simulation method will give a complete solution for the entire human body and car seat assembly inside an automotive structure under real life operating condition without conducting any real experiment and testing. Accomplishment of this project will take the existing technology to an advanced level to assess the dynamic interaction between the automotive seat and human mass and help to understand the effect of vibration in a more clear way by judging the three directional stiffness and damping values, mode shapes, random vibration, power spectrum, resonance frequencies and vibration transmission. This research will help to predict the final vibration data at different locations of the human and automotive seat, thus will try to fill up the gap in the latest technologies and omit the necessity of the expensive and robust experimental methods. A cutting edge technology will be achieved by this unique bio-dynamic simulation technique to understand the effect and estimation of level of vibration inside the car seat and its occupant.

Keywords—simulation; bio-dynamics; human body vibration; automotive seat vibration; car; seat; human; vibration; simulation; stiffness; damping; modal analysis; natural frequency; finite element

INTRODUCTION

Automotive vehicles are the primary medium of transportation in the world and should consider the highest levels of safety and comfort for the occupants. The health and safety of the drivers and passengers inside an automotive structure can be judged by studying the dynamic interaction between the occupants and moving automotive. Dynamic investigations are very common in the modern various transportation industries like railways, naval, aviation and automobile sectors, where the moving structure and its occupants are exposed to unwanted vibration. The basic intention of investigation is to judge and reduce the level of vibration by designing the system or sub-system in the extreme operating conditions.

Unwanted vibration inside the automotive structures is produced by the uncontrolled and random excitation which can cause the resonance and large displacement on the automotive car seat and occupant human bodies. Dynamic simulation analysis of the car seat and human body is known a very complex and non-linear phenomenon and hence, a complete evaluation of all the non-linear parameters is needed to carry out an effective simulation to estimate level of vibration inside human body and car seat. This research work will put the effort to characterize and optimize the most important factors required for the analysis of the human body-car seat assembly, establish a computerized simulation model in finite element for the entire car seat and human body and finally to estimate the acceleration, velocity or displacement values along with a comparison to the real life experimental data.

There are many existing technologies which can judge the level of vibration inside the human body seated on a car seat, though these technologies offer the solutions only to a small segment of the entire human-car seat assembly. Furthermore, most of these technologies don't consider the real life factors like car speed, car acceleration, seat properties, three dimensional stiffness values for the human segments, human bone and muscle properties, human postures etc. So, main focus will be to establish a non-linear bio-dynamic simulation model of a car seated human based on the anthropometric data and a car seat made of polyurethane foam material to evaluate the vibrations at different locations of the structure and avoid the laborious and costly testing procedure.

THE EXISTING TECHNOLOGIES: OVERVIEW

Mathematical Model and Computer based Simulation

For past many years, vibration and its effects in different parts of human body and automotive seat have been getting assessed, measured, monitored and characterized by both the mathematical model and the numerical simulation. Full vehicle study using finite element tool ABAQUS (Hellman, 2008) concluded that cause of the high costs associated with the production of a new vehicle, the computerized simulation methods are gaining more and more importance during the design process of the automotive structures.

Numerical algorithm along with multiple Degrees of Freedom (DOF) theory was applied during the biodynamic study of the car seated human using one number of seven DOF model and two numbers of four DOF models (Abbas *et al.*, 2010) to understand the vibration transmissibility.

