Development of an Evaluation Methodology for Low-Frequency Flow Phenomena

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Motivation

Flow noise is important in the automotive industry, as it significantly influences driving comfort. This is especially true for battery electric vehicles (BEV). Since they generate barely any drive noise, flow induced sound is already crucial at lower driving speeds. [1] Moreover, there are no engine noise masking effects. Despite their typically streamlined underbody shape, significant pressure fluctuations can be observed for certain vehicle configurations and frequencies below 30 Hz. These low-frequency pressure fluctuations excite the vehicle interior, leading to reduced passenger comfort. In the simulation presented here, it is assumed that the vehicle interior functions as a Helmholtz resonator, excited by the coupling of pressure fluctuations through the forced ventilation air path into the cabin. This excitation mechanism has already been simulated and validated by Weber in [2]. The flow phenomenon will hereinafter be referred to as "underbody buffeting." No structural excitation is considered in this analysis; such effects could be simulated using Finite Element Method (FEM) or Multibody System (MBS) approaches.

Simulation Setup

For the investigations, a research model was developed based on the SAE-body designed by the SAE Committee in [3]. This model allows the flow phenomenon to be isolated due to its simple and well-defined shape, which minimizes the influence of other interfering aeroacoustic noise sources. Both the Computational Fluid Dynamics (CFD) simulations and the wind tunnel experiments are conducted at a scale of 1:4. The underbody buffeting was generated by mounting add-on components to the vehicle's underbody: Circular cylinders were used to represent the wheels, while rectangular plates were attached to simulate the wheel spoilers. Wheel spoilers are aerodynamic components located in front of the wheels. Their purpose is to optimize the airflow around the wheels by reducing turbulence and minimizing aerodynamic drag. However, previous investigations have shown that especially the front wheel spoilers are relevant for the development of the underbody buffeting [4]. The scaling of the model according to the dimensionless parameters results in the flow phenomenon occurring at slightly higher frequencies in the model scale compared to the original scale. Therefore, the maximum levels are expected to occur at approximately 80 Hz. Figure 1 shows the generic reference model.

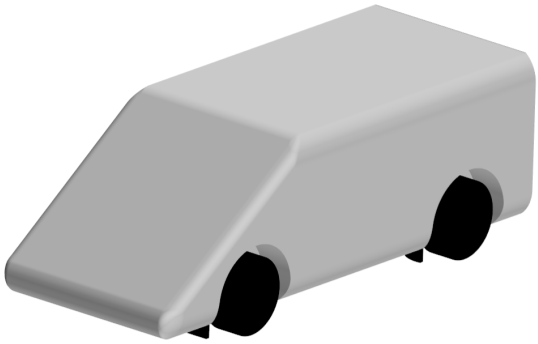

Figure 1: Generic vehicle model based on the SAE-body

For this study, a commercial software package based on the Lattice Boltzmann method (LBM) was utilized. Unlike conventional CFD solvers, which rely on the solution of discrete partial differential equations such as the Navier-Stokes equations that describe the continuum, the Lattice-Boltzmann method employs a discrete particle approach for the simultaneous simulation of flow and acoustics. This method is based on the kinetic gas theory and is inherently explicit, transient, and compressible. To facilitate the efficient solution of the Boltzmann equation, it is discretized on a three-dimensional Cartesian grid. The simulation employs a Very Large Eddy Simulation (VLES) framework with a RNG k-ϵ two-equation turbulence model for the unresolved scales. A wall model is implemented to reduce computational time when simulating the fluid near the walls.

At the inlet of the virtual wind tunnel, air flows in at a velocity of 180 km/h, while the ambient pressure serves as the boundary condition at the outlet of the wind tunnel. A stationary and frictional floor is simulated, and the boundary layer thickness is implemented according to the model wind tunnel specifications. A Cartesian grid is used for discretization, with cell sizes defined by variable resolution areas. The largest cells are located at the walls and ceiling of the wind tunnel, and the cell size decreases with proximity to the simulated geometry. Since the focus of this work is primarily on the examination and analysis of the underbody flow, this area is particularly finely resolved. Computational steps are performed for the finest variable resolution areas at each time step. The next cell size is twice as large. These cells are computed only every second time step. The smallest grid cells have an edge length of 0.5 mm, and the smallest time step is $\Delta t = 8.4 \cdot 10^{-7}$ s. A total simulation time of 2.5 s is conducted, with post-processing commencing after a settling time of 0.3 s.

