Virtual Audio Tuning of a Car Cabin

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Abstract: For automotive applications, acoustical simulation methods are used to optimize the position and orientation of the loudspeakers to get the best listening experience. The goal of the present paper is to evaluate the accuracy of the Pressure Acoustics (Finite Element, wave-based method) and the Ray Tracing (geometrical acoustics) modules to predict the acoustic responses in the vehicle interior and to virtually tune the audio system. For this study, nine loudspeakers (subwoofers, woofers, midranges and tweeters) were simulated. To validate the simulation, an experimental comparison between simulated and measured responses was performed. A planar microphone array, located at the four seat positions, was employed to capture the responses in the experimental and virtual setups. Based on material sample measurements, frequency-dependent absorption coefficients were assigned as boundary wall conditions. For the FEM simulations, the loudspeaker was modeled as a fully rigid piston. For the Ray Tracing module, the speaker was modeled by means of a measured sensitivity and directivity performed in an anechoic room. The Matlab Livelink module was used to pre-process, solve, and export simulation data. For all speakers, acoustic impulse responses were computed. The comparison in the frequency domain shows that the combination of the Pressure Acoustic and Ray Tracing solvers can perform accurate speaker simulations in a vehicle. Furthermore, Equalization filters based on measured and simulated SPL were compared. To include the influence of the speaker packaging in the car cabin (e.g. waveguide and grille assembly), the coupling between the FEM and Ray Tracing is discussed.

Keywords: acoustic, car cabin, loudspeaker, accuracy, EQ

1. Introduction

For automotive applications, simulation methods are used to optimize the position and orientation of loudspeakers to get the best acoustic performance in the vehicle interior[1][2]. Systems Engineers use the following process to reach the best audio allowances:

- Sound pressure measurement on the 4 seat positions (utilizing a 6 microphones arrays)
- Equalization (EQ) of the amplitude of the sound pressure with different filtering methods

For each audio channel, the delay and the gain are optimized.

The use of numerical methods to predict the sound pressure allows to import simulated data into an EQ-process.

2. Governing Equations

From the definition of the boundary specific impedance:

$$z = p/u \qquad (1)$$

It is possible to obtain a relationship for z in terms of either p or u using**:**

$$\eth p/\eth n = -\rho\, \eth u/\eth t \qquad (2)$$

where ρ is the air density and n is a vector normal to the boundary surface at each boundary discretisation point. The specific reflection coefficient R can be computed as:

$$z = \rho c\ (1+R/1-R) \qquad (3)$$

The normal incidence specific absorption coefficient α can be computed as:

$$\alpha = 1 - |R|^2 \qquad (4)$$

2. Car Cabin Material Measurement

To obtain more realistic values for the acoustic boundaries of the car cabin interiors, the normal incidence sound absorption coefficients can be measured in situ using the acoustic impedance tube per ASTM E1050[1].

The photo in Figure 1 shows the tube's open end is directly placed on the car seat, measures the transfer function between two microphones installed at the sidewall of the tube, and estimates the normal incidence sound absorption coefficients as shown in equation (4).

In general, the in-situ method imposes measurement errors due to the tube end's open condition, which requires reasonably cleaning the noisy data to use them for the car cabin model. In this study, we measured multiple spots and used them to estimate the theoretical poroelastic model[2] to get the smooth curves. Once the poroelastic model reasonably fits with the measurements, it goes into the 3D cabin model as an acoustic boundary impedance.

In Figure 1, the solid blue curve shows the theoretical model reasonably fitted with the four measurements shown as dotted lines. Sound absorption coefficients measurement have been performed for 6 acoustic boundaries and applied them to a 3D car cabin model.