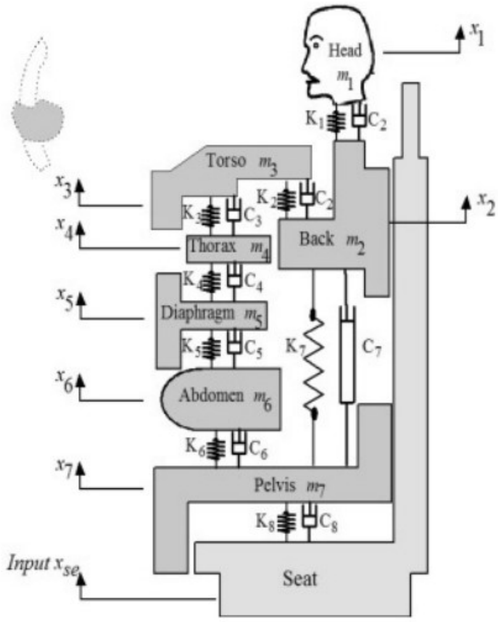
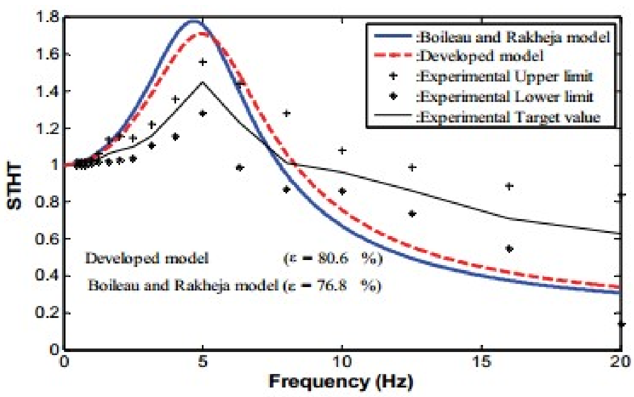


FIGURE 1. Developed simulation model with seven degrees of freedom (Abbas *et al.*, 2010)

The same study considered some optimized parameter values for the simulation like stiffnesses, frequencies, damping coefficients etc. mainly for the response due to vertical vibration and recommended that consideration of full vehicle body would be beneficial for finding more accurate resonance frequency of the system.



Mass (kg)	Damping coefficient (N.s/m)		Spring constant (N/m)	
	Before	After	Before	After
m_1 = 5.31	c_1 = 400	c_1 =460	k_1 = 310000	k_1 = 356370
m_2 = 28.49	c_2 = 4750	c_2 =5400	k_2 = 183000	k_2 = 208570
m_3 = 8.62	c_3 = 4585	c_3 =5190	k_3 = 162800	k_3 = 187110
m_4 = 12.78	c_4 = 2064	c_4 =2370	k_4 = 90000	k_4 = 103480

FIGURE 2. Optimized parameters for human-seat response under vertical vibration (Abbas *et al.*, 2010)

Damping coefficients and damping ratios were co-related while investigating vibration inside one fourth of a car model (Thite, 2012) using Maxwell's vibration and concept of lumped mass parameter method. The investigation made a comparative study using different combinations of stiffness and damping and concluded that the use of series stiffness would help to reduce the damping inside the vehicle.

Kinematics of the car seat under pre-stressed condition was considered along with the contact between the car seat and human occupant (Williamson, 2005) and the results showed that a bio-dynamic simulation to be successful, highest priority to be given to establish the accurate contact mechanism between the mating parts. Vibration distribution was found to be the most serious problem while establishing a relationship (Burdzik and Konieczny, 2014) between acceleration and vibration parameters at the different locations of a car. Numerical model was developed for understanding the vibration transmissibilities of the car seat and human occupant (Mansfeld and Griffin, 2000) which made a conclusion that magnitude of the vibration would increase while lowering the frequency value. Investigation on the resonating frequency for a car seat in vibration (Batt, 2013) exhibited that the energy dissipation in an automotive car seat mainly happened cause of the movement of the upper platen and not all kinds of car seats were suitable for absorbing that energy at the level of primary natural frequency. Human body movement and seating posture were given the highest importance in the bio-dynamic simulation (Kitazaki and Griffin, 1998) and stated that without determining those two parameters, the forces responsible for creating vibration could not be well estimated. The same research group carried out a modal analysis of the human body on a seat for first seven modes up to the frequency value of 10 Hz (Kitazaki and Griffin, 1997) where the human spine was made of rigid elements and the inter-vertebral discs were constructed by deformable bodies. That study showed the variable pressure distribution between the human thigh and car seat with respect to different sitting postures.

