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Evaluation of Acoustic Performance of Automotive Seats by Experimental and Simulation Techniques

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ABSTRACT

Automotive seats play a vital role for improving the overall sound absorption inside the vehicle. To understand the acoustic performance of automotive seats in the passenger compartment of a vehicle, various types of seat assemblies were tested by the reverberation chamber method as per ASTM C423. The methodology has been developed to test the seats based on seats position in the chamber and minimum requirement of seats to evaluate the accurate sound absorption and Reverberation Time (RT). The effect of various seat cover materials like leather and cloth fabrics on the seat sound absorption and RT has been determined experimentally. Study of various cover materials (leather/vinyl and cloth fabrics) with PU foam for sound absorption characteristics has been carried out using simulation technique. The intrinsic parameters used as inputs in above steps are evaluated using specialized test rigs. The complex sound speed, propagation constant and surface impedance characteristics are predicted for a typical multilayer seat configuration. Further Sound absorption is predicted and compared with impedance tube results to validate the predicted parameters. Finally effect of various seat configurations on operator ear Sound Pressure Levels (SPL) at driver/passenger ear location inside a typical car cabin studied using Boundary Element Method (BEM) simulation.

Keywords: *Sound Absorption, Reverberation Time, Seats, Noise Reduction.*

INTRODUCTION

Automotive components like floor carpets, headliner, hood liner, seats are important sources for absorption of sound and overall noise reduction inside vehicle. Hence study of absorption and noise reduction due to these components is essential from design aspect of vehicle. For typical vehicles seats contribute more than 50% of absorption as compared other sound package components [1]. For a porous material to absorb sound, the thickness of the material must be large relative to the wavelength of the sound. Typically, the thickness needs to be 1/4 of the wavelength to achieve effective absorption. This requirement makes the seats the major noise absorbing components. To optimize the performance of seats essential parameters are seat fabrics/leathers, foams types used in cushions etc. [2]. A seat cover is typically a laminate (i.e., face material bonded to slab foam). Face materials range from textiles to leather and vinyl. Test results show that textiles are drastically different from leather and vinyl in noise absorption. To check the overall performance of seats, the random incidence sound absorption test in reverberation room was carried as per ASTM C423 on different types of seats assemblies with different configurations [3]. Simulation of fabric/Leather seats material was carried out to predict the sound absorption of multilayer configurations of seats. The main purpose of simulation is to compare sound absorption coefficient at material level using impedance tube as per ASTM E1050 and use this strategy for overall improvement in seat absorption [4]. Further, FEA analysis was carried out at vehicle level using intrinsic properties of multilayer configurations of different seats to predict sound pressure level at Operator Ear Level (OEL).

OVERVIEW

1. Sound absorption testing in Reverberation chamber
2. Minimum requirement of seats – one, two and four nos.
3. Different configuration and position of seats in chamber
4. Effect of sound absorption due to fabric/leather of seats

5. Impedance tube testing and simulation of seats
6. BEM analysis to predict SPL at driver in a vehicle cabin

TEST METHODOLOGY

Sound Absorption Test in Reverberation Chamber

Reverberation chamber test method is the most appropriate test for determination of sound absorption for seats and other sound package materials such as headliners, carpets, package trays, hood insulators etc. The test was carried out in a Reverberation chamber 80 m^3. Absorption by reverberation room is calculated from reverberation time (RT_{60}) using an empirical formula. First, the amount of absorption in the empty room is calculated from the RT_{60} of the empty room. Then a seat is placed in the room and the RT_{60} is measured and the amount of absorption calculated. The difference in sound absorption of empty room and with seats yields the absorption due to the seat alone. The absorption is expressed in metric sabins, m^2. Further to calculate the absorption coefficient, absorption in metric sabins can be divided by the surface area of the sample. As per standard, minimum area requirement for testing is 4.3 m^2 for 80 m^3 chamber. The test set up consists of an omni directional source, rotating boom with a microphone, multichannel data acquisition system and a power amplifier as shown in Fig. 1.

Figure 1. Test Set Up for Measurement of Reverberation Time and Sound Absorption of Automotive Seats in Reverberation Chamber.

Minimum Requirement of Seats for Testing

Initially single, two and four seats were tested inside a reverberation chamber to arrive at the sound absorption and evaluated per seat absorption by dividing the number of seats from the overall sound absorption.

