

Prediction of Interior Noise in a Sedan Due to Exterior Flow

Alexander Schell
Daimler AG

Vincent Cotoni
CD-adapco

ABSTRACT

Aero-vibro-acoustic prediction of interior noise associated with exterior flow requires accurate predictions of both fluctuating surface pressures across the exterior of a vehicle and efficient models of the vibro-acoustic transmission of these surface pressures to the interior of a vehicle. The simulation strategy used in this paper combines both CFD and vibro-acoustic methods. An accurate excitation field (which accounts for both hydrodynamic and acoustic pressure fluctuations) is calculated with a hybrid CAA approach based on an incompressible unsteady flow field with an additional acoustic wave equation. To obtain the interior noise level at the driver's ears a vibro-acoustic model is used to calculate the response of the structure and interior cavities. The aero-vibro-acoustic simulation strategy is demonstrated for a Mercedes-Benz S-class and the predictions are compared to experimental wind tunnel measurements.

CITATION: Schell, A. and Cotoni, V., "Prediction of Interior Noise in a Sedan Due to Exterior Flow," *SAE Int. J. Passeng. Cars - Mech. Syst.* 8(3):2015, doi:10.4271/2015-01-2331.

INTRODUCTION

Wind noise is becoming increasingly important for automotive development due to significant reductions in road and engine noise. For many vehicles, wind noise is the dominant contributor to interior noise at higher vehicle speeds. Small changes in the exterior shape of a vehicle can sometimes result in significantly different levels of interior wind noise. For external aerodynamics, the impact of changes in the exterior shape can, in principle, be evaluated using clay models in wind tunnel tests. However, such models cannot be used for assessing interior noise. Furthermore, due to cost reductions and shorter development cycles clay models are often not available at the point at which design decisions need to be made about vehicle shape. In order to predict the impact that early development design changes to the shape of a vehicle have on interior noise it is essential to have validated simulation methods. In some instances it is possible to investigate the effects of design changes by only considering the exterior sources in the flow. However in most problems, the computation of the interior acoustic response at the driver's ear is also needed in order to evaluate different design changes.

A numerical model for interior wind noise requires two main ingredients: (a) an accurate description of the excitation field applied to the exterior of the vehicle and (b) a vibro-acoustic model of the main transmission paths from the exterior of the vehicle to the driver's ear. The frequency range of interest, and vibro-acoustic analysis methods used, vary depending on the region and source of interest. For example, noise transmitted through the side glass is often a dominant contributor to interior wind noise from 1 - 5 kHz. A typical side glass only has a few hundred structural modes below 5

kHz and is therefore well described using Finite Elements (FE). The excitation applied to the side glass from the flow is typically spatially inhomogeneous and the side glass exhibits transmission characteristics that depend on the details of individual structural modes. Such transmission characteristics are difficult to describe using Statistical Energy Analysis (SEA) due to the averaging of detailed modal properties inherent in the method. However, across the frequency range of interest, the interior cavity and sound package of the vehicle typically exhibit short wavelength behavior that is difficult to describe efficiently using deterministic methods such as FE. SEA is therefore better suited for describing the short wavelength reverberant response of the interior cavities. The use of different vibro-acoustic methods for different physical regions is therefore used in the current approach.

An accurate prediction of fluctuating surface pressures also requires an accurate model of the flow over the exterior of the vehicle. The fluctuating surface pressures typically consist of distinct concentrations of energy at convective and acoustic wavenumbers which can be analyzed by their wave-number-frequency spectra [1]. For side glass noise, the acoustic wavenumbers are often the dominant contributor to interior noise despite being much lower in level than the convective wavenumbers [2].

In order to avoid the difficulties associated with a direct noise calculation [3, 4] (e.g. disparity of scales, disturbances and acoustic reflections at boundary conditions and mesh transitions, hydrodynamic masking of acoustic near field content) it is useful to instead describe the contributions to convective and acoustic surface pressures separately by using an acoustic analogy [5]. Due to this

separation no backward coupling of the acoustics to the flow field is considered which might be for instance necessary to capture resonant buffeting phenomena but is negligible for side mirror noise. Increases in computational resources have made it feasible to implement such hybrid Computational Aero-Acoustic (CAA) strategies using a variety of numerical approaches such as FE, Finite Volume (FV), Finite Differences (FD) or Discontinuous Galerkin (DG) techniques, beside the original integral methods. Regardless of the numerical discretization used, the most important requirement for a hybrid CAA is that it can provide a self-contained acoustic solution to describe the acoustic near field for the vehicle exterior. Volume based hybrid CAA approaches can be implemented in the frequency domain (typically using a CFD code combined with a standalone aero-acoustic code). However, such frequency domain acoustic analogies are typically not practical for side glass applications because of the requirement to store and process large amounts of time domain volume data (this can lead to the exterior aero-acoustic analysis taking longer than the original CFD analysis [4]). A more efficient approach is to embed a time domain acoustic analogy into a flow code and make use of the HPC architecture of the flow code when designing this acoustic analogy.

