

New FKFS Technology at the Full-Scale Aeroacoustic Wind Tunnel of University of Stuttgart

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ABSTRACT

For many years FKFS has operated the full-scale aeroacoustic wind tunnel of University of Stuttgart. To keep this wind tunnel as one of the most modern ones of its kind, it has again been upgraded significantly. The upgrade improved the aerodynamic as well as the aeroacoustic performance and accelerated the operational processes. Additionally, new innovative features have significantly enlarged the test capabilities. A new patented, modular belt system (FKFS **first**®) allows high performance measurements for race cars in a 3-belt mode as well as efficient measurements for production vehicle development in a 5-belt mode. The belt system is accompanied by a new, larger turntable and a new under-floor balance which enables high-accuracy measurements of forces and moments also for a high resolution in time. For the elimination of parasitic forces generated at the wheel drive units, a specific correction procedure has been implemented, which is patented, too (FKFS **pace**®). A new type of boundary layer conditioning system rounds up the enhanced road simulation. Unsteady aerodynamics can be investigated by means of a unique, active side wind generator (FKFS **swing**®). It consists of 8 wing-like profiles with independent drives which can deflect the whole airflow around the car in the test section with a frequency of up to 10 Hz. This system can also be used for unsteady aeroacoustics. The acoustic performance of the wind tunnel has been improved mainly by acoustic linings in the first diffuser. Special patented profiles in the nozzle (FKFS **besst**®) and a Helmholtz resonator suppress low frequency pulsations of the open jet very efficiently. The profiles also reduce the high-frequency broad-band noise of the wind tunnel.

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INTRODUCTION

For several decades, wind tunnels have served for vehicle development. During the first few decades, they were used for aerodynamic development. Later, the development of thermal management and aeroacoustics was added. Wind tunnels simulate real driving conditions but with limitations due to technical (or economical) restraints. Although driving on roads would provide per se the real conditions, the reproducible boundary conditions in wind tunnels are the necessary and preferable environment for vehicle development. The limitations in wind tunnels require a detailed understanding of the underlying physics; on the one hand to interpret the measurement results correctly, and on the other hand to improve the wind tunnel technology for a more realistic simulation of real road conditions [1].

FKFS has been operating wind tunnels for more than 80 years. Besides operating the wind tunnel for vehicle development, FKFS does research in the field of wind tunnel technology. Since 1989, it has been operating the full-scale automotive wind tunnel of University of Stuttgart [2]. As a result of the research work and due to the necessity for innovations, the wind tunnel has undergone comprehensive upgrades several times. In 1993, the wind tunnel was reconditioned for aeroacoustic measurements and equipped with traversing gear. In 2002, a 5-belt system including a boundary layer

conditioning system was implemented, and the wind tunnel control and data acquisition system was improved [3]. The 5-belt system was the first one in the world using steel belts.

In 2014, the latest upgrade was completed. The following goals were envisaged:

- Improvement of the road simulation, for both production cars and for race cars
- Suppression of the low-frequency pulsations (buffeting or booming noise) by low-noise means
- Reduction of the broad-band background noise of the wind tunnel
- Simulation and measurement of unsteady effects for aerodynamics as well as for aeroacoustics
- Improved productivity by faster processes

Investigations on the past have shown that unsteady aerodynamics and aeroacoustics is seen to be indispensable for future vehicle development [4, 5, 6]. The frequency-dependent, dynamic behavior of the vehicle due to the unsteady incoming flow is a characteristic of a vehicle which should not be ignored for safety and comfort reasons.

The same holds true for aeroacoustics. The modulation of the noise due to the unsteady incoming flow leads to earlier driver fatigue and passenger discomfort.

The aim of the present paper is to offer an overview of the recent upgrade of the full-scale aeroacoustic wind tunnel of the University of Stuttgart, but not to discuss details of the results. The latter will be given in future papers so as to be able to focus more deeply on the individual topics.

INNOVATIONS IN THE FULL-SCALE AEROACOUSTIC WIND TUNNEL

Four key innovations have been developed and implemented in the wind tunnel to reach the goals described above. These key innovations are described in the following sections. Additional improvements are also briefly described below.

A new primary boundary layer suction system was installed. It is a double distributed suction system, located in the nozzle for the purpose of gaining space for a larger turntable and a longer center-belt. A new crane that covers most of the test section allows to handle heavy parts, as for example components of the belt system.

For the reduction of the broad-band background noise in the wind tunnel, the first diffuser was equipped with about 300 m² of absorbing material (foam absorber covered by a robust fabric layer) at the walls and ceiling. Prior to that, the collector and parts of the downstream test section wall had been covered by a deep-pile absorbent material.

New Modular Belt System

To improve the road simulation for production cars as well as for race cars, to be able to measure the unsteady aerodynamic effect on the vehicle, and to improve productivity, a new rolling road system (RRS) including a new modular belt system has been developed and patented [7]. It is called FKFS **first**[®] which stands for fully interchangeable road simulation technology. FKFS **first**[®] is combined with a new, larger, double-diameter turntable and an under-floor balance capable of measuring forces and moments in a high time resolution. The development was based on the experience in operating belt-systems for decades and on numerical investigations [8]. However, the constraints of boundary conditions such as the existing building had to be taken into account.

