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A STUDY ON HOW SMALL CHANGES TO VEHICLE PANEL BOUNDARY CONDITIONS VARY THE OVERALL SYSTEM RESPONSE

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ABSTRACT

An experimental investigation carried out on a luxury sedan door observed the effect of making small changes to trim boundary conditions by removing and replacing a series of small polymer clips that held the trim to the aluminium door. Structural testing was carried out by exciting the system with a shaker and recording the response with accelerometers placed at three different locations about the door. Acoustic response measurements were also taken with the use of a sound intensity probe. The study found that the removal of even a single clip could vary the response significantly for certain clip locations. The spread of structural data was also found to range by more than 15 dB for certain frequency bands. Similar large deviations were observed for the noise transfer response measurements. This is significantly large spread of data for what might be perceived as a relatively small change to the structure, highlighting the importance of reduced variability at material joints.

INTRODUCTION

The modern automotive design places a significant premium on luxury and low levels of noise and vibration in the passenger cabin. Customers and passengers wish to have quiet interiors with low levels of noise and vibration transmitted from the road or powertrain. Noise, Vibration and Harshness (NVH) engineers have the challenge of ensuring that the product performs as required whilst meeting targets for noise and vibration (1).

Coupled with this is the requirement to get a product to market in a short timeframe, without the expense of many experimental test platforms or prototypes. This requires computer aided design tools and simulation tools which can accurately predict the frequency response function (FRF) of automotive components, typically in the form of discretized finite element models of the volume with appropriate choices of materials, dimensions and boundary conditions. The frequency response function is the amplitude of vibration or noise generated when the design is excited by a force of 1N. Once the design is finalized and prototypes built, it is usually too late to alter the design significantly as the tooling has already been formed (so moving hard mounting points becomes impractical). Instead, the focus is on solving immediate problems using damping materials, themselves heavy and costly.

The finite element software can predict the amplitude and phase of a frequency response function at every node point in the model, when a forcing point or area is chosen for study. The amplitude of this FRF can be band averaged to obtain an average forcing amplitude for particularly important points of the vehicle, for example, the vibration or acoustic response at the driver's head position when the sub-frame mounts are excited. These can lead to design targets which can be benchmarked against competitor vehicles.

The amplitude of the frequency response functions have been studied for typical automotive components, see for example windscreens (2) and body structures across a number of vehicles (3-5). Whilst the finite element prediction only provides for one design prediction for a given set of inputs (neglecting the use of statistical simulation tools such as Monte Carlo where the statistical spread of input data must be known in advance), in reality the components all show variability in their frequency response functions. It is the source of this variability that is of concern in this paper.

It is often considered that the controlling factor of a vehicle interior trim component's frequency response function would be the dimensions and materials, density and thickness of panels. In previous work (6), it has been shown that typical automotive panels FRFs are affected by small changes in the location of mounting points and the interfacial stiffness of the mounting points. The loss factor of the plate and any damping that comes from the joint is not of significant concern.

In this paper, the interior trim from an automotive door is tested to examine the impact of the mounting bolts and attachments on the frequency response function. In particular, the clips that hold the trim onto the door structure are designed to be easy to assembly, for use on a production line. As these are easy to assemble, the joint stiffness can vary from practically zero (a case where the joint rattles) to rigid. The key research question is whether variability of these joint attachments can lead to an appreciable difference in the frequency response function and therefore whether the finite element models can replicate this problem. In this study, the numerous joints on a door structure are removed one at a time, to assess the impact on the frequency response function.

BACKGROUND

Variability of frequency response functions of automotive components

The variability in frequency response functions can be attributed to measurement error or measurement variability. Often, the force is applied to a component using an impact hammer or electromagnetic shaker. The former is highly flexible, allowing access to remote sections of the vehicle in a rapid time, allowing an operator to characterize a vehicle relatively quickly. The variation in the angle between the workpiece and force transducer need not be a concern, providing that the coherence is of a high quality. However, a force transducer delivers a short, sharp impact (the operator is usually concerned with ensuring no double hits or rebounds occur) which leads to both a drop off of amplitude with frequency and frequencies at which no energy is provided to the system at all. Conversely, the electromagnetic shaker can provide a broad band amplitude of force but requires a mounting bracket to attach onto.

Environmental considerations have been previously reported, which especially affect plastic trim components and rubber joints (where the stiffness alters).

