INVESTIGATION OF ACOUSTIC PROPERTIES OF VEHICLE COMPARTMENTS USING REDUCED-SCALE SIMPLIFIED MODELS

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1 INTRODUCTION

Vehicle interior noise has been an important problem for the car industry for at least the past four decades.[1] With many noise generation mechanisms, including structural and airborne sources, it is a very complex subject that employs a variety of modelling techniques. These include experimental techniques using excitation of sound inside cavities by means of a loudspeaker [2] or an electromagnetic shaker.[3,4] Finite Element Analysis and Trefftz-based method are being used widely to predict acoustic responses of both regular and irregular cavities.[5,6] In spite of noticeable progress, there is still insufficient understanding of the acoustic resonant properties of a vehicle interior which are paramount in defining levels and frequency contents of vehicle interior noise.

The present paper investigates the acoustic resonant frequencies and the corresponding modal shapes in a quarter scale model of a generic five-door saloon. As a first step, a simple rectangular cavity is investigated using experimental techniques similar to the ones employed in References 2,3,7. A Spectrum Analyser is used to measure the frequency response and spatial patterns of the cavity via a microphone. A small speaker is placed in one corner of the cavity at an angle of 45˚ to the floor, outputting white noise at the frequency range of 100Hz – 2100Hz. The speaker is then used to output these frequencies as a single sinusoidal mode to measure the spatial distribution of the acoustic pressure. The results are compared with analytical calculations to determine errors within experimentation.

As a second step, the rectangular cavity is modified with added sides to create an octagonal cavity. Similar measurements are taken and analysed to help determine the induced irregularity on both frequency response and mode shapes of the cavity. The final modification to the cavity involves added wooden seats, giving a more realistic representation of a vehicle interior. Again this is measured and analysed using the same techniques. The results of these measurements are compared with the earlier experimental work [8] in which the authors measured the effects of added seats and noticed that the sound pressure level of the frequency response has been lowered and resonant frequencies shifted depending on the orientation of the seats.

To model the effects of trim, felt is added to the wooden interiors of all of the three above mentioned quarter scale cavities. This is to help understand the effects of different absorption materials in the cavity, of a real car interior. Measurements of the frequency response are then compared with the BIW (Body In White) cavities.

To perform theoretical analysis of the above models, Finite Element Analysis (FEA) is used, with the boundary properties of the walls set as rigid. Different mesh sizes are used to better understand the capabilities and accuracy of the FEA programs, such as Patran and Nastran software packages. The results of both frequency response and mode shapes are compared with the obtained experimental data.

Finally measurements are taken of the frequency response and mode shapes of a compartment of a real car, the Ford Fiesta. The results are compared with measurements for the model of the irregular cavity lined with felt, as this is the closest representation to a real car interior.

2 EXPERIMENTAL TECHNIQUES

A rectangular box has been made to represent the simplest quarter scale model of a car interior, with the dimensions 0.55 x 0.35 x 0.25m^3 (see Figure 1). The model was made out of 12mm thick wood, thus simulating rigid wall conditions. The top section of the model has been made with a sliding Perspex plate of 10mm thickness, which was able to move across the X plane. The rectangular box is the basic element of construction, so that other sections could be added at a later stage. A gap in the Perspex held a wooden slider, which held the microphone in a section of metal piping. The wood was able to move across Z plane, and the piping could move up and down the Y plane allowing the microphone to reach all parts of the box. A grid of 30mm squares was marked on the bottom of the box, so that the microphone could be positioned accurately. An 8Ω, 2 inch Visaton medium range speaker was used to generate the sound inside the cavity. The speaker was attached to a small section of wood at a 45º angle so that it could be positioned in the corner of the cavity, guaranteeing that the acoustic modes are excited fully.

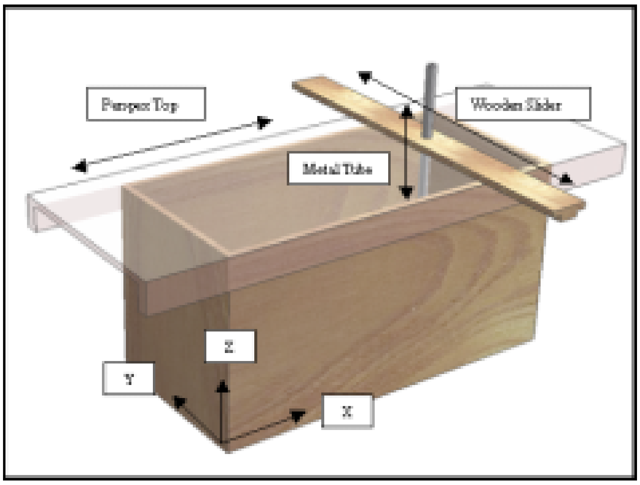

Figure 1. Diagram of the Rectangular Cavity

A HP 3566A PC Spectrum Analyser was used to measure the frequency response of the cavity. To measure frequency response of the cavity, the speaker was excited in the frequency range of 100 - 2100Hz, in 400Hz bands, so that greater accuracy could be taken. This range is within the modal region, and gives an ample supply of modes to compare with the analytical and numerical solutions. The speaker was moved in three positions, and the measurements were repeated to give an average.