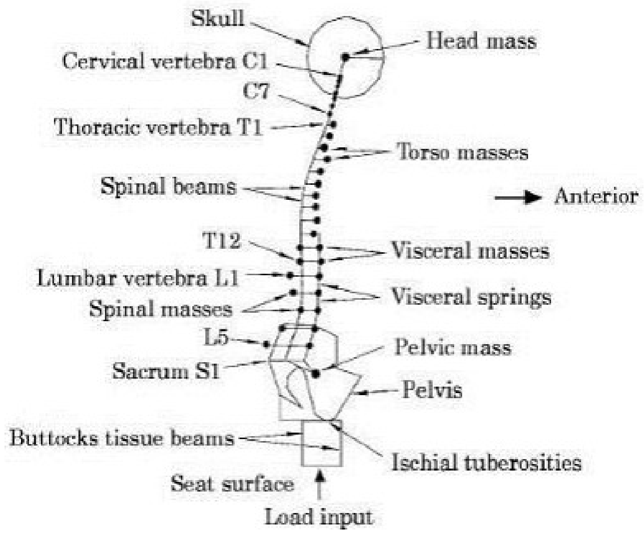


FIGURE 3. Simulation for finding mode shapes of human body in car seated condition (Kitazaki and Griffin, 1997)

Natural frequencies of the human spinal segments were investigated using finite element (Guo *et al.*, 2011) and found that the amplitudes of vibration are different at different locations of a certain human segment. Similar type of conclusions were made by the studies on bio-dynamics of human lumbar (Kasra *et al.*, 1992) joint and finding the nature of vibration (Goel *et al.*, 1994).

A computer simulation using finite element method was developed for the contact interaction between the car seat and seated human body (Tang *et al.*, 2010), which determined the positions of the minimum and maximum levels of vibrations at the contact interface surface between occupant human body and car seat. That simulation model was effective during the design process of an automotive structure for reducing the vibration transmission. But the entire simulation was based on two dimensional environment and could be taken to advanced level by considering three dimensional environment.

Analysis for the car bonnet under harmonic excitation using finite element tool was conducted (Nesaragi *et al.*, 2014) in-between the frequency of 1 Hz and 100 Hz, considering the engine was in ideal condition operating at 1000 rpm. The simulation stated the bonnet frequency as 20 Hz, which was well distant from the engine frequency of 16 Hz. Vibration transmission inside the car engine components was simulated (Fang, 2013) using stiffness and damping co-efficient parameters were selected from engineering databse, which concluded that the positions of the sensors for vibration measurement would play important parts for judging the level of vibration inside the engine.

Vibration Measurement: Testing and Experiment

The simulation and numerical techniques are based on the theoretical perception with the limitations in many areas and this is the reason why besides the computer simulations and mathematical models, techniques for vibration measurement also play vital roles for assessing and monitoring the vibration characteristics.

The significance of the practical vibration measurement for the car seat and occupant system was described (Ittianuwat *et al.*, 2014) in compliance with the international vibration measuring standard ISO 2631-1 (1997). The mode shapes and natural frequencies were considered at different positions of the car seat while the vibration parameters were measured.

Vibration is usually measured by mounting the sensors at the central location of the automotive seat, though, the data received from the central location of the car seat is not accurate to measure the vibration transmission to the human body from automotive seat. Relevant study (Tamaoki *et al.*, 2012) found that the vibration measurement data obtained from the seat central position are greatly relying on the natural frequencies in the range between 1 Hz and 10 Hz. While characterizing the structural dynamics for human- car seat system (Lo *et al.*, 2013), the same idea got supported strongly when the coupling of the car seat and human body occurred in the frequency range between 10 Hz and 50 Hz and three numbers of natural frequencies with three mode shapes were found below 80 Hz. Another similar experiment (Cho and Yoon, 2001) on the human body and car seat system showed that for all the transmissibilities the fundamental mode shape was occurring at 4.2 Hz, while for the transmissibility of the human head two mode shapes appeared at 4.2 Hz and 7.7 Hz.

For the investigation of the in-vehicle transmission (Qiu and Griffin, 2004), a car model (V817 LAR, Zetec, Ford) was considered at a speed between 35 miles/ hour and 45 miles/ hour maintaining at fourth gear. Two masses of 70 kg and 80 kg were taken into account and the primary peak for the transmissibility appeared in-between 4Hz and 5Hz. The investigation further concluded that a single output – single input experimental model would be effective for measuring vertical vibration, though might not be effective for measuring the horizontal vibration.

