Advanced Aeroacoustic Vehicle Development in a Full-Scale Wind Tunnel

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The full-scale wind tunnel at Stuttgart University, which is operated by FKFS, has been a well-established test stand for aeroacoustic development of production vehicles for many years. Recently, this wind tunnel has been significantly improved, among other things, with respect to aeroacoustic testing quality.

INTRODUCTION

For several decades, the aeroacoustic development of production vehicles has been based on low-noise full-scale aeroacoustic wind tunnels with an open test section [1]. To comply with increasing demands regarding the acoustic quality of vehicles, these wind tunnels have to be continuously improved. In addition, more realistic simulation of the approaching air flow and advanced measurement techniques are now in demand. For this and other reasons, the full-scale aeroacoustic wind tunnel at Stuttgart University (operated by FKFS) has recently been upgraded to improve acoustic testing quality and to reduce the wind tunnel's self-noise.

WIND TUNNEL SELF-NOISE REDUCTION

With regard to acoustic testing, one of the most important wind tunnel characteristics is the total sound pressure level in the test section. The acoustic target for the upgrade was to reduce the sound pressure level in the empty test section by around 5 dB(A).

As can be seen by the results shown in **FIGURE 1**, this target was met due to the combination of different acoustic measures. In particular, a new acoustic treatment of the collector and the downstream plenum wall as well as the application of acoustic linings in the first diffuser led to a reduction in self-noise. All measures resulted in a total sound pressure level of 64.7 dB(A) at 140 km/h (out of flow, empty test section), which means that the intended reduction in sound pressure level of 5 dB(A) was achieved.

PULSATION CONTROL

The shear layer created at the nozzle exit in the open test section contains coherent vortex structures. They are generated

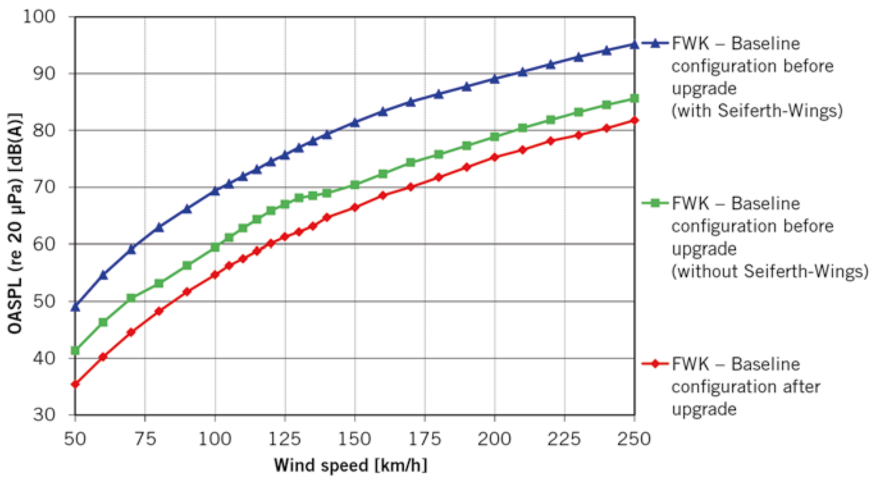

FIGURE 1 Overall sound pressure level measured out of flow in the empty test section before and after the wind tunnel upgrade (© FKFS)

along the nozzle edge and increase in a downstream direction, which affects the jet stability. This instability causes static pressure fluctuations in the frequency range below approximately 20 Hz, which is sometimes called wind tunnel buffeting. Thus, they have a negligible effect on the A-weighted sound pressure level. They may, however, result in a modulation of the vehicle's aeroacoustic noise, which impedes psychoacoustic evaluations. Although the resonant frequency itself is below the threshold of human hearing, the modulation effect is audible.

