

Validation and Application of Digital Simulation for Improving Rear Side Window Buffeting of a Sedan

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ABSTRACT

In this paper we present the work which was done at Shanghai-VW for using computational aero-acoustic (CAA) simulation in the vehicle development process to assess and improve the buffeting behavior of a vehicle when the rear side window is open. In the first step, a methodology was established and validated against wind tunnel tests using a Sedan. The methodology consists of a calibration of the CAA model to represent the properties of the cabin interior of the real car in terms of damping, wall compliance and leakage followed by CAA simulations of the full vehicle at different wind speeds to obtain the transient flow field around the exterior shape and inside the passenger compartment. The interior noise spectra are directly calculated from the transient pressure inside the cabin. For validation, frequency and level of the main buffeting peak at different wind speeds were compared to respective measurements taken in the aero-acoustic wind tunnel of the Shanghai Automotive Wind Tunnel Center. After results with good accuracy were obtained, the simulation methodology was applied to evaluate the effect of various design changes on the buffeting behavior. The successful execution of the proof of concept type project showed that CAA simulation is a viable tool for assessing and improving the buffeting behavior of vehicles in the vehicle development process.

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INTRODUCTION

The improvement of the noise quality of vehicles has always been a major focus of vehicle manufacturers. The successful reduction of engine noise and tire noise has increased the relative importance of wind noise which is therefore much more noticeable by the passengers and often leading to customer complaints. A part of the wind noise problem is the buffeting effect which is occurring at certain driving speeds when the sunroof or a side window of the vehicle are open [1]. Buffeting is a flow induced low frequency resonance of the vehicle cabin volume and happens depending on the car type around 60 to 70 km/h [2]. Open sunroof buffeting has been studied for a long time and is therefore a well understood phenomenon. Effective counter measures like deflectors or partial opening of the sunroof to the comfort position have been developed by the industry and are accepted by the consumers. Studies of open side window buffeting have begun only in recent years because of the complexity of the flow and the related modeling requirements. While especially buffeting from an open rear window can be very strong compared to buffeting from an open front window [3], no effective counter measures have been developed.

Published studies are subdivided in active and passive control of the flow induced resonance [4]. Active control is implemented through air vents in the sunroof opening or through speakers in the car for generating an opposite phase sound waves to reduce or completely cancel the resonance. The active control method has not gained popularity due to complex installation, high cost and a number of other disadvantages. For the passive control method the most accepted solution are various types of deflectors for preventing the sunroof buffeting. This approach is however not accepted for rear side window buffeting. Solutions like additional holes or a beam in the middle of the window [5] are having big challenges from styling or technology point of view.

PROCESS IMPLEMENTATION AND VALIDATION

Theoretical Considerations

The cabin volume of a car with an open sunroof or side window acts as a Helmholtz resonator which can be described as a single degree of freedom mass-spring-damper system (Figure 1).

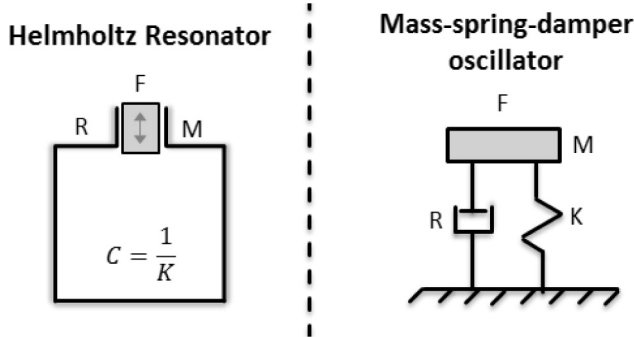


Figure 1. Helmholtz resonator (left) and equivalent mass-spring-damper oscillator (right).

When buffeting happens, the acoustics of the resonator couples with the outside flow over the opening. The free shear layer of the flow over the opening generates a periodic vortex shedding and acts as an excitation force. When the shedding frequency of the shear layer matches the resonance frequency of the Helmholtz resonator, the strong very strong resonance causes the loud buffeting noise. This is a two-way coupling between shedding and acoustic response as the vortex released from the front corner of the opening travels downstream, hits the rear corner of the opening from where a low pressure wave is traveling upstream which will in turn trigger the release of the next vortex from the front corner. The frequency of this periodic phenomenon is given by the equation

$$f = \frac{1}{3} \left(n - \frac{1}{4} \right) \frac{U}{h} \quad (1)$$

U and d are the upstream velocity and the opening length respectively, n is the number of vortices in the opening. The natural frequency of the Helmholtz resonator can be calculated by the following equation

$$f = \frac{c}{2\pi} \sqrt{\frac{A}{VL}} \quad (2)$$

where c is the speed of sound, and A , V , L are opening area, volume of the chamber and opening height respectively. For a vehicle the opening height should be modified by the equation $L = l + \delta L$, where l is the distance between the outer surface of the opening window and the auto-inner ornament, and $\delta L = 0.96\sqrt{A}$ [1].

