Wind Noise Contribution to Vehicle Interior SPL - Case study

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Recent developments in the prediction of the contribution of wind noise to the interior SPL (Sound Pressure Level) have opened a realm of new possibilities. The main physical mechanisms related to noise generation within a turbulent flow and the transmission through the vehicle greenhouse are nowadays better understood and can be easily and accurately modelled. Several simulation methods such as CFD, FEM, BEM, FE/SEA Coupled and SEA can be coupled together to represent the physical phenomena involved. The main objective being to properly represent the convective and acoustic component within the turbulent flow to ensure proper computation of the wind noise contribution to the interior SPL of a vehicle. This paper introduces the reader to the various physical mechanisms involved in wind noise prediction, it also describes the most common ways of characterizing the source and representing the transmission paths to the interior and finally it presents the validation of a vehicle vibro-acoustic model before presenting the correlation between simulations results and measurements for the case with and without mirror.

1 INTRODUCTION

In order to model wind noise it is necessary to understand the source, the paths which typically involve direct vibro-acoustic transmission through certain regions of the structure, transmission through nearby leaks/seals and isolation and absorption provided by the interior sound package and the receiver and in particular, the frequency range(s) in which wind noise provides an audible contribution to the interior noise in the occupant's ears. While many regions

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of a vehicle can contribute to wind noise, the fluctuating surface pressures on the front side glass due to vortices and separated flow generated by the A-pillar and mirror are often an important contributor. This paper describes the physical phenomena involved in wind noise simulation. It also describes a method used to couple CFD fluctuating surface pressure time history data to a vibro-acoustic model based on the use of the Curle formulation of the Lighthill analogy and the BEM (Boundary Element Method) representation of the exterior acoustic pressure field.

2 FROM TURBULENT FLOW TO VEHICLE INTERIOR SPL

A turbulent flow generated outside a vehicle can potentially be transmitted to the interior of a vehicle and be detrimental to the sound quality experienced by occupants. The turbulent flow outside a vehicle generates a fluctuating surface pressure field on the side glass which includes a convective and an acoustic component. The convective component is related to the pressure field generated by eddies travelling at the convection speed. The acoustic component is related to acoustic waves travelling within the flow and being generated on various surfaces before reaching the side glass.

The acoustic component on the side glass outer surface is typically very small in amplitude compared to the convective component and as will be shown later in this paper, can be the major contributor at coincidence frequency of the side glass. Furthermore, the acoustic waves reaching the side glass are highly directional. The turbulences at the rear face of the mirror and on the A-Pillar create acoustic waves that travel rearward towards the side glass with a specific heading.

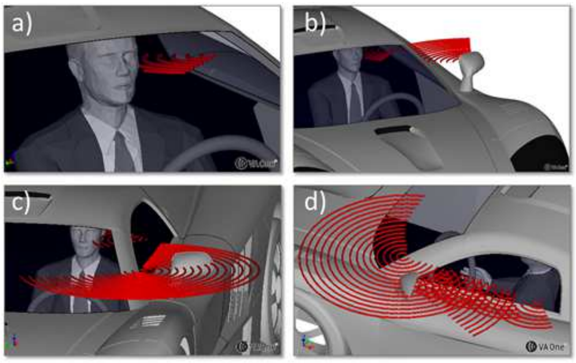

Fig. 1 – Sketch of acoustic waves propagating: a) from side glass to driver's ear, b) from side mirror to driver’s ear, c) from A-Pillar to driver’s ear, d) away from A-Pillar, side mirror and side glass and interfering with each other before reaching side glass

This phenomenon is associated to a dipole source (surface terms). The acoustic waves travelling towards the side glass are likely to be transmitted inside the vehicle through the side glass and to the driver’s ear as illustrated in Figure 1a,b,c. Eddies within the turbulent flow and not in contact with any surfaces can also generate noise and therefore constitute acoustic sources. These sources act as quadrupole acoustic sources and are referred to as volume source terms. These acoustic sources are at close proximity to the side glass however at automobile speeds, these source terms are considered negligible since flow Mach number is below 0.3. Pressure fluctuations on the side glass also generate acoustic waves that propagate away from side glass. These waves can interfere with incoming acoustic waves from A-Pillar and mirror. It is believed to have a negligible impact on driver‘s ear SPL (Figure 1d).

The Navier-Stokes equations are notoriously difficult to solve numerically and a wide range of approximate strategies has been developed (LES, RANS, etc) to do so. In particular it is very difficult to solve for both turbulent flow and acoustic radiation at the same time, since turbulence is small scale and requires a very fine grid of computational mesh points and acoustic waves and sound radiation require a large spatial region to be modelled. Most CFD codes avoid this problem by assuming that the flow is incompressible which removes the acoustics. This section discusses how the acoustics can be added to an incompressible CFD simulation.

