15th AIAA/CEAS Aeroacoustics Conference (30th AIAA Aeroacoustics Conference)
11 - 13 May 2009, Miami, Florida

AIAA 2009-3348

Numerical Simulation of Leakage Effects on Sunroof Buffeting of an Idealized Generic Vehicle

Ganapathi Balasubramanian, Bernd Crouse and David Freed,
Exa Corporation, Brisbane, CA, 94005

Sunroof buffeting is a flow-acoustic resonance phenomenon that causes high interior noise leading to discomfort for the passengers. In order to make *a priori* predictions about the tendency of a given vehicle to experience buffeting with a high degree of reliability, it is important to understand the sensitivity of this phenomenon to various noise parameters. The current investigation studies the mechanism and the effect of leakage on an SAE Type 4 body. For this, the CAA tool PowerFLOW was used and good agreement of the peak SPL over a wide range of velocities between experiment and simulation was observed for the baseline configurations and the leakage configurations. This allows the analysis and identification of the mechanism for how the artificial leakage affects the buffeting behavior.

I. Introduction

SUNROOF and side-window buffeting in passenger vehicles results in high sound-pressure levels in the interior and can cause considerable discomfort for the passengers. It is well understood that this phenomenon is a result of an unsteady shear layer in the sunroof or window opening which induces an acoustic resonance in the passenger compartment. Pragmatic design solutions for suppressing sunroof buffeting at various wind speeds and geometric configurations are well-known. However, a complete solution to this problem without resorting to expensive design measures has not been achieved in the industry. Recent numerical investigations[9,10] on real cars exhibiting real world effects have successfully predicted the effect of a deflector on buffeting suppression in an SUV. In a validation study[9], the efficiency of a deflector system was studied on a sedan and an SUV. It was shown conclusively that a sunroof system which works well to mitigate buffeting on one vehicle cannot be assumed to be universally effective. Ref. 16 provided a detailed review of previous experimental and numerical investigations of this problem and concluded that many open questions remained in previous experimental and numerical studies and attempted a systematic investigation of the phenomenon of buffeting in automotive applications. Experiments were carried out on an SAE Type 4 body, a geometrically simple and structurally rigid vehicle model. This removed experimental uncertainties associated with geometric details and structural and acoustic properties of real vehicles. Two different wind tunnels were used to measure the acoustic response of the body at various wind speeds, in order to address wind tunnel affects.

Ref. 15 which covered only the experimental portion of the study also investigated the effect of leakage on the overall buffeting behavior at various wind speeds. The leakage was represented by a round hole of 200 mm in diameter in the rear wall of the SAE Body. This study validates the buffeting behavior of the leakage configuration using numerical predictions over the relevant range of velocities.

