Investigations of Sunroof Buffeting

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Introduction

This paper describes experimental results and numerical simulations of an investigation - carried out by a consortium of the German automotive manufacturers Audi, BMW, Daimler, Porsche and Volkswagen in collaboration with the software vendors CD adapco an Exa - regarding the feasibility of predicting buffeting phenomena by means of computational fluid dynamics (CFD). [1], [2]

Sunroof buffeting is a common phenomenon in passenger cars, and can cause considerable discomfort for the passengers due to the high sound pressure levels (SPL) that are generated.

The general physical mechanism of sun roof buffeting is well understood and pragmatic design solutions for suppressing buffeting are widely known. However, experience in vehicle development has shown that making a priori predictions with the required degree of reliability and accuracy is not possible. Previous work carried out by members of the consortium has shown that clearly identifying and isolating the individual factors that influence buffeting in real vehicles is very difficult.

In order to conduct out a systematic analysis of these issues, the consortium devised a long term project in which the first step isolates and investigates the issues related to fluid dynamics only, and ensures that the other aforementioned factors influencing buffeting play no role.

Generic Vehicle Model

For the presented study, an idealised generic vehicle model (s. Figure 1 and Figure 2) based on the SAE Type 4 (fullback) body was designed and built in order to

- capture the relevant physical phenomenon with a minimum of geometric complexity,
- maximise structural rigidity to rule out fluid structure interaction,
- allow access for optical experimental techniques for a variety of geometric configurations.

To investigate various configurations, the model was built with a:

- variable sunroof for different sized openings,
- removable deflector,
- variable leakage opening in the back oft the model.

The results in this paper refer to a baseline case with a sunroof opening of 300 mm sunroof with and without a leading-edge deflector.

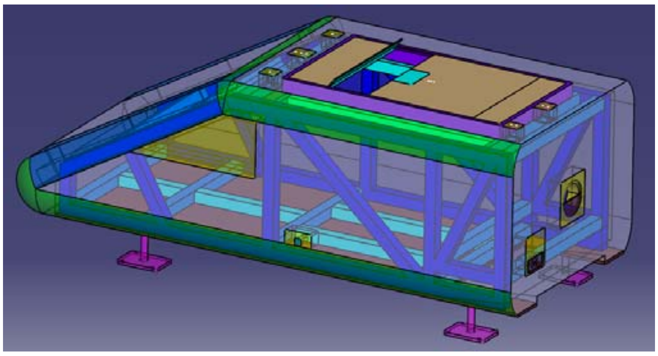

Figure 1: SAE Type 4 body: stiff design and leakage opening in the back of the model [1]

Figure 2: SAE Type 4 body: modular design of the sunroof opening and removable deflector [1]

Experimental Techniques

In order to assess any possible influence of wind tunnel effects on the acoustic behaviour of the model, a wide range of aerodynamic and aeroacoustic investigations were carried out in the aeroacoustic wind tunnels of Audi and BMW:

- basic aerodynamic force measurements
- qualitative flow visualisation with oil drawings (s Figure 3)
- interior noise measurements with a microphone inside the model (s. Figure 4)
- quantitative flow visualisation with high-speed stereo PIV (s. Figure 4, 5 and 6)
- vibration measurements on different panels of the model
- measurements of wall pressure fluctuations with flush mounted surface microphones
- hot-wire anemometry to characterise the flow

Figure 3: Oil Drawings [1]

Figure 4: Microphone and PIV Cameras inside the model [1]

