

CFD/CAE Combinations in Open Cavity Noise Predictions for Real Vehicle Sunroof Buffeting

Fred G. Mendonca
CD-adapco

ABSTRACT

Though some practitioners consider the simulation process for sunroof and side window buffeting to be mature, there remain considerable uncertainties and inefficiencies as how in predictive methodologies to account for interior panel flexibility, vehicle structural stiffness, seals leakages and interior materials surface finish. Automotive OEMs and component suppliers rightly target flow simulation of open sunroofs and passenger windows with a view to reducing the severely uncomfortable low-frequency booming disturbance. The phenomenon is closely related to open cavity noise experienced also in other transportation sectors; for example in Aerospace, landing gear and store release cavities, and in Rail Transportation, cavities for HVAC intakes and the bogie environment.

Recent studies published by the author demonstrate that the uncertainties can be correctly quantified by modeling. This publication defines a hierarchy of CFD/CAE based methods which overcome many of the a-posteriori tuning of simulations based on experiment, and considerably improve the predictive nature and efficiency of the simulation process. The methods range from fully deterministic simulations to phenomenological models requiring standard experimental pre-qualifications of the acoustical response of the system. The former involves CAE-coupling of CFD (Computational Fluid Dynamics) to CAA (Computational Aeroacoustics) and to CSM (Computational Structural Mechanics). The latter incorporates new correlation models published here for the first time.

CITATION: Mendonca, F., "CFD/CAE Combinations in Open Cavity Noise Predictions for Real Vehicle Sunroof Buffeting," *SAE Int. J. Passeng. Cars - Mech. Syst.* 6(1):2013, doi:10.4271/2013-01-1012.

INTRODUCTION

Sunroof buffeting and cavity resonance predictions for rigid sealed structures and clean surface finishes are widely accepted as being representative and accurate in terms of the absolute deciBel (dB) noise level experienced by the vehicle occupants. The volume of the vehicle cavity uniquely determines the acoustic resonance frequency, typically in the range 15-30Hz. It is excited by the unstable shear layer which sheds coherent vortex structures over the open sunroof or front/rear window open aperture, at a frequency in the same range, and which is linearly proportional to the vehicle speed. At a certain vehicle speed (range), the vortex shedding locks-in on the cavity natural frequency causing a maximization of the booming noise dB level. Flexible interior panels and non-stiff (compliant) structures can change the cavity volume's natural resonant frequency. Interior surface material finish increases the acoustics damping response. The HVAC system, doors and boot/trunk seals introduce leakages which affect the passage of flow inside the vehicle and interact with the oscillating shear-layer shedding mechanisms. All these factors can change with the age of the vehicle.

Several predictive studies have quantified these mechanisms. One of the earliest reports of the use of CFD for interior vehicle and open sunroof leakage effects dates back to Lee (2002), which helps to quantify the experimental observations by Großmann (1996, 2010). Mendonça (2003) and Allen (2004) were one of the first to demonstrate the importance of Large Eddy Simulation (LES-based) turbulence modeling for cavity flows over a wide range of Mach numbers from low subsonic, through transonic to supersonic free-stream conditions. Read (2005) later showed that the hybrid approach to aeroacoustics could be used to combine the flow excitation mechanisms with the damping effects of the materials used for seating and flooring. The experiments performed by the Aeroacoustics Consortium of German Automotive companies and published by Islam (2008) showed clearly that the flexibility, or compliance, of the interior paneling resulted in a change in the lock-off behaviour characterized by the dB-speed curve. Mendonça (2011) later demonstrated how fully-coupled fluid-structure interaction (FSI) can correctly simulate the aeroacoustic effect of flexible panel compliance at these low frequencies.

There continues some debate as how best to represent flexible-panel compliance. Therefore, this paper repeats some of the key findings of the previous studies for completeness, and espouses new correlations to help to increase the efficiency of modeling process. A hierarchy of methodologies is enumerated, and applied to test vehicle programmes which have been previously and recently released to the public domain. All modeling reported here was performed with the commercial CFD code STAR-CCM+ v7, 2012.