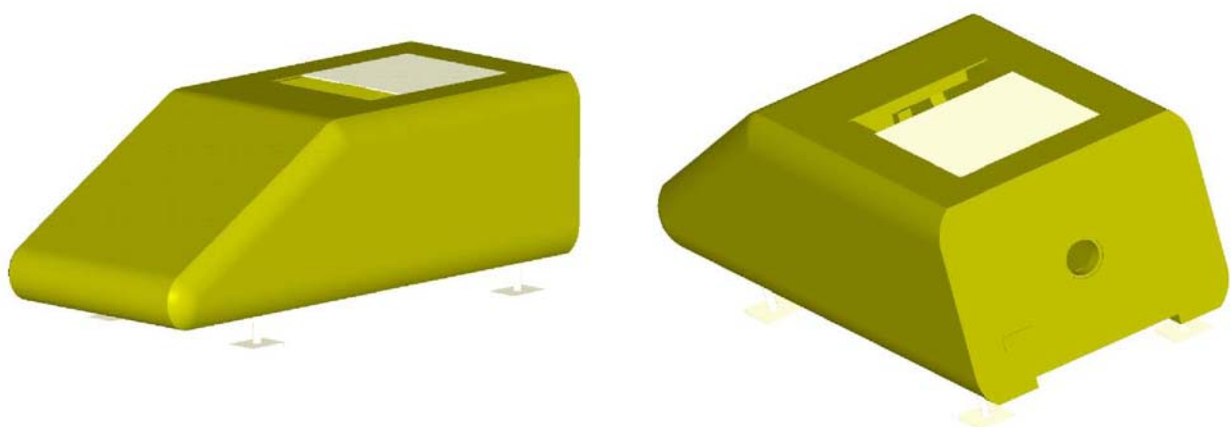
II. Simulation Methodology

A. The Lattice-Boltzmann Method

The simulations are performed using the commercial code PowerFLOW version 4.0. The numerical scheme is based on the Lattice-Boltzmann method (LBM) and recovers the transient, compressible Navier-Stokes equations. The scheme is solved on a grid composed of cubic volumetric elements called voxels, and variable resolution is allowed, where the grid size changes by a factor of two for adjacent resolution regions. Unlike conventional methods based on solving the macroscopic continuum Navier-Stokes equations as Partial Differential Equations (PDFs), LBM starts from a “mesoscopic” kinetic equation based on the discrete Boltzmann equation for the particle distribution function, where the correct macroscopic fluid dynamics is obtained as a result of evolving the underlying particle distributions. By recovering the compressible Navier-Stokes equations including the ideal gas equation of state, the LBM also inherently recovers acoustics. Pressure waves are propagated at the so called lattice sound speed, which is a function of the state space of the particle distribution function. When sound waves are important, such as in problems with coupled aerodynamics and acoustics, the simulated flow is specified to have the same Mach number as the physical conditions. Sound wave dissipation occurs due to the bulk viscosity of the LBM scheme, which, like the shear viscosity, is controlled by the relaxation time. Additional details about the LBM scheme, including the fundamental LBM dynamical equation, fluid turbulence model, boundary condition and wall-shear stress modeling are summarized in Ref. 10 and discussed in detail elsewhere.[1-8, 11, 17-22]

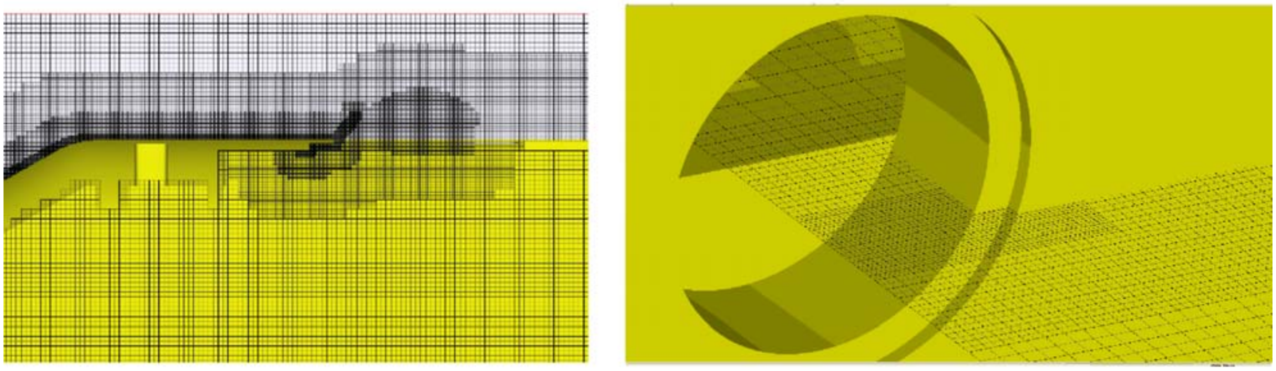
III. Numerical Procedure

The geometry of the SAE Body with the open sunroof and the leakage is shown in Fig. 1.



(a) **(b)**
Figure 1. SAE Body showing sunroof (a) and leakage (b) locations.

In Fig. 2, cross sections of the SAE Body show the grid in the sunroof shear layer and leakage location. The finest cell size is 1.5 mm and the simulation case size is 8.3 Million finest equivalent cells and 17 Million total cells for the half model. The boundary conditions in the digital wind tunnel included constant velocity at the inlet, constant pressure at the outlet, no-slip walls for the floor and ceiling, and free-slip condition for the side walls.