The second stage of the experiment was to find the spatial distributions of acoustic pressure in the modes to compare with the analytical results. A plane across Y = 0.18m represents an approximation of the head position of the passengers in the car, so this plane was used for measurements of modal distributions of 3 modes: (1,0,0), (0,1,0) and (3,1,0). Because a single plane was being used, axial and tangential modes could be measured in the X and Y directions only. If a mode in the Z direction or if an oblique mode was required, a plane in either the X or Z direction would need to be used. The speaker was excited at the chosen resonant frequencies of the modes, according to the measurements of the initial experiment: 306Hz, 579Hz and 1093Hz respectively. The microphone was positioned on the chosen plane, and the Sound Pressure Level (SPL) was measured for every point on the grid (every 30mm^2). The results were then plotted in Matlab to give the spatial distribution of the modes.

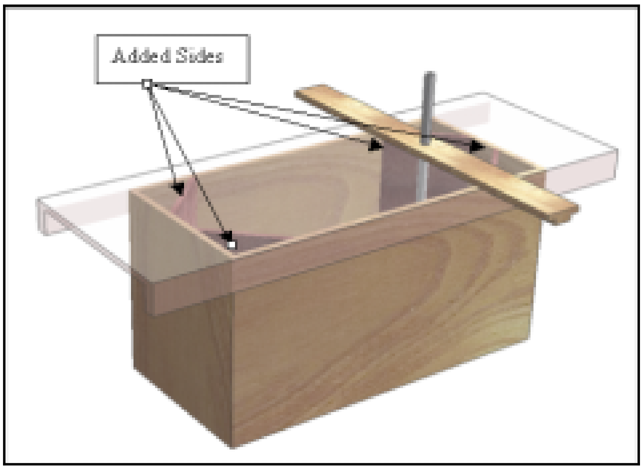

Figure 2. Diagram of Octagonal Cavity

To give a better representation of a car interior, extra sides made of 12mm wood were added to the corners of the model giving an octagonal shaped cavity, (see Figure 2). As before, the frequency response of the cavity was investigated. The first 11 modes of the cavity were measured this time (their values taken from the first 11 peaks on the graph of its frequency response).

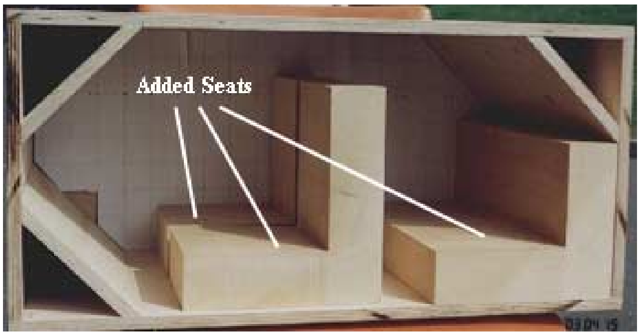

Figure 3. Irregular Cavity with Added Seats (photograph)

The final quarter scale model represented the above-mentioned octagonal cavity with added seats made out of 50mm wooden blocks. One of the sides making the octagonal cavity was taken out to give extra room in the model, (see Figure 3). As with the rectangular and octagonal cavities, the resonance frequencies and modal shapes were measured. As a section of the seats obscured part of the plane being measured, so on the spatial distribution graphs a corresponding gap was left.

3 EXPERIMENTAL RESULTS

3.1 Rectangular Cavity

The measured resonance frequencies of the rectangular cavity before alterations are reproduced in Figure 4. The comparison of the experimental results with the analytical ones, calculated according to the well known formula, shows that the resonant frequencies found in the experiment agree well with the analytical solutions for lower order modes, with an error of less than 3% for the first 8 modes. It is harder to predict which of the higher measured frequencies corresponds to a specific mode calculated analytically as the modes become denser the higher they are. In this case, the modal shapes need to be measured to confirm which particular modes are excited at measured frequencies.