In the following sections, the key phenomena in buffeting are discussed, starting with cabin resonance/shear layer instability lock-in, and continuing with wall compliance effects on the cabin acoustical environment. A hierarchy of predictive methodologies is enumerated, including measures to include wall compliance and acoustical impedance effects. These include assessments of the acoustics response of the virtual vehicle via a frequency response test (FRET), fluid/structural acoustical interaction, and the use of empirically based acoustic corrections and damping correlation.

KEY PHENOMENA IN SIDE-WINDOW AND SUNROOF BUFFETING/WIND-THROB

Cabin Resonance/Shear Layer Lock-In

The shear-layer oscillation frequency, which is driven by vortex shedding from the unstable shear layer over the open aperture, increases linearly with vehicle speed. Interaction of the shed vorticity with the aperture trailing edge creates acoustic pressures waves, which propagate inside the passenger compartment. The passenger compartment and open aperture constitute a Helmholtz resonator. If the frequency of the shear-layer oscillation corresponds with the frequency of the Helmholtz resonance, then lock-in occurs and the flow-acoustic feedback causes the noise intensity to be maximized (throb). The resonant frequency of the passenger cavity relates closely to the natural frequency of a Helmholtz resonator, f_0 (Hz), which can be approximated as follows;

$$f_0 \approx \frac{a}{2\pi} \sqrt{\frac{A}{Vol.(l + \Delta l)}} \quad (1)$$

where, a is the speed of sound (m.s^{-1}), A (m^2) is the area of the aperture, $(l + \Delta l)$ is the length + correction factor of the resonator neck (m), and Vol is the volume of the cavity (m^3).

The frequency, f_c (Hz), of the shear-layer oscillation referred to by Inagaki (2002) can be approximated as follows

$$f_c \approx C.V \quad (2)$$

where V is the vehicle speed (m.s^{-1}) and C is a constant,

$$C = \frac{1}{3L} \left(N - \frac{1}{4} \right) \quad (3)$$

where N takes an integer value 1, 2, 3 ... etc., representing the shedding mode (number of vortices present in the length, L (m)) sometimes also referred to as Rossiter cavity modes in higher Mach number flows.

Inagaki (2002) and Caro (2005) showed for simple cavities that the phenomenon of noise intensity maximization can only be reproduced in CFD by including compressibility in the modeling; that is, requiring the solver to be able to propagate pressure waves at the local speed of sound even though the flow is formally in the so-called incompressible regime (Mach number less than 0.3 everywhere).

The lock-in phenomenon can be observed in Figure 1, taken from Islam (2008), in the form of a maximization of the overall Sound Pressure Level (OASPL) at the vehicle speed between 60-70kph. The lock-off velocity is therefore considered to be the velocity at which the deciBel level sharply reduces with increasing vehicle speed (between 80-90kph in Figure 1). Lock-off occurs as a result of unequal shear-layer / cabin-resonant frequencies and/or breakdown of oscillating shear-layer into strongly turbulent flow for which the modal frequencies expressed by equations (2) and (3) no longer apply.

Compliance Due to Flexible Walls

Islam (2008), representing the collective efforts by the German Aeroacoustics Consortium (GAC) of Automobile Manufacturers, performed a series of experiments on the SAE Body modified to include a sunroof and passenger cabin volume. In the conclusion to the experimental study, they noted that the aeroacoustic buffeting noise levels at the driver's ear location were significantly affected by the flexible panels in the model. Figure 1, therefore, also shows the effect of 'compliant' walls in the vehicle interior.

The baseline case most closely represents a rigid, non-compliant structure, comprising stiff aluminium panels everywhere. Here we observe a lock-in peak at ~70kph and lock-off at ~90kph. Replacing a floor panel with a material of lower density and Young's Modulus causes the lock-off velocity to reduce to ~85kph. Similarly, replacing a roof panel causes a further reduction in the lock-off velocity to ~80kph, but also a reduction in the lock-in peak velocity to ~60kph. The latter indicates that the overall acoustics response of the system significantly changes with flexible panels.

Acoustical Attenuation, Surface Admittance/Impedance and Cabin Leakage Effects

We see, therefore, that the system-wise acoustics response is a combination of many factors; wall compliance, but also surface finish and leakage flows to/from other interior cavities such as the trunk volume, HVAC ducts and imperfect exterior seals, Großmann (1996).