(a) **(b)**
Figure 2. Grid located at the center plane (a) and at leakage (b).

IV. Results

In Fig. 3, we show the velocity sweep plot of the overall SPL in the cabin for the baseline and leakage configurations for the experiments (Ref. 15) and the simulations performed in this investigation.

The baseline simulation results and corresponding conclusions were reported in Ref. 16. To summarize the findings in Ref. 16, the baseline velocity sweep shows that the onset (defined as the velocity at which buffeting levels steeply increase) at velocity greater than 40 kph is predicted accurately. The highest overall SPL at 70 kph is the same in the experiment and simulation. The offset (defined as the velocity at which buffeting levels steeply decrease) occurs earlier in the simulation (between 80 kph and 85 kph) than in experiment (between 85 kph and 90 kph). We see evidence for a delayed onset in the simulation of the leakage configuration which is also seen in experiment. The lower level of buffeting due to leakage as compared to the baseline in the onset region is clearly shown. There is a slight over-prediction (1-2 dB) in the levels in the onset region. The difference in the levels is accurately captured over a range of velocities. The lack of influence of leakage on the peak buffeting overall SPL and offset is clearly shown and accurately predicted. The sensitive phenomenon of a 2^{nd} Rossiter mode, that is, presence of two vortex cores simultaneously in the shear layer, is captured very well for both configurations at around 25-30 kph.

A. Flow Field and Acoustics Analysis

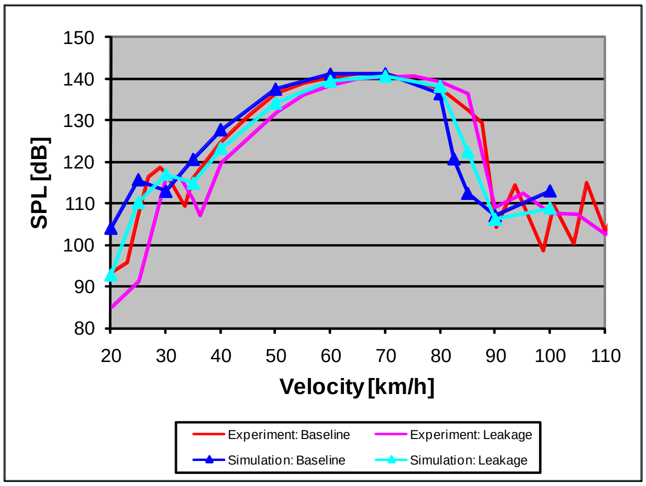
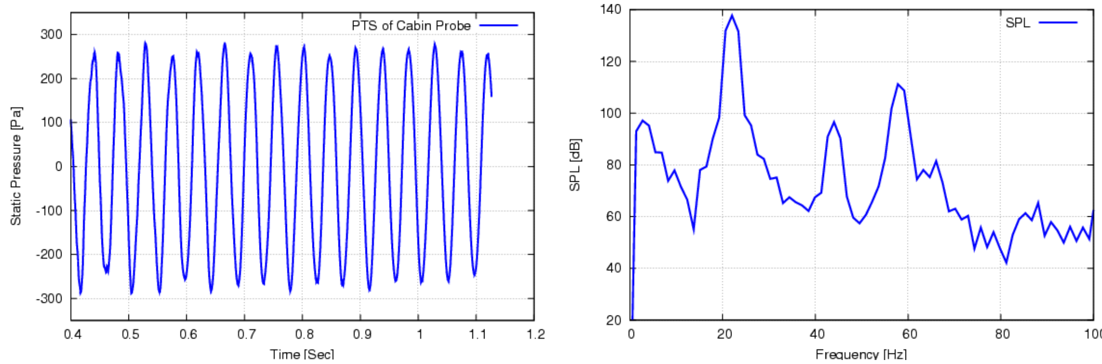


Figure 3. Velocity sweep showing buffeting behavior for baseline and leakage.