The current paper describes the full aero-vibro-acoustic simulation process applied to side window noise (since this is one of the most important transmission paths for mid and high frequency wind noise). First, the hybrid CAA and vibro-acoustic analysis methods are discussed in more detail. In a second part, the experimental setup as well as the aero-acoustic and vibro-acoustic model of a Mercedes-Benz S-class are presented. Finally the results of the simulation strategy are discussed, including the validation of the three-dimensional flow field in the wake of the side mirror and the A-pillar vortex. The results give insights into the exterior acoustic field and the origins of acoustic waves responsible for the side window excitation. The models are validated by comparing the predicted interior noise levels with those obtained through wind tunnel measurements.

METHODS

Hybrid CAA

The hybrid computational aero-acoustic calculation used in this study is based on an incompressible Detached Eddy Simulation (DES), meaning the solved unsteady pressure fluctuations contain no acoustic information. By using a DES the advantages of a Large Eddy Simulation (LES) and an unsteady Reynolds Averaged Navier-Stokes simulation (URANS) are combined. Within the LES region, which requires a highly resolved mesh, the turbulent flow structures and acoustic source mechanisms can be captured accurately. The unsteady RANS part reduces the computational effort and enables the usage for larger industrial applications.

In order to design a suitable acoustic near field analogy one has to follow Lighthill's original idea [5] in calculating equivalent noise sources which can be subsequently used in a wave equation:

$$\frac{\partial^2 p'}{\partial t^2} - c_0^2 \nabla^2 p' = \frac{\partial^2 T_{ij}}{\partial x_i \partial x_j} \approx \rho_0 \frac{u_i u_j}{\partial x_i \partial x_j} \quad (1)$$

Unfortunately Lighthill's equation solves rather a total pressure than an acoustic pressure in the acoustic near field as long as source terms are present [7]. But certainly in the vicinity of the side glass due to the mirror wake and A-pillar vortex strong source terms are present. To get rid of the hydrodynamic pressure fluctuations which mask and can distort the acoustic near field content [3] recent approaches use a splitting of variables into hydrodynamic/acoustic [7, 8] as well as thermodynamic parts [9].

In the same way the pressure fluctuations p' can be separated into hydrodynamic p^{inc} and acoustic p^a perturbations. Applied to Lighthill's equation one can form a wave equation for the acoustic pressure:

$$\frac{\partial^2 p^a}{\partial t^2} - c_0^2 \nabla^2 p^a = - \frac{\partial^2 p^{\text{inc}}}{\partial t^2} \quad (2)$$

The source term on the right hand side reduces to the second time derivative of the incompressible pressure fluctuations since the poisson's equation for the incompressible pressure is fulfilled [10].

This wave equation is implemented in the STAR CCM+ software package [11] and can be executed on-the-fly in time domain beside an incompressible CFD. To limit data transfer and avoid mapping influences, the incompressible flow, the acoustic source terms and the exterior sound propagation are calculated on the same mesh at each time step. The main advantage of this strategy is that the interpretation of the results is much easier as hydrodynamic and acoustic solutions are obtained separately.

Vibro-acoustics

The vibro-acoustic model used in the current analysis consists of a FE side glass meshed with QUAD8 shell elements and a series of SEA acoustic cavities to model the interior acoustic spaces of the vehicle. Model setup and calculations were done with the commercial vibro-acoustic software wave6 [12]. To obtain the parameter for the vibro-acoustic simulation various measurements were carried out and post-processed. The vehicle analyzed in the current study has a tempered side glass and so a uniform thickness physical property was applied to the elements of the side glass. The damping of the side glass was obtained by post-processing mobility measurements performed on an in-situ glass. A frequency dependent glass damping was then used in the model.