Fig. 2 shows the variation in sound absorption at low frequencies in case of single and two seats. The results arrived with four seats are more consistent also satisfies the minimum test sample requirement as per standard as well as vehicle conditions.

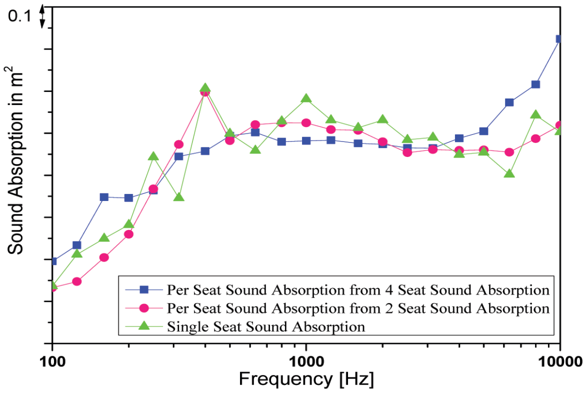

Figure 2. Comparison of Per Seat Absorption.

Different Configurations and Positions of Seats Considered in Reverberation Chamber for Testing

Two different types of seats Leather and fabric were tested for sound absorption. Seats were tested at different test locations in reverberation chamber.

Data for sound absorption for different test configurations at different test locations was compared and test position was finalized which is giving consistent results. These test configurations and positions are given in Table 1. The results are compared in Fig. 3.

Table 1. Different Test Configurations.

Configuration 1	Facing Reverberation chamber opening
Configuration 2	Facing Test opening
Configuration 3	Near to Reverberation chamber opening

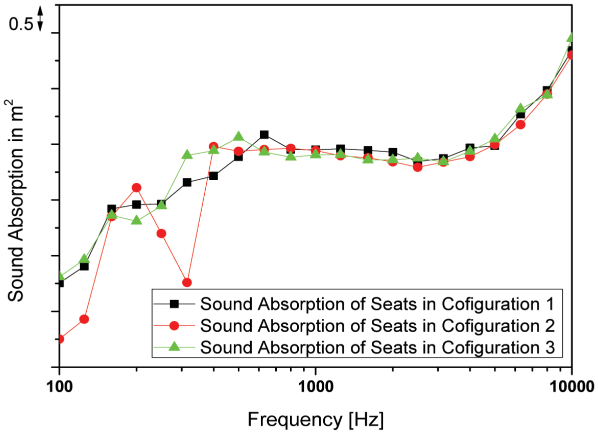

Figure 3. Effect of Different Test Positions and Configurations.

Effect of Seat Fabric/Leather on Sound Absorption

Two different types of seats with leather and fabric covers were tested in reverberation chamber. The results for leather and fabric seats are compared in Fig. 4. From this figure, it is clear that fabric seat is superior from low to high frequencies. Fabric covered seats usually perform well because they have a high porosity and allow sound to pass through to the seat cushions where the absorption is good. Leather or vinyl covered seats have very low porosity i.e. impervious film resulting in a peak of absorption in a narrow frequency range with poor absorption outside this range as they act as mass-spring system. This is the area where simulation plays a vital role in design of the seats for improvement of sound absorption.

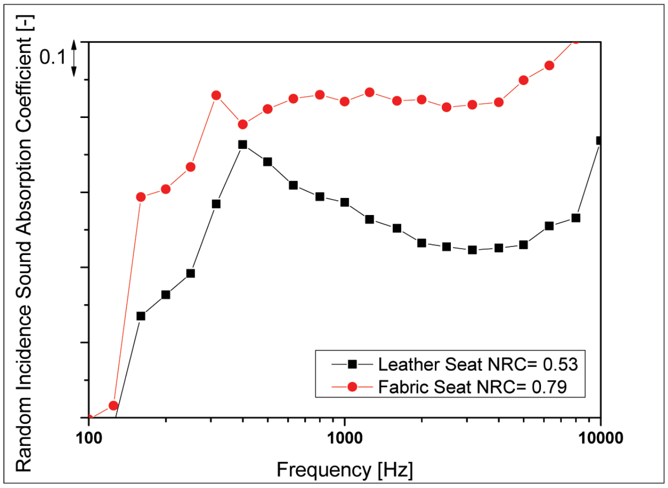

Figure 4. Comparison of Sound Absorption Coefficient for four Leather and Fabric Seats.