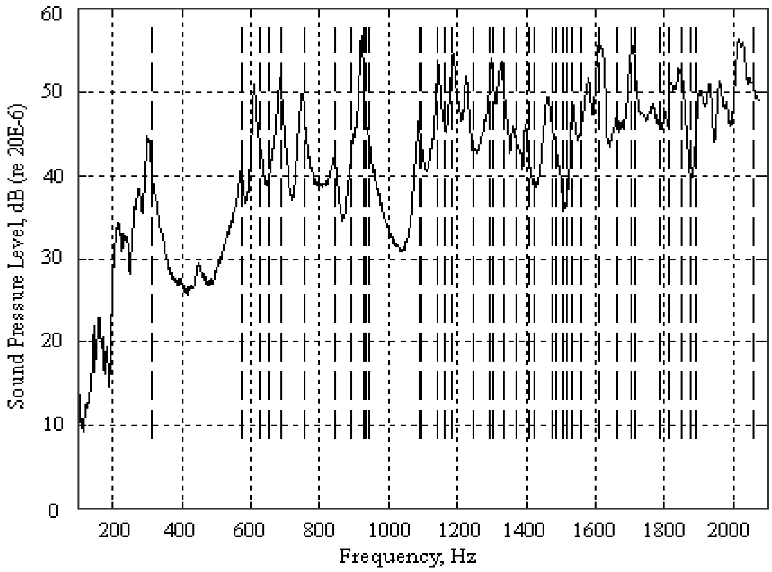

Figure 4. The measured frequency response of the rectangular cavity-vertical lines show theoretical resonant frequencies.

The sound pressure distribution was measured for 3 modes: (1,0,0), (0,1,0) and (3,1,0), to compare it with the well-known analytical solutions and to confirm their association with the measured resonant frequencies. Figure 5 shows the measured shape of the mode (1,0,0) compared with the analytical form.

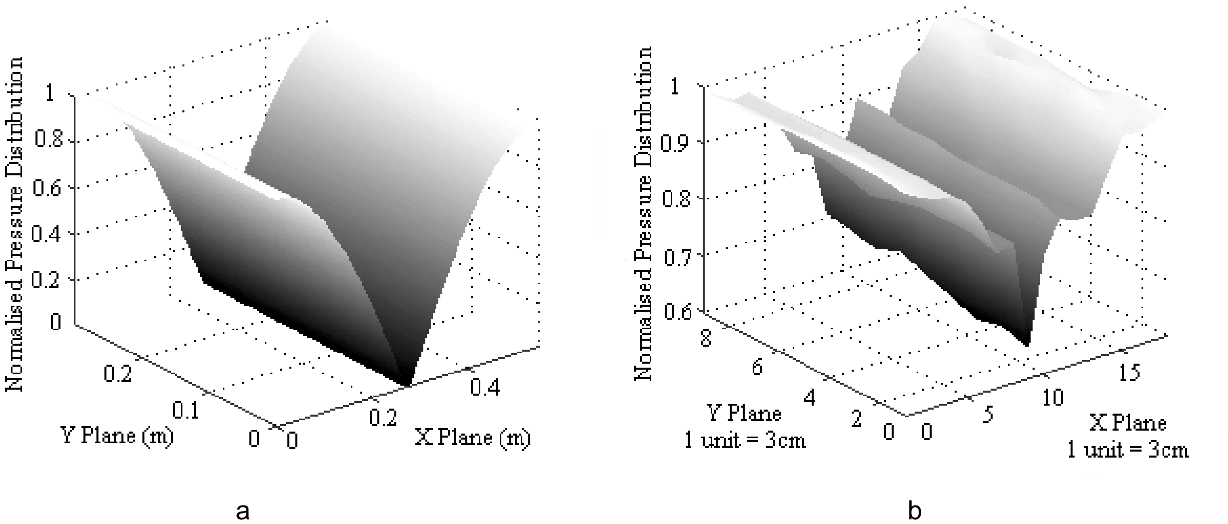

Figure 5. Sound pressure distribution in the rectangular cavity for the mode (1,0,0) at Z = 0.18m, and f = 306Hz; a – calculation according to equation (2), b – experimental

The error in the measured resonant frequencies for the rectangular cavity is small for low frequencies, with the maximum of 2.66% (2dp). These errors are within usual limits known from earlier papers on similar topics [2,8]. The errors are due to a number of factors, e.g. frequency-dependant absorption of the cavity walls, added reflections from the speaker and the microphone, temperature variations in the room, etc.

Finally the cavity would have been subjected to outside noise from the various electrical appliances used, including the Spectrum Analyser, computer and amplifiers. This sound could have shifted the resonance frequencies slightly.

3.2 Octagonal Cavity

The frequency response of the octagonal cavity was measured using the same techniques as in the previous section. The results show that in this case the peaks are less frequent and generally lower in amplitude, (see Figure 6). The sound pressure distribution was measured for the first 9 peaks of the frequency response and also for 2 frequencies, 702Hz and 967Hz, which were significant troughs on the graphs of the single speaker position. Thus, the frequencies of the chosen 11 modes were 360Hz, 578Hz, 685Hz, 702Hz, 729Hz, 881Hz, 967Hz, 1056Hz, 1128Hz, 1221Hz and 1280Hz. Two different planes of the box, the Y plane and the X plane were measured for some of the modes to determine all X, Y and Z values, because the cavity is no longer rectangular.