For wind noise automotive application, this means using BEM to propagate acoustic waves generated from the fluctuating surface pressure locations such as mirror and A-Pillar surfaces towards the side glass (see Figure 4). New derivation of the acoustic analogy based on Curle's integral version of the Lighthill equation for BEM allows the use of CFD incompressible analysis to model the turbulent flow. Figure 2 show the computation scheme related to this approach. More info on the full content of figure 2 can be found in [1,2].

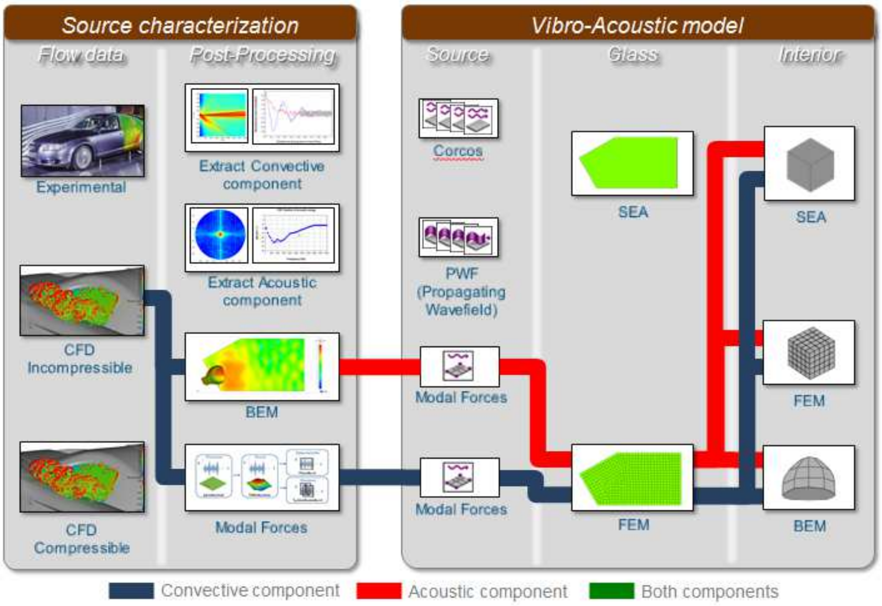

Fig. 2 – The computation scheme: Using BEM to add acoustics to an incompressible CFD computation

When an incompressible CFD simulation is performed, the acoustic component is not included in the time domain fluctuating pressure and BEM can be used to add this acoustic component. As shown in figure 2, the incompressible CFD time domain fluctuating pressures can be coupled to a BEM and the Curle's integral version of the Lighthill equation can be used to compute surface source terms to apply to the BEM fluid representing the external sound field of a car. Then, these frequency domain pressures can be projected onto the FEM glass modes to compute the acoustic contribution to the driver's ear SPL.

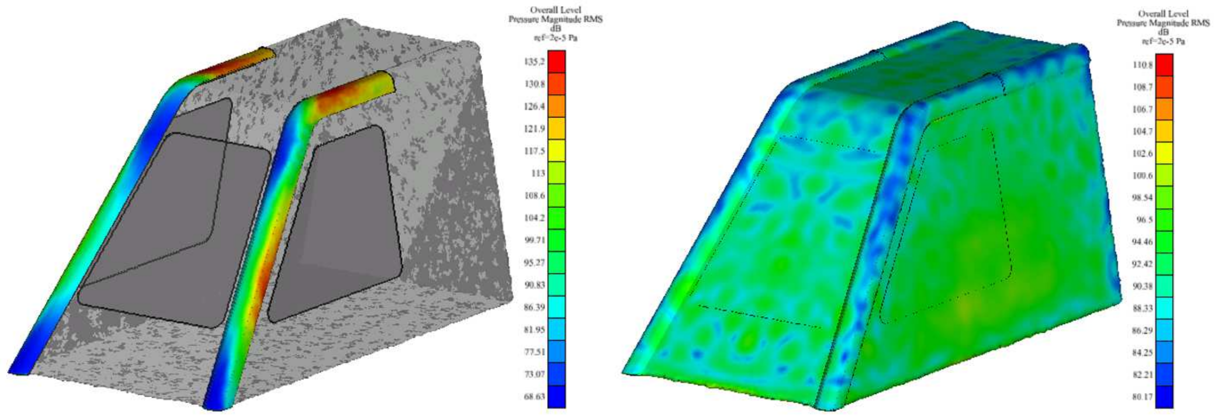

Fig. 3 – CFD fluctuating surface pressure imported on A-Pillar (left) applied as a boundary source term on a BEM model that propagates acoustic waves from A-Pillar to rest of structure outer surfaces (Right)

When FEM is used to represent the side glass, one can directly use the time domain fluctuating surface pressure and convert them into modal forces. The process is illustrated in Figure 5. The time domain pressures are converted into forces and projected onto the modes of the side glass.

