Low Frequency Aerodynamic and Aeroacoustics Phenomena of Vehicles with Flat Underbody

Laura Breitenbücher, Prof. Dr.-Ing. Andreas Wagner, Dr.-Ing. Thomas Wiegand, Dr.-Ing. Maarten Brink
Dr. Ing. h.c. F. Porsche AG
Porschestraße 911
71287 Weissach
laura.breitenbuecher1@porsche.de
andreas.wagner@ifs.uni-stuttgart.de
thomas.wiegand@porsche.de
maarten.brink@porsche.de

Abstract: Due to the increasing importance of drag minimization and the absence of an exhaust system, battery electric vehicles (BEVs) typically feature a very streamlined underbody. While this shape of underbody is typically characterized by a low acoustic interference potential, significant flow resonance can be observed for certain vehicle configurations and frequencies below 30 Hz. The goal of this study is to identify the exact origin of the aforementioned low-frequency flow resonances at the vehicle underbody in order to subsequently develop stable and robust measures with which the flow phenomenon can be avoided while simultaneously meeting aerodynamic requirements. In order to isolate the flow phenomenon and to be independent of a specific vehicle configuration, an abstract model was developed with the help of which the flow phenomenon can be investigated in detail. Computational Fluid Dynamic (CFD) simulations were carried out on the one hand and wind tunnel experiments on the other. The investigations unanimously show that the flow around the front wheel spoilers has a decisive influence on the low-frequency resonance. Due to flow separation at the front-wheel spoilers and at the front wheels, vortices that are growing substantially while being transported with the flow downstream are generated. At the rear section of the vehicle, the separations caused by the front and rear components superimpose, which results in very high levels of pressure fluctuations. The excitation of the vehicle interior as a Helmholtz resonator then takes place by coupling the pressure fluctuations via an "air path" and leads to reduced comfort for the passengers.

1 Introduction

Since aeroacoustics considerably influences the passengers' comfort, it is increasingly gaining importance in the vehicle industry. Even small changes in flow around the vehicle can lead to significant sources of noise. It is a general goal to execute aeroacoustics investigations early in the vehicle development process.

Noise emissions of a vehicle which are important for the interior as well as for the exterior noise consist of engine noise, tire-road noise and flow noise. For a conventional combustion engine, the first two dominate at low speeds, whereas at high speeds from about 130 km/h onwards the flow noise dominates the overall noise emission. In contrast BEVs generate almost no drive noise. This is the reason why flow noise becomes more important at significantly lower speeds.

Due to the desired reduction of drag and lift, BEVs typically are characterised by a streamlined underbody. Although this shape of underbody is typically characterised by a low acoustic interference potential, significant flow resonance can be observed for certain vehicle configurations and frequencies below 30 Hz. As a consequence, the interior of the vehicle is excited as a Helmholtz resonator by coupling these low-frequency periodic pressure fluctuations via the forced ventilation in the rear of the vehicle.

The present frequency range of this flow phenomenon falls into the range of the human auditory threshold. The perception of the high levels of pressure fluctuations varies greatly from one individual to another. In addition to an audible impression, they are very often experienced as an unpleasant feeling of pressure on the ears, as a so-called "buffeting". Due to this way of perceiving the phenomenon, as well as the fact that the emergence of the pressure fluctuations can be attributed to the flow around the vehicle, the phenomenon is hereinafter referred to as "underbody buffeting".

The aim of this work is to investigate the flow phenomenon in detail. Based on previous investigations, the first step consists of the development of an abstract research model that is used to investigate the phenomenon using both CFD simulations and wind tunnel experiments [1, 2]. After the flow phenomenon is generated, variant studies are carried out to investigate the influencing parameters in order to identify the exact formation mechanism.

Subsequently, these findings will be used to identify stable and robust measures to prevent the phenomenon. The major challenge here is the interaction between aerodynamics and aeroacoustics because the geometric modification of aerodynamic add-on components on the underbody influences the aerodynamic performance of the vehicle.

2 Research Model

In order to identify the exact origin of the low-frequency pressure fluctuations it is necessary to isolate the flow phenomenon. Therefore, and to be independent of a specific vehicle configuration, an abstract model was developed. Moreover, simplification of the geometry features the possibility of a theoretical observation of the flow around the particular geometries.