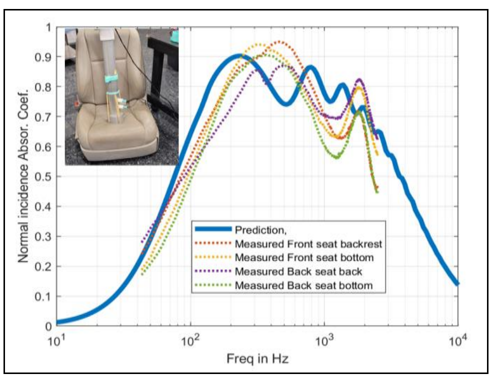

Figure 1*: In-situ acoustic material measurement*

3. FEM and Ray Tracing Solvers

From the CAD geometry the prominent features of the car interior are simplified to reach an optimized mesh in terms of number of elements and mesh quality. That allows to mimize the calculation time. For the FEM model, the minimum mesh size is linked with the upper frequency limit. The same mesh is used for the Ray Tracing Solver (RT). The mesh corresponds to a fully sealed car cabin which is not the case in reality where numerous leakages exist.

The FEM-modeling is based on a full domain discretisation approach. At each node, the FEM algorithm approximates the steady state Helmotz equation. The acoustic field at each mesh point varies harmonically with time. For the FEM, the loudspeaker membrane is modeled as a rigid component. The piston location and orientation are the same as for the real speaker. The area of the flat piston is equal to the effective surface of the loudspeaker. The speaker motion is defined with a normal acceleration. The Comsol Pressure acoustic solver can be used to simulate the SPL in the car interior even if no vibro-acoustic coupling is included in the simulation workflow[3].

The Ray Tracing theory is suitable for large room acoustic[4][5]. This geometrical acoustic approach can also be used in a car interior when a high mode density is reached (above the Schroeder frequency)[6]. For the speaker definition, the speaker sensitivity and directivity measurements in an anechoic room are used. These input parameters do not include the car cabin speaker packaging by default.

4. Livelink in Matlab

To perform the calculation of the flat piston normal acceleration (complex number), the Matlab Livelink module is used. The main interest is to simplify the pre-processing and post-processing steps. All steps are fully optimized and automatic which allows to sequentially launch the next simulation when the previous one is performed. A Lumped Parameter Model (LPM) is used to compute the speaker motion (frequency dependant). The LPM model does not include the influence of the enclosure air resonance and the vibro-acoustic coupling between the loudspeakers and the car components (e.g. enclosure, door trim). The input parameters for the LPM simulation are:

- the voltage at the voice coil terminals
- the stiffness of the suspension (Kms including the surround and the spider)
- the surface of the speaker membrane (Sd)
- the weight of the moving mass (Mms)
- the resistance of the voice coil (Rscc)
- the force factor (Bl)
- the mechanical Q factor (Qms)

- the volume of the enclosure where the speaker is mounted

5. Experimental Data - Car Measurement

A 6 microphone array is used to measure the sound pressure on the 4 seat positions (Arrays A, B, C and D). The car used in this experiment was a mid-sized vehicle including a premium audio system.

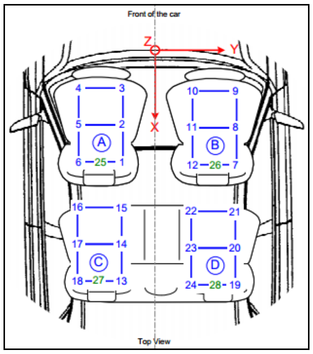

Figure 2: *Mic Array (Top View)*

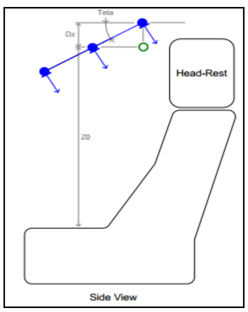

Figure 3: *Mic Array (Side View)*

For the measurement, the combination of the vehicle interior and the loudspeaker can be assumed as a time invariant system with a transfer function. With the use of a low voltage at the speaker terminals, the transfer function is mainly linear. Audio measurements are performed with a logarithmic swept sine approach[7].

6. Sound Pressure Comparison

This section presents the sound pressure comparison between the measurement and the simulation for the left midrange. The midranges are the only speaker where a FEM and RT simulations are merged to cover the audible frequency range.