Transient flow parameters are stored only for specific

evaluation planes, which are located beneath the vehicle's underbody and are parallel to the wind tunnel floor. Additionally, an array of virtual microphones is defined on the underbody of the SAE-body, for which the corresponding pressure information is recorded.

Validation

The CFD simulation is intended to serve as a reliable tool for evaluating various vehicle configurations regarding underbody buffeting early in the vehicle development process. Two vehicle configurations are used for validation purposes: one variant in which the underbody buffeting is very pronounced and another variant in which this phenomenon does not occur. Given that the front wheel spoilers are significant for the development of this flow phenomenon, two vehicle configurations are investigated: one with front wheel spoilers and the other without.

Extensive measurements are carried out in a model wind tunnel for validation purposes. This includes measuring the transient flow velocity in an evaluation plane below the vehicle's underbody using high-speed Particle Image Velocimetry (PIV), as well as the installation of surface microphones on the underbody [6].

To enable a reliable comparison of results from CFD simulations and wind tunnel experiments, the same post-processing settings should be applied, and uncompressed data should be used whenever possible. Consequently, the necessary raw data are exported and subsequently processed using a uniform external method. For the comparison of transient data, the frequency spectra of the pressure fluctuations measured by the surface microphones are calculated using Fourier transformation.

The PIV measurements provide the transient flow velocity, which is averaged over the measurement period for comparison of the mean velocity. Two analysis tools are employed to investigate whether the physical conditions are accurately represented by the CFD simulation. Delta plots are calculated from the subtraction of the mean velocities, highlighting the differences in the velocity fields. Additionally, velocity profiles are analyzed, representing the change in velocity along the y-axis at a fixed x-position. Since the computational grid from the simulation differs from that of the experiment, a direct subtraction of velocities is not feasible. Therefore, the data are first linearly interpolated onto a uniform base grid.

The pressure fluctuations in the rear area of the vehicle are relevant for the sound pressure in the cabin; thus, a microphone located in the rear area is considered as a reference for the frequency spectra. Figures 2 and 3 illustrate the comparison of the frequency spectra for the variant with and without front wheel spoilers at this microphone. Notably, the spectra from the experiments are significantly smoother compared to those from the CFD simulation. The primary reason for this discrepancy lies in the substantial difference in measurement durations between the experiment (60 s) and the simulation (2.5 s). Overall, the fluctuations from the simulation align well with the experimental results for both configurations.

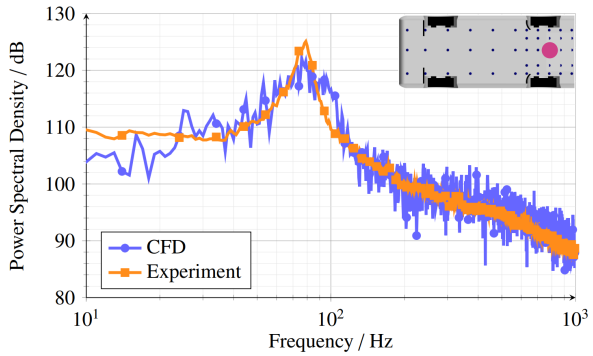

Figure 2: Comparison of the frequency spectra of the variant with front wheel spoilers at the reference microphone

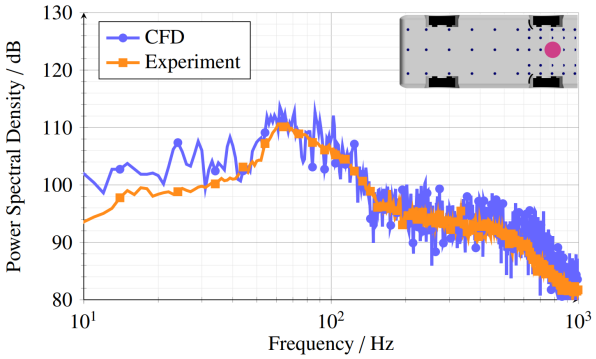

Figure 3: Comparison of the frequency spectra of the variant without front wheel spoilers at the reference microphone

Figure 4 illustrates the delta plot of the mean u-velocity component between experiment and CFD simulation for the underbody buffeting configuration. The corresponding velocity profiles for the x-positions marked in this plot are shown in Figure 5. Overall, the delta plot indicates that the deviations are relatively small and that the flow is well depicted. The largest deviations occur at y=0, where the simulation exhibits unphysical fluctuations of unclear origin. In general, the velocity profile resembles a developing turbulent channel flow. Furthermore, the results demonstrate that both the flow parameters and the acoustic quantities can be reliably predicted by the CFD simulation.