IMPEDANCE TUBE TESTING AND SIMULATION

Poroelastic Material Modelling

Biot's theory was originally developed for wave propagation in granular porous media and subsequently adapted for wave propagation in elastic porous sound absorbing materials. It relates the acoustical performance of the materials, typically measured in terms of absorption coefficient and transmission loss, to the intrinsic material and macroscopic intrinsic properties. It presents a powerful framework for the numerical modeling of stress waves propagating in an elastic-porous material as it explicitly accounts for the different wave types that are known to propagate in poroelastic materials.

Equivalent Fluid Model

Now considering porous material as a fluid with effective properties may be of interest in some situations and for some kinds of porous materials. Since the porous medium is considered as an equivalent fluid, Helmholtz equation becomes the governing equation. Thus, for an equivalent fluid with effective properties, one can write

$$\nabla^2 p + \omega^2 \frac{\rho_c}{K_c} p = 0 \tag{1}$$

where ρ_c and K_c are the effective properties of an equivalent fluid and this equation (1) represents the propagation of a single compressional wave through the porous medium. The wave number can be directly related to the effective density ρ_c and the effective fluid bulk modulus K_c.

The fluid effective density ρ_c in the pores is frequency dependent and also depends on five porous material macroscopic properties like porosity (ϕ), flow resistivity (σ), tortuosity (α_∞) and characteristic lengths (Λ) and (Λ'). 'These parameters are related to Johnson-Champoux-Allard (JCA) model as follows.

$$k_c = \omega\sqrt{\frac{\rho_c}{K_c}} \tag{2}$$

$$\rho_c = \rho_0 \alpha_\infty \left[1 + \frac{\sigma\phi}{j\omega\rho_0\alpha_\infty}\sqrt{\frac{4j\alpha_\infty{}^2\eta\omega}{\sigma^2\Lambda^2\phi^2}}\right] \tag{3}$$

$$K_c = \gamma P_0 \left[\frac{\gamma - (\gamma - 1)}{1 + \frac{8\eta}{j\Lambda' N_{pr}\omega\rho_0}\sqrt{1 + j\rho_0\frac{\omega N_{pr}\Lambda'}{16\eta}}}\right]^{-1} \tag{4}$$

The characteristic impedance Z_c and propagation constant k_c are predicted using the equation (3) and (4).

$$z_c = \sqrt{\rho_c K_c} \tag{5}$$

$$k_c = j\omega\left[\rho_c / K_c\right] \tag{6}$$

In this section, Transfer Matrix Method (TMM) used to predict acoustic behavior of sound package materials is explained in detail [5, 6]. The general representation for a transfer matrix of a single layer acoustic system (Fig. 5) is

$$\begin{bmatrix} P_n \\ V_n \end{bmatrix} = \left[T\right]\begin{bmatrix} P_{n+1} \\ V_{n+1} \end{bmatrix} \tag{7}$$

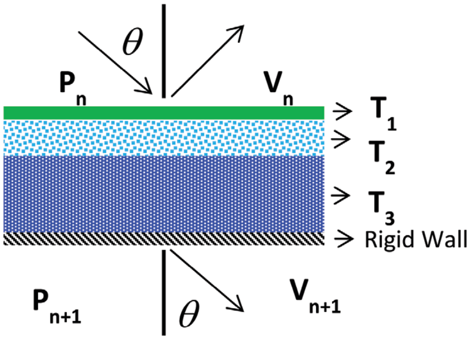

Figure 5. Schematic of Transfer Matrix.

Where P_n is sound pressure and V_n is sound velocity and T_{11}, T_{21} and T_{22} are four pole parameters or transfer matrix elements of matrix T. For multilayer configuration, the overall Transfer Matrix T, is obtained by multiplying the matrices for required configurations as follows.

$$[T]=[T_1][T_2].....[T_n] \tag{8}$$

For resistive scrims and foils, the transfer matrix is represented as

$$T_1=\begin{bmatrix}1 & Z_f\\ 0 & 1\end{bmatrix} \tag{9}$$

where Z_f is normalized impedance of scrims/foils.