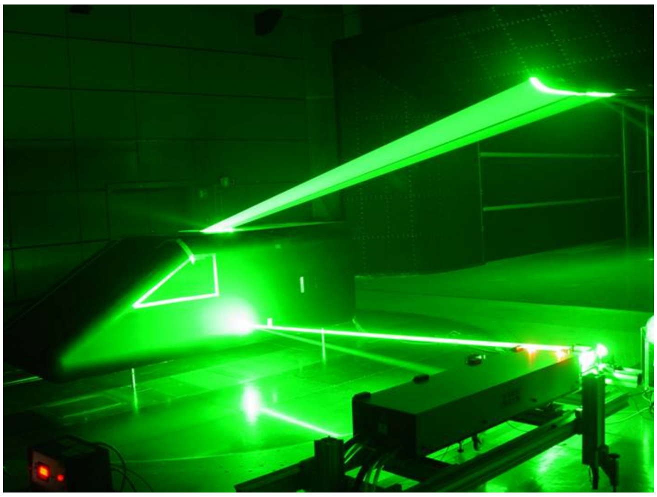

Figure 5: High speed stereo PIV in the Audi aeroacoustic wind tunnel [1]

Experimental Results

Flow Visualisation

As one of the primary goals of the present study was to generate an extensive set of experimental results for the validation of CFD simulations, quantitative determination of the unsteady flow-field was required. For this purpose, high-speed stereo PIV was employed. It enables non-intrusive time-resolved determination of all three velocity components of the instantaneous flow-field with a temporal resolution of 1,5 kHz in the measurement windows. (s. Figure 6)

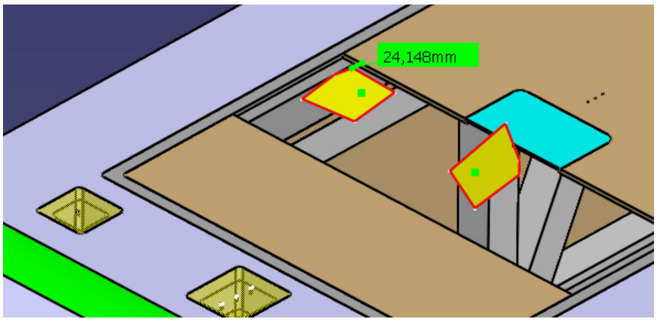

Figure 6: PIV measurement windows marked in the sunroof opening (marked in orange) [1]

Figure 7 shows instantaneous velocity fields in the centre-plane measurement window of the sunroof opening in a sequence of increasing free-stream velocity. The velocity field exhibits in the case of buffeting (30 - 80 kph) very dominant vortical structures. Only at the two highest speeds, 90 and 100 km/h where the offset of buffeting was observed, the coherent vortices have broken down to a moderately oscillating free shear layer.

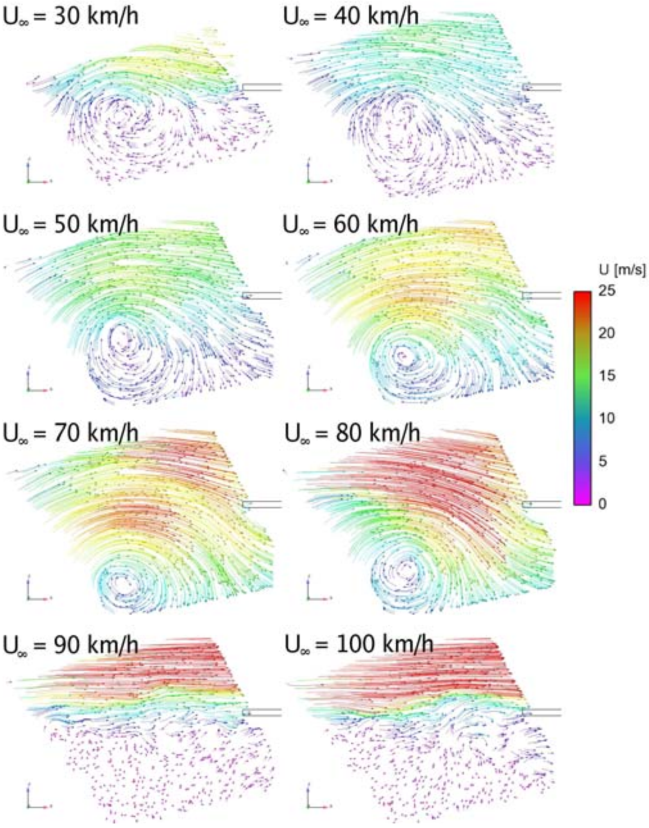

Figure 7: PIV images of instantaneous velocity fields [1]