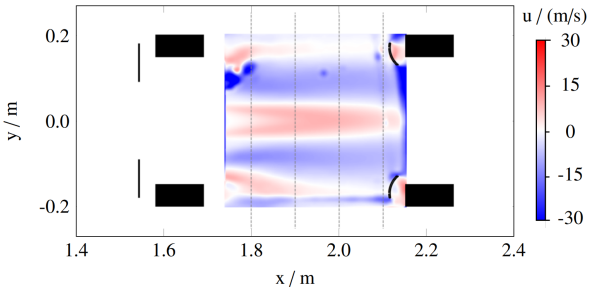

Figure 4: Delta plot of the mean u-velocity component between experiment and CFD simulation of the variant with front wheel spoilers

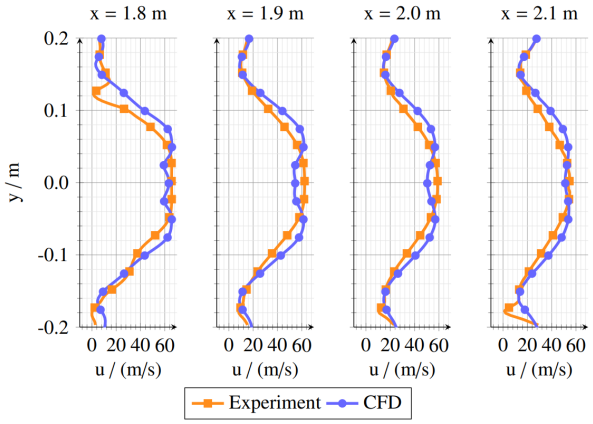

Figure 5: Velocity profiles of the variant with front wheel spoilers

Evaluation Method

The evaluation method developed in this study is presented using the baseline variant with front wheel spoilers. The frequency spectra obtained from the virtual surface microphones serve as the initial analysis tool to assess a vehicle configuration concerning underbody buffeting. Figure 6 illustrates such a frequency spectrum for the variant with front wheel spoilers at the reference position in the rear area.

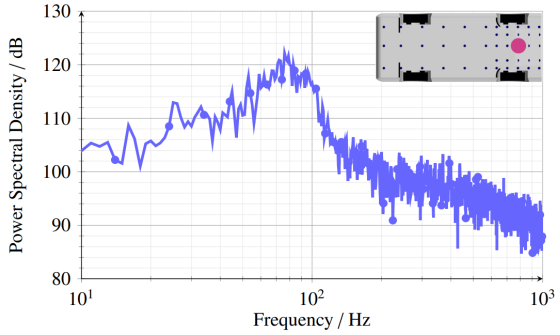

Figure 6: Frequency spectra of the baseline configuration with front wheel spoilers at a microphone in the diffusor area of the vehicle

However, the frequency spectra only display the pressure fluctuation levels at individual measurement points. To obtain a more detailed understanding of the overall underbody flow, decibel maps are generated for the evaluation planes below the vehicle's underbody. This enables the analysis of both the overall sound pressure level and the power density spectrum for specific frequency bands, making it easier to identify the locations of maximum pressure fluctuations at certain frequencies.

Figure 7 shows the overall sound pressure level, while Figure 8 presents the power density spectrum around 80 Hz. This frequency was determined from the microphone spectrum as the frequency of the maximum level. The power density spectrum clearly indicates that the maximum levels - within the relevant frequency range - occur in the diffuser area between the rear wheels. The decibel map of the overall sound pressure level aids in identifying additional areas in the underbody that may require further analysis.

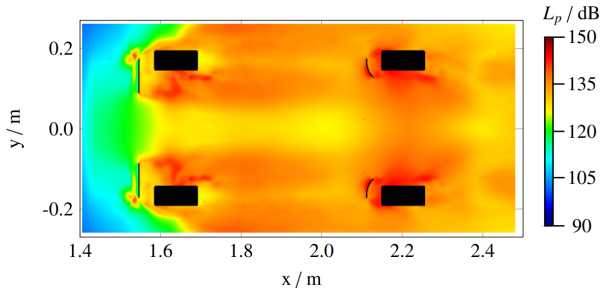

Figure 7: Decibel map of the overall sound pressure level of the baseline configuration with front wheel spoilers - evaluation plane: z = 25 mm