As one can see from , the modes of the octagonal cavity are less frequent, but have a similar average Sound Pressure Level to the original cavity. Because the box is no longer rectangular, the standard analytical equations are no longer applied, although they can still give some idea of the resonant frequencies and the shapes of the modes.

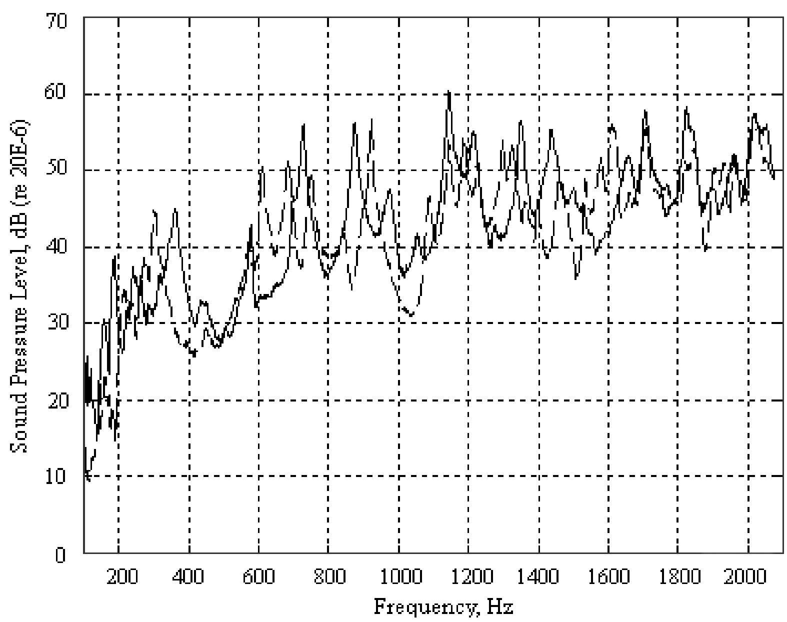

Figure 6. Comparison the frequency responses of the rectangular and octagonal cavities, dashed and solid curves respectively

3.3 Irregular Cavity with Added Seats

The third and the last type of cavity measured had added blocks of wood representing seats in the cavity, (see Figure 3) to make it more realistic to a vehicle interior. The frequency response was measured again and compared to the previous two experiments The results are shown on Figure 7. It can be seen that the peaks are similar in Sound Pressure Level at lower frequencies to the rectangular cavity, but are less frequent. At higher frequencies the peaks have reduced amplitudes and increased bandwidths, and again they are less frequent. Unfortunately for the irregular cavity it is impossible to obtain any simple classification of the modes corresponding to the measured resonant frequencies: 267Hz, 576Hz, 642Hz, 700Hz, 770Hz 870Hz, 932Hz, 942Hz, 1042Hz and 1115Hz (first ten modes have been investigated).

It can be seen from Figure 7 that the sound pressure has been reduced significantly, with results up to approximately 25dB lower than for the rectangular cavity. This is in agreements with Reference 9 that has also shown that by adding chairs to a model the sound pressure is reduced, with results of up to 15-20dB lower for a frequency range of 300-800Hz. Authors of Reference 10 concluded that the seats in a vehicle account for nearly half of its absorption. This is probably because there is a greater area of absorption and reflection from the added blocks of wood and the previously added sides of the cavity. It can also be seen that the resonant frequencies have generally been shifted lower than the results measured for the empty cavity. The results presented here are again in close agreement with previous works. [9,11] As was suggested in Reference 11, this phenomenon might be due to an increase in the effective length of the cavity due to the presence of seats. It was also noticed [9] that seat positions had an effect on these resonant frequencies, but this area was not investigated here.