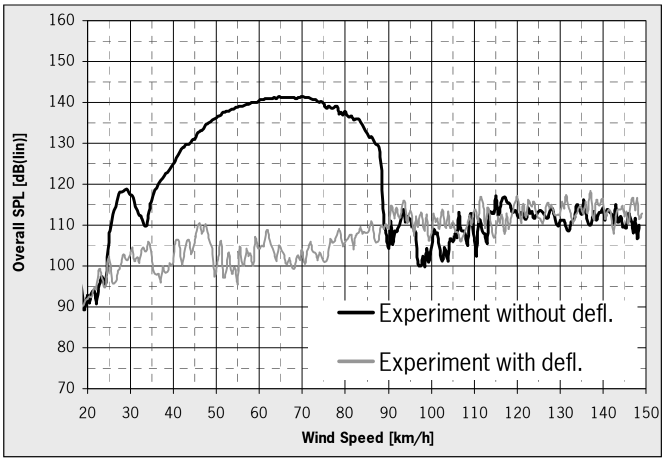

Figure 8: Baseline test-case with 300m sunroof opening [1]

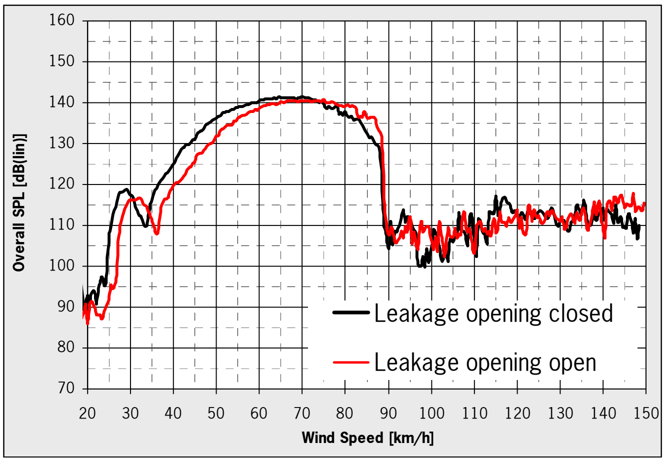

Figure 9: Leakage effect [1]

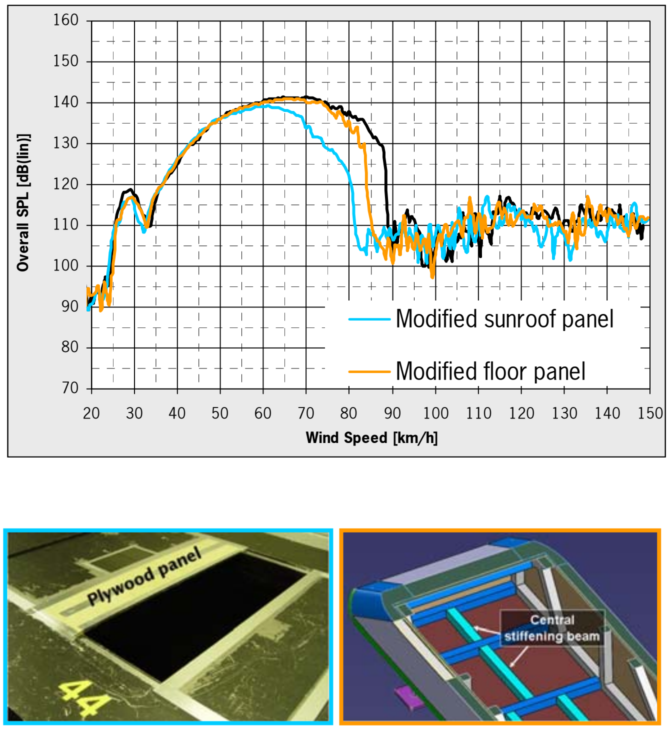

Figure 10: Effect of structural rigidity [1]

Acoustic Results

The buffeting behaviour of the model was characterised and analysed on the basis of the signal obtained from the interior microphone. Figure 8 shows a plot of the overall SPL as a function of wind speed for the baseline configuration with and without wind defector. The figure shows typical buffeting behaviour of the model very clearly.

