

Assessment of Broadband Noise Generated by a Vehicle Sunroof at Different Flow Conditions using a Digital Wind Tunnel

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ABSTRACT

For the automotive industry, the quality and level of the wind noise contribution has a growing importance and therefore should be addressed as early as possible in the development process. Each component of the vehicle is designed to meet its individual noise target to ensure the wind noise passenger comfort level inside the vehicle is met. Sunroof broadband noise is generated by the turbulent flow developed over the roof opening. A strong shear layer and vortices impacting on the trailing edge of the sunroof are typical mechanisms related to the noise production. Sunroof designs are tested to meet broadband noise targets. Experimentally testing designs and making changes to meet these design targets typically involves high cost prototypes, expensive wind tunnel sessions and potentially late design changes. To reduce the associated costs as well as development times, there is strong motivation for the use of a reliable numerical prediction capability early in the vehicle design process.

Previous investigations have shown the possibility to use transient CFD/CAA simulations based on Lattice Boltzmann Methods to assess the wind noise performance of mirrors, wipers, underbody designs and buffeting performance of sunroofs and open side windows. This paper presents the use of this computational approach on two production vehicles to assess the broadband noise generated by a fully open sunroof. Computational predictions of mesh deflectors as well as yaw effect were validated against wind tunnel measurements. Also, detailed flow analysis was performed to understand the noise generation mechanisms and to explain the effect of the mesh deflector and flow yaw angle on the interior noise. Accurate prediction of the wind noise performance of the sunroof and the insight provided by the flow analysis proves that this computational approach can be used to make design decisions during the vehicle development process.

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INTRODUCTION

The study presented in this paper corresponds to the most recent outcomes of a collaborative project between Jaguar Land Rover and Exa Corporation. The main goal of this study was to develop a digital solution that can be used starting from early design stages to help address the main noise issues faced while designing a sunroof. Buffeting and sunroof broadband noise are the most common noise issues from a sunroof. Buffeting generally occurs at low speeds up to 80 kph and is characterized by strong noise levels over 120 dB at low frequencies, generally around 20 Hz. Use of deflectors is the most common practice followed in the auto industry to address sunroof buffeting. However, the addition of a deflector can create broadband noise which may become a significant noise issue at higher speeds for the frequency range of 400-6000 Hz. Therefore the broadband wind noise performance of deflectors should be evaluated when designing a deflector to address buffeting.

The prediction of the complex transient behavior (including vortex formation, shedding, and convection through the shear layer over the sunroof) is necessary for accurate broadband noise estimation and requires a compressible flow solution. Road vehicles experiencing sunroof broadband noise are in a regime of high Reynolds numbers, hence the flow is highly turbulent. These considerations make vehicle sunroof design a challenging problem in the CFD (computational fluid dynamics) and CAA (computational aeroacoustics) communities, especially with regard to predicting the severity of the problem for a given vehicle design and the effectiveness of various buffeting suppression options.

Details of the vehicle configurations used for this study and the experimental process are presented in the first section. CFD/CAA methods and the corresponding geometry are then presented in the second section. In the following sections, the paper focusses on assessing the sunroof broadband noise performance with no deflector (deflector down) and with the addition of a mesh deflector for two

sedan vehicles. The effect of yaw angle is also investigated and the noise inside the cabin is compared to the experiments. In each vehicle configuration, detailed flow analysis was completed to understand the noise generation mechanisms and provide an explanation of the mesh deflector and yaw effect.

EXPERIMENTAL SETUP DESCRIPTION

Two Jaguar cars, XJ (Sedan 1) and XF (Sedan 2), were tested experimentally to obtain data to validate computational predictions. Both Sedans are from the same era and therefore have a similar design; the main difference is the size of the sunroof which is larger on Sedan 1. The experimental work was performed at the Ford Merkenich aeroacoustic wind tunnel facility in Cologne, Germany (see Figure 1). For each vehicle, data sets for two sunroof configurations (see Figures 2 and 3) with deflector down and mesh deflector were obtained at different flow speed covering the velocity range between 40 and 120 kph. Four binaural heads, with microphones positioned at each ear location were used to take measurements of the noise inside the cabin. A total of 8 microphones were used to validate the numerical approach.