NUMERICAL SIMULATION

The CFD/CAA simulations were using the commercial software PowerFLOW. The solver of PowerFLOW is based on the Lattice Boltzmann Method (LBM). Turbulence modeling is based on the Very Large Eddy Simulation (VLES) approach where non-isotropic eddies are supposed to be resolved and simulated while a two equation model based on an RNG formulation is applied to the isotropic and dissipative range of the turbulence spectrum. Further details of the numerical method and its application to open sunroof

buffeting can be found in [6]. Examples for the application of this numerical method to open side window buffeting have been presented in [7,8].

For the simulation model, a well facetized triangular surface mesh was generated from a detailed CAD model of the vehicle to represent the geometry of the vehicle (Figure 2). A very fine facetization was applied for A-pillar, mirrors and rear side window opening to accurately represent the geometry. The total number facets was 7.5 million. The automatically generated computational grid consisted of 70 million cubic cells (voxels). Local refinement areas with finest resolution of 1.5 mm cells were concentrated around critical flow regions, such as the wake regions after the A-pillar and the mirrors and the free shear layer over the opening area of the window (Figure 3).

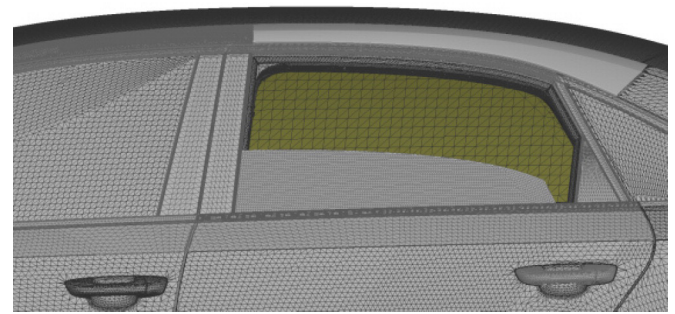


Figure 2. Surface mesh around the rear side window

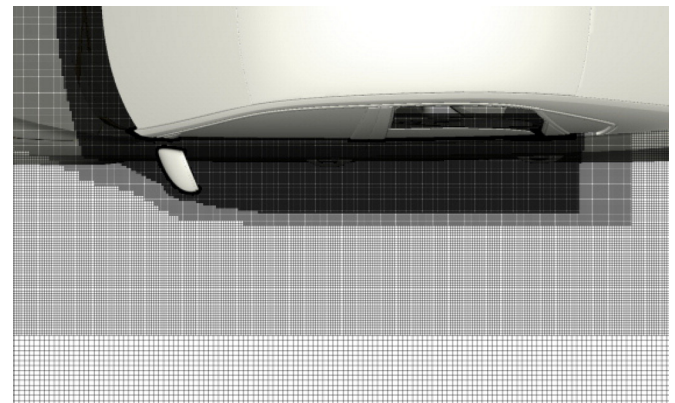


Figure 3. Computational grid with highest resolution concentrated near vehicle side area.

Several properties of the real vehicle which contribute to the damping properties of the Helmholtz resonator must be included in the digital model in order get a valid comparison between real world test and numerical simulation:

1. Wall compliance

The vehicle cabin is not a strictly rigid body and as a consequence it will slightly expand when under high inside pressure which lead to a smaller natural frequency and will also absorb energy resulting in a damping loss and thus lower buffeting SPL.

2. Damping

The interior trim of the cabin absorbs energy resulting in a damping loss and thus lower buffeting SPL.

3. Leakage

Leakage flow into the cabin will typically exit through the opening and thereby affect the behavior of the free shear layer.

A series of ART (acoustic response test) simulations is done to determine the acoustic properties of the simulation model and adjust these to match the properties of the real car.

Wind Tunnel Test

All testing was done at the test facilities of the Shanghai Automotive Wind Tunnel Center (SAWTC) at the Tongji University. The testing consisted of two major parts. The first part the acoustic properties of the vehicle with fully open rear side window, such as resonance frequency and cabin damping were determined in an Acoustic Response Test (ART). The second part consisted of a wind tunnel test where the cabin interior noise spectrum was measured for a series of wind speeds.

For the ART, white noise was played in the cabin until a stable sound field is reached. At the same time the sound signal inside cabin is recorded and from the spectral analysis of this signal the natural frequency is determined. In order to get the damping loss of the cabin, three microphones are placed inside the cabin. The transfer functions between the recorded signals are then used to calculate the damping loss factor. The obtained data for natural frequency and damping loss were later used to calibrate the resonance frequency and damping adjustment of the digital model.