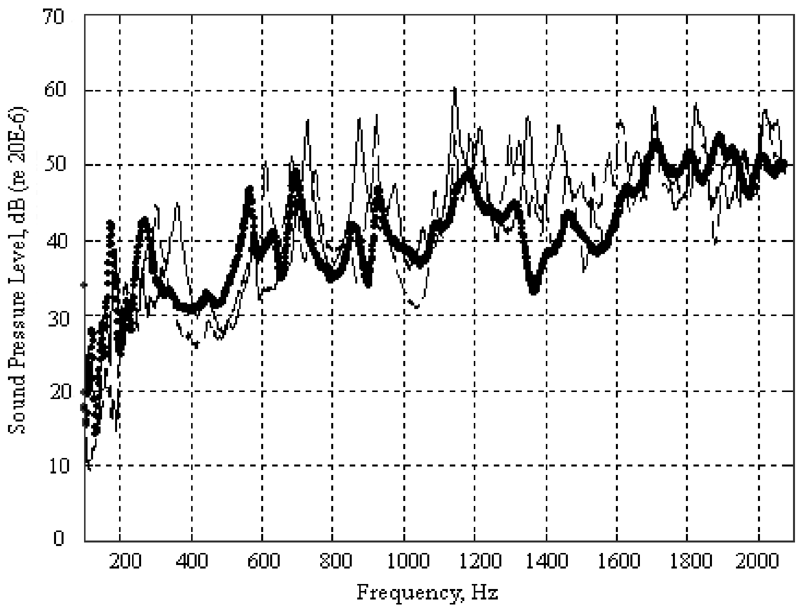

Figure 7. Comparison of the frequency response of the rectangular cavity (dashed curve), the octagonal cavity (solid curve) and the irregular cavity with added seats (dotted curve)

4 ADDING ABSORPTION MATERIAL

Felt material was added to all three cavities under investigation to study the absorption effect of trim in a real vehicle interior. The felt was attached to the wooden interior walls of the cavities, leaving the Perspex top uncovered to give the effects of windows. The frequency response of the cavities with the added felt was measured in the same way as before, taking an average of the three speaker positions.

Figures 8, 9 and 10 show the comparisons of the three cavities with added felt, the rectangular, octagonal, and irregular cavities, respectively. It can be seen comparing the rectangular cavities that the felt has reduced the overall Sound Pressure Level (SPL). The higher frequencies have been affected the most with a drop in SPL of 36dB toward the 2kHz range, and only 6dB difference in the 300Hz range. As with the added chairs, the frequency responses have tended to lower and the peaks less frequent, with a flatter response towards the high frequency end.

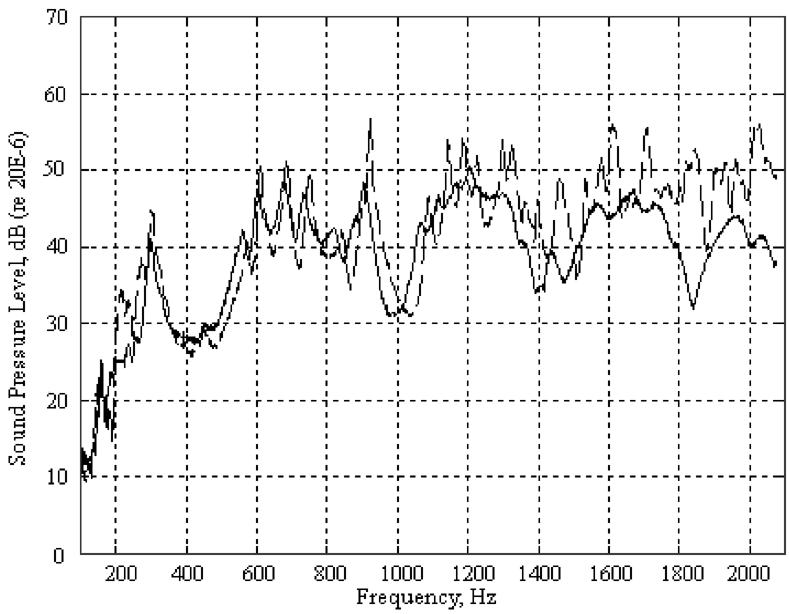

Figure 8. Frequency response of the rectangular cavity with and without felt, solid and dashed curves respectively

For the octagonal cavity, the SPL had reduced considerably overall, to about 35dB. The peaks have a flatter response, especially at higher frequencies. For the irregular cavity the SPL is only slightly reduced in comparison to the un-felted cavity, up to 19dB drop. There are fewer peaks, which have a very flat response in the high frequency region. For both the octagonal and irregular cavities the resonant frequencies are once again shifted to the left of the spectrum.

Thus, the SPL for all three cavities has been reduced with the added felt. The best absorption is in the high frequency range. This is due to the fabric used having a higher absorption coefficient at the high frequency end. The thickness of the material would have to be large to reduce the SPL at lower frequencies, as investigated in Reference 10. It can be seen that there is relatively little difference to the SPL for the irregular cavity. As was suggested in Reference 10, the seats account for about a half of the absorption in the cavity already, so the felt probably has little effect when added to this.