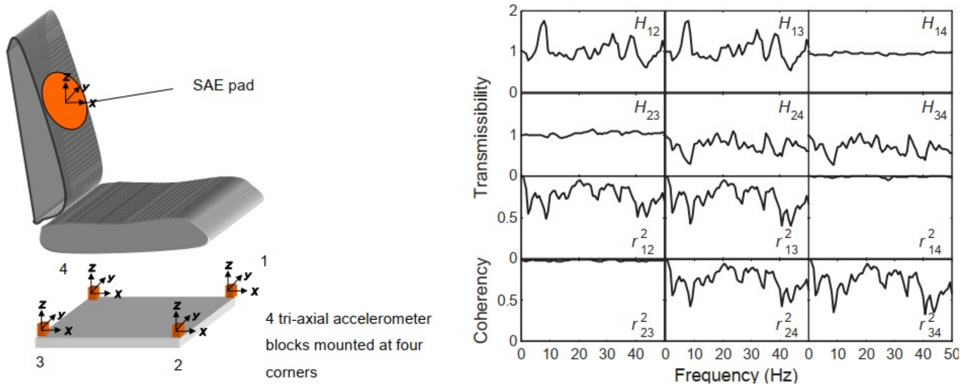


FIGURE 4. Accelerometers on automotive seat and frequency responses (Qui and Griffin, 2004)

Transmissibility level for the car seated human changes with the adjustment of vertical position of human body and this fact was proved by the experiments on nonlinearity transmissibility of human body in vertical direction (Tufano and Griffin, 2012) and fore-aft transmissibility of car backrests (Jalil and Griffin, 2007).

Testing on human body seated on a car seat was conducted using multi-degrees of freedom human-car system (Cho and Yoon, 2001) and gave a useful data table of estimated stiffness and damping values with some associated tolerances.

TABLE 1. Estimated stiffness and damping values of multiple degrees of freedom model (Cho and Yoon, 2001)

Mass (kg), inertia (kg m^2)		Stiffness (kN/m)		Damping (N s/m)	
m_1	15.3 ± 2.5	k_{v1}	72.0 ± 25.3	c_{v1}	29.4 ± 14.4
m_2	36.0 ± 6.0	k_{h1}	46.3 ± 10.9	c_{h1}	447.0 ± 167.1
m_3	5.5 ± 0.9	k_{v2}	2.3 ± 0.8	c_{v2}	0.4 ± 0.8
I_1	0.90 ± 0.20	k_{h2}	20.2 ± 7.1	c_{h2}	446.0 ± 165.4
I_2	1.10 ± 0.25	k_{t1}	17.2 ± 4.6	c_{t1}	380.6 ± 77.5
I_3	0.03 ± 0.00	k_{t2}	25.0 ± 18.4	c_{t2}	182.1 ± 40.1
		k_{r1}	0.0 ± 0.0	c_{r1}	2576.5 ± 1006.4
		k_{r2}	0.1 ± 0.0	c_{r2}	1.3 ± 1.7

A shaker table, rigid seat, real human body and Kistler 3803A/2G sensor were used (Verver, 2004) in the laboratory for understanding the resonating behaviour of the human-car seat system. The experiment was repeated using a standard car seat later. That study did not find any natural frequency below 15 Hz.

(a) Rigid seat *(b) Standard car seat*

FIGURE 5. Experiment for resonance in human body and power spectral response (Verver, 2004)

To provide a low cost on-road testing method, a Skoda sedan car model, accelerometer and computer with data acquisition system had been used (Stein *et al.*, 2011). The test data were obtained successfully without any special instruments, though the procedure didn't follow the vibration standard ISO 8041. Similar kind of testing was carried out (Lakušić *et al.*, 2011) on the vehicle chassis and wheel to find out the vibration in terms of velocity.

FIGURE 6. On-road practical and low cost vibration measurement (Stein *et al.*, 2011)

Combined Simulation and Vibration Measurement

The numbers of researches carried out for both the simulation and measurement for the vibration assessment inside human body and car seat are very less. Only few of the past works conducted comprehensive simulation and laboratory measurement studies together, though those research works mainly focussed on a very specific area or portion of human-car seat system without doing real life measurement.

