

A Numerical Study of Trailing Edge Serrations on Sunroof Buffeting Noise Reduction

Zhenyu Wang and Mei Zhuang
Ohio State University

ABSTRACT

A numerical study on sunroof noise reduction is carried out. One of the strategies to suppress the noise is to break down the strong vortices impinging upon the trailing edge of the sunroof into smaller eddies. In the current study, a serrated sunroof trailing edge with sinusoidal profiles of wavelengths is investigated for the buffeting noise reduction. A number of combinations of wavelengths and amplitudes of sinusoidal profiles is employed to examine the effects of trailing edge serrations on the noise reduction. A generic vehicle model is used in the study and a straight trailing edge is considered as a baseline. The results indicate that the trailing edge serration has a significant impact on the sound pressure level (SPL) in the vehicle cabin and it can reduce the SPL by up to 10~15 dB for the buffeting frequency. In addition, the transient flow field visualization and vorticity magnitude contours substantiate that the large shedding vortices are broken down into small eddies by using the serrated trailing edges. As a result, the SPL in the cabin is reduced. Furthermore the effectiveness of the trailing edge serrations is investigated for various freestream velocities. The results demonstrate that the trailing edge serration strategy is a promising solution for reducing automobile sunroof buffeting noise.

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INTRODUCTION

Sunroof noise is a very important aerodynamic noise source due to flow over an open sunroof. A strong shear layer over the sunroof the vortices shed from the leading edge impinging on the trailing edge of the sunroof are typical mechanisms related to the noise generation¹. Buffeting noise is the most common noise issue from a sunroof. It generally occurs when the transient characteristics of the shear layer over the sunroof are able to excite the Helmholtz mode of the car cabin leading to a self-sustained oscillation of shear layer². After many years of numerical, experimental and theoretical investigations, the phenomenon of buffeting was well characterized by its low frequency and high intensity³. However, it is difficult to give an accurate prediction of how severe the buffeting noise for the specific vehicle before a physical model of the vehicle is available⁴. In order to avoid the incoming airflow impinges on the trailing edge directly and attenuate the buffeting noise, a passive control device called deflector was often implemented at the upstream of the sunroof leading edge by many vehicle manufactures as the most common strategy. It is effective to reduce the low-frequency noise but results in a high pressure fluctuation in the separated shear layers coming off the top edge of the deflector⁵. Such an additional deflector would cause a significant broadband noise issue when the vehicle travels at high speeds and also lead to a higher drag force when it tilts up.

As we can find in the previous literatures, most of the passive control strategies to reduce the buffeting noise are employed at the leading edge of sunroof. However, buffeting noise is mainly generated in the region near the sunroof trailing edge. In this paper, a serrated sunroof

trailing edge is constructed to overcome the drawback in using a deflector near leading edge to reduce buffeting noise. In fact, edge serrations in noise reduction have been investigated by many researchers. Narayanan et al⁶ used a serrated airfoil leading edge to reduce the interaction between an airfoil's leading edge and impinging turbulence. They found the leading edge amplitude acts as a key parameter for enhancing the noise reduction levels in flat plates and airfoils. Hersh et al⁷ also observed that the leading edge serrations to reduce the tones generated by the periodic fluctuating forces near the trailing edge by forming vortices, which alter the velocity fluctuations from periodic to random. All these studies indicate the edge serrations could be a useful strategy to reduce the buffeting and broadband noise on vehicle sunroof.

With the rapid development of high-speed computers, CFD technique has been becoming an essentially effective way to predict the aerodynamic and aeroacoustic performance of a vehicle model. An accurate estimation of buffeting and broadband noise requires a precise prediction of the complicated transient behavior (e.g., vortex formation, shedding and breakdown in the shear layer over sunroof). In the present study, as the airflow impinging on the downstream edge of the sunroof, the serrations on the trailing edge with sinusoidal profiles of three combinations of wavelengths (λ) and amplitudes (h) are studied for noise reduction. A Detached Eddy Simulation (DES) will be performed to provide detailed flow fields for a comprehensive analysis.