The interior cavity absorption could, in principle, be predicted by including information about the vehicle sound package. However, in the current analysis the cavity absorption was obtained by performing various T60 tests inside the vehicle. The frequency dependent absorption spectra were then applied to the various SEA cavities.

The fluctuating surface pressures obtained from the hybrid CAA analysis were post-processed and converted to the frequency domain within the vibro-acoustic software. It should be noted that the analysis process described in this paper does not require the fitting of any semi-empirical loads to the fluctuating surface pressure data but instead retains a detailed spatial description of the load. The use of semi-empirical loads homogenized over various spatial regions was found to be not sufficiently accurate to describe changes in interior noise associated with typical design changes.

MODEL SETUP

The aero-vibro-acoustic simulation strategy is applied to a Mercedes-Benz S-class. In order to allow a detailed comparison of experimental and simulation results all three models - experimental, aero-acoustic and vibro-acoustic model - have to be built up in the same manner.

Experiment

The experimental tests were performed in the FKFS aero-acoustic wind tunnel at the University of Stuttgart. All measurements of the unsteady flow topology and interior noise refer to a free stream velocity of $U_0 = 140$ kph and a signal length of 30 s. The experimental setup is illustrated in [figure 1](#).



Figure 1. Mercedes-Benz S-class with blocked underbody flow and interior noise measurement at the driver's ears

As the simulation strategy in this paper concentrates on side mirror noise transmitted through the side glass it has to be ensured that all other transfer paths to the interior are eliminated in the experiment. For the current vehicle the contribution from other glass panels in the vehicle were found to have a minor influence at the driver's ear position (particularly when free-field microphones were used instead of an artificial head). To reduce the low/mid frequency contribution from underbody sources a wooden skirt blocks the complete underbody flow avoiding the generation and transmission of noise sources there. In addition all relevant gaps and sealings are taped and cooling air flow is eliminated.

The experimental test considers two different side window panels:

1. A stiff aluminum panel equipped with 8 flush mounted surface microphones (Brüel & Kjær, type 4949) to capture the flow topology of the A-pillar vortex and the mirror wake over the side window.
2. A 4.85 mm tempered side glass (ESG) for interior noise measurements

Aero-Acoustic Model

The S-class CFD/CAA model is presented in [figure 2](#) and is set up similar to the experimental model concerning no cooling air and underbody flow. Due to the fact that the same mesh is used for the incompressible CFD as well as for the acoustic source term calculation and sound propagation the model has to regard all aspects: a proper solution of the hydrodynamic flow structures especially in the regions of interest and the possibility of a sufficient less dissipative sound transport.

The computational domain extends to 55 m length, 30 m width and 30.36 m height. Since the aero-acoustic results concentrate on the side glass proximity only a half model is carried out to reduce the total amount of cells. One advantage of the hybrid approach is the definition of different boundary conditions at the same boundaries. While it is necessary to have a symmetry boundary condition for solving the flow field of a half model, a nonreflecting boundary condition can be applied independently for the acoustic wave equation.

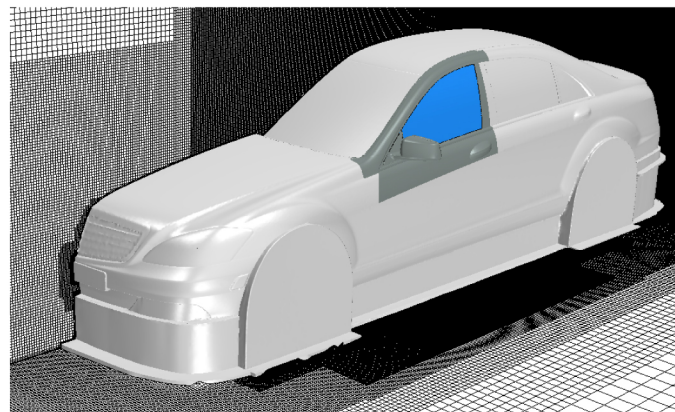


Figure 2. Hybrid CAA model of the Mercedes-Benz S-class with blocked underbody flow

Most of the cell count is applied to the highly resolved side window region marked as blue and grey in [figure 2](#) in order to capture the acoustic noise sources mechanisms up to high frequencies.

To limit the calculation of acoustic source terms to highly resolved regions and avoid the appearance of spurious sources which can occur at grid interfaces, a noise source weighting function is applied to the region of interest ([figure 3](#)).