For foam and fibrous materials of thickness d, the transfer matrix is given as

$$T_2=\begin{bmatrix}\cos(k_c.d) & {}^{j}\!/\!_{z_c}.\sin(k_c.d)\\ j\,z_c.\sin(k_c.d) & \cos(k_c.d)\end{bmatrix} \tag{10}$$

where Z_c and k_c are characteristic impedance and complex wave number respectively. The total impedance Z_s is given by

$$Z_s=-\,jz_c\coth\left(k_c.d\right) \tag{11}$$

When the pressure amplitudes for the incident and reflected sound waves on the surface are A and B respectively, the complex amplitudes of the pressure and particle velocity, that is, the state variables, on the surface of the acoustic system can be expressed in terms of matrix elements and the P_{n+1} and V_{n+1} for the right end plate, as follows

$$A+B=P_1=T_{11}P_{n+1}+T_{12}V_{n+1} \tag{12}$$

$$\left(A-B\right)/\rho_0c_0=V_1=T_{21}P_{n+1}+T_{22}V_{n+1} \tag{13}$$

Since the particle velocity is zero on a rigid wall, the pressure reflection coefficient $R = B/A$ can be expressed by the transfer matrix elements as

$$R=\frac{T_{11}-\rho_0c_0T_{21}}{T_{11}+\rho_0c_0T_{21}} \tag{14}$$

The normal incidence sound absorption (α) for an absorbing material with rigid backing is given by [7]

$$\alpha=1-\left|R\right|^2 \tag{15}$$

Intrinsic Parameters, Simulation and Testing

In this section, experimental techniques used to evaluate intrinsic physical parameters and acoustic parameters are discussed in detail. As discussed above, the performance of sound package materials can be predicted with prior measurement of five intrinsic physical parameters like porosity, flow resistivity, tortuosity, VCL and TCL etc. and three mechanical parameters like Young's modulus, Poisson ratio and loss factor. The experimental measurement of these parameters requires specialized test rigs like; porosity is measured using an air porosity meter based on Boyle's law [8]. Flow resistivity can be measured using flow resistivity test rig based on ASTM C522 standard [9]. Tortuosity and characteristic lengths are inverted using optimization technique based on Genetic Algorithm [10]. This technique requires prior measurement of sound absorption coefficient with surface impedance in two microphone impedance tube. Then this experimental data with porosity and flow resistivity is used to fit a mathematical model. The global solution of this optimization problem will give tortuosity and characteristic lengths. The acoustic absorption of the sound package materials is measured using a two microphone impedance tube in accordance with ASTM E1050. The test setup is shown in Fig. 6.

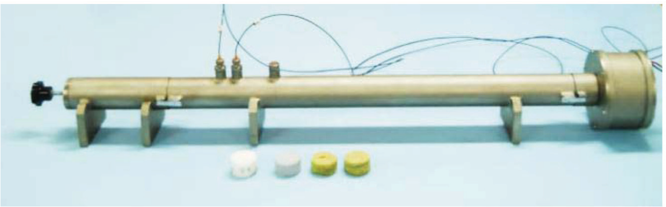

Figure 6. Impedance Tube Setup - ASTM E1050.

This method is rapid and requires only a small size sample of the material. The test uses an impedance tube with a sound source connected to one end and the test sample mounted within the tube at the other end. The specimen holder is a detachable extension of the tube and makes an airtight fit with the end of the tube opposite the sound source. Random noise is generated by a digital signal analyzer Fast Fourier Transform (FFT) and the acoustic pressure at two fixed locations close to the sample is measured using two pressure field microphones. Then applying FFT and using the complex acoustic transfer function from signals of two microphones to compute the normal incidence absorption and reflection coefficient. As discussed above, two seats with leather and fabric cushions were considered for this study. The configuration of the seats is shown below.

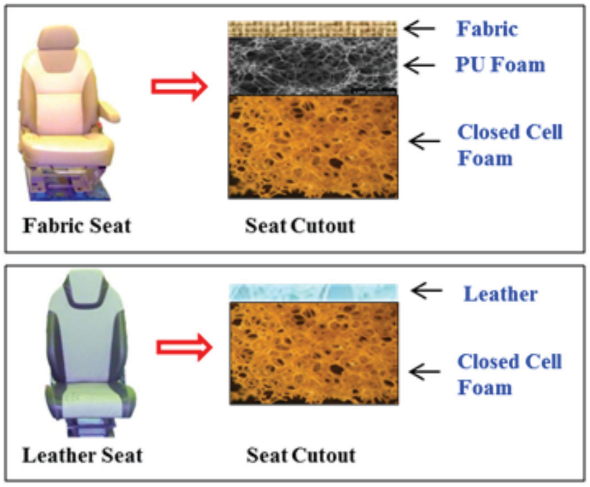

Figure 7. Fabric / Leather Seat Cutouts.