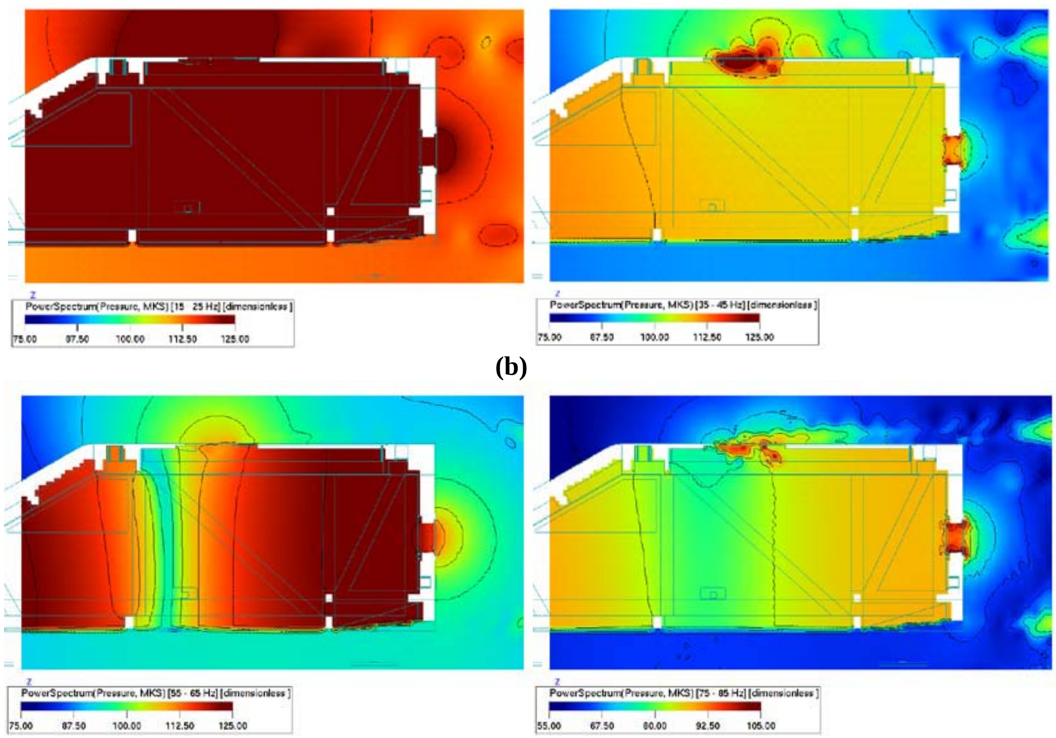
Figure 4 shows the cabin pressure history (left) and the sound pressure level spectrum (right) for the leakage configuration at 60 kph. The peak value of 138 dB occurs at 22.0 Hz, and smaller peaks are seen at around 40 Hz and 60 Hz. The spectrum is narrow compared to the one in Fig. 5 of Ref. 16 just because a larger time window was available. The peak frequency has increased from 20.5 Hz in baseline to 22.0 Hz for the leakage, which explains the slight shift in the buffeting curve to higher velocities. In Fig. 5, we show contour maps of the sound pressure level in bands surrounding these peak frequencies. Figure 5a (15 Hz – 25 Hz) is clearly seen as the Helmholtz peak with an almost uniform SPL in the cabin. Figure 5b (35 Hz – 45 Hz) looks like a weak harmonic of the Helmholtz peak, whereas cabin modes are identified in Fig. 5c-5d for the 55 Hz – 65 Hz and 75 Hz – 85 Hz bands. These cabin modes were also observed in the experiments and shown in Fig. 5 of Ref. 15. It can be shown that the cabin modes correspond to the longitudinal lengths inside the cabin. There are radiation losses from the leakage, but as seen from Figure 3, the buffeting levels are not affected significantly.

The mean velocity in the vertical direction (Fig. 6) indicates a large recirculation characteristic of lock-on at a buffeting velocity. The large pressure fluctuations are accompanied by large velocity fluctuations in the shear layers of the two openings, as shown in Fig. 7. Next, in Fig. 8 we show every quarter cycle snapshots of vorticity in the shear layer combined with the pressure fluctuation in the cabin. As explained in Ref. 16, the shear layer is displaced inwards (outwards) when the cabin pressure is at a minimum (maximum). The dominant vortex descends into the interior when the pressure is near the mean value and is increasing (Fig. 8b) , and reaches the trailing edge when the pressure is near the mean value and is decreasing as shown in Fig. 8d.