To significantly reduce wind tunnel buffeting for both aerodynamic and aeroacoustic reasons, a system of airfoils was developed and was installed in the nozzle exit area of the FKFS wind tunnel, see **FIGURE 2** (top). The system prevents the formation of coherent vortex structures in the shear layer. It is called FKFS Best (Beland Silent Stabilizer). The cambered airfoils change the flow angle locally at the nozzle exit and generate axial conical vortices. As a result, the uniformity of the jet shear layer and the coherent ring vortex structures at the nozzle exit are disrupted. Resonance is thus prevented and the jet itself is stabilised. In contrast to Seiferth wings or comparable measures placed in the air flow at the nozzle exit, the self-noise of the airfoils is negligible. Moreover, due to the stabilised shear layer, the airfoil system contributes to a reduction in wind tunnel self-noise.

The resulting rms value of the pressure fluctuations $c_{p,rms}$ measured out of flow is shown in the lower part of **FIGURE 2** as a function of the flow velocity (red line). Additionally, the configuration without any counter-measures (green line) and former results attained with Seiferth wings (blue line) are shown. The Seiferth wings at the nozzle edge achieve similarly low values, but, as mentioned above, they generate an unacceptable increase in background noise levels.

GROUND SIMULATION

In aeroacoustics, a realistic ground simulation in wind tunnels is usually seen to be less important than in aerodynamics. However, since the underbody can represent a significant low-frequency in-cabin noise source, it is worth investigating the underbody flow in more detail.

To improve the road simulation, a new modular belt system has been developed [3]. It is called FKFS First, which stands for fully interchangeable road simulation technology, and is integrated into a new, larger turntable which allows the system to yaw relative to the wind tunnel centre line. The development was based on decades of experience in operating belt systems and on numerical investigations

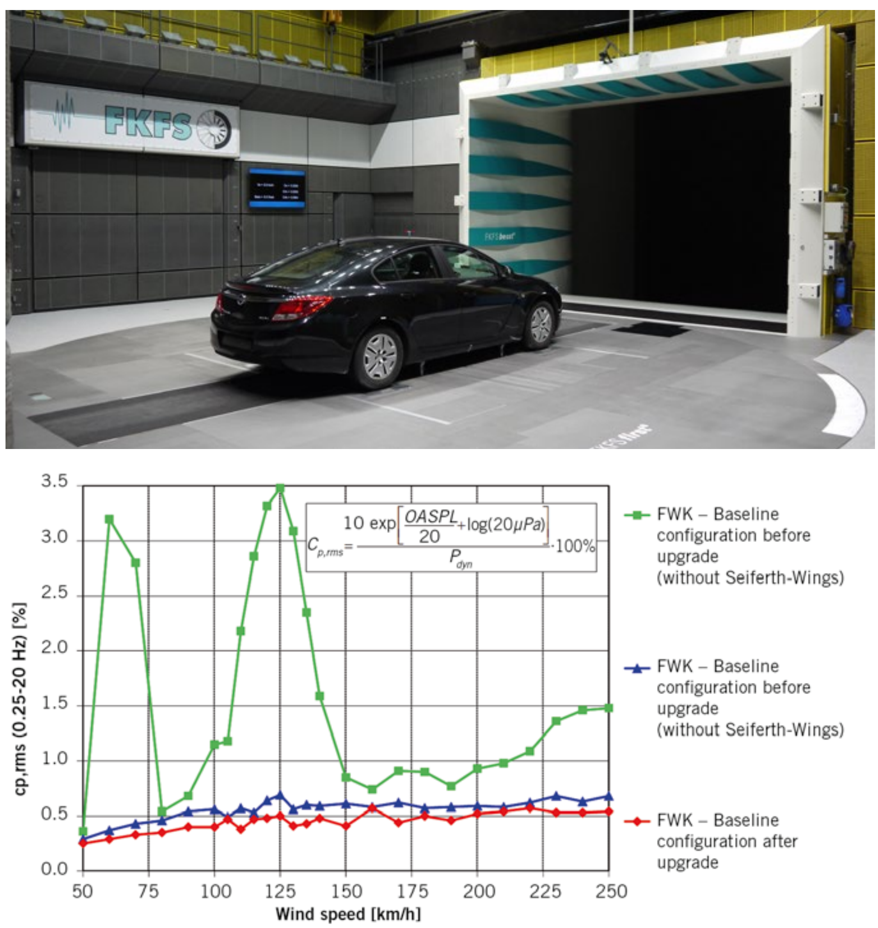

FIGURE 2 Wind tunnel nozzle with integrated flow guides of FKFS besst (top, green installations) and measured pressure fluctuation coefficient of FKFS wind tunnel (bottom) [2] (© FKFS)

