Study of a Loudspeaker in a Vehicle Door

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Abstract: Comsol Multiphysics was used to evaluate the performance of a woofer coupled to an automotive door. The Acoustic Shell Interaction solver was used to perform the simulation of the speaker membrane displacement for a rigid and a non-rigid door structure. The Pressure Acoustic module was used to simulate the sound pressure in the vehicle at the driver position. The comparison between the *in situ* measurement and the simulation data shows that the non-rigid boundary condition allows to reach a good simulation accuracy below 500 Hz.

1. Introduction

Nowadays plenty of simulation methods are used to support various aspects of a vehicle design. One of the most challenging ones is to design a superb sound system for a vehicle.

The steady-state vibro-acoustic simulation allows investigation of the interaction between loudspeaker and door construction in terms of structural dynamics. Speakers are usually coupled to door cavities; hence it is extremely important to take vibro-acoustic effects into consideration when designing a "good" door. Careful design of the door influences positively the overall performance of the audio system and improves in-vehicle acoustic comfort.

2. Theoretical Background

A Lumped Parameter Model (LPM) is used to describe the speaker, i.e. coupling between the magnetic field in the motor system and the current in the voice coil. Such approach allows not to include the motor geometry in the simulation in order to speed up the calculation time.

For the rigid door simulation, the speaker membrane is based on a LPM approach where no mechanical modes of the speaker membrane are included. This approach is only valid in the low frequency range where the speaker components are moving as rigid body[1]. In other words, coil acceleration is directly translated into cone acceleration. It is assumed that the first break-up mode of a given speaker defines the upper frequency limit for such behavior.

For the non-rigid door simulation, a finite element model is used for the mechanical domain to perform more realistic simulations including all mechanical modes of the speaker membrane.

3. Numerical Model

Numerical simulations were performed in Comsol Multiphysics using Acoustic-Shell Interaction and later Pressure Acoustic modules. Also, LiveLink to Matlab was used for pre- and postprocessing of simulation.

Simulation process was divided into two sub stages. Firstly, only a door model with an attached speaker was modelled. Secondly, sound pressure level inside a vehicle was simulated. All models were simulated in a frequency domain from 20 to 500 Hz, which corresponds to the operating range of the speaker.

3.1 Door Model

A door assembly is a complex structure, which has to be accurately represented in the virtual domain in order to capture all structural effects associated with a given design. Of course, a vehicle door can be treated only as a resonance volume with fully rigid boundaries, but in that case no effects of coupling between the acoustics and mechanics would be considered. In other words, the simulated response of the speaker would be free of any coupling coming directly from a door assembly.

In order to prove the need of accurate modelling, two cases of door definition were investigated.

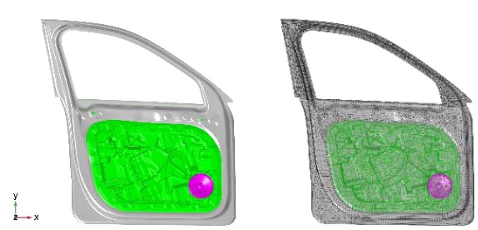

Figure 1. CAD model of a vehicle door and corresponding structural mesh.

In the first model all door components, both internal (crash beams, etc.) and external (panels) were described as fully rigid sound hard boundary. The speaker was represented as a rigid piston with a spring foundation, which is valid for a given speaker and investigated frequency domain.

Second model consisted of an accurate description of the door assembly in terms of material definitions, thickness and internal coupling between structural components. In order to reduce the computational time, some features, like for example window lift motor, were represented as added masses. Also the speaker definition was improved and now consisted of all moving parts (cone, suspension, etc.).

Thiele/Small parameters of the loudspeaker were measured using a professional measurement solution. In both cases, a defined driving force derived from measured parameters was applied to the speaker and resulting cone displacement was then applied as an input for further investigations.

3.2 Car Cabin Simulation

The car cabin model was based on a SUV vehicle, currently available on the market. A discretized representation of the vehicle was created based on the CAD data. The element size was calculated to fulfill the requirement of at least six nodes per wavelength. Additionally, all surfaces were described with absorption coefficients[2][3].

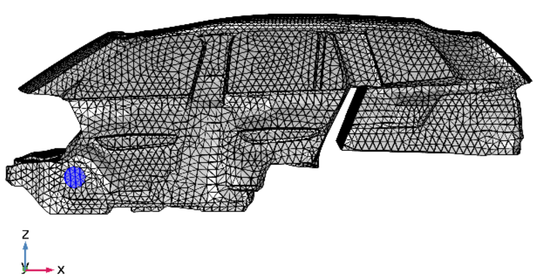

Figure 2. Cabin mesh with a speaker in the door.

With the assumption, that the given speaker acts as a rigid piston below 500 Hz, Pressure Acoustic solver was used.

The air domain is excited by the front door speaker, which is defined as a flat rigid piston with a surface area corresponding to the effective surface of the woofer. Normal acceleration was prescribed to that surface and was calculated based on the speaker displacement from the rigid and non-rigid door models.

4. Measurement

A six microphone array was used to measure sound pressure level on four seating positions in the car. Each microphone array was carefully placed according to Harman's standard defined by Acoustic Systems Engineers.

Input signal (swept sine[4]) was directly applied to speaker terminals, omitting car's amplifier. With such approach, no sound system EQ is present in the measurement. For further comparison with the simulation, the data was averaged for each microphone array.