(a) **(b)**

Figure 4. Cabin: (a) pressure history and (b) sound pressure level spectrum.



(c) **(d)**

Figure 5. Mode identification at various frequency bands.

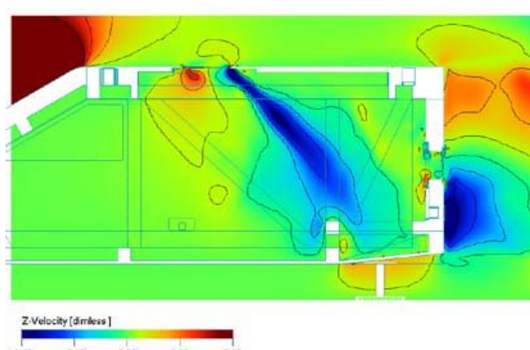


Figure 6. Mean Vertical Velocity.

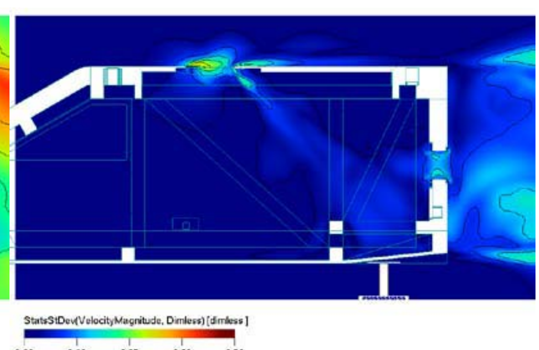


Figure 7. RMS of Velocity

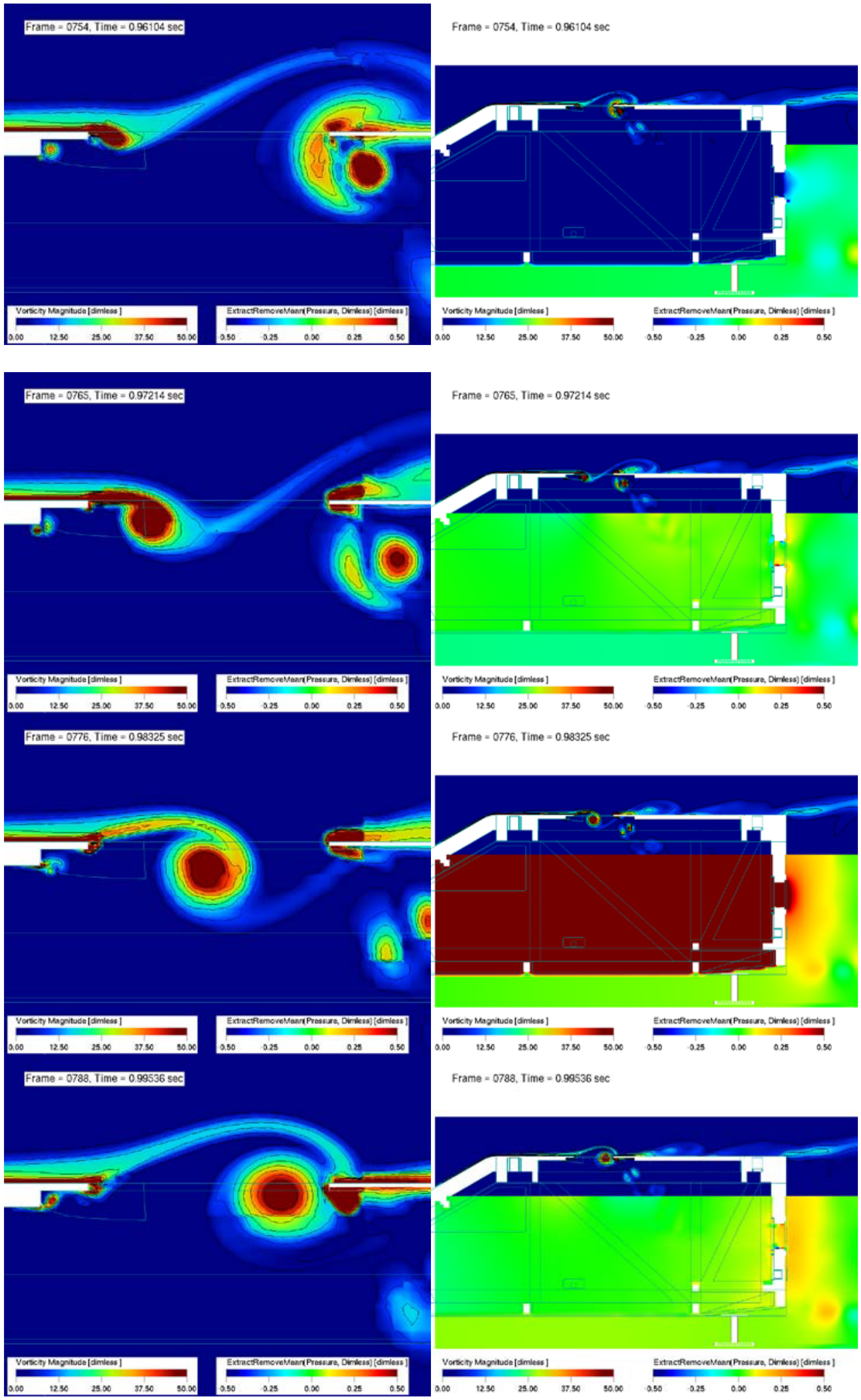


Figure 8. Quarter cycle snapshots of vorticity in shear layer (zoomed in view, left), and vorticity and cabin pressure fluctuation (zoomed out view, right).

B. Volume Flow Rate through Leakage Opening: 60kph