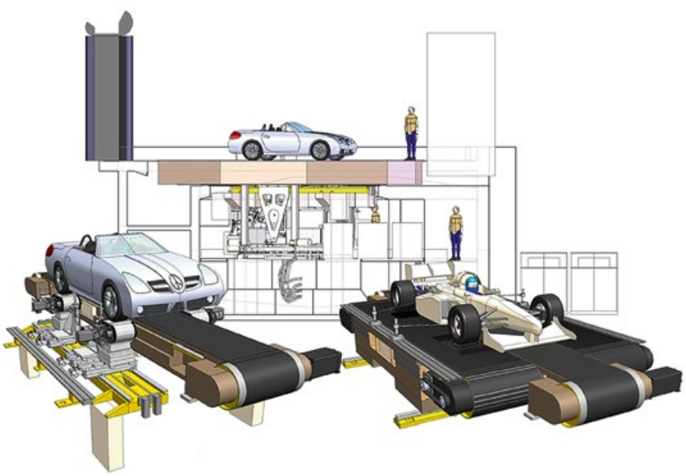

FIGURE 3 Illustration of the fully interchangeable 5-belt (left) and 3-belt (right) rolling road system [2] (© MTS)

[4], [5]. However, the constraints regarding boundary conditions, such as the existing building dimensions, had to be taken into account.

The new stainless-steel belt system can be used in a 5-belt and 3-belt configuration, **FIGURE 3**. It provides moving ground simulation and rotating wheels. Whereas the rotating wheel configuration is not suited for aeroacoustic measurements, as the rolling noise of the tyres would affect the wind noise signals, the centre belt can be used to improve the underbody flow for aeroacoustic measurements due to its low-noise design. The latter has been verified by measurements with a vehicle in the FKFS aeroacoustic wind tunnel in different configurations. A comparison of measurements with wind but without centre belt in operation and vice versa (wind off, centre belt on) has shown that the signal-to-noise ratio is sufficiently high for measuring the vehicle's wind noise. For interior noise, the signal-to-noise ratio is around 20 dB(A) at 140 km/h. Even for exterior noise measurements, around 10 dB(A) between the signal and noise are obtained at this velocity [6]. To determine the effect of the more realistic underbody flow on the interior wind noise, more detailed investigations are planned.

WIND GUST AND TURBULENCE SIMULATION

The aeroacoustic development of production vehicles is still mainly done in low-turbulence aeroacoustic wind tunnels. On the road, however, side wind gusts, vehicles driving in front, etc. disturb the approaching flow significantly. The resulting flow fluctuations cause an audible effect on the flow noise in the interior of the vehicle. Time-varying changes in flow speed result in an amplitude-modulated noise signal. Changes in the yaw angle affect both the amplitude and the frequency spectrum. Thus, in a real on-road situation, the interior noise is modulated in both amplitude and frequency [7, 8].

In recent years, there has been increasing interest in investigating wind noise under these realistic on-road flow conditions. In particular, the increasing demand for even more comfort and thus the need for enhanced psychoacoustic evaluations underline this trend. Thus, in order to simulate typical unsteady flow scenarios with regard to aeroacoustics and aerodynamics, a new active side wind gust and turbulence generator has been developed for and implemented in the full-scale aeroacoustic wind tunnel at Stuttgart University. The system, which is called FKFS Swing (side wind generator), consists of eight wing profiles that are vertically positioned at the nozzle exit (see picture page 46 or [9]). Each profile is operated by its own drive and activated by signals measured on the road, as well as by other time histories.

The maximum flow deflection and the maximum frequency that are necessary to reproduce typical on-road situations for aeroacoustics have been determined by on-road measurements and by considering psychoacoustic aspects. The maximum frequency is 10 Hz, with a maximum deflection angle at the vehicle of approximately 3°. For lower frequencies, larger deflection angles are possible.