NUMERICAL METHOD

1. Computational Vehicle Model

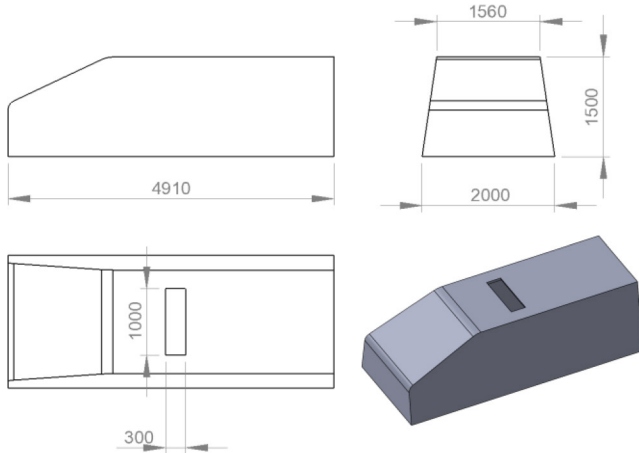


Figure 1. Schematic diagram of the computational vehicle model

As the real design of vehicles is very complicated, a simple vehicle model shown in Fig. 1 was used in this computational study. The computational vehicle model has a body length (L) of 4910 mm, a height (H) of 1500 mm and a top width (W) of 1560 mm and a bottom width of 2000 mm. An opening (1000 mm $\times$ 300 mm) at the vehicle top surface was constructed to represent a typical sunroof shape. There is no side mirror and no clearance between the vehicle model and ground in current simulation. Figure 2 shows a schematic of sinusoidal serrations employed in the shape design, where h indicates the wave amplitude and λ is the wave length. In the present study, the wave amplitude (h) is kept as a constant and three combinations of $h=0.5\lambda$, $h=\lambda$ and $h=2\lambda$ are constructed to find the effects from the wave length variation.

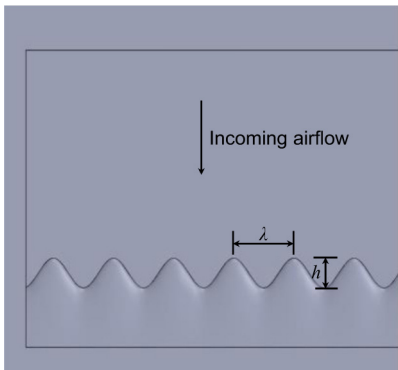


Figure 2. Schematic of sinusoidal serrations employed on the sunroof trailing edge

2. Computational Settings

An vehicle model with minor structure differences but the same computational settings was used in current study to validate the experiments conducted by Huco8. The commercial CFD code, Star-CCM+, was used to generate the mesh and simulate the flow over the vehicle model. The aeroacoustic analysis here was carried out by unsteady calculations, the mesh and settings therefore need to be optimized to capture noise sources and frequencies that are only relevant in this study. Since the vehicle geometry is symmetric in spanwise direction, a half vehicle model was selected in the

computational model to reduce the mesh size and avoid long-time calculations. A computational grid of approximately 68.3×10^6 structured cells was generated to give a required resolution. A block shape with 2mm $\times$ 2mm $\times$ 2mm grids was implemented in the region around the open cavity to ensure the accuracy for capturing the turbulent noise source with frequencies up to 3kHz and for propagating acoustics up to 8.5kHz. Ten prism layers were extruded from the vehicle surfaces at a growth ratio of 1.3 to capture the flow characteristics in the boundary layers. The normal resolution on the vehicle surface for all the computational cells is below $y^+=1$. Figure 3 illustrates the computational grids in the middle symmetric plane.

The inlet boundary is extended to $4L$ upstream the vehicle frontal surface. There are two incoming airflow velocities: 20m/s and 30 m/s, to represent a vehicle traveling in city and on freeway, respectively. The downstream pressure outlet is located about $8L$ to the vehicle base surface. Symmetric boundary conditions were applied on the far field boundaries of sides and top surfaces to avert reflecting effects.