The volume flow rate through the opening is shown in Fig. 9, fluctuates around a mean value of 0.0037 m^3/s and is locked onto the buffeting frequency of 22.0 Hz. The flow enters (in the mean) through the leakage opening and exits the sunroof. The mean flow rate is about an order of magnitude smaller than for real cars.[12, 14]

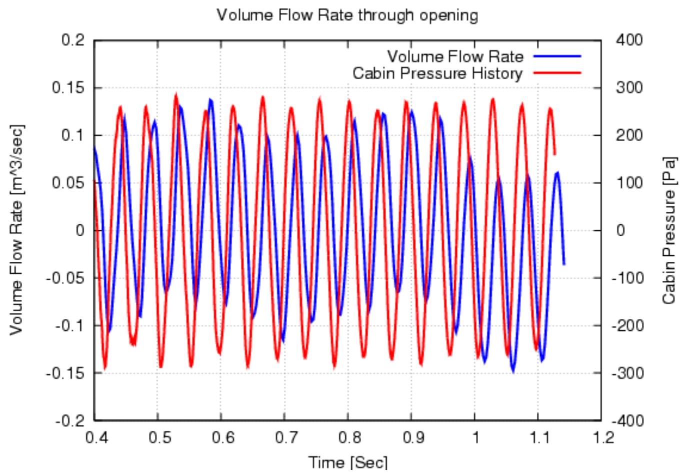


Figure 9. Volume flow rate through leakage opening (blue) and cabin pressure fluctuation history (red).

Figure 10 shows a plot of the mean static pressure in a vertical plane, 5 mm from the centerline of the SAE Body. It indicates that the leakage flow is driven by the pressure difference between the cabin and the leakage location.