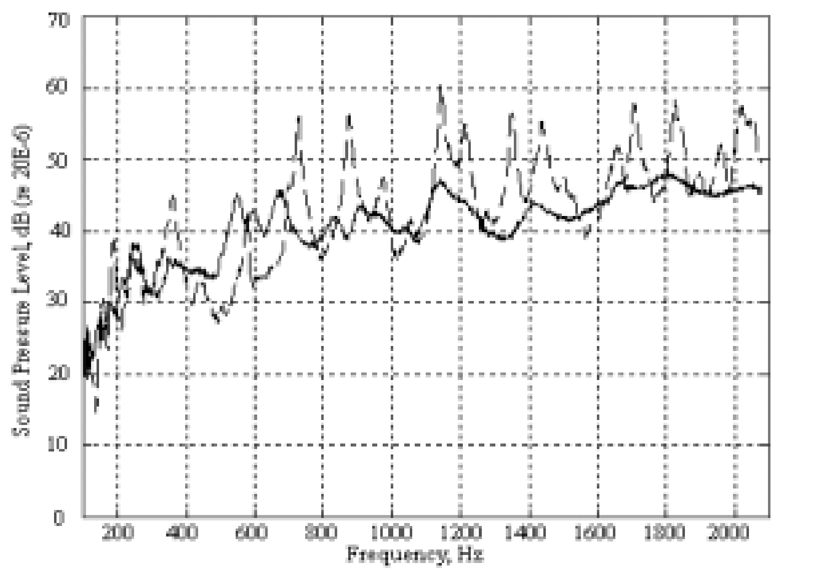

Figure 9. Frequency response of the octagonal cavity with and without felt, solid and dashed curves respectively

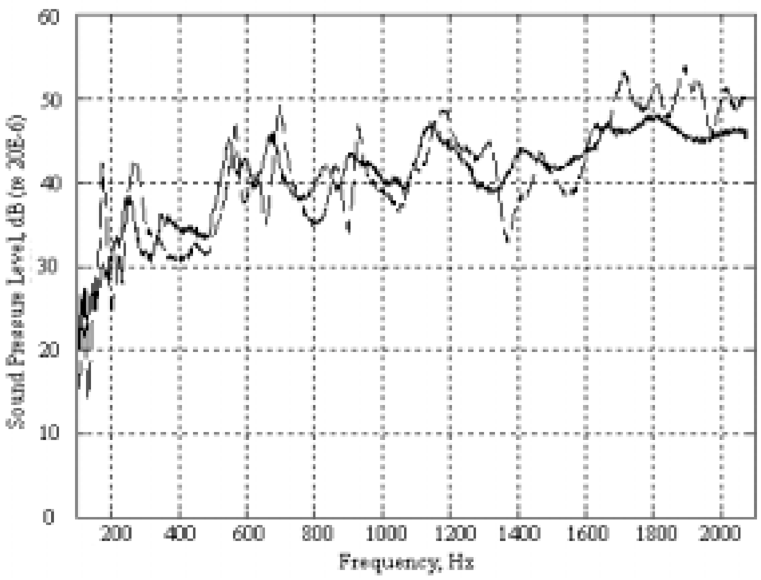

Figure 10. Frequency response of the irregular cavity with and without felt, solid and dashed curves respectively

It was found that the number of peaks have been reduced at the higher frequency end. This agrees with the results of Reference 9. The peaks also have a flatter response, which agrees with the results of Reference 8. Finally the peaks have been shifted to the left of the spectrum as with the irregular cavity with added seats. This was also shown in Reference 12 where it was concluded that the presence of non-rigid boundaries could shift the values of acoustic resonance frequencies.

5 FINITE ELEMENT ANALYSIS

5.1 Introduction

Finite Element Analysis (FEA) for determining the frequency response and mode shapes of acoustic cavities was first introduced in the 60-ies. In the present paper hexahedral and tetrahedral element were used to analyse the three above mentioned quarter scale models of the vehicle interior. Patran and Nastran software packages were used to create and analysis the FEA of the cavities, investigating frequency response and mode shapes. Hexahedral elements were used for the rectangular cavity, using IsoMesh. For the octagonal cavity, the surface of the octagonal face was split into three sections, creating four sized surfaces to enable analysis. Isomesh and Paver were used to mesh the surfaces of the octagon, and then these elements were extruded into the three-dimensional cavity. TetMesh was used to mesh the irregular cavity, using tetrahedral elements.

