

A Computational Approach to Assess Buffeting and Broadband Noise Generated by a Vehicle Sunroof

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ABSTRACT

Car manufacturers put large efforts into reducing wind noise to improve the comfort level of their cars. 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 designs are tested to meet low-frequency buffeting (also known as boom) targets and broadband noise targets for the fully open sunroof with deflector and for the sunroof in vent position. 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.

In the past, a computational approach based on a Lattice Boltzmann Method has been extensively validated for assessing 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 the Range Rover production vehicle to assess the sunroof buffeting performance with and without a mesh deflector added, which are commonly used to improve the buffeting performance. This approach was extended to assess the broadband noise generated by the deflector up and the sunroof at vent position. Computational predictions were validated against wind tunnel measurements for all these configurations. Also detailed flow analysis was performed to provide insight into the noise generation mechanisms. Accurate prediction of the wind noise performance of the sunroof and the insight provided by the flow analysis prove 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, also commonly known as cabin boom, is the most common noise issue from a sunroof, which generally occurs at low speeds up to 80 kph. It occurs when the transient characteristics of the shear layer over the sunroof (Rossiter mode) are able to excite the Helmholtz mode of the car cabin leading to a self-sustained oscillation of shear layer. Bi-directional coupling takes place between the flow over the opening and the acoustic response of the cabin leading to a lock-on of the excitation frequency of the vortices traveling over the sunroof to the resonance frequency of the cabin, for a certain velocity range. Quantitative prediction of the flow-excited resonance requires an accurate prediction of complex transient behavior including vortex

formation, shedding, and convection through the shear layer. The direct capture of the acoustic interaction requires a compressible flow solution. Road vehicles experiencing buffeting are in a regime of high Reynolds numbers and hence the flow is highly turbulent. These considerations make vehicle buffeting 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. Usage of deflectors is the most common practice followed in the auto industry to address sunroof buffeting. However, addition of deflectors creates broadband noise which becomes a significant noise issue at high speeds. Therefore the broadband wind noise performance of deflectors should be evaluated when designing a deflector to address buffeting.

Details of the vehicle configurations used for this study and the experimental process are presented in the first section. In the second section, the methods and the corresponding geometry are then presented in the

second section. In the following sections, the paper focusses on assessing the buffeting performance with no deflector (deflector down) and with the addition of a mesh deflector. The effect of flow speed on buffeting is investigated and the noise inside the cabin is compared to the experiments. Also the broadband noise of the same vehicle is assessed for mesh deflector up and vented sunroof configurations and compared to experiments. In each case, detailed flow analysis was completed to understand the noise generation mechanisms.

EXPERIMENTAL SETUP DESCRIPTION

The Range Rover SUV was tested experimentally to obtain data to validate computational predictions. The experimental work was performed at the aeroacoustic wind tunnel facility in Cologne, Germany (see Figure 1). Data sets for three sunroof configurations (see Figure 2) were obtained at different flow speed covering the velocity range between 40 and 120 kph. Four binaural heads, with microphones positioned at both ears location for each binaural head were used to take measurements of the noise inside the cabin. A total of 8 microphones were used to validate the numerical approach.

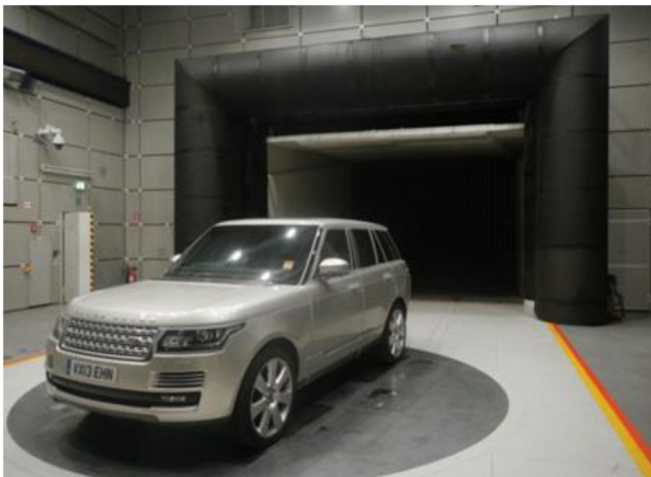


Figure 1. Tested Range Rover Vehicle



Figure 2. Range Rover sunroof configurations: (top left) deflector down; (top right) deflector up; (bottom) tilted sunroof

NUMERICAL APPROACH DESCRIPTION

The CFD/CAA solver PowerFLOW 5.0 based on the Lattice Boltzmann Method (LBM) is 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, 33, 34]. 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 as shown in Figure 3. Geometries of the microphones and cables inside the cabin were not included in the model because it was judged a minimal effect. However the binaural heads are modeled. The CFD simulations for this study were done by matching experimental wind tunnel conditions, in the aeroacoustic digital wind tunnel of the commercial software PowerFLOW 5.0. The inlet velocity was set at a value corresponding to the test. 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 1.5 s for buffeting and 3 s for broadband noise. Measurements from the simulation were taken at a rate of 25 kHz for a duration of 1 s starting from 0.5 s and 2 s for buffeting and broadband noise respectively.