The so-called SAE-Body represents the Basis for the research. It is a generic car reference model which is based on the Ahmed body, and which was developed by a consortium of German car developers [3]. It has an abstract vehicle shape with a smooth underbody and a diffusor. Due to the simple and well-defined shape it does not have many other interfering aeroacoustics noise sources. Hence, the flow phenomenon will be easier to isolate.

To generate the flow phenomenon on the SAE-Body, add-on components were mounted on the vehicle's underbody. Here, in addition to cut-off cylinders representing the wheels, rectangular plates were used to model the wheel spoilers. In developing the model, care was taken to represent the flow phenomenon as accurately as possible in terms of flow variables and acoustic quantities. Simultaneously, the geometry was kept as simple as possible in order to enable a theoretical analysis of the flow.

The geometry of the developed basic configuration of the research model is illustrated in Figure 1. Subsequently it was possible to investigate the flow phenomenon both, with CFD simulations and wind tunnel experiments.

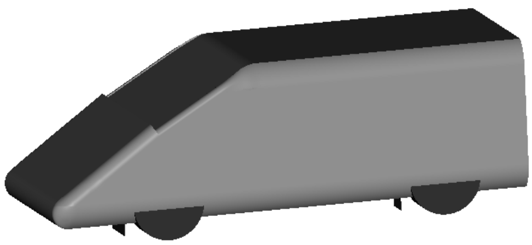

Figure 1: Geometry of the basic configuration of the research model with wheels and wheel spoilers

3 Simulation Setup

All simulations were carried out with the software PowerFLOW of 3DS Simulia. The research model described in Chapter 2 was used as simulation model. It was located in a virtual wind tunnel. The incoming flow velocity was 140 km/h. When performing the variant study, the calculation time was reduced by using a half model. The physical time of the transient simulation was 2.5 seconds.

The discretization in PowerFLOW was done using a cartesian grid. The individual grid cells were not all the same in size, but their size was defined by variable resolution areas. Since the focus of this work is mainly on the observation and analysis of the underbody flow, this area was discretized particularly finely.

In PowerFLOW, the flow is solved using the Lattice-Boltzmann method. A Very Large Eddy Simulation turbulence model and a wall law are also implemented to simulate high Reynolds numbers and flows near the wall. All simulations were performed with a moving floor configuration and with stationary wheels.

4 Simulation Results

Since very large amounts of data are generated during the transient simulation, evaluation planes were defined in advance on which the time data should be stored. For the images shown below, an evaluation plane is considered which is parallel and which is located 100 mm above the wind tunnel floor. In addition, virtual surface microphones were placed on the underbody of the SAE body, for which the particular pressure information is stored.

Frequency spectra were generated using this pressure information. In the following, spectra at a reference microphone in the rear area of the vehicle model are considered. The spectrum of the basic configuration of the research model is shown in Figure 2. Significantly increased pressure fluctuation levels are present in the low frequency range between 10 and 20 Hz. This important result shows that it is possible to model the flow phenomenon in CFD simulation on an abstract vehicle model, which provides the opportunity to study the flow phenomenon and its exact formation mechanism in more detail in the following.

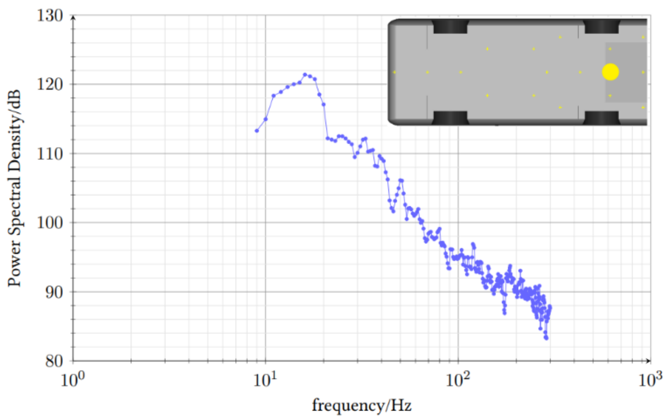

Figure 2: Frequency spectrum of the basic configuration of the research model at the reference microphone

Figure 3 (a) shows a dB-Map filtered by 16 Hz on the evaluation plane below the vehicle underbody. The map shows very clearly that the highest-pressure fluctuation levels occur in the rear area between and especially on the inside of the wheels. The averaged flow velocity on the same plane is shown in Figure 3 (b). The flow separates at the front wheel spoilers and at the front wheels. The wake behind this area extends until the rear wheels. Moreover, there is a shear layer with a strong gradient between the wake and the area of undisturbed flow.