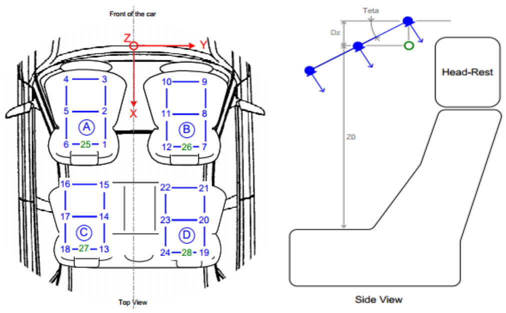

Figure 3. Microphone array definition for *in situ* measurements.

It is worth mentioning the differences between the measured car and car cabin simulation model. The vehicle was organized for measurements after CAD discretization, hence some optional features, like the panorama roof, are not present in the FEA model.

5. Simulation Results

Cone displacements for both door configurations are shown in Figure 4.

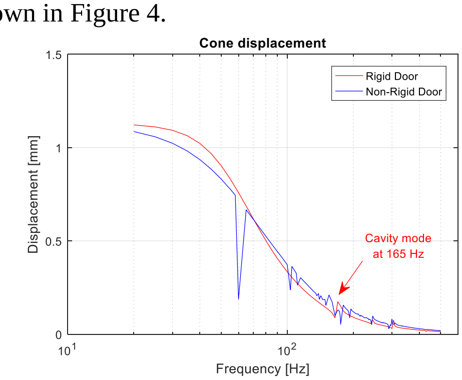

Figure 4. Simulated cone displacement for a rigid and non-rigid door model

It can be clearly identified, that having a full vibro-acoustic model of a door allows to capture more details in the frequency response. For example, for a fully rigid case only acoustic mode of the door cavity can be identified at 165 Hz (marked with an arrow in Figure 4).

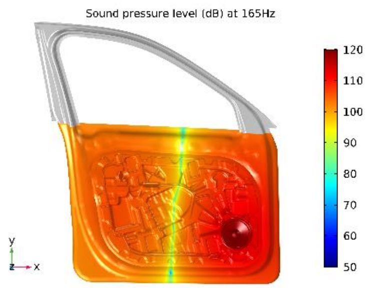

Figure 5. Sound pressure level at 165 Hz, door cavity, rigid model

For the non-rigid case, the response is additionally showing the mechanical response of the door assembly. It can be noticed, that there is a huge drop of cone displacement at 60 Hz. Careful investigation of the simulation results indicated, that at that particular frequency the inner panel is heavily excited. The displacement pattern corresponds to the first Eigenmode of the inner panel.

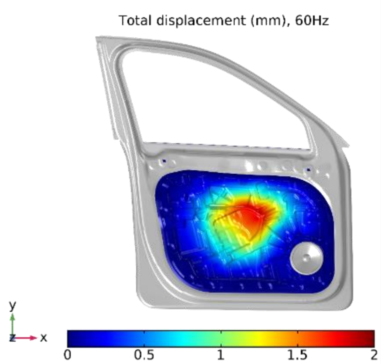

Figure 6. Inner panel displacement at 60 Hz.

The second step of the simulation chain required calculating sound pressure level inside a cabin with a given cone displacement. Figure 7 shows the cabin response at the driver seat for rigid and non-rigid door definitions compared against the *in situ* measurement. Even though a simplified, fully rigid case, can provide a good estimation of the sound pressure level inside the cabin, it is not fully matching the *in situ* measurement. For example, at around 60 Hz a significant notch in sound pressure level is recorded. This is corresponding to a smaller cone displacement, as simulated in the non-rigid example.

The 5 Hz difference in the region of 60 Hz between the car cabin simulation and the measurement is well within the acceptable tolerance. It can be easily explained by necessary approximations in the modelling of the non-rigid door, as explained in chapter 3.1. Furthermore, as mentioned before, some specific behavior at 20-30 Hz recorded by the *in situ* measurement is not recreated in the simulation model.

It is down to lack of a panorama roof in the virtual representation of a cabin. Furthermore, it is believed that in order to improve accuracy in that region, it would not be enough to describe the glass roof only with an absorption coefficient. The panorama roof would have to be defined in a similar manner to the non-rigid door model, to ensure a proper fluid-structure interaction.

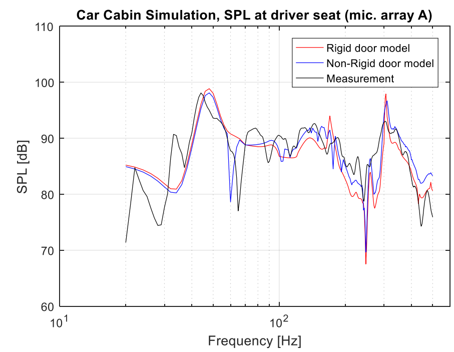

Figure 7. Comparison of sound pressure level, driver seat.

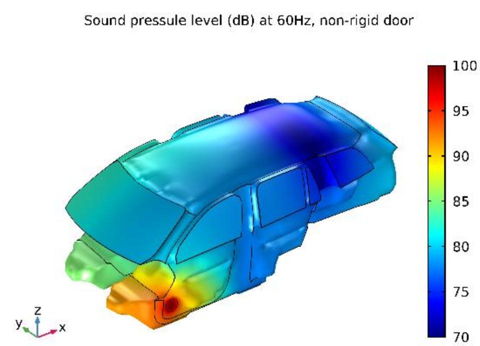

Figure 8. Sound pressure level distribution inside a cabin at 60 Hz, right front woofer active.

Conclusions

It has been shown, that it is possible to simulate the acoustic pressure inside the cabin considering the specific effects of the door structure. A satisfactory correlation with the measurement can be reached when using Comsol Multiphysics.

Additionally, this type of simulations can help in designing and evaluating the sound system of car at the very early stages of the design. Knowing a specific interaction between the structure and the acoustic domain is only beneficial, especially for such a complex acoustic environment like a car cabin.

References

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