Without the deflector at the sunroof opening's leading edge, the overall SPL inside the model rose rapidly as the free-stream wind speed increases from 20 kph. At 30 kph, the SPL reached a local maximum, decreasing up to 35 kph, characteristic of the second shear-layer mode identified by Rossiter, whereby two vortices were present in the sunroof opening's shear layer.

As the speed exceeded 35 kph, the overall SPL increased rapidly, reaching a maximum value of 141 dB at a speed of 66 kph. Thereafter, the SPL began to drop at a continually increasing rate, until buffeting was ceased just below 90 km/h. At speeds above 90 km/h, the relatively low overall SPL is representative of the broadband nature of the wind noise in the absence of buffeting. The figure also shows clearly that the leading-edge deflector entirely suppresses buffeting.

Leakage Effect

The influence of leakage in the model was investigated by utilizing the circular opening in the rear of the model. Figure 9 shows the buffeting behaviour of the model with the leakage opening fully opened in comparison with the baseline configuration. With leakage, the onset of buffeting was shifted to higher speeds by about 5 km/h, and a very slight reduction in maximum overall SPL was observed.

The results show that leakage in this model had only a small effect, much smaller than expected. Experience shows that buffeting in real vehicles can very often be suppressed by opening one of the windows by a small amount. The mechanism by which leakage of this type suppresses buffeting in real vehicles may be different from that investigated here. Further investigation of this point is required.

Structural Rigidity

A plywood panel shown in Figure 10 was screwed to the side edges of the sunroof frame. For a second modification, the screws fastening the wooden floor panel to the frame of the model were removed. The effects of these modifications on the buffeting behaviour are shown in the diagram of Figure 10.

The overall SPL reached a maximum at 60 kph for all configurations whereas the SPL drops off rapidly for the cases with structural modifications.

This result shows clearly that structural effects can strongly influence buffeting behaviour and can therefore certainly not be neglected either in experimental or numerical studies. Work on this topic is ongoing.

Numerical Simulations

Two different commercial CFD codes were applied for the simulations: The finite volume code StarCD, yellow and orange curves in Figure 11, and the Lattice Boltzmann code Power-Flow, light and dark blue curves in Figure 11.

The numerical simulations were performed by the software vendors CDadapco and EXA themselves over a range of wind speeds and for various numbers of representative configurations of the model, with and without buffeting, with the goal of determining whether the buffeting behaviour can be predicted with sufficient accuracy.

Comparison to the Experimental Results

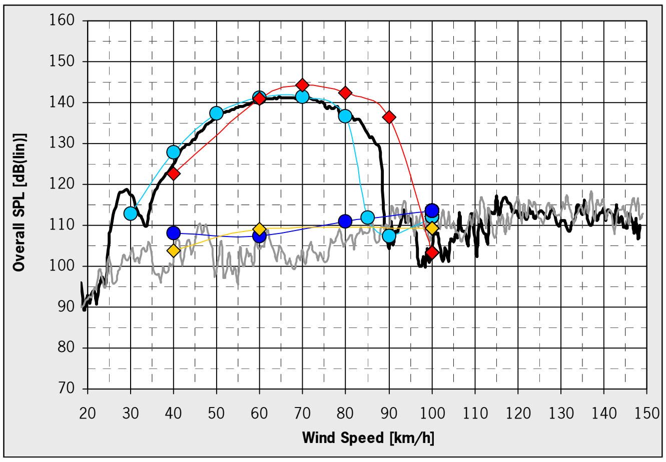

Figure 11: Baseline test-case with 300m sunroof opening [2]