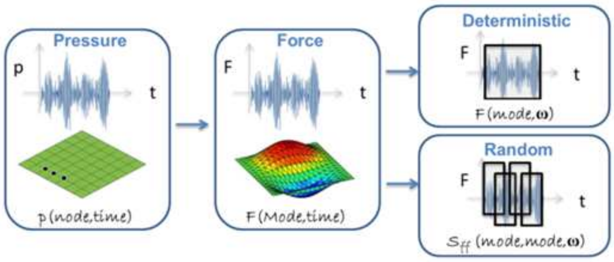

Fig. 4 – Using modal forces to represent forcing function

The full time domain modal force signal is then either used in its entirety as a single window and used in the AVA model as a deterministic excitation or the time signal is post-processed and averaged using overlapping segments to generate a random source.

The vibro-acoustic model is composed of FE panels for the front and side glasses. The walls of the structure are considered rigid. For both the FE structure and BEM fluid meshes, the criteria of 6 elements per wavelength is used. See [3] for more details on the vibro-acoustic model validation.

3 CFD COMPUTATION

For the prediction of sources for the aero-vibro-acoustic evaluation, a computational fluid-dynamics model was built to run in OpenFOAM with the help of Visual-CFD (Visual-Environment). The tools and utilities of the OpenFOAM toolbox (v2.3.0) were used in all the steps in the CFD simulation:

- Meshing with snappyHexMesh
- Steady-state simulation with simpleFoam (incompressible)

• Transient simulation with pimpleFoam (incompressible)

The CAD of the simplified cabin was halved, to reduce mesh cell count taking advantage of the symmetry of the geometry (and the expected symmetry of the flow). This geometry was put into a virtual wind tunnel, with sizes defined such that the boundary conditions did not affect the flow around the simplified cabin, as follows:

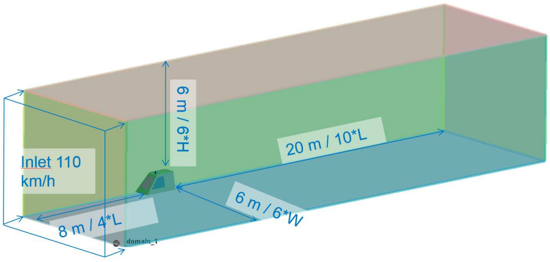

Fig. 5 – Virtual wind tunnel dimensions

For the definition of the mesh, a preliminary steady state aerodynamic simulation was performed to obtain the requirements of cell sizes around the cabin to reach the desired 4000Hz, and to define the layers of prisms to get a suitable first cell height to be able to run the final transient case using IDDES.
This preliminary study pointed out the requirement to define a fine mesh the areas around the A-Pillar, extending this cell sizes downstream of the side window.

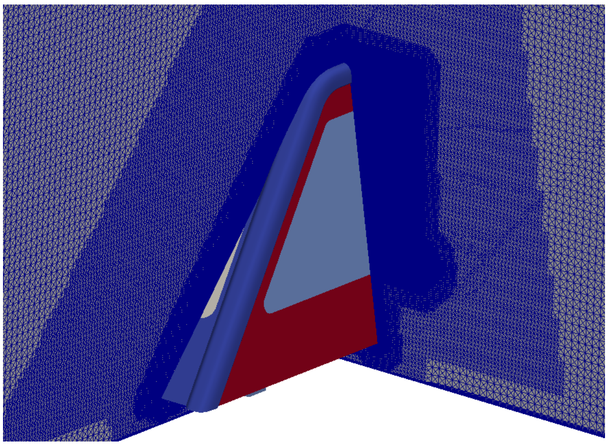

Fig. 6 – CFD mesh size around window

Final mesh consisted of around 58 Million volume cells. Cells are predominantly perfectly hexahedral, deformed only to accommodate wall-adjacent layers to capture the boundary layer, resulting is a very high quality mesh with average non-orthogonally of *** and a maximum non-orthogonality of 65 degrees. Before proceeding to the transient simulation to obtain pressure fluctuations, a steady-state simulation was performed to stablish a meaningful flow field and to reduce the required time for the transient flow to wash-out any start-up effects. This steady state simulation started from potential flow, run for 500 iterations in first order, and the rest in second order.