Variability is also a natural consequence of manufacturing and assembly considerations, where different materials made at different times in different locations may have slightly different densities, dimensions or clearances. The use of lots of different materials means that the component may behave slightly differently with a change of climate, due to different thermal expansions.

Example of an automotive trim interior on a door, to illustrate the difference between panel and joint importance.

In many cases of investigations of the variability of frequency response functions in the literature, it is common to find that the authors have examined the whole vehicle response at once, under controlled conditions. Whilst this shows the whole vehicle, it does not allow the difference between joints and panel importance to be understood.

In this paper, the component assembly comprising panels, electrical conduits and joints to be investigated is the door of a saloon vehicle. This is chosen as it has two large panels back to back which are connected with a series of bolts and mechanical plastic clips. In order to obtain the response of the door itself, the whole assembly is mounted on a heavy frame which can be moved between a vibration laboratory and a large anechoic chamber. This is shown in figure 1.

The door assembly itself comprises an outer frame which holds the glass and electric motor, door handles and hinges. There is an inner trim panel which holds the speaker and door inner handle, see figure 2. This interior trim panel is one of the direct connections between the passenger and the vehicle noise and vibration and thus it is essential that the prediction of a frequency response function is as accurate as possible, with the variability due to manufacturing tolerances estimated correctly.

An example of one of the plastic attachment clips is shown in figure 3. On one side of the clip is a rubber washer which applies a preload onto one surface, when the clip is inserted into a hole. This is a quick and simple method to join two materials together in a way in which they may be dismantled for repair. The other side of the clip has a slot in which a material may be inserted. Due to manufacturing tolerances, this side of the clip can either be tight (in which case force may be required to assemble the door trim), relatively loose (where it behaves like a linear spring) (6), or very loose where it does not provide any interfacial stiffness. It is this last case which will provide the extreme case under consideration in this paper.

Fig. 1 – Picture of the full door assembly mounted on a heavy frame

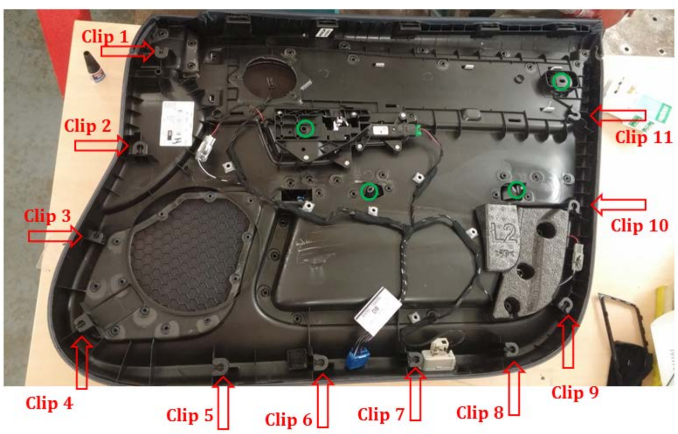

Fig. 2 – Picture of the door interior trim panel on the reverse. The green circles show the locations of the rigid bolts and the red arrows show the locations of the plastic attachment clips. These plastic clips can either rattle or be rigid in their attachment (the variability due to manufacturing tolerances and the need to assemble the product quickly on a production line).

Fig. 3 – Plastic trim attachment clip.

Outline of the method used to investigate the importance of the trim attachment clips as a cause of variability of frequency response functions

In order to identify the importance of these simple, plastic clips on the frequency response function of the door assembly, the following controlled experiment and numerical tests are developed. It is assumed that each clip can either be tight or relatively tight, or completely loose.

The frequency response function is defined as the acoustic sound pressure / sound power emitted when a harmonic force is applied to one of the door hinges. The baseline measurement is when all clips are present in the assembly. Then, as an extreme case to demonstrate variability, one clip at a time will be removed from the door assembly and the frequency response function obtained. By examining the spread of measurements, it is possible to understand what the typical spread of variability might be for a production vehicle.

The sound pressure at a given radius is one possible output, however, in this paper, the overall sound power radiated by the structure is of concern.

NUMERICAL MODELLING

Description of the model

A finite element mesh of the door assembly was created and imported into Siemens NX. A 1N harmonic force was applied to the door hinge over a frequency range between 0-300Hz, corresponding to the range of interest for interior noise and vibration. An illustration of the mesh is shown in figure 4.

The clips were represented by linear springs and a solution 108 response was determined for the case where all clips were in place and then one spring was completely removed at a time. The normal velocity of the surface of the assembly was obtained for each frequency and nodal position. Damping of between 1-3% was applied to the door materials, the amount changing depending on the type of material.