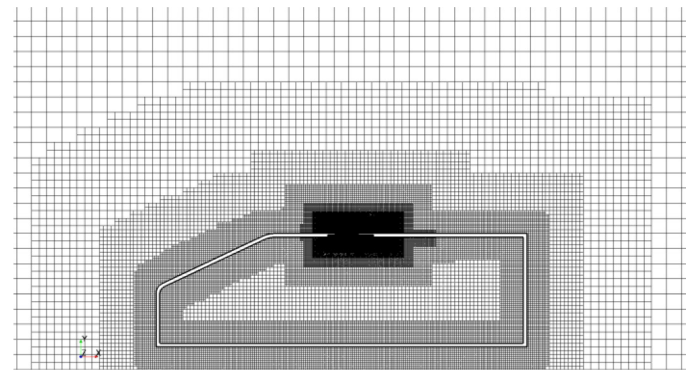


Figure 3. The computational grid in the middle symmetric plane

Two approaches were used in the present simulation study. Although the Reynolds Averaged Navier-Stokes (RANS) simulations have been successfully applied in prediction many parts of the flow around vehicles, they have limited capability to capture the eddy structures that have essential contributions on noise generation. As a result, the SST $k-\omega$ DES, which combines features of RANS model in the boundary layer and Large Eddy Simulation (LES) model in unsteady and separated regions, was employed in this research to gain more important characteristics in the flow field. The steady RANS results were used to provide a fully-developed initial flow field for the DES calculations. In order to calculate the aeroacoustic characteristics, the Ffowkes Williams-Hawkings (FWH) model was used to obtain the cabin noise SPL spectrum at a specified location.

RESULTS AND DISCUSSION

1. Computational Model Validation

In the experimental tests used for the validation, the streamwise velocity profiles were measured at three probe locations (probes A, B and C) at the vehicle top surfaces which shown in Fig. 4. It should be noted that the inlet velocity used in the tests was 60 kph and the sunroof was closed for measurements, the vehicle shape has a similar configuration compared with the vehicle model used in this simulation. The velocity profiles were computed based on the

time-averaged DES data at the same locations in current numerical simulation. Figure 5 illustrates the comparison between the simulated results and the experimental measurements. The x-axis indicates the absolute streamwise velocity and the y-axis indicates the distance away from the vehicle top wall surface. It can be easily found that the simulated streamwise velocity profiles both in the boundary layer and outer core region agree well with the experimental results at all the measuring locations. This ensures that the mesh in this computational study is adequate to capture the detailed flow characteristics.

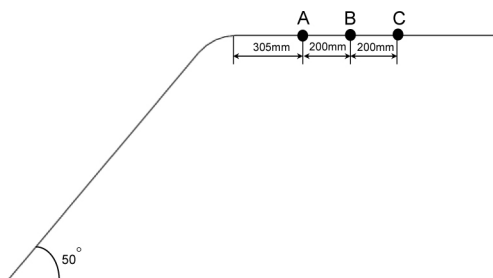
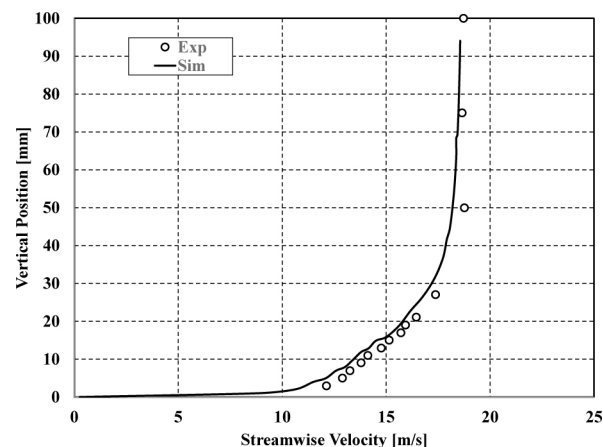