Car seating and human comfort were analysed using finite element simulation (Verver, 2004) considering the seat foam properties and human body stiffness and damping values. The simulation considered different thicknesses of the car seat and human bodies and made a conclusion that the level of acceleration transmission greatly dependant on the human body posture and car seat material type. Standard for seating pressure ISO 2631 was not taken into account and the seat was made without the frame and springs. It was recommended to use multi-body simulation tool for more accurate vertical vibration monitoring. The simulation was validated later by the results from laboratory experiments. Similar simulation in finite element on the seating dynamics (Zhang, 2014) considered the human segmental stiffness, human segmental damping and seat cushion material properties to estimate the car seat transmissibility. The study arranged an experimental set up for validating simulation and concluded that the vibration transmission in the vertical direction would be affected by the thickness of the car seat.

Vibration measurement for the entire human body in car seated position (Ruetzel and Woelfel, 2005) took two sample human bodies with masses 50kg and 95kg and established the relationship between human mass, damping and frequency. Later, a finite element simulation model was set up for the same arrangement and comparison made between test data and simulation results.

PROPOSAL OF NOVEL SIMULATION PRACTICE AND ASSOCIATED METHODOLOGY

A novel simulation technique is outlined here for the entire car seat and human body. A flowchart for the relevant processes involved, is shown here.

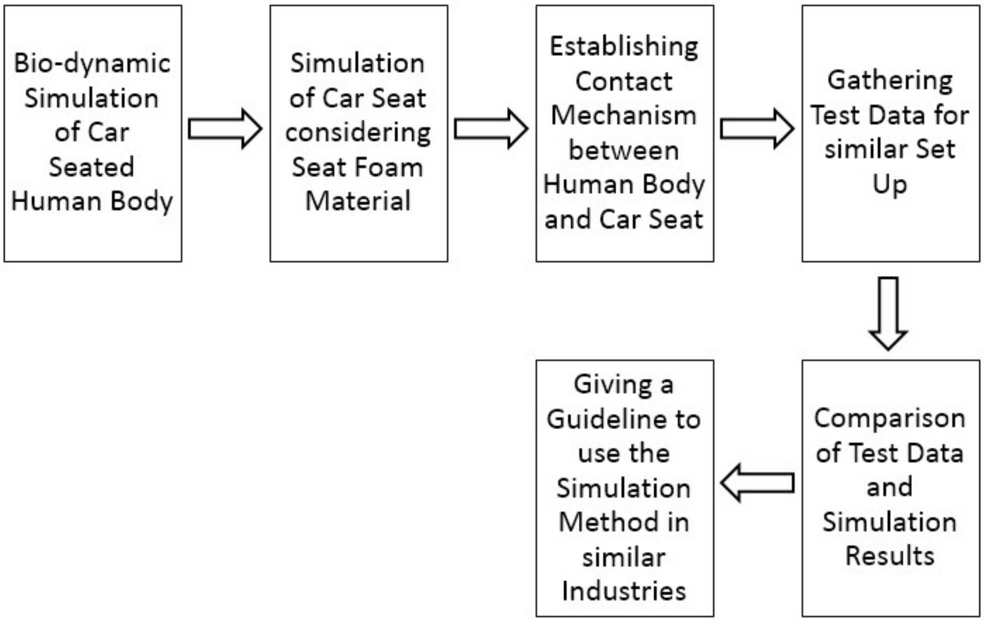


FIGURE 7. Methodology of Research Study

Bio-dynamic response for the human body under the effect of vibration can be simulated through lumped mass parameters, finite element environment or multi-body dynamics. Classic mathematical model is the most appropriate way for evaluating the effects of vibration inside any dynamic structure. Portions or sub-portions can be isolated from rest of the system and equations of motion under forced or free vibration can be set up. From the set of the equations, through the repetitive iteration process, the mode shapes and natural frequencies can be found and an overall judgement on the system can be concluded. This mathematical model is time consuming and has got limitation cause of human capability, hence, computerized simulation tools like ABAQUS or ANSYS can be used for a rapid results related to mode shapes and natural frequencies. Efforts will be made to explore the different techniques using lumped mass, finite element and multi-body dynamics methods. The best option will be chosen for this research work and the three dimensional stiffness and damping values will be calculated based on the real human shapes and sizes. Anthropometric data table and the information from the vibration testing laboratory will be consulted as well before finalising the posture and other input parameters. The simulation will be carried out using ABAQUS.