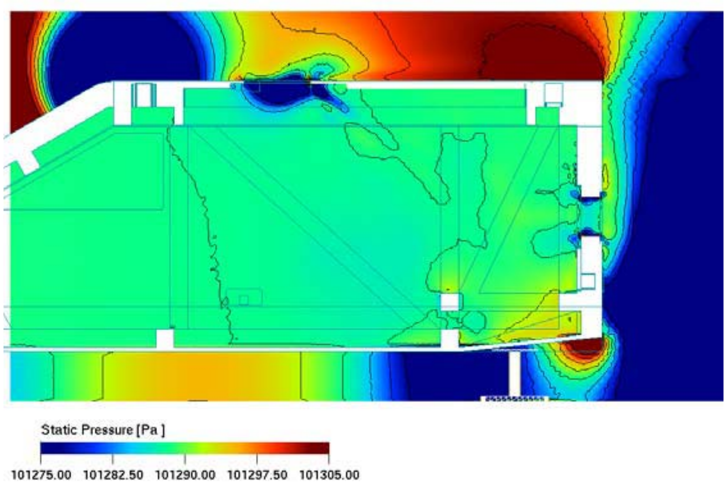


Figure 10. Mean Static Pressure in a vertical plane.

C. Discussion

The analysis above indicated that the proposed artificial leakage has a rather small effect on the overall buffeting curve. It is interesting to note that the peak frequency was increased by 1.5 Hz while offset velocity and peak SPL remain almost identical. The onset velocity is slightly shifted to higher velocities. This indicates that not only the Helmholtz frequency was increased but the damping of the Helmholtz resonance must have been increased.

Further analysis has shown that the volume flow rate through the leakage opening is correlated with the buffeting phenomenon. The same frequency of pressure fluctuations and fluctuations of volume flow rate is predicted in simulation. The constant phase difference in the volume flow rate and the cabin pressure, with the cabin signal leading the leakage flow, indicates that the system is acoustically active and that the cabin drives the system. The mean flow rate is smaller than observed in many real car configurations and is directed from the high-pressure rear panel, through the leakage opening into the cabin, and then out the sunroof opening to join the low-pressure roof flow. This contrasts with the direction of leakage flow in production vehicles, where flow typically enters the car through leakage openings and exits the cabin through the sunroof.[13]

V. Concluding Remarks

The buffeting characteristics of the baseline and leakage configurations of a Type 4 SAE Body are accurately predicted using the investigated numerical approach. Most of the results for the baseline configuration were reported in an earlier paper. Results show excellent agreement between experiment and simulation values of overall sound pressure levels in the cabin over the range of the velocity sweep. The leakage configuration used here causes only a slight shift in the onset and offset of buffeting but there is negligible change in the highest overall SPL. This is in contrast to leakage related buffeting suppression that is typically achieved in real vehicles, suggesting that the related physical behavior important for real vehicles was not present for the configuration used in these experiments. Study of the volume flow rate indicates negligible net mean flow injected into the sunroof shear layer. This could explain why the present configuration doesn't achieve the leakage related buffeting suppression of the real vehicles, where there is a significant net mass injection. Future studies with different size, number and position of leakage openings could help achieve a better correspondence to the real vehicle situation.

References

[1]Bhatnagar, P., Gross, E. and Krook, M., "A Model for Collision Processes in Gases. I. Small Amplitude Processes in Charged and Neutral One-Component System", Physical Review E, Vol. 94, 1954, pp.511-525.

[2]Brès, G., Pérot, F, and Freed, D., "Properties of the Lattice-Boltzmann Method for Acoustics", AIAA Paper 2009-3395, 30th AIAA Aeroacoustics Conference, 2009.

[3]Chen, H., "Volumetric Formulation of the Lattice Boltzmann Method for Fluid Dynamics: Basic Concept", Physical Review E, Vol. 58, 1998, pp. 3955-3963.

[4]Chen, H., Orszag, S., Staroselsky, I. and Succi, S., "Expanded Analogy between Boltzmann Kinetic Theory of Fluid and Turbulence", Journal of Fluid Mechanics, Vol. 519, 2004, pp. 307-314.

[5]Chen, H., Teixeira, C. and Molvig, K., "Realization of Fluid Boundary Conditions via Discrete Boltzmann Dynamics", International Journal of Modern Physics C, Vol. 9, No. 8, 1998, pp. 1281-1292.

[6]Chen, H., "Extensions in Turbulent Wall Modeling", Exa internal publication, 1998.