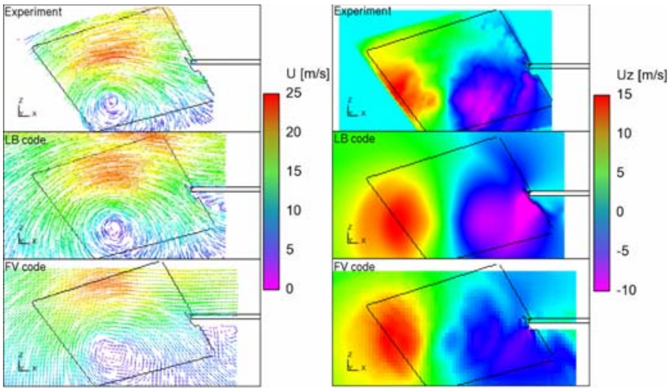

Figure 12: Baseline case, 60 km/h: Instantaneous flow field, centre plane [2]

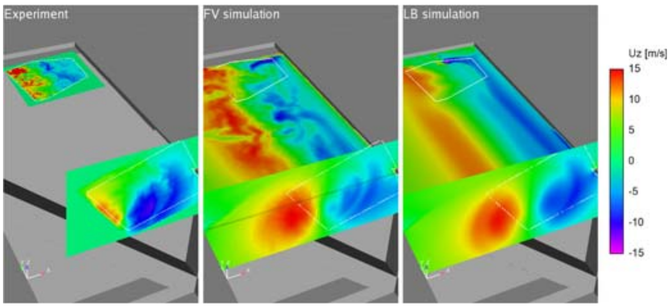

Figure 13: Baseline case, 60 km/h: Instantaneous flow filed, in the sunroof plane [2]

StarCD (CD-adapco)

Turbulence Model	LES, Smagorinsky SGS Model
Temporal Discretization	Crank-Nicholson
Physical Time [s]	2
Time-step size [s]	0.2×10^{-4} - 1×10^{-4}
Mesh size [cells]	1.3 M / 2 M (full models)
Smallest cell size [mm]	8 / 4
Mesh-generation Time [h]	3
Run Time [CPUh / 1s sim. Time]	610 / 820

PowerFlow (EXA)

Turbulence Model	RNG, k-epsilon
Temporal Discretization	n / a
Physical Time [s]	1
Time-step size [s]	3.2×10^{-6} - 6.4×10^{-6}
Mesh size [cells]	9 / 17.6 M (half-models)
Smallest cell size [mm]	3 / 1.5
Mesh-generation Time [h]	5
Run Time [CPUh / 1s sim. Time]	575 / 2600

Conclusions

- An experimental test case for sunroof buffeting was established with a
  - simple geometry with well-defined boundary conditions and
  - a robust, repeatable behaviour.
- The basic buffeting mechanism was confirmed as a shear layer with coherent vortical structures triggering a cavity resonance of interior volume of a vehicle.
- A high-quality experimental data set was generated with
  - acoustic data describing buffeting behaviour,
  - quantitative flow-field visualisation confirming fluid-acoustic mechanisms and is therefore
  - well-suited for CFD validation of both acoustics and hydrodynamics.
- Structural effects have a strong influence on buffeting behaviour and require extensive further investigations.
- Both commercial CFD codes capture buffeting successfully with minor discrepancies.
- But: Boundary conditions in simulations must accurately correspond to those in the experiment. Still open questions:
  - How to treat effects such as finite structural rigidity, surface impedances?
  - Therefore predictive simulation of real vehicles are currently not feasible.

References

[1] M. Islam: Investigations of Sunroof Buffeting in an Idealised Generic Vehicle Model - Part I: Experimental Results, AIAA Paper 2008-2900, 2008

[2] M. Islam: Investigations of Sunroof Buffeting in an Idealised Generic Vehicle Model - Part II: Numerical Simulations. AIAA Paper 2008-2901, 2008