Understanding the behaviour of the car seat material is an important factor for the effective simulation process. Car seats are made of polyurethane foam material which exhibit non-linear behaviour and can be constructed with elastic, hyper-elastic or viscoelastic material models. Efforts will be made to combine both the hyper-elastic or viscoelastic material properties, though depending on the computer capability to solve non-linear problem within justified time limit, some properties of the non-linear material may be curtailed.

Once the human body and car seat simulations are built up, next stage will be to establish the contact between all the necessary mating areas. Human bone, human muscle and seat foam are having non-linear material properties and addition of contact mechanism into the entire system will make the simulation more complex. Careful consideration will be required while selecting the contact interfaces for ease in contact formulations.

The last stage of the simulation method will be to impose the real life driving conditions to the entire human-car seat assembly. Based on the limitations of the software and hardware capabilities, the simulation running time to be optimized. The desired results will be frequency and vertical acceleration with respect to time. In the modern industries power spectrum densities with respect to frequency are more popular for monitoring the vibration inside a dynamic structure. So, effort will be made to plot the power spectrum for the human body and car seat at different locations.

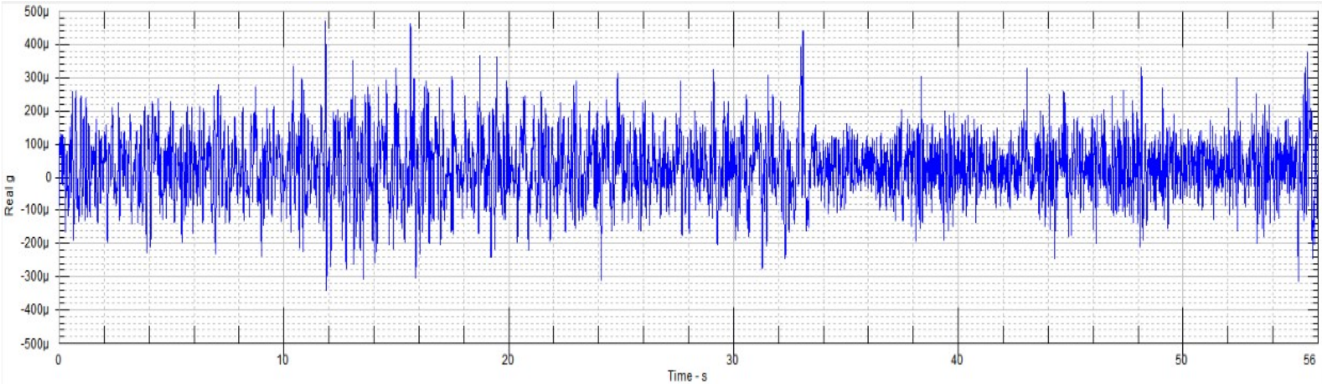


FIGURE 8. Potential output from the simulation (Frequency vs Time)

In the next stage, data from the real life human- car seat testing will be gathered and the simulation results will be compared to the testing data. The estimated input and out parameters from the automotive testing are summarized next.

TABLE 2. Potential Testing Input and Output Parameters

Speed of the vehicle	Around 35miles /hour
Human body weight	In-between 70 kg and 80kg
Desired output	Frequency and Acceleration Vs time
Time span	To be decided. Expected not more than 60 seconds
Expected positions of the sensors to be mounted	Occupant body- • Foot • Leg/ Lower Leg • Thigh/ Upper Leg • Waist/ Pelvis • Head • Hand • Chest • Upper Arms • Lower Arms
	Automotive Seat- • Cushion • Headrest • Backrest

Once all the simulation and testing data are gathered, a matrix based comparison model will be established. A detailed technical instruction will be prepared which will guide the transportation industries how to implement this simulation method for their specific seat-occupant system under specific operating environment.

CONCLUSIONS

Many simulation and experimental technologies are existing in the market for providing the solutions related to vibration of dynamic structures, though there is a huge gap among those technologies to provide solution to predict the level of vibration inside whole human-car seat system without carrying out real life vibration measurement

This paper proposes a unique simulation method to evaluate the level of vibration inside the car seated human body and car seat itself without carrying out any hands-on testing. This novel technique will provide the solution for the entire human- car seat system rather than only for a very specific module. This research will fill the gaps in the latest technologies and remove the requirements of the costly time consuming vibration measurement methods.

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