In the wind tunnel test the vehicle was placed in the aero-acoustic wind tunnel of the SAWTC with open rear side window (Figure 4). The test was done for a series of different wind speeds (velocity sweep) and the noise signal was recorded at the driver's ear (Figure 5) and three other locations inside the cabin. The peak SPL level and its frequency were found to be independent of the microphone location and therefore only the driver's ear location will be used to show the results. The peak SPL numbers and their respective frequencies for the complete velocity sweep are shown in Table 1.

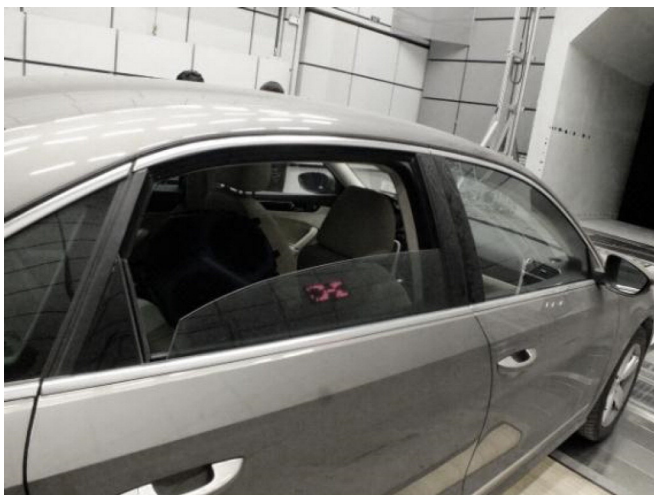


Figure 4. Vehicle with fully open rear side window in the wind tunnel.

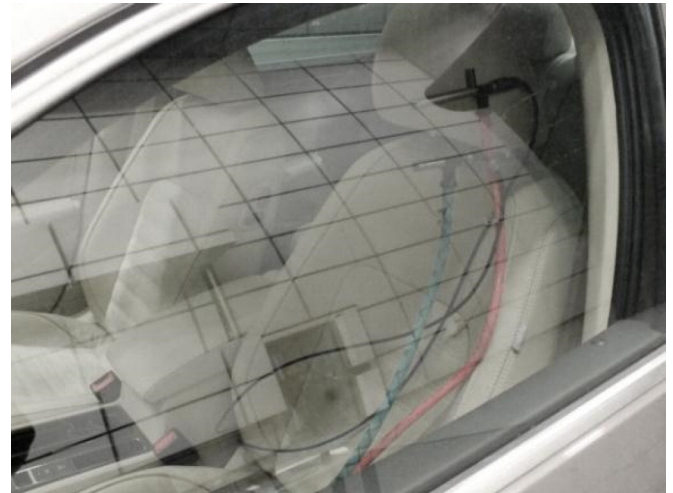


Figure 5. Microphone inside the cabin at the driver's left ear.

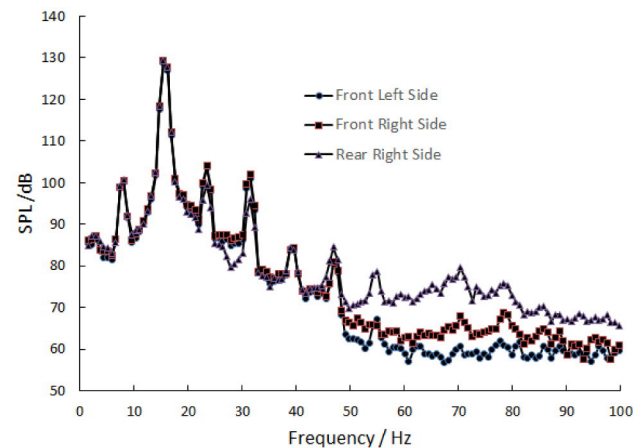


Figure 6. SPL spectra from recordings at different locations in the cabin at 90km/h.

Table 1. Measured SPL numbers and their respective frequencies at different wind speeds.

Wind Speed [km/h]	Peak SPL [dB]	Peak Frequency [Hz]
40	109.7	14.7
50	110.9	10.3
60	114.7	12.5
70	121.5	13.2
80	126.1	14.7
90	128.7	15.4
100	127.5	16.7
110	125.1	16.9

Simulation Results

In contrast to the situation for an open sunroof, the flow along the side of a car and the open rear window is highly influenced by turbulent wake regions for the A-pillar and the door mirror. As can be seen from Figure 7, these turbulent flow structures influence the top and the bottom of the rear side window while the middle area has rather smoothly attached flow. This flow area is seen to act as the main source for the buffeting [9].