Table 2. Physical parameters of Scrim / Leather.

Physical Parameters	**Scrim**	**Leather**	**Units**
Thickness	0.6	1.5	mm
Density	10	50	kg/m^3
Flow Resistivity	50000	-	Ns/m^4

Table 3. Physical Parameters of Porous Materials.

Physical Parameters	**PU Foam**	**Closed Cell**	**Units**
Thickness	6	40	mm
Density	8.8	90	kg/m^3
Porosity	0.99	0.95	-
Flow Resistivity	17280	8510	Ns/m^4
Tortuosity	2.79	1.54	-
VCL	186	105	μm
TCL	187	105	μm

These intrinsic parameters are used in software based on transfer matrix method and sound absorption coefficient is simulated. The comparison of simulated sound absorption coefficient with experimental values is done in Fig. 8 for fabric seat. The simulation results are correlates well with experimental values till 1500 Hz for fabric seat. After that there is a significant deviation in predicted and experimental results. Fig. 9 shows comparison of predicted sound absorption coefficient with experimental results for leather seat. Here correlation is good till 2000 Hz after that there is slight variation.

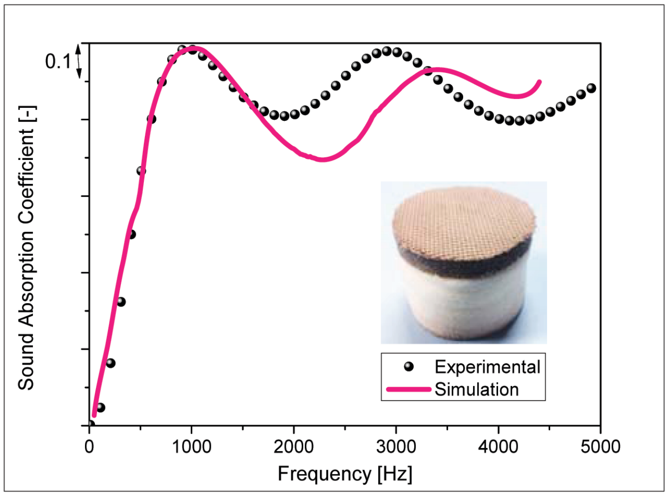

Figure 8. Comparison of Sound Absorption Coefficient for Fabric Seats-Simulation and Validation.

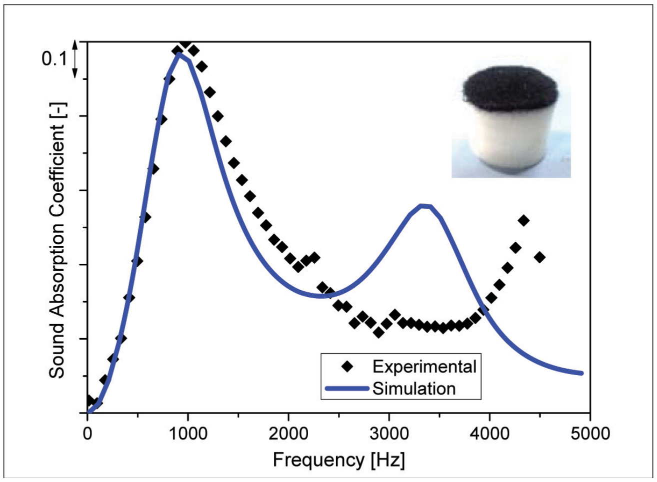

Figure 9. Comparison of Sound Absorption Coefficient for Leather Seats-Simulation and Validation.