[7]Chen, S. and Doolen, G., "Lattice Boltzmann Method for Fluid Flows", Annual Review of Fluid Mechanics, Vol. 30, 1998, pp. 329-364.

[8]Chen, S., Chen, H., Martinez, D. and Matthaeus, W., "Lattice Boltzmann Model for Simulation of Magnetohydrodynamics", Physical Review Letters, Vol. 67, No. 27, 1991, pp. 3776-3779.

[9]Crouse, B., Balasubramanian, G., Senthooran, S., Freed, D., Ih, K. and Shin, S., "Investigation of Gap Deflector Efficiency for Reduction of Sunroof Buffeting", SAE Paper 2009-01-2233, 2009.

[10]Crouse, B., Senthooran, S., Balasubramanian, G., Freed, D. and Karbon, K., "Computational Aeroacoustics Investigation of Automobile Sunroof Buffeting", SAE Paper 2007-01-2403, 2007.

[11]Frisch, U., Hasslacher, B. and Pomeau, Y., "Lattice-Gas Automata for the Navier-Stokes Equations", Physical Review Letters, Vol. 56, 1986, pp.1505-1508.

[12]Großmann, H., "Der Luftstrom durch den Fahrgastraum, Leckluftströme und Strömungswalzen", Lehrgang-Nr. 21751/67.059, Technische Akademie Esslingen, 1996.

[13]Hucho, W.H., "Aerodynamik des Automobiles", 5. Auflage, Chapter 13.4, Viewek+Teubner Verlag, 1981.

[14]Lee, Y.L., "Effects of Body Leakage on Ventilation and Wind Noise around a Sunroof", Proceedings of the Institute of Mechanical Engineers, Part D: Journal of Automobile Engineering, Vol. 216, No. 5, 2002, pp. 363-371.

[15]Islam, M., Decker, F., Hartmann, M., Jäger, A., Lemke, T., Ocker, J., Schwarz, V., Ullrich, F., Schröder, A. and Heider, A., "Investigations of Sunroof Buffeting in an Idealised Generic Vehicle Model – Part 1: Experimental Results", AIAA Paper 2008-2900, 29th AIAA Aeroacoustics Conference, 2008.

[16]Islam, M., Decker, F., Hartmann, M., Jäger, A., Lemke, T., Ocker, J., Schwarz, V., Ullrich, F., Crouse, B., Balasubramanian, G. and Mendonca, F., "Investigations of Sunroof Buffeting in an Idealised Generic Vehicle Model – Part 2: Numerical Simulations", AIAA Paper 2008-2901, 29th AIAA Aeroacoustics Conference, 2008.

[17]Li, Y., Shock, R., Zhang, R., and Chen, H., "Numerical Study of Flow Past an Impulsively Started Cylinder by Lattice Boltzmann Method" Journal of Fluid Mechanics, Vol. 519, 2004, pp. 273-300.

[18]Qian, Y., d'Humieres, D. and Lallemand, P., "Lattice BGK Models for Navier-Stokes Equation", Europhysics Letters, Vol. 17, No. 6, 1992, pp. 479-484.

[19]Rubinstein, R. and Barton, J. M., "Nonlinear Reynolds Stress Models and the Renormalization Group", Physics of Fluids A, Vol. 2, No. 8, 1990, pp. 1472-1476.

[20]Shock, R., Mallick, S., Chen, H., Yakhot, V., and Zhang, R., "Recent Simulation Results on 2D NACA Airfoils using a Lattice Boltzmann based Algorithm", AIAA Journal of Aircraft, Vol. 39, No. 3, 2002, pp. 434-439.

[21]Teixeira, C., "Incorporating Turbulence Models into the Lattice-Boltzmann Method," International Journal of Modern Physics C, Vol. 9, No. 8, 1998, pp. 1159-1175.

[22]Yakhot, V., Chen, H. A., Staroselsky, I., Qian, Y., Shock, R., Kandasamy, S., Zhang, R., Mallick, S., and Alexander, C., " A New Approach to Modelling Strongly Non-Equilibrium, Time-Dependent Turbulent Flow" Exa internal publication, 2001.