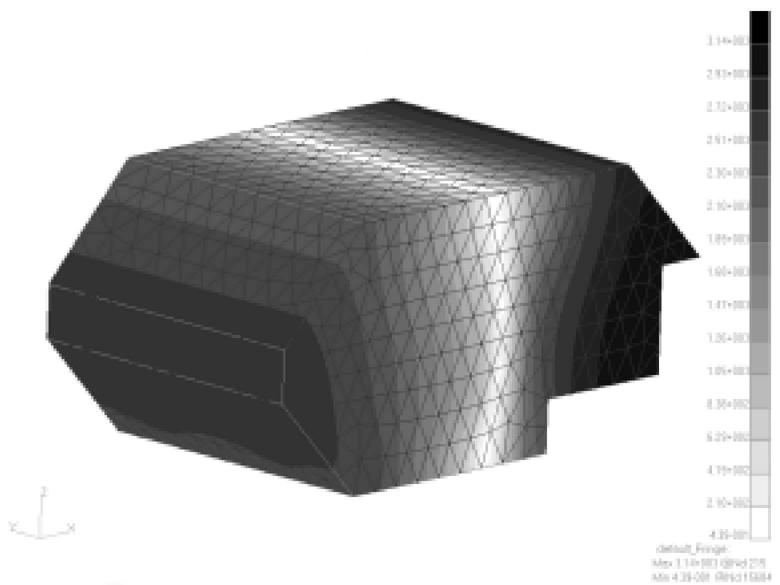

Figure 11. FEA picture of Mode (1,0,0) of the Irregular Cavity

Different mesh sizes were investigated to test the ability of the FEA programs. At high frequencies the error is increased due to the short wavelength in relation to the element size. In practice, the ideal size of elements used is about six per wavelength of the highest frequency of interest. In the measurements described above the highest frequency is 2100Hz, (a wavelength of 0.16m). Therefore, the maximum element size is approximately 27mm. The models were scaled up in the analysis to a full size vehicle interior and the same measurements were taken, to see whether the FEA would work better with lower frequencies. Unfortunately, the increase in size to the models added errors because of the larger processing power needed, so had little effect on the results.

The analysis of the rectangular cavity was very successful when compared to the analytical solutions, with only a 2% error for the first 25 resonant frequencies. There was only one discrepancy with the mode shapes, mode numbers 22 and 23, where the mode shapes have been swapped. This is probably because the difference in frequency is a fraction of a Hertz.

For the octagonal cavity, the FEA results for the first six resonant frequencies are very accurate compared to the experimental data, within 1% error. Also the mode shapes are the same. The next five modes though have large errors up to approximately 16%, with no similar mode shapes. The tetrahedral mesh was also used for this cavity, but created larger errors of up to approximately 19%.

Mode shapes for the irregular cavity are difficult to determine experimentally, so they cannot be compared with the FEA results. The resonant frequencies values for the FEA are in good agreement for the first six modes, with an error of up to 4%. The next four modes are less accurate, with an error of up to 10%. (See Figure 11 for the first mode). FEA is an especially good tool for calculating resonant frequencies for irregular cavities at low frequencies. At higher frequencies the errors are increased due to the high modal density and damping factors.

6 REAL VEHICLE INTERIOR

Measurements of sound pressure level and mode shapes were taken in an interior of a Ford Fiesta. A speaker was set up in the foot well of the front passenger and a microphone was placed in four locations in the vehicle interior; the driver's right ear, the front passenger's right ear, the back left passenger's left ear and the back right passenger's right ear. Each position was measured in the same way as in the quarter scale models, but with the frequency range quartered, therefore 25Hz-525Hz in 100Hz bands. Mode shapes were plotted of the first four peaks from the frequency response, across the horizontal plane of the car in head position.

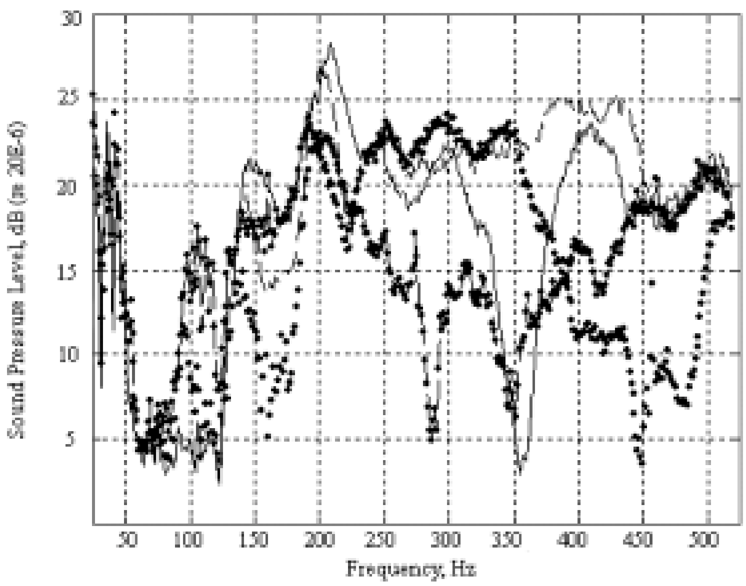

Figure 12. Frequency response of the Ford Fiesta at 4 different positions: rear left passenger's ear (solid curve), rear right passenger's ear (dashed curve), driver's ear (dotted curve) and front passenger's ear (dashed and dotted curve)

Figure 12 shows the frequency response curves for the four positions of the microphone in the vehicle interior. It can be seen that the front passengers have the largest peaks in sound pressure, at around 200Hz. Figure 12 shows the average of the four microphone positions, showing few prominent peaks below approximately 200Hz, and then a fairly flat response up to 525Hz.