Figure 3. Numerical Range Rover model

The configurations considered for this study (see Figure 4):

- Open sunroof with deflector down to assess the buffeting performance.
- Open sunroof with deflector up to assess the effectiveness of the deflector to suppress buffeting and the broadband noise generated by it.
- Tilted sunroof to assess the broadband noise

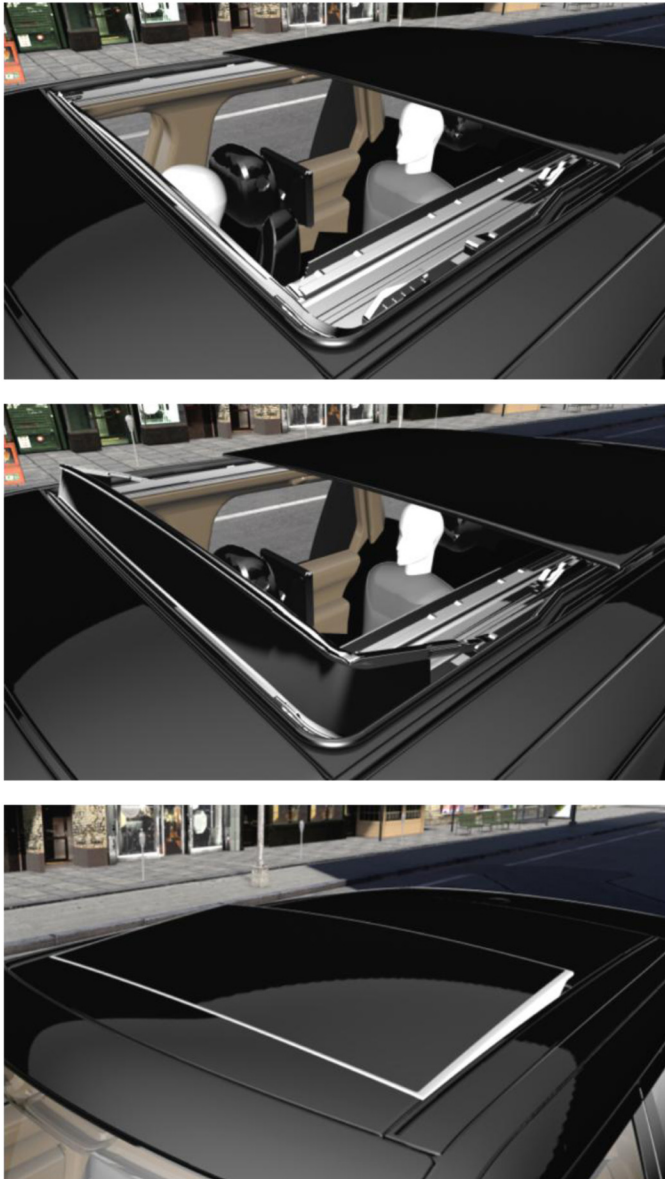


Figure 4. Simulated configurations: (top) deflector down; (middle) mesh deflector; (bottom) tilted sunroof

BUFFETING RESULTS

Deflector Down Analysis

Buffeting phenomena, as explained above, occurs when the Rossiter mode matches the Helmholtz mode of the cabin. The frequency and the dB level of the SPL (sounds pressure level) peak depend on many parameters. Absorption of the cabin components as well as the cabin

compliance need to be considered in the simulation to replicate the acoustic response of the cabin. Also all available geometry details of the sunroof opening and surroundings should be included to accurately predict the behavior of the shear layer.

Figure 5 shows the evolution of the maximum dB level of the interior cabin microphone when the speed varies between 50 and 90 kph. Both simulation and experiment are designating 70 kph to be the worst buffeting scenario. The buffeting frequency is also well predicted by the simulation within 5% of uncertainty as shown in Figure 6. For flow speeds higher than 70 kph, the buffeting is significantly reduced and disappears at 90 kph.

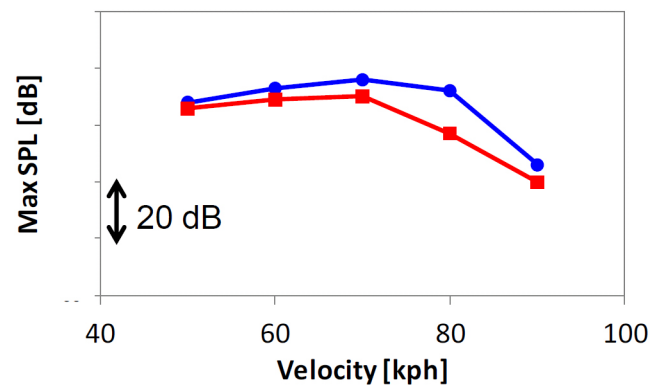


Figure 5. Velocity-SPL curves for deflector down: (red squares) experiment; (blue circles) simulation.

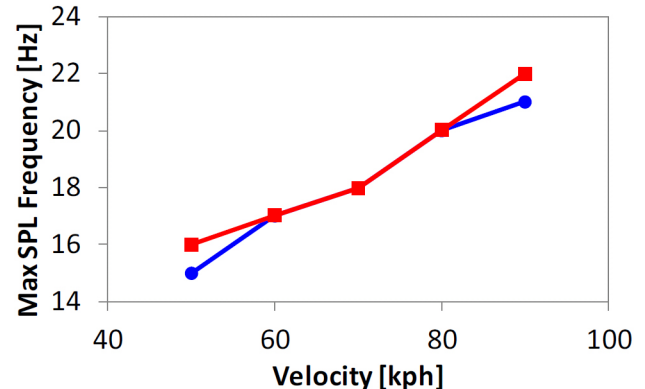


Figure 6. Velocity - Max SPL frequency for deflector down: (red squares) experiment; (blue circles) simulation.

Figure 7 shows a snapshot of the volume visualization of the core vortices. Red areas show intense vortices. Three different flow structures are highlighted:

- Sunroof shear layer: A strong single vortex is generated at the sunroof opening,
- A-pillar vortex: Developed around the A-pillar. A part of it is convected over the roof. No interaction is observed with the sunroof shear layer,
- Flow structure impact on the sunroof trailing edge: Small structures are generated after the crash of the large single vortex onto the trailing edge.