A standard experimental is used to characterize the acoustic response of the cabin environment. This acoustic test

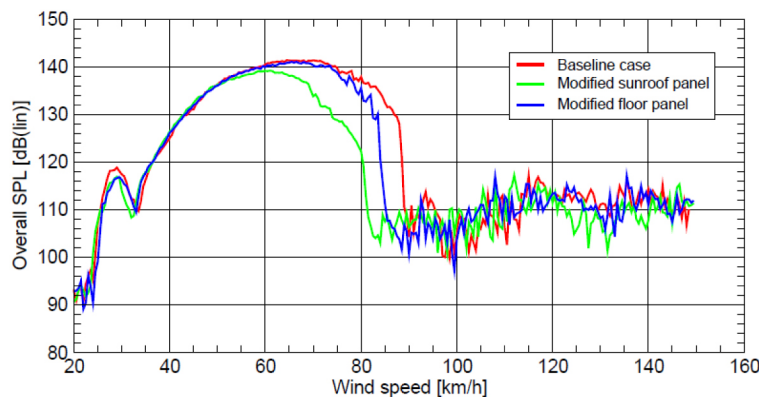


Figure 1. Buffeting behaviour of the generic SAE body with sunroof and passenger compartment, comparing the baseline configuration (aluminum structure) with modified sunroof and floor panels - taken from Islam (2008)

measures the pressure-time variation, $p_{exp}(t)$, at any representative location inside the cabin volume following the imposition of an artificial acoustical disturbance. The measurement identifies two key system features; its natural frequency and acoustical damping, summarized by

$$p_{exp}(t) = M_{exp} e^{-\alpha t} \cos(\omega_n t) \quad (4)$$

where M_{exp} represents the magnitude of the initial disturbance (Pa), the exponent α is the damping coefficient, ω_n is the natural frequency of the system (rad/s), and t , the time (s) following the initial disturbance.

α and ω_n are the complete set of system characteristics which incorporate all the real vehicle effects enumerated above, except external leakages.

Großmann (2010) separately deals with external leakage effects, experimentally correlating the mean leakage mass-flow, $\dot{m}$, to the mean pressure coefficients difference, dC_p , between outside and inside the vehicle.

$$\dot{m} = a \cdot q^k \cdot (dC_p)^k \quad (5)$$

Here, q is the dynamic pressure head (Pa), incorporating the square of the vehicle velocity, k is an experimentally determined exponent quoted as 4/7, and a is an experimentally determined constant of proportionality. This phenomenological model is likely to be imperfect for two reasons; there is a large error-band in the value of dC_p depending on the nature and location of the actual leakage, and because the leakage phenomenon is inherently transient due to fact that the interior pressures are oscillating through the buffeting cycle. The instantaneous leakage magnitude and direction are likely to change significantly from the mean value implied.

Therefore, explicit modeling of the leakage is recommended.

MODELLING THE KEY PHENOMENA

Virtual Frequency Response Test (FRET)

The exact counterpart of the experimental acoustic test is the virtual frequency response test, FRET. A virtual disturbance is applied inside the cabin environment of the CFD system, and the decay of pressure is measured as the initial disturbance partially propagates to the external environment, and partially resonates inside the cabin. The resonance then represents the natural frequency of the perfectly rigid CFD system, and the pressure decay represents the damping of the virtual system devoid of surface impedances, leakage volumes and other leakage paths.

Figure 2, at a few instants after the disturbance is imposed, shows the pressure distribution inside a generically shaped cabin environment and the spherical pressure wave propagation outside the sunroof aperture.

Figure 3 shows the pressure variation with time at a location inside the cabin representing the driver's ear location. The initial decay of the pressure amplitude determines the acoustic damping in this idealized CFD system. We also observe that standing waves are set up at the natural frequencies of this idealized system, $\sim 30\text{Hz}$ and $\sim 105\text{Hz}$ in this case.

In general, the damping and natural frequencies of geometrically idealized and perfectly rigid CFD system will not correspond to the experimentally measured natural frequency and damping of the equivalent real vehicle, for the reasons implicit in the idealization of the CFD model.

The difference between the experimental measurements and FRET gives rise to the ideal-to-real vehicle correlations which, as explained below, are applied to the CFD modeling and directly affect the SPL vs. speed curve.

Conversely, if the structural/material components of the system can be characterized in a suitable way, fully deterministic fluid-structure acoustical impedance simulations may be performed in one of two possible ways.