Figure 1. Tested Jaguar vehicles; (left) Sedan 1; (right) Sedan 2



Figure 2. Sedan 1 tested sunroof configurations; (Left) deflector down; (right) mesh deflector up



Figure 3. Sedan 2 tested sunroof configurations; (Left) deflector down; (right) mesh deflector up

NUMERICAL APPROACH DESCRIPTION

The CFD/CAA solver PowerFLOW 5.0 based on the Lattice Boltzmann Method (LBM) was used to calculate unsteady flow physics and the corresponding flow-induced noise generation and

radiation. Lattice-based methods are by nature explicit, transient and compressible, and are an alternative to traditional CFD methods based on the discretization of the Navier-Stokes equations and derived variations [1, 2, 3, 4, 5, 6]. The basic idea of LBM is to track the advection and collisions of fluid particles. Since the average number of particles in a representative volume of fluid far exceeds the compute power required to track them individually, the particles are grouped into an integer number of discrete directions with index i . The computation follows the particle distribution function f_i which represents the number of particles per unit of volume, also called voxel, at a specific time and location moving with velocity c_i . As in statistical physics, the flow variables such as density and velocity are determined by taking the appropriate moments, i.e. summations over the set of discrete directions, of the particle distribution function [7, 8, 9, 10, 11, 12, 13, 14, 15]. LBM is used and validated across many aeroacoustics applications such as automotive wind-noise [16, 17, 18], HVAC system noise [19], acoustics propagation [20-21], airframe noise [22-23] and sunroof buffeting [24, 25, 26, 27, 28, 29, 30, 31, 32]. Further details on LBM can be found in the cited references.

The CAD models used in the current computational studies are complete geometrical replicas of the experimental set up and are shown in Figure 4. The CFD simulations for this study were done by matching experimental wind tunnel conditions in the aeroacoustic digital wind tunnel. The inlet velocity was set at 100 kph. A variable resolution scheme was used in the simulations. Fine resolution was used in critical regions and the resolution was progressively coarsened away from the critical regions for computational efficiency. Simulations were executed for a physical time of 3 s. Measurements from the simulation were taken at a rate of 25 kHz for a duration of 1 s starting from 2 s. Both flow and acoustic fields are solved simultaneously.



Figure 4. Numerical Sedan 1 (left) and Sedan 2 (right)

For each sedan vehicle, two sunroof configurations were numerically assessed for the broadband noise. Deflector down and deflector up are considered (see Figures 5 and 6). The mesh deflector was used in both vehicles to address the buffeting phenomena. In the simulation, the mesh deflector is modeled as porous media and an experimentally measured pressure drop across the mesh deflector was used to obtain the porous media characteristics. For Sedan 1, 0° and 10° yaw were investigated for the mesh deflector configuration and for Sedan 2, 0° and 10° yaw were also investigated for both sunroof configurations.



Figure 5. Simulated Sedan 1 configurations; (left) deflector down; (right) mesh deflector



Figure 6. Simulated Sedan 2 configurations; (left) deflector down; (right) mesh deflector

SEDAN 1

Broadband Noise Analysis (0° Yaw)

Broadband noise was assessed on Sedan 1 for the fully open sunroof configurations with and without mesh deflector at 100 kph and 0° yaw angle. The third-octave SPL at four microphone locations are presented in Figures 7 and 8 for deflector down and up respectively. The microphones positioned at the left side of the vehicle are presented since they are typical of the overall performance.

The absolute dBA levels are well predicted compared to the experiment with an uncertainty of 3 dB for the frequency range of 400 to 4000 Hz. Above 4000 Hz there is a divergence between the prediction and experiment. Increasing mesh resolution of the model can improve this, however with a corresponding increase in computational expense.

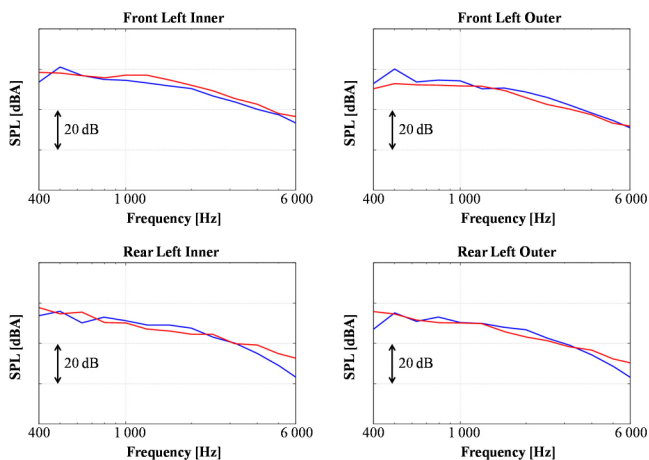


Figure 7. Deflector down SPL at four ears positions; (light red) experiment; (dark blue) simulation