The RRS and balance system is incorporated into a turntable, which allows the system to yaw relative to the wind tunnel center-line. The turntable includes a vehicle lift system to apply changes to the vehicle underbody inside the test section. The belt systems provide moving ground simulation and rotating wheels. The vehicle restraints provide means to fix the vehicle in the wind tunnel and provide vehicle attitude positioning and force measurement.

In addition to the major equipment of the RRS, which are described below, the following components have been installed:

- A quiet hydraulic power unit
- Water conditioning unit

- Data Acquisition System (DAS)

Belt Systems

The state-of-the-art moving ground system for the full-scale wind tunnel was ordered at the end of 2010. The integration of the MTS rolling road systems (RRS) into the wind tunnel provides precise and reliable aerodynamic simulation for advanced passenger car development. Parts of the RRS (for the time being the center belt) can also be used to improve the road simulation for aeroacoustic measurements.

The new stainless steel belt rolling road system is an interchangeable 5-belt / 3-belt configuration (see [figure 1](#)). The 5-belt configuration consists of a long center-belt and four wheel drive units. The wheel drive units are located under each tire. The 3-belt configuration consists of a long center-belt and two side-belt units. The side-belts are located under the left and right pair of tires and provide more moving ground simulation for high performance ground effect and race vehicles.

Integral to this is the under-floor balance, which has been developed specifically for ground simulation applications, meaning optimum performance in the presence of rolling wheels and moving ground belt systems. The balance is designed to allow aerodynamic testing at industry standard levels of accuracy and repeatability. The high stiffness balance maintains fixed position of the wheel drive units in the turntable under load. This also provides cross force load rejection and relatively high system eigenfrequencies with the test vehicle installed.

In the 5-belt mode, the wheel drive units also provide measurement of vehicle wheel tractive forces through purpose-built force measurement transducers under each wheel. In the 3-belt mode, the side-belts provide measurement of the vehicle wheel vertical force by through-the-belt wheel force measurement transducers. These purpose built measurement systems incorporate load sensing technologies used by a wide variety of force transducer applications to allow a high accuracy, repeatability and sensitivity.

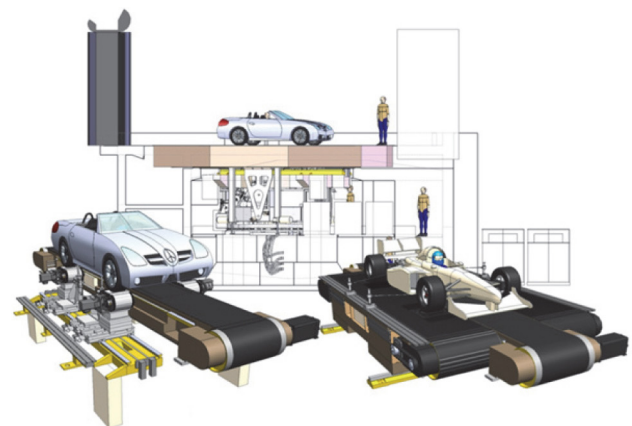


Figure 1. Drawing of the interchangeable 5-belt (left) and 3-belt rolling road system (right, source: MTS).

The under-floor balance comprises a packaged solution, allowing the full system of yaw bearing, balance, and rolling road to be packaged into a height that did not require extensive modification to the existing balance foundation.

The Rolling Road System consists of the following moving belts and vehicle restraint units.

- Center-belt, length 7.8 m, two available widths 900 mm and 1,100 mm. The center-belt is installed in the turntable and runs between the wheels of the test vehicle. It provides a moving ground plane under the vehicle.
- 4 Wheel drive units (WDU), 280 mm or 360 mm wide belts: The test vehicle is vertically supported under each wheel by 4 small belt units. The WDU's are attached directly to the measurement platform of the under-the-floor external balance system.
- Rocker Panel Restraints (RPR) with X-Y positioning system: In horizontal directions four vertical actuators restrain the test vehicle via vertical struts. The RPR's are attached directly to the measurement platform of the under-the-floor external balance system. These are used with the WDU's in the 5-belt mode. These RPR can operate in fixed or in float ride height mode.
- 2 Side-belts, 5.7 m long, 1.1 m wide: The side-belt units can be installed as an alternative to the WDU and RPR assembly. The side-belts are attached directly to the measurement platform of the under-floor external balance system.
- Vehicle Post Restraints (VPR): In horizontal directions two manually adjustable posts restrain the test vehicle. The VPR's are attached to the measurement platform of the under-floor external balance system via the side-belts. These are used with the side-belts in the 3-belt mode.

This new RRS significantly increases the accuracy and reliability of the rolling road simulation in the full-scale aeroacoustic wind tunnel and can deliver the difficult incremental increases in vehicle performance through drag reduction and improved flat surface roadway aeroacoustic development.

Turntable and Yaw System

The turntable, as usual, provides the interface between RRS and facility as well as the capability to yaw the vehicle. It has two different diameters to exploit the available space in an optimum way. The front diameter amounts to 4.4 m and the rear diameter to 4.7 m. Besides the belt systems, it also provides support for a vehicle lift with a maximum lifting capacity of 4,000 kg and a secondary