BEM Simulation of Vehicle Cavity

A typical car cabin cavity is modeled by surface mesh of enclosing panels including seats as shown in Fig. 10. The mesh size is selected to have a maximum analysis frequency of 1400 Hz. A direct BEM analysis is carried out using commercial vibro-acoustic software. Seat absorption is modeled using surface impedance characteristics obtained in preceding section. Objective of the work is to study effect of seats alone hence rest panels are modeled without any sound absorption. A typical source excitation is given to the firewall panel replicating engine noise source. SPL is evaluated using field points located at driver/passenger ear location. As is evident from comparison of sound absorption curves of both seats (Fig. 11), fabric seat gives less SPL than leather seat (Fig. 12). Overall difference in SPL is around 1.5 dB at OEL.

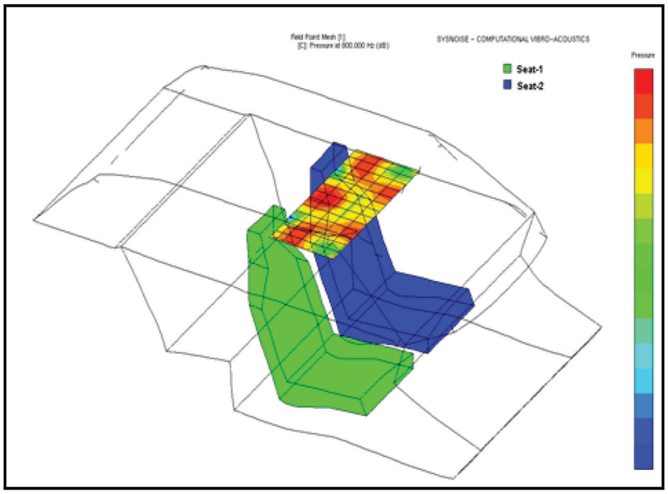

Figure 9. BEM Setup of Driver SPL Prediction.

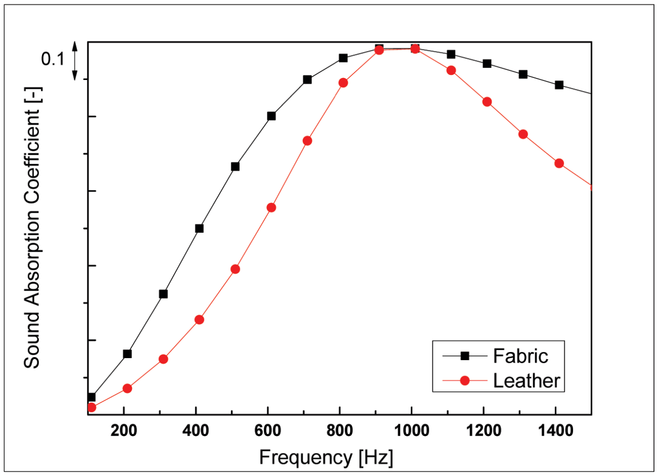

Figure 11. Comparison of Sound Absorption of Two Different Seats.

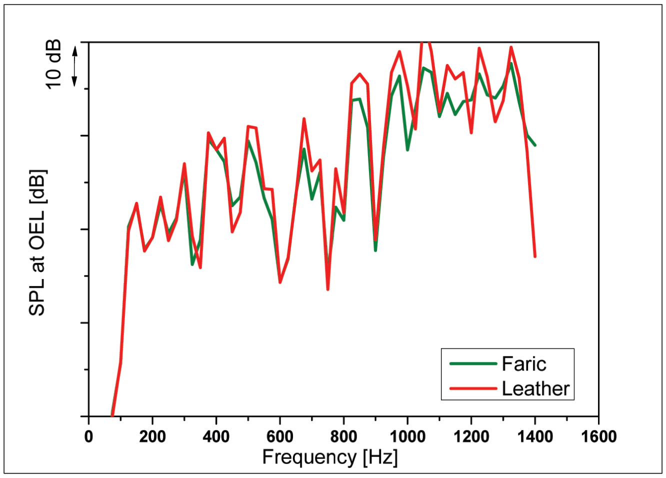

Figure 12. SPL Comparison at OEL.

CONCLUSIONS

An experimental as well as simulation study was carried out for evaluating acoustic performance of seats. In this study, it has been observed that fabric seats have superior noise absorbing capability compared to leather/vinyl seats. Fabric/cloth seats give good sound absorption at all frequency range. It is possible to tune sound absorption of leather/vinyl seats by choosing the percentage perforated area. Simulation gives a better understanding of the seat structure. It can also be used as a design tool for designing and improvement of acoustic performance of seats as well as in-cab noise prediction.

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