The detail of the models and the exact methods used to determine the vibration and sound radiated by the door in the simulation can be found in reference (8), for completeness, should readers be interested in replicating the problem. An outline of this method is provided in this paper.

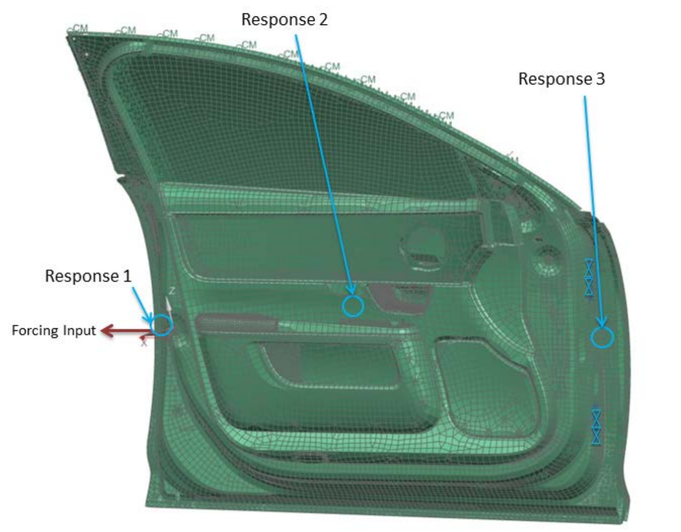

Fig. 4 – Finite element representation of the door assembly.

The sound pressure level p(r) at a given radius r, from the door is given by

$$p(r) \quad = \frac{\omega\rho}{2\pi}\int\frac{1}{r}v_n(r)e^{ikr}ds \qquad (1)$$

Where the density, normal velocity, wavenumber and element area of the door are given by $\rho, v_n(r), k, ds$ respectively. The surface velocity at each element is obtained using the finite element solution and outputted to a single file. A processing routine in Matlab then takes these surface velocities, sound pressures and calculates the radiated sound power.

The sound pressure can be used to obtain the intensity I and therefore the sound power level W based on the particle velocity u.

$$I = pu \qquad (2)$$

$$W = \int IdS \qquad (3)$$

Results

The sound power level obtained from the door assembly when all clips are in place is shown in figure 5 as the blue line (sound power against frequency). At each frequency, the maximum and minimum sound power levels are found when a single clip is removed.

The blue line in figure 5 is the case when all clips are represented in the finite element simulation as rigid attachments. One clip at a time is removed (representing a rattling extreme) and the sound power calculated. Once all 11 clips have been removed and the sound power calculated, one at a time, the overall extremes of the sound power are plotted as the spread of green lines.

It may be seen that for the majority of the frequencies, the removal of one clip in the simulated case leads to an increase of sound power (although there are higher frequencies where this isn't the case). As the door trim is less well attached, it can vibrate with a greater velocity. Hence this shows that it would be preferable to have firmly attached trim clips, regardless of the manufacturing and assembly disadvantages, if the objective were to reduce noise and vibration variability.

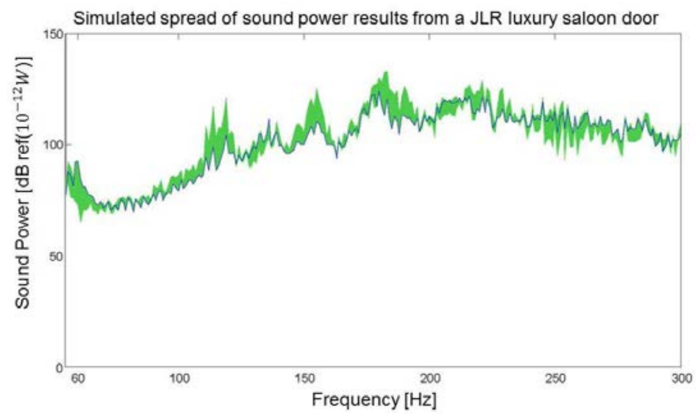

Fig. 5 – Simulated spread of sound power measurements from a door assembly when one of eleven clips is removed.

EXPERIMENTAL ANALYSIS

Experimental Method

The same problem which was considered using numerical analysis is now addressed using experimental measurements. This is important as the finite element solver represents and idealisation of the problem, and is only linear, whereas the experimental method represents what can happen in the real world.