Figure 4. Measurement positions of the velocity profiles



c. Velocity profiles at location C

Figure 5. (cont.) Streamwise velocity comparisons at monitor locations

2. RESULTS AND ANALYSIS

Freestream Velocity at 30m/s

According to the studies conducted by Kumar⁹ and Mendonca¹⁰, the peak frequency of sunroof buffeting would be mainly dependent on the incoming velocity and the internal geometry of vehicle. In order to capture the buffeting frequency, a monitoring probe shown in Fig. 6 was placed under the sunroof leading edge which corresponds to the location of driver's right ear in the vehicle cabin to obtain the acoustic data. Figure 7 illustrates the calculated sound spectra for different vehicle designs at an incoming velocity of 30m/s, the peak frequency for the buffeting noise is found to be around 60Hz and the designs with trailing edge serration are observed to attenuate at least 10dB at the peak frequency when compared with the baseline case. As described above, the edge serration geometry could be beneficial for breaking the large eddy to small eddies, therefore several smaller peaks are found in these modified designs instead of only one peak frequency existing in the baseline model. Except the peak buffeting frequency, the sound pressure level in the case of $h=2\lambda$ is found to be mitigated about 15dB at the frequency of 25Hz. The design with the edge serration of $h=2\lambda$ seems to have the best spectra behavior among all the modified models. Although the noise level in the case of $h=0.5\lambda$ has a similar magnitude at the buffeting frequency, it has a much stronger noise level than the other two configurations at high frequencies ($f > 1000\text{Hz}$).

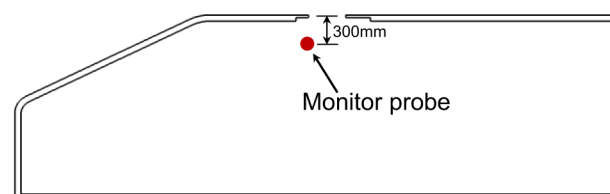
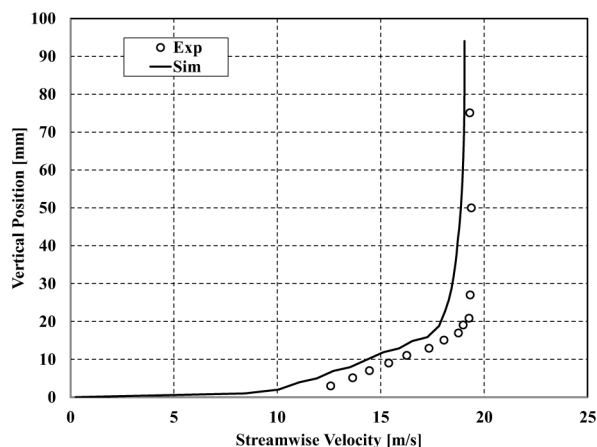
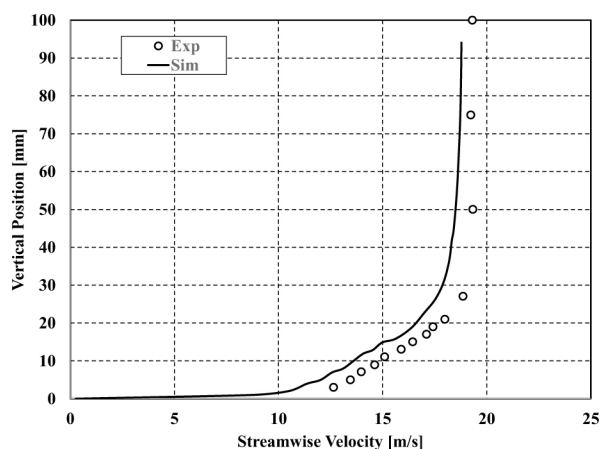


Figure 6. Position of the monitoring probe



a. Velocity profiles at location A



b. Velocity profiles at location B

Figure 5.