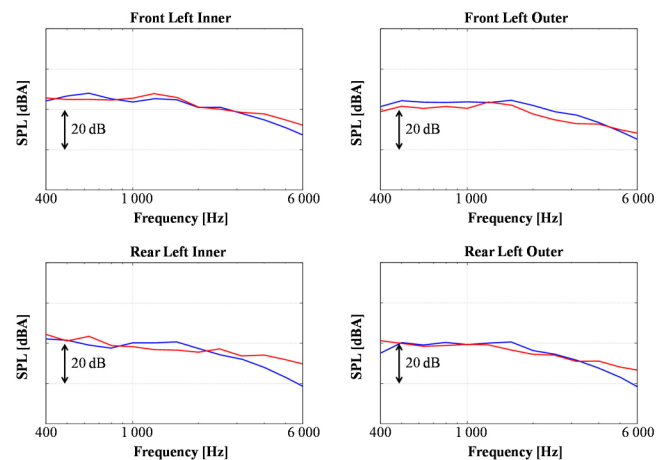


Figure 8. Deflector up SPL at four ears positions; (light red) experiment; (dark blue) simulation

In Figure 9, the effect of the mesh deflector is highlighted by both experiment and simulation. A significant noise reduction is observed:

- 15 dB of noise reduction at low frequencies.
- 3-5 dB of noise reduction at high frequencies.

The predicted numerical interior noise effect of the mesh deflector is satisfying. In the next sections, the focus will be limited to the usage of the numerical results to explain the observed noise reduction.

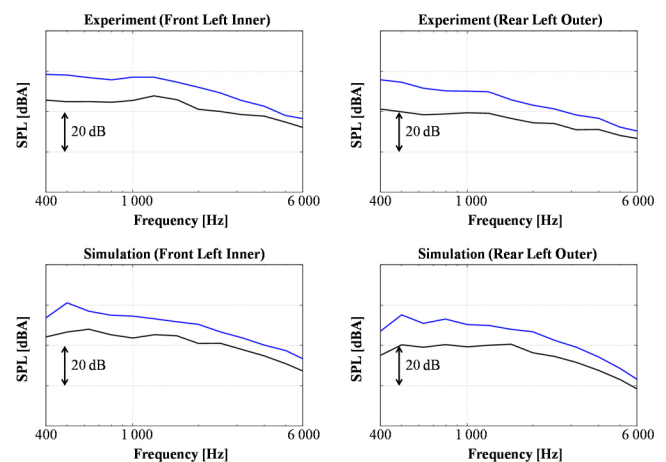


Figure 9. SPL at two ears positions; (top) experimental effect; (bottom) simulation effect; (dark blue) deflector down; (black) deflector up

Transient Flow Analysis (0° Yaw)

In order to understand the interior noise effect of the mesh deflector, the transient flow was investigated. Figures 10 and 11 show a snapshot of the core vortices colored by vorticity for both sunroof configurations. Figure 10 provides an overview of the main flow structures around the vehicle. The fluid volume for which numerical data is saved does not include the mirror regions, therefore, the mirror wakes are not shown in Figure 10. The following flow structures could be listed:

- Two vortices are generated from the front inlet grille. They mainly impact the windshield and are oriented to the roof corners. They are very intense at the front hood but progressively weakened before impacting the windshield.
- A strong shear layer develops over the sunroof.
- An A-pillar vortex develops and convects down the side of the vehicle. No interaction with the sunroof shear layer is observed.
- Cowl vortex.

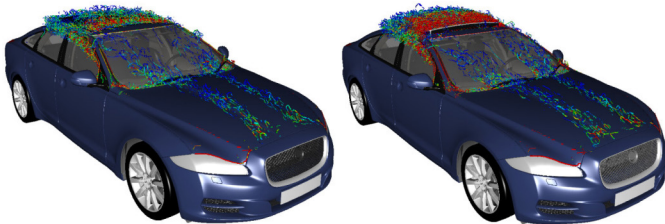


Figure 10. Core vortex colored by vorticity; (left) deflector down; (right) deflector up

In Figure 11, the focus is limited to the sunroof shear layer. The mesh deflector generates smaller and stronger vortices. The core vortex analysis provides a global picture of the main vortices around the sunroof. However, it is not sufficient to explain the mesh deflector noise reduction effect. Further transient flow analysis was required.