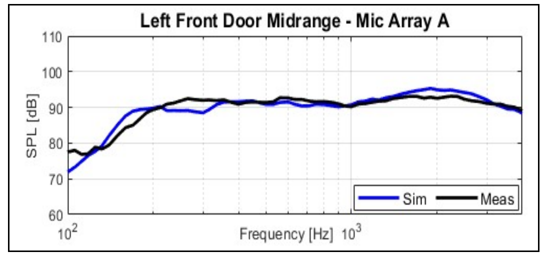

Figure 4: *Sound Pressure on Mic Array A*

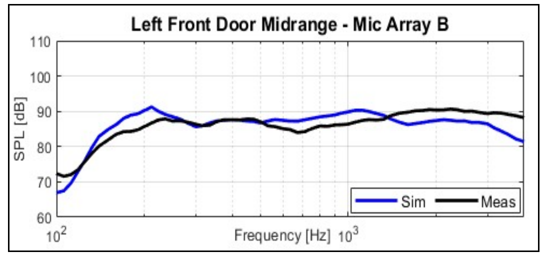

Figure 5: *Sound pressure on Mic Array B*

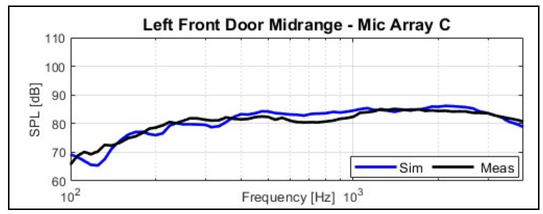

Figure 6: *Sound pressure on Mic Array C*

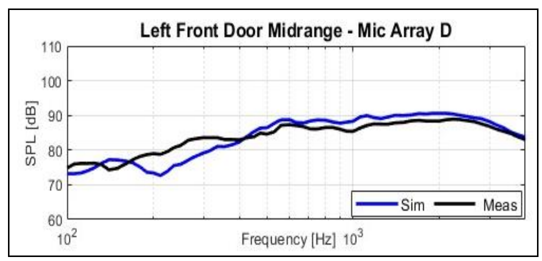

Figure 7: *Sound pressure on Mic Array D*

A similar curve is observed between the measured and the simulated SPL for the 4 seat positions. The difference between the measurement and simulation is within the statistical variation of structural-acoustic characteristics of automotive vehicles[8].

7. Audio Virtual Tuning

To fully optimize the listening experience, the audio channels are tuned using EQ Filters, a corresponding gain and delay. The same EQ tool including the same SPL target curve has been used. The real (measurement) and virtual (simulation) EQ filters have been compared in the frequency and in the time domains.