The transient simulation started from the latest steady state results with IDDES turbulence model, to be able to simulate the flow structures that cause variations in pressure at the walls (i.e. vortices and eddies). Transient simulation was run for 0.5 seconds, recording surface pressure for the last 0.4 seconds. The first 0.1 seconds of simulation the flow did not show stable fluctuations, hence none of this initial data was used for the aero-vibroacoustic simulation. Simulation was done at rescale (www.rescale.com) computers, with 128 CPUs.

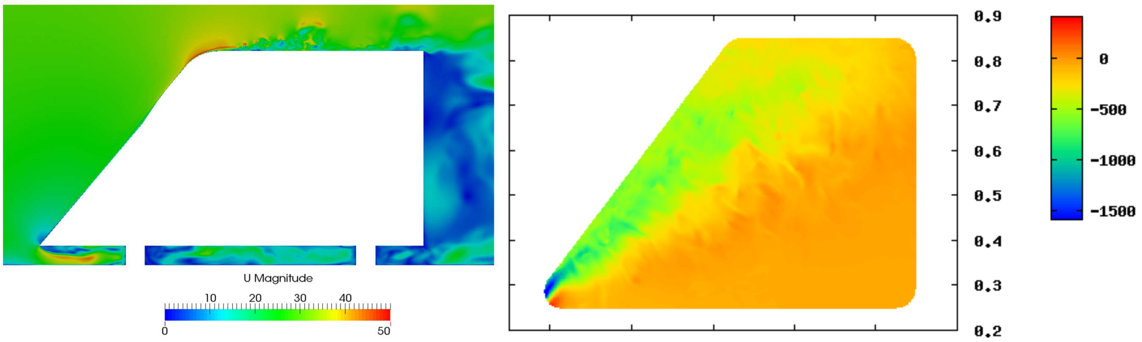

Fig. 7 – Left: flow velocity around the studied stucture. Right: Fluctuating pressure on the side glass

At the end, FSP at the A-Pillar, and side walls was exported to VAOne, for the acoustic processing.

4 VALIDATION OF AVA MODEL

Three different cases were studied. Case 0 has no mirror and a rounded A-Pillar front section. Case 1 has no mirror and a sharp front edge A-Pillar and finally Case 2 has side mirrors on both sides and the A-Pillar of case 0 (see figure 8).

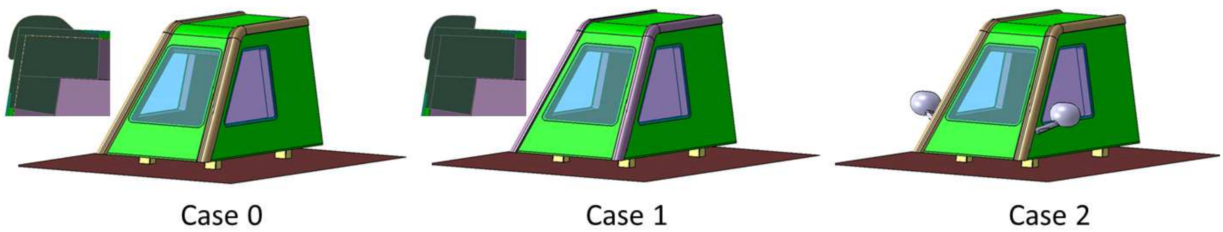

Fig. 8 – Case 0,1 and 2 geometry studied

The interior SPL was measured and predicted at 2 microphone locations as illustarted in figure 9.

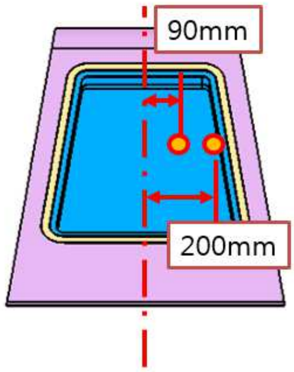

Fig. 9 – Two microphone locations: Mic1 is closest to the side glass

The following presents the results for the 3 cases studied. Each graph includes the contribution from the convective and acoustic component as computed according to the computation scheme described in figure 2. Results are consistent with expectations. A better correlation would be possible if more time and effort can be invested in validation of the vibro-acoustic model alone. This constitutes the weak part of this work since no time and limited experimental data were available during this benchmark.