There are only a few peaks in the sound pressure level in the vehicle interior. This is due to high frequency sound being absorbed by the trim, including the seats and fabric in the vehicle. The prominent peaks are approximately at 50Hz, 100Hz, 147Hz and 210Hz. The lowest peak is probably due to electrical mains noise. The last three do not give an accurate mode shape, but do however give significant peaks and troughs across the plane of the car.

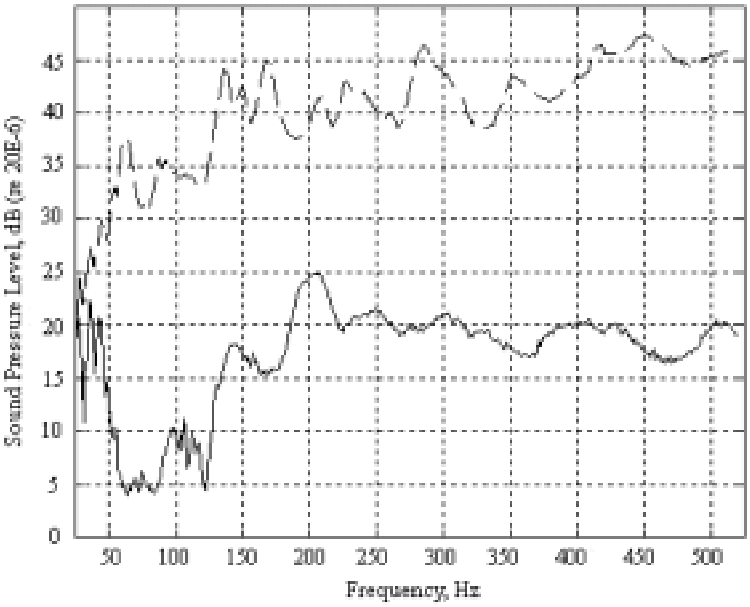

Figure 13. Frequency response of the Ford Fiesta compared with the response of the irregular cavity with added felt, solid and dashed curves respectively

When compared with the irregular quarter scale mode (with quartered resonant frequencies), it can be seen that the SPL in the real vehicle is considerably lower (see Figure 13). Also the peaks of the vehicle interior are shifted in comparison and also have a flatter response. This is mainly due to the larger volume of the real vehicle compartment (by 4^3 = 64 times, which corresponds to 36 dB). Since the volume of the enclosure is present in the denominator of the acoustic Green's function, the average theoretical SPL of a real vehicle should be by around 36 dB lower. Also, the trim may cause additional correction to SPL. There are also more irregular surfaces in the real vehicle interior, allowing for more reflections and dissipation of sound energy.

7 CONCLUSIONS

From the investigations of the first model (the rectangular cavity) it was concluded that the experimental results agree well with the analytical calculations, with errors of less than 2.66% for the first 8 modes. The spatial distributions were accurate, even for higher frequencies. The second model (the octagonal cavity) has a frequency response which is similar to that of the rectangular cavity. The modes are less frequent and are also shifted to higher frequencies. The third model (the irregular cavity) has a frequency response of up to approximately 25dB lower than in the case of the rectangular cavity. The modes are shifted to lower frequencies, possibly attributed to the increase in effective length of the cavity.[11] The spatial distributions of the modes vary, and are difficult to classify.

The addition of felt to the three cavities gave a reduction in SPL for all three cavities, although not greatly reduced for the irregular cavity. This is probably due to the added seats giving the largest contribution (see Reference 10), therefore the felt having little effect. The modes also seem to have shifted toward the left of the spectrum, in agreement with the results of Reference 12.

Finite Element Analysis (FEA) of all three cavities was carried. The results for the rectangular model agree extremely well, with errors of only 2% for the first 25 modes, when compared to analytical calculations. It was found that FEA agrees well with the experiments also for irregular shapes, but only at low frequencies. The errors are only up to 1% when compared to the experimental results of the octagonal cavity for the first 6 modes, and the mode shapes were the same. Further mode shapes, when compared, were inaccurate though, and the error in frequency response increased to 16% for the next five modes. The error for the irregular cavity with added seats was up to 4% for the first 6 modes. As with the octagonal cavity, the error increases for higher frequencies, of up to 10% for the next four modes. Measured mode shapes of the irregular cavity are not accurate, so they could not be compared with the FEA results.

The results for the real car (Ford Fiesta) demonstrate that the frequency response of the cavity has few peaks, with a very smooth frequency response in the higher regions. When compared with the irregular cavity with added felt, it shows a great reduction in amplitudes and fewer peaks across the spectrum. This is mainly due to the larger volume of the enclosure and to the higher absorption by the trim in the real vehicle. Investigation into reduced scale models of more realistic shapes and materials should be made to add further knowledge of the acoustics properties of vehicle interiors.

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