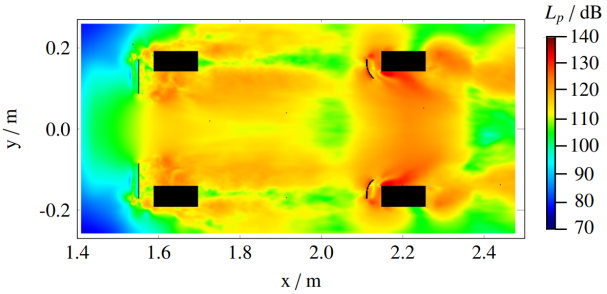

Figure 8: Decibel map of the power density spectrum around 80 Hz of the baseline configuration with front wheel spoilers - evaluation plane: z = 25 mm

Decibel maps are employed to identify the positions of maximum sound pressure levels. For the quantitative assessment of sound pressure and the comparison of different vehicle configurations, gradient plots are utilized. The sound pressure level is calculated for the frequency band from 50 to 100 Hz, as this frequency range is significant for underbody buffeting. Subsequently, it is plotted for a fixed x-position along the y-axis. Figure 9 displays the sound pressure level of the frequency band from 50 to 100 Hz for x = 2.2 m. In the area of the wheels, there are no meaningful values; therefore, these regions are shaded. The diagram indicates that the maximum fluctuations occur at the inner edge of the wheels.

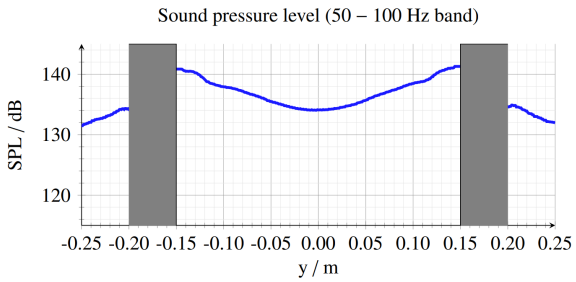

Figure 9: Sound pressure level in the frequency range of 50 - 100 Hz at x = 2.2 m

To evaluate a new vehicle configuration according to this scheme, the frequency spectra of the virtual surface microphones are first analyzed to determine the frequency

of the maximum pressure fluctuations. A decibel map of the power density spectrum can then be created for this frequency. From this decibel map, x-positions for visualizing the overall sound level in the frequency band of 50 to 100 Hz are derived. The creation of a decibel map of the overall sound pressure level is optional but can be helpful in localizing relevant x-positions. For the assessment and optimization of countermeasures, the sound pressure level in the frequency band of 50 to 100 Hz of the respective vehicle configuration can be compared with that of the baseline variants - both with and without front wheel spoilers.

Conclusions

A comprehensive evaluation method for investigating low-frequency flow phenomena of vehicles has been developed in this paper. To achieve this, a generic car model was created, and extensive wind tunnel measurements were conducted. A numerical simulation setup was established, accompanied by a standardized post-processing approach for both the experimental and CFD simulation data. Subsequently, the results of the numerical simulation were validated against the wind tunnel data. A numerical evaluation method was introduced, which enables the examination of future vehicle configurations in the early stages of the vehicle development process concerning low-frequency flow phenomena. This method will be utilized to assess and develop countermeasures in subsequent studies.

References

[1] Schütz, T.: Hucho-Aerodynamik des Automobils: Strömungsmechanik, Wärmetechnik, Fahrdynamik, Komfort. Springer-Verlag, Wiesbaden, 2013.

[2] Weber, C.: Aufbau einer aeroakustischen Simulationsmethode zur Bewertung der Fahrzeug-Unterbodenströmung. Master's thesis, Institute of Automotive Engineering, Stuttgart, 2018.

[3] SAE Road Vehicle Aerodynamics Committee: Aerodynamic Testing of Road Vehicles in Open Jet Wind Tunnel. SAE Report J2071 (Open Throat Wind Tunnel Adjustments), 2004.

[4] Breitenbücher, L.: Untersuchung von tieffrequenten Strömungsresonanzen am Fahrzeug-Unterboden. Master's thesis, Institute of Aerodynamics and Gas Dynamics, Stuttgart, 2022.

[5] Kotapati, Rupesh, et al.: The lattice-Boltzmann-VLES Method for automotive fluid dynamics simulation, a review. No. 2009-26-0057, SAE Technical Paper, 2009.

[6] Breitenbücher, L., Wagner, A., Wiegand, T., and Brink, M.: Experimental Investigation of Low-Frequency Flow Phenomena on the Vehicle Underbody Using Particle Image Velocimetry. Tech. rep., SAE Technical Paper, 2024.