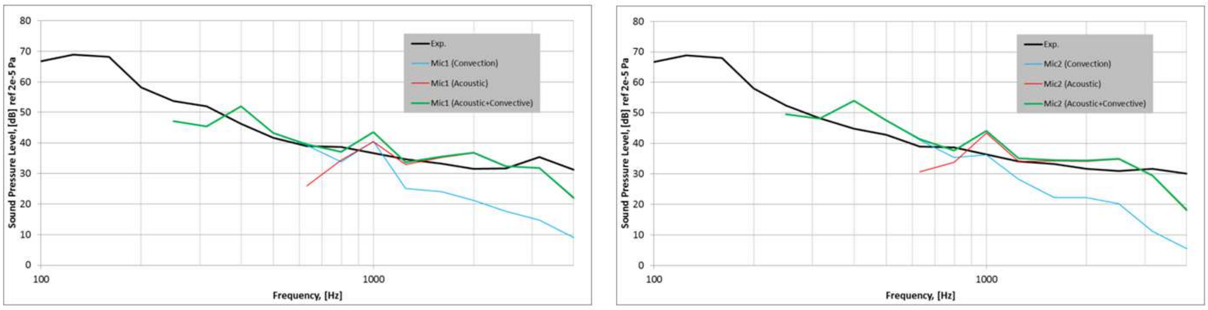

Fig. 10 – Interior SPL at mic1 and mic2 for Case 0

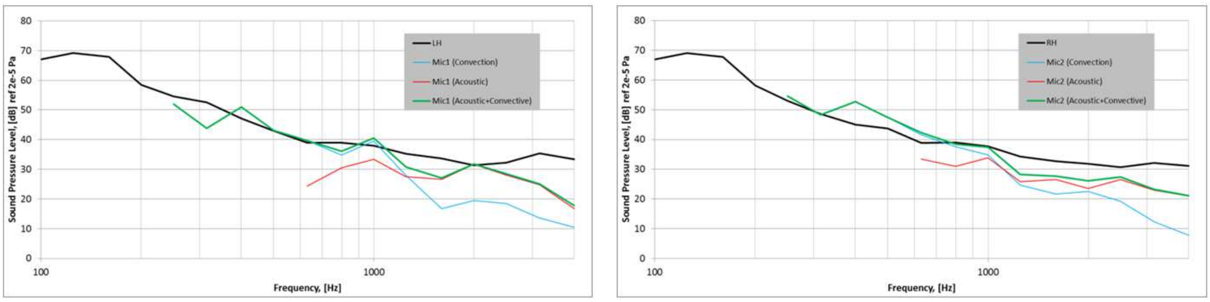

Fig. 11 – Interior SPL at mic1 and mic2 for Case 1

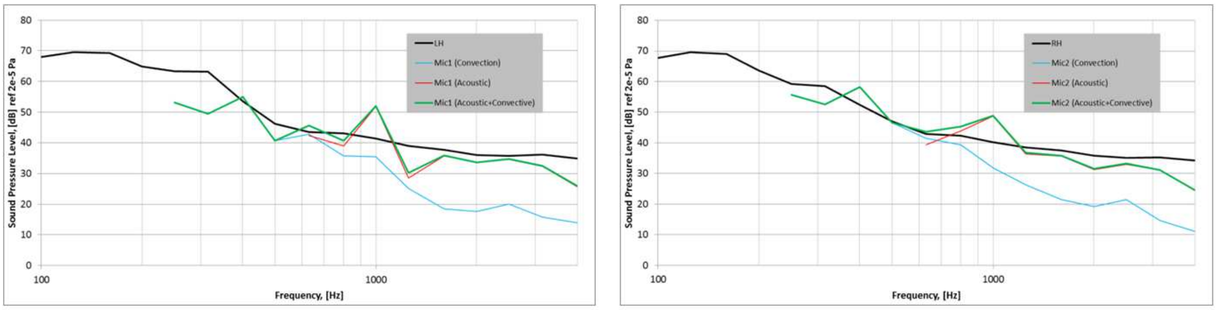

Fig. 12 – Interior SPL at mic1 and mic2 for Case 2

4 CONCLUSIONS

This paper has presented recent results obtained in the framework of the benchmark BMT 4 requested by Hyundai Motor Corporation. Results shown are in line with expectation considering the time, effort and budget available to generate these predictive results. This paper has shown that it is possible to coupled CFD incompressible with a VA model using the Curle formulation with BEM.

6 REFERENCES

1. Blanchet, D., and Golota, A., “Predicting automotive wind noise using various methods: latest results ”, SAE N&V, Grand Rapids, USA, 2015,
2. VA One 2014, The ESI Group. http://www.esi-group.com
3. Blanchet, D., Golota, A., Almenar, R. Lim, J. Combining CFD/FEM/BEM/SEA to Predict Interior Vehicle Wind Noise – Validation Case Hyundai BMT4, KSNVE, Spring 2014