For vehicle tests, time history data from on-road measurements or artificially generated noise signals are usually used. To reproduce the flow angle at the vehicle in the wind tunnel as accurately as on the road, the transfer function of the whole system, from data input to flow at the vehicle, has to be known. Once this has been determined and by using the inverse of this transfer function, the on-road flow situation in terms of the yaw angle can be accurately reproduced by the system. A comparison between the on-road time history (solid blue line) and its reproduction in the wind tunnel (dashed red line) is given in **FIGURE 4**.

First, basic investigations were carried out using two different vehicles. Whereas vehicle 1 is well rated on the road regarding wind noise under tran-

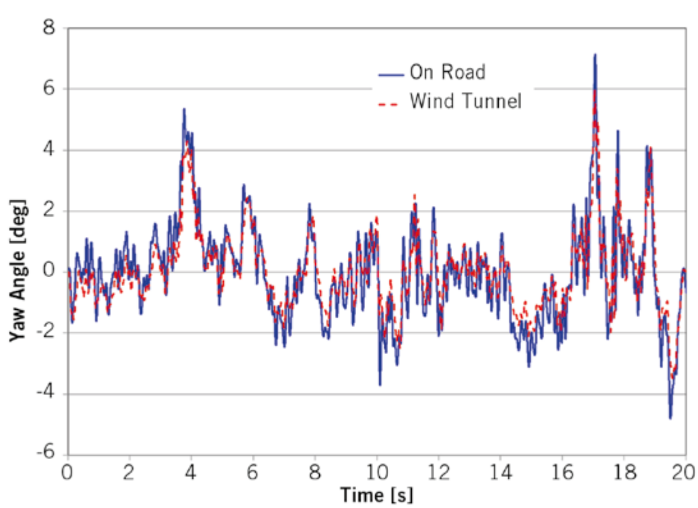

FIGURE 4 The flow yawing angle above the vehicle roof measured while driving on the road (solid blue line) and measured using FKFS Swing in the wind tunnel (dashed red line) [10] (© FKFS)

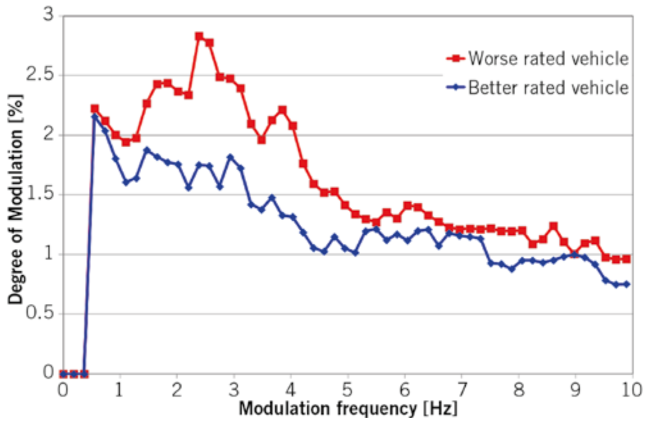

FIGURE 5 Modulation spectra in the 4 kHz octave band of the interior noise from two differently rated passenger vehicles exposed to the same unsteady on-road flow reproduced in the wind tunnel [10] (© FKFS)

sient flow conditions, vehicle 2 is less well rated under these conditions. Since modulations of around 2 to 6 Hz are most important for the psychoacoustic value of "fluctuation strength", one investigation focused on the determination of the part of the interior noise frequency spectrum which is most affected by this modulation. The difference in the modulation degree of the two vehicles in the noise levels of the octave bands from 500 Hz to 8 kHz showed that the negatively rated vehicle 2 produces higher values, especially in the 4 kHz octave [10]. Therefore, this octave band was chosen for further analysis of the unsteady aeroacoustic measurements.

FIGURE 5 shows the modulation spectra of the 4 kHz octave band of the interior noise of vehicle 1 (blue line with diamonds) and vehicle 2 (red line with squares). The vehicles were exposed to the same on-road flow simulated in the wind tunnel. As can be seen in **FIGURE 5**, the modulation degree for vehicle 2 is considerably higher than that for vehicle 1 over the whole frequency range. Hence, it can be concluded that these modulation spectra can be used for rating vehicles with respect to their acoustic behaviour in turbulent flow. Additionally, it proves that the system is able to reproduce on-road flow fluctuations in such a way that the perception of the interior noise is similar to that on the road. It leads to similar ratings of different vehicles. Further investigations are necessary, however, to underline these findings and to enhance the range of application.