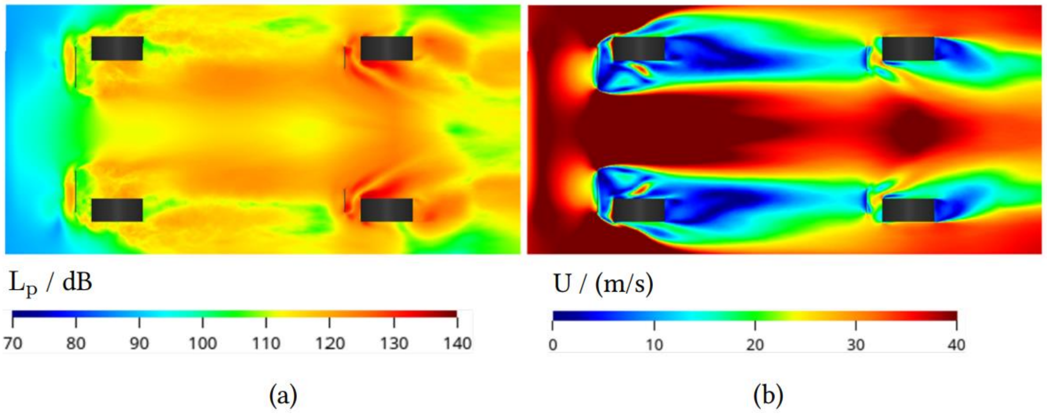

Figure 3: dB-Map of the pressure fluctuations filtered by 16 Hz (a) and averaged flow velocity (b) of the basic configuration of the research model - evaluation plane: 100 mm above the floor

In the following, some geometrical modifications were conducted in order to investigate the flow phenomenon and its origin in detail.

First, all cut-off cylinders and the rear wheel spoilers were removed, resulting in the SAE-body with only the front wheel spoilers as add-on components. The frequency spectra of this configuration in comparison to the basic configuration is illustrated in Figure 5. Significantly increased pressure fluctuation levels are present in the frequency range between 10 and 20 Hz. Hence, the front wheel spoilers seem to be decisive for the development of the underbody buffeting. The filtered dB-Map of this configuration is shown in Figure 4. Since a half model was simulated, only the driver's side is presented. In this case, the maximum levels occur behind the front wheel spoilers and no longer in the rear area. However, even there, the levels are still significantly increased.

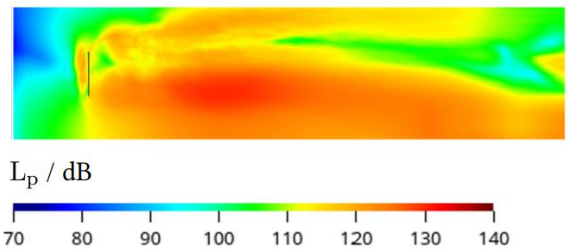

Figure 4: dB-Map of the pressure fluctuations filtered by 18 Hz of the configuration with front wheel spoilers - evaluation plane: 100 mm above the floor

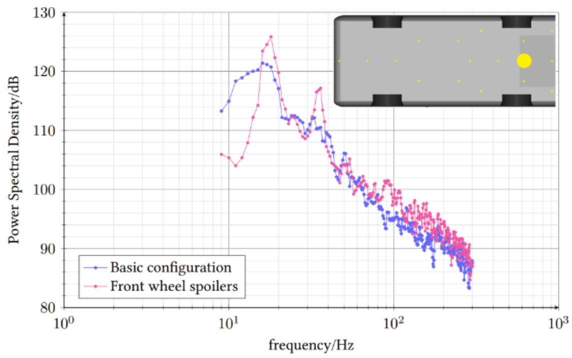

Figure 5: Comparison of the frequency spectra at the reference microphone - Basic configuration and configuration with only the front wheel spoilers

In a second version, the vehicle has the same wheel spoiler as the basic configuration, but instead of cylindrical wheels, splitter plates were attached behind the wheel spoilers. The splitter plates are rectangular plates mounted directly behind the wheel spoilers in streamwise direction. The frequency spectrum is illustrated in Figure 6 and shows 1 to 2 dB higher pressure fluctuation levels as the basic configuration. However, the curve progression as well as the values are comparable with it.