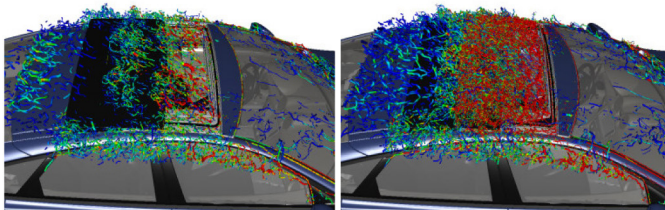


Figure 11. Vortex centerlines colored by vorticity; (left) deflector down; (right) deflector up

In Figures 12 and 13, the velocity magnitude and vorticity magnitude are shown for both deflector configurations on a vertical plane that cuts through the sunroof opening. The shear layer developed over the sunroof was different between the two configurations:

1. For the deflector down configuration, there is just one strong shear layer which is very coherent and contains large flow structures which strongly impact the trailing edge of the sunroof.
2. For the deflector up configuration, the shear layer is divided into two components. The first is developed on the top of the deflector due to the velocity gradient between the high flow speed over the deflector and the lower flow speed through its mesh. This shear layer corresponds to the wake of the deflector support. Strong flow structures are generated and propagated downstream. Unlike the deflector down configuration, most of these structures are deflected over the sunroof and are not impacting the trailing edge. The second shear layer develops on the bottom part of the deflector. It is generated by the velocity gradient between the flow through the deflector mesh and the low flow speed inside the cabin. This shear layer is less intense compared to the upper one.

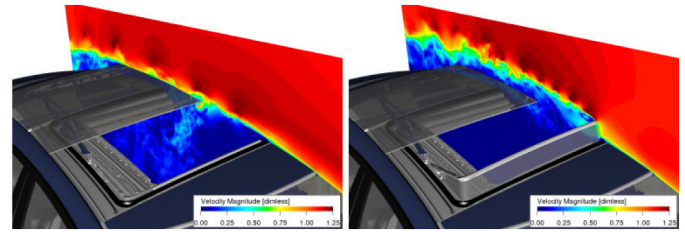


Figure 12. Snapshots of the transient velocity magnitude; (left) deflector down; (right) deflector up

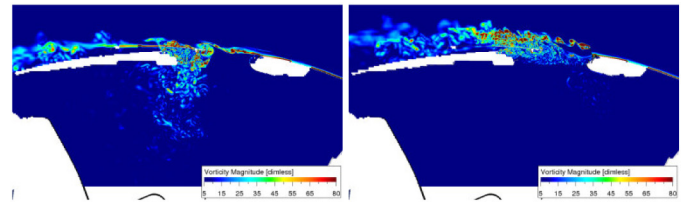


Figure 13. Snapshots of the transient vorticity magnitude; (left) deflector down; (right) deflector up

The instantaneous dilatation field is shown in Figure 14. This helps to differentiate between turbulent and acoustic field and provides a clear visualization of the propagated acoustic waves. Based on the apparent origin of these acoustic waves, it is inferred that the noise is radiated mainly from the trailing edge of the sunroof for the deflector down configuration and from the turbulence of the upper shear layer for the deflector up configuration (the motion and stretching of vortices are two noise generation mechanisms known to be strong aeroacoustic sources).

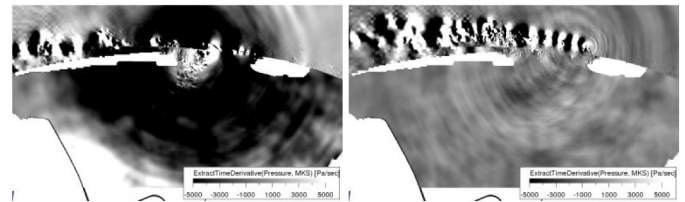


Figure 14. Snapshots of the dilatation field; (left) deflector down; (right) deflector up

This is also confirmed by the analysis of the 1000 Hz third octave SPL maps in Figure 15; even though the shear layer intensity is seen to be stronger in the mesh deflector case, fewer acoustic waves are propagated inside the cabin. The impact of the vortices on the trailing edge of the sunroof is shown to be the main noise source for the deflector down case. For the deflector up case, the shear layer is identified as the main noise source, however this source, and therefore the noise inside the cabin, could likely be reduced further by working on the shape and size of the bluff-bodied deflector support.

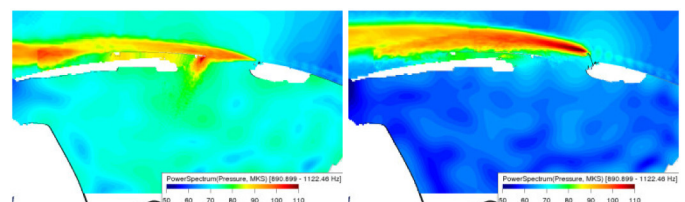


Figure 15. Plane SPL map for 1000Hz third octave band; (left) deflector down; (right) deflector up