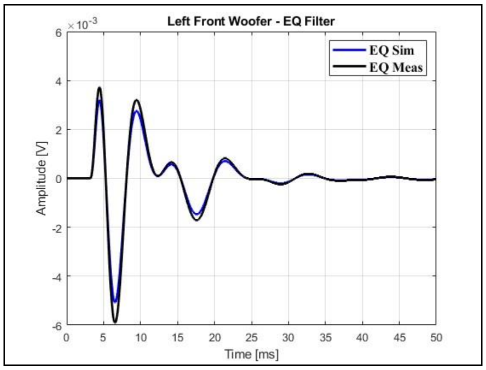

Figure 8: *Woofer EQ Filter (Frequency domain)*

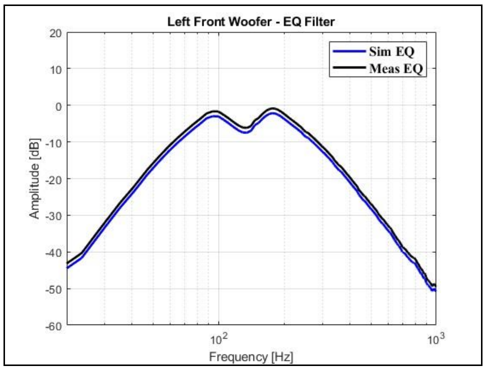

Figure 9: *Woofer EQ Filter (time domain)*

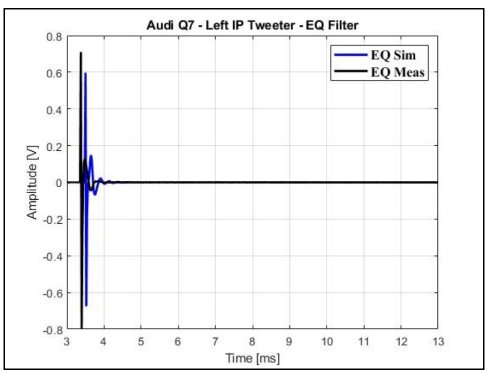

Figure 10: *Tweeter EQ Filter (time domain)*

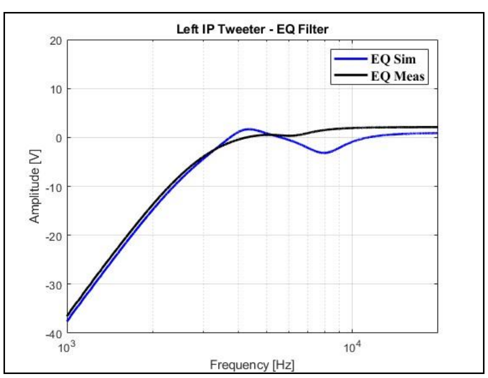

Figure 11: *Tweeter EQ Filter (Frequency domain)*

EQ filters based on measured or simulated SPL are similar in the frequency and time domains. It shows that a virtual tuning can replace a real tuning.

7. FEM / RT Coupling

The RT simulation workflow could improve by adding the influence of the speaker packaging in the simulation (loudspeaker wave guide, grille, …). The idea is to have 2 air domains:

- a narrow air domain including the speaker packaging (FEM solver)
- a RT air domain contiguous to the FEM air domain where the FEM results are used as an input parameter for the RT simulation.

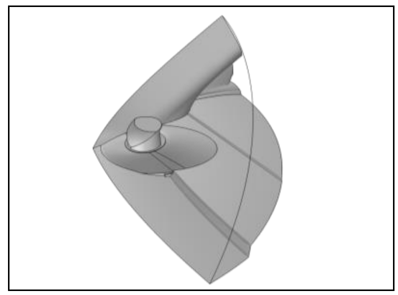

Figure 12: *Air Domain for FEM solver*

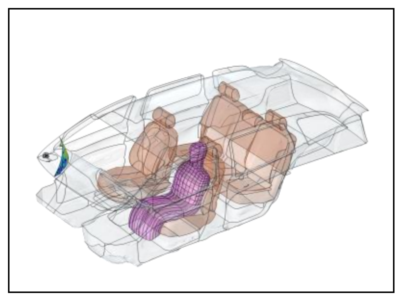

Figure 13: *Full Cabin Model*

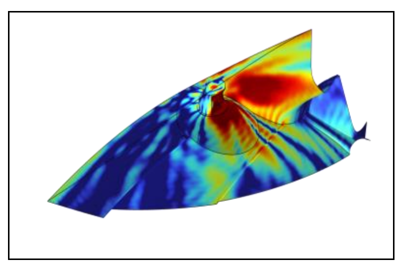

Figure 14: *SPL for FEM Solver (14 kHz)*

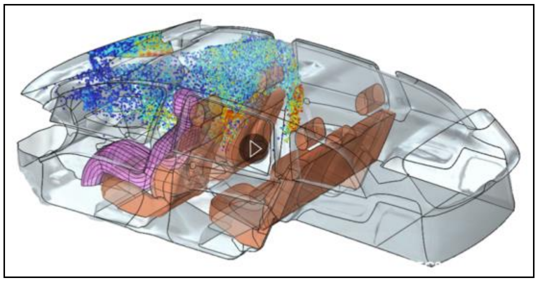

Figure 15: *Ray trajectories calculated from FEM solver*

8. Conclusions

Even if the simulation workflow includes few approximations (sealed car cabin, no speaker packaging, no vibro-acoustic coupling), the FEM and RT acoustic solvers can be used to perform accurate acoustic simulations. Furthermore, EQ filters based on simulated or measured SPL are similar. It shows that a virtual audio tuning can be used to improve the audio listening experience. Setting up a playback system that will, “based on simulation results and signal processing, allow the user to listen, evaluate, and compare any optimized audio system including any type and number of speakers. The simulation process allows to add freedom in design decisions and to lower the cost of any design changes.

9. References

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