Figure 7 shows the dB-Map of this configuration. As same as for the basic configuration, the maximum pressure fluctuations are located in the rear area between the splitter plates. Interactions between the separations from both sides of the wheel spoilers are only possible behind the splitter plates in the front. In this region, there is a strong increase of pressure fluctuations. Therefore, the interaction between the two shear layers behind both sides of the front wheel spoiler seems to play a significant role for the development of the underbody buffeting. The similarity of dB-Maps and spectra of this configuration and the basic configuration hypothesise, that the wheels have the same effect as splitter plates: They suppress the interaction between the shear layers directly behind the front rear spoiler, which may lead to lower pressure fluctuations compared to the configuration without wheels.

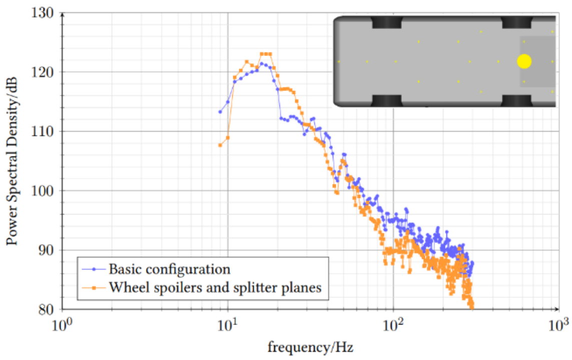

Figure 6: Comparison of the frequency spectra at the reference microphone – Basic configuration and configuration with wheel spoilers and splitter plates

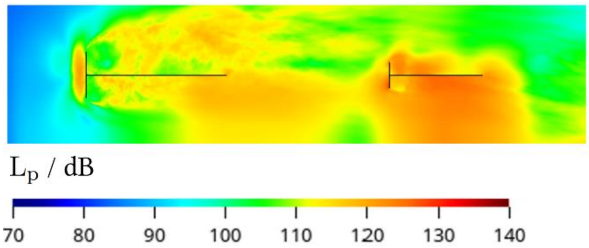

Figure 7: dB-Map of the pressure fluctuations filtered by 17 Hz of the configuration with wheel spoilers and splitter plates - evaluation plane: 100 mm above the floor

5 Formation Mechanism of the Underbody Buffeting

Subsequently the formation mechanism of the flow phenomenon is described. The variant study has shown the significance of the flow around the front wheel spoiler for the underbody buffeting. Therefore, it is discussed below.

The simplified wheel spoiler will be observed as a normal flat plate. This represents a simplification since the flow is affected by the underbody of the vehicle and by the wind tunnel floor. There are three tearing edges on which flow separation occurs. As a consequence, free shear layers develop. The velocity difference in the shear layer leads to the rotation of the fluid and its instability cause the formation of vortexes. The flow passing the lower edge of the wheel spoiler leads to a unilateral shear layer development. Consequently, a so-called "roof vortex" is generated. In contrast, the flow around the lateral edges causes a bilateral shear layer development. Due to the interaction between the two shear layers, a Kármán vortex street evolves. Its dimensionless frequency is around Str = 0.15. In the frequency spectra a dominating frequency f was visible. It can be calculated with the inflow velocity u, the characteristic length l and the dimensionless frequency Str via

$$f = \frac{\mathrm{Str} \cdot u}{l}. \qquad \text{(eq. 1)}$$

Besides, splitter plates can be used to suppress the development of a Kármán vortex street. For this configuration a significant reduction of the pressure fluctuation levels in the front area of the vehicle's underbody was visible. As a consequence, the bilateral shear layer development is the dominating mechanism for the underbody buffeting.

The generated vortexes are transported streamwise within the fluid flow. Thereby they grow in size, especially in regions with a strong gradient of the fluid velocity. This leads to the assumption of vortexes growing through the energy which they detract from the fast external flow. Flow separation occurs also at the rear wheel spoilers and at the rear wheels. In the rear part of the vehicle's underbody the separations of all spoilers and wheels superimpose. As a consequence, extremely high levels of pressure fluctuations arise in this area.

Furthermore, plots of the averaged velocity show that the rear add-on components are located inside the wake of the front add-on components. Therefore, the flow around the rear add-on components cannot be considered isolated from the front geometries. In [4], the flow around two cylinders in tandem configuration is investigated. The examination showed that the transient pressure fluctuations at the rear cylinder are 10 to 15 dB higher than the ones at the front cylinder if the rear cylinder is located inside the wake of the front cylinder. The wake interaction seems to be the reason for the strong pressure level increase. The wake of the add-on components in the front leads to a slower but higher turbulent inflow of the rear add-on components. The resulting pressure fluctuations at the geometries on the rear part of the underbody are therefore higher than the ones generated through vortex shedding in front of the underbody.

Figure 8 shows schematically the development of the flow phenomenon. Vortex shedding occurs at the front rear spoilers and at the front wheels. The vortexes are transported within the fluid flow. Thereby the grow in size and strength. Finally, the superposition of separations from front and rear add-on components together with wake interaction lead to extremely high levels of pressure fluctuations in the rear part of the vehicle's underbody.

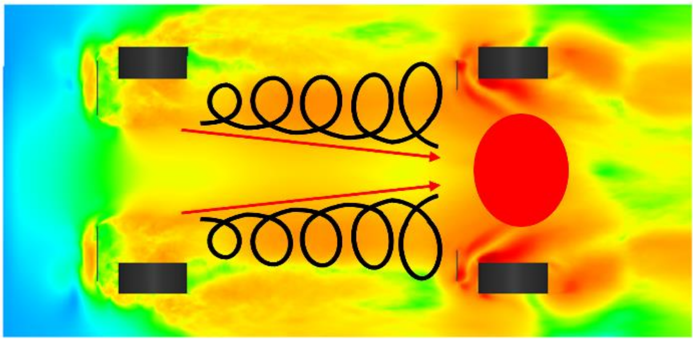

Figure 8: Schematic representation of the formation mechanism of the underbody buffeting

The SAE body was used to examine the external airflow and the external acoustics of the vehicle. For a real vehicle, the pressure fluctuations in the diffuser area are relevant for the resulting sound pressure levels in the vehicle’s interior. Finally, these are decisive for the evaluation of customer comfort. The transmission of pressure fluctuations from the underbody flow takes place via the air path of the forced ventilation. The excitation of the vehicle interior takes place when the low-frequency pressure fluctuations match the Helmholtz resonance frequency of the passenger cabin. Here, the air path represents the neck of the Helmholtz resonator, while the vehicle interior acts as a resonance volume. [5]

6 Experimental Setup

All experiments were conducted in the aeroacoustics wind tunnel of the Porsche AG. The same model geometry was used for CFD simulations and experiments. In order to ensure the closest possible matching in comparison to the CFD simulations, they were carried out with a moving center belt. All experiments were carried out at an inflow velocity of $U_\infty = 140 \frac{km}{h}$. Moreover, surface microphones were placed at the vehicle's underbody, consistently to the virtual microphones of the CFD-simulations. They served as quantification of the aeroacoustics performance of different vehicle configurations. Figure 9 shows the SAE-body in its basic configuration inside the wind tunnel.

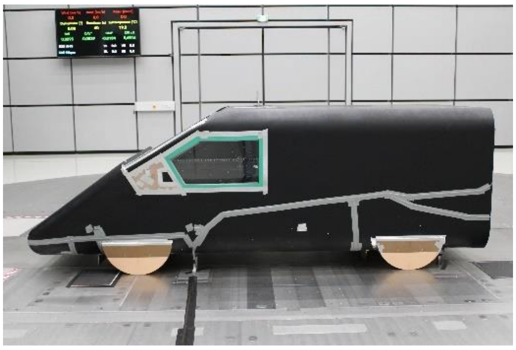

Figure 9: Basic configuration of the research model inside the wind tunnel

7 Experimental Results

The possibility of modelling the underbody buffeting with the software PowerFLOW was already shown. The next goal was to generate the flow phenomenon in the wind tunnel. Therefore, the research model described in Chapter 2 was designed and investigated.

Figure 10 shows the frequency spectra of the SAE-body on the reference microphone, which is located in the rear part of the vehicle, analogous to the CFD simulations. In the frequency range between 10 and 20 Hz, there are significantly increased pressure fluctuations, and the maximum is located at 15 Hz. Hence the flow phenomenon was successively generated in the wind tunnel at the SAE-body. This allows a detailed investigation of the underbody buffeting at the generic vehicle model.

The CFD simulations have already shown the significance of the front wheel spoilers for the underbody buffeting. The goal of the following variant study was therefore to investigate and evaluate different wheel spoiler geometries and their influence on the flow phenomenon.

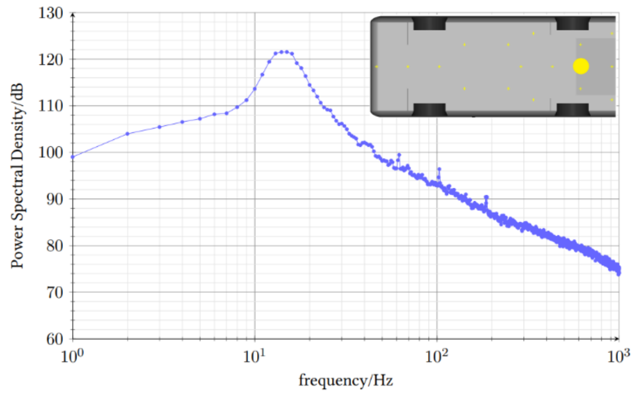

Figure 10: Frequency spectrum of the research model at the reference microphone

Firstly, the width of the front wheel spoiler is modified. The frequency spectra at the reference measuring point are illustrated in Figure 11. All curves show increased pressure levels in the lower frequency range. However, the frequency of the maximum pressure fluctuations as well as the pressure level varies with the wheel spoiler width. In general, the trend is that the maximum level increases with increasing wheel spoiler width, while the frequency at which this occurs decreases. The latter can be seen directly from eq. 1 if the wheel spoiler width is assumed to be the characteristic length. An exception to this trend is the variant with the highest wheel spoiler width. The frequency of the maximum level has also been reduced in this case, but the value of the maximum is reduced compared to the initial variant, in which the front wheel spoiler has a width of $b = 350\,mm$. The decrease in the maximum level may be related to the mutual influence of both wheel spoilers, since their distance is relatively small in this configuration. In addition, Kármán's vortex street may be weakened by the greater distance of the wheel spoiler side edges. In the case of very narrow wheel spoilers that do not protrude beyond the front wheel, the underbody buffeting does not exist since there are only slight level increases in the spectra. They can probably be traced back to detachments on the wheels and the rear wheel spoilers.

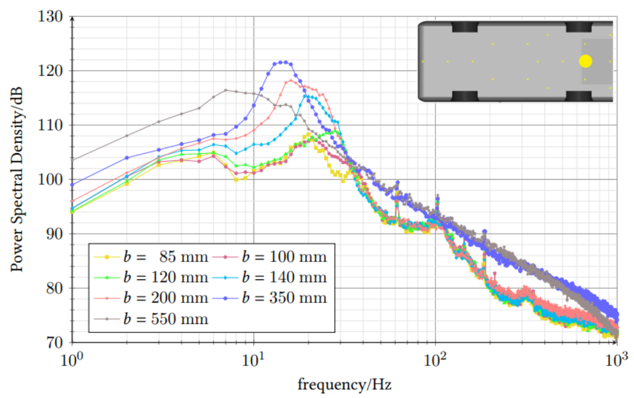

Figure 11: Comparison of the frequency spectra at the reference microphone by varying the width b of the front wheel spoilers

Although the underbody buffeting could be prevented by a small wheel spoiler, this geometric modification is not possible for aerodynamic reasons however, since this wheel spoiler do not generate sufficient front axle lift. Subsequently, two further wheel spoiler geometries were examined. One wheel spoiler has a reduced height compared to the original wheel spoiler, while the wheel spoiler width of the second wheel spoiler has also been increased. The resulting frequency spectra are shown in Figure 12. All spectra show the level increase in the frequency range between 10 and 25 Hz, which is typical for the flow phenomenon. The level maximum and the frequency at which this occurs differs between the different versions. For the variant with a lower wheel spoiler, the maximum level is reduced by 8 dB and the frequency shifts by 4 Hz to higher frequencies compared to the basis variant. The latter could be attributed to the fact that the Strouhal number increases slightly with increasing ground clearance. Due to the greater distance between the lower edge of the wheel spoiler and the wind tunnel floor, the roof vortex described in the second paragraph of Chapter 5 can evolve more strongly. This could weaken the formation of the Kármán vortex street and thus be the cause of the level reduction. By additionally increasing the width of the wheel spoiler, the maximum level can be further reduced. In addition to the stronger roof vortex, this could also be due to the increased spacing of the wheel spoiler side edges and the resulting weakened Kármán vortex street. In addition, the aerodynamic performance of this wheel spoiler improves compared to the first modification, because a wider wheel spoiler generates more front axle lift.

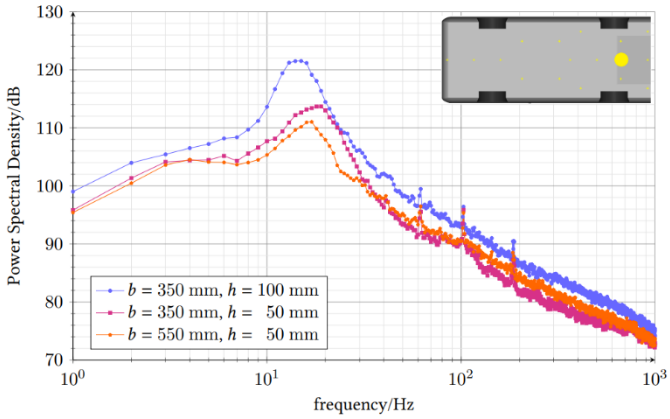

Figure 12: Comparison of the frequency spectra at the reference microphone by varying the height h and width b of the front wheel spoilers

8 Conclusion

In the present paper the flow phenomenon “underbody buffeting” was investigated. For this purpose, a research model was developed and used to generate the flow phenomenon both in CFD simulation and in the wind tunnel. Consecutively, the underbody buffeting was investigated by variant studies in order to subsequently identify the fluid mechanical mechanisms of the phenomenon.

The investigations have shown that the flow around the front wheel spoiler and the periodic vortex formation, evolved through the interaction of the bilateral shear layer development, cause the dominant separation frequency. The generated vortices are transported within the fluid flow, whereby they increase in strength and size. The high levels of pressure fluctuations in the rear part of the vehicle's underbody are decisive for the sound level in the vehicle's interior because they excite the interior Helmholtz resonator.

Future work will cover the development of measurements to suppress the underbody buffeting by simultaneously satisfy the aerodynamic requirements. These will first be designed on the research model and then transferred and optimised to real vehicles.

9 Acknowledgement

My special thanks go to Professor Wagner, my boss and supervisor Dr. Thomas Wiegand and my supervisor Dr. Maarten Brink for the professional exchange as well as the supervision and support in my doctoral thesis.

Furthermore, I would also like to thank all my aerodynamics and aeroacoustics colleagues as well as the concept building and wind tunnel team.

10 Bibliography

1. Benedikt Staudenmayer. „Analyse der tieffrequenten Strömungsphänomene bei Fahrzeugen mit geschlossenem Unterboden“. Master's thesis. University Stuttgart, 2021
2. Laura Breitenbücher. „Untersuchung von tieffrequenten Strömungsresonanzen am Fahrzeug-Unterboden“. Master's thesis. University Stuttgart, 2022
3. Hartmann, M., Ocker, J., Lemke, T., Mutzke, A., Schwarz, V., Tokuno, H., Toppinga R., Unterlecher P. and Wickern, G. Wind Noise caused by the Apillar and the Side Mirror flow of a Generic Vehicle Model. 18th AIAA/CEAS Aeroacoustic Conference, AIAA paper (2012), 2012-2205
4. Lockard, D., Khorrami, M., Choudhari, M., Hutcheson, F., Brooks, F. and Stead, D. „Tandem cylinder noise predictions“. 13th AIAA/CEAS Aeroacoustics Conference (28th AIAA Aeroacoustics Conference), S. 3450
5. Christian Weber. „Aufbau einer aeroakustischen Simulationsmethode zur Bewertung der Fahrzeug-Unterbodenströmung“. Master's thesis. University Stuttgart, 2018