The sound power was obtained using a Bruel and Kjaer sound intensity probe with the door excited by an electromagnetic shaker and the method applies following ISO 9614-3 (7). Once again, an outline of the method is provided in this paper, however, the full details are available from the Loughborough University repository in the form of the PhD thesis. This contains all details needed should a reader need to replicate the experiment (8).

The average amplitude of force generated at a given frequency was lower than the simulated case (see the average amplitude between figure 5 and figure 7). The pattern of taking the intensity measurement with the probe is shown in figure 6, along with the door on the frame, a microphone on stands to take sound pressure measurements and a power amplifier. Not shown are the National Instruments data acquisition equipment and GRAS power modules.

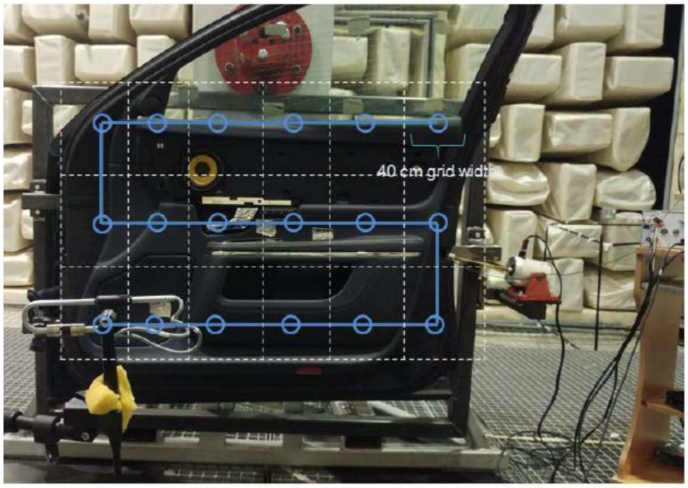

Fig. 6 – Experimental measurements of sound power using a Bruel and Kjaer sound intensity probe.

Experimental results

The experimental spread of sound power measurements which are found when one clip is removed from the trim assembly are shown in green, with the baseline in blue being the case where all of the clips are present is shown in figure 7.

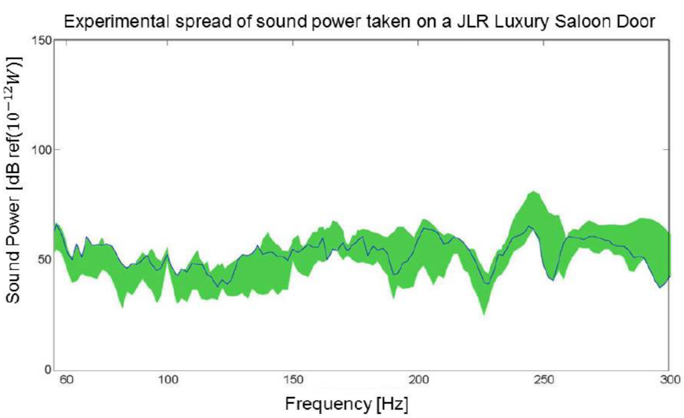

Fig. 7 – Experimental measurements of sound power on a car door. The blue line is the FRF when all clips are rigidly attached, with the green shading the spread of measurements when one clip at a time is removed.

The variability in sound power can be as high as 15dB, depending on which clip is missing. This shows that the small change in boundary condition can lead to a relatively significant change in output. The experimental trends show the opposite behaviour when compared to the numerical prediction, in terms of frequency, perhaps due to the perfect simulation behaviour of the springs when compared to real life. The simulation does also not take into account potential rattling of the clips in the seat, which is a highly non-linear contact phenomena. It should be noted that the model used was not a current one, rather a depreciated model that was made available for academic research.

It is clear, however, that the interfacial stiffness between large components is of high importance in terms of the variability of frequency response functions and the modelling of these in simulation should be given due importance.

Whilst attention is often given to larger components in terms of their contribution to the frequency response function, this study has shown that the joints between these large components are also highly important and care should be taken in both modelling and the representation of these in linear finite element programs.

CONCLUSION

The importance of the interfacial stiffness in joints and in particular, the consistency of the stiffness has been highlighted when considering noise and vibration measurements in vehicles. This study has shown that there is an argument to be made that rapid assembly and manufacturing considerations might not always lead to less variable performance in terms of noise and vibration.

Simulations based on finite elements have been used to obtain the sound power on a door assembly. Similar experimental measurements have been taken, the trends showing that the assumptions behind the modelling can lead to the right level of spread but inconsistencies in terms of trend analysis.

ACKNOWLEDGEMENTS

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