MEASUREMENT TECHNIQUES

Acoustic measurements in the vehicle interior during wind tunnel tests can be carried out in the usual way as in vehicle acoustics. For example, artificial heads or single microphones can be used. To be able to determine the sound radiation

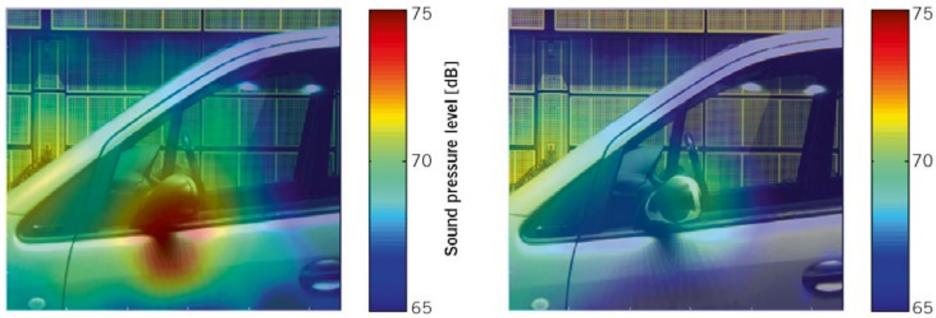

FIGURE 6 Sound pressure level map (5 kHz third octave band) of array-based mirror measurements of the side-view mirror of a mid-size car in baseline condition (left image) and with improvements (right image) (© FKFS)

of specific areas in the cabin, such as a door for example, more advanced techniques can be applied. One of such a technique is called near-field acoustic holography (NAH), which is based on intensity measurements using microphones. NAH covers a relatively broad frequency range. Another technique for near-field measurements to determine the sound source is based on PU probes, which consist of a microphone and a hot wire anemometer to measure the sound particle velocity.

For exterior noise, the use of conventional acoustic measuring techniques is problematic due to the air flow around the vehicle body. When measurements are taken in the air flow, so-called 'pseudo sound' occurs at the microphones, resulting from the fact that the measuring diaphragm is exposed to the fluctuating flow pressure. Additionally, flow noise and thus extraneous noise is generated at the microphone housings, pre-amplifiers and fixtures. As a consequence, measuring techniques developed specifically for these cases are used. For example, microphones and sound intensity probes have to be equipped at least with nose cones or the like and a low-noise fixture has to be used.

Usually, aeroacoustic wind tunnels are open-jet wind tunnels, as is the case with the wind tunnel at Stuttgart University. The open-jet test section allows for out-of-flow measurements. However, due to the relatively large distance to the vehicle, the measuring system should be able to focus on the area under examination in order to precisely localise existing sound sources. In most cases, microphone arrays are used for this purpose.

An alternative method, which has been developed and implemented by FKFS, is the use of a parabolic acoustic mirror. The conventional acoustic mirror is equipped with one microphone which is placed at the focal point of the mirror. Compared to measurement with a microphone, focus on the area under examination and an enhanced signal-to-noise ratio is achieved. However, only one focus can be set at once.

A further stage of the acoustic mirror, a so-called array-based acoustic mirror, has been developed for the upgrade of the Stuttgart University wind tunnel. Here, the reflected sound is recorded not only by one microphone but by a large number of microphones on a plate around the focal point of the mirror [11]. This allows the simultaneous recording of several sound sources in a larger area of the object being investigated. The array-based acoustic mirror at FKFS consists of a relatively easy to handle mid-sized parabolic mirror and includes 108 microphones [12]. Compared to conventional acoustic mirrors, fewer measurements are necessary. Compared to beam-forming arrays, it needs less space and is usually less expensive.

As an example, **FIGURE 6** illustrates the results of a measurement using the array-based mirror focusing on the A-pillar region of a mid-size car. The sound pressure level maps for the 5 kHz third octave band show that the side rear-view mirror is the most relevant sound source and also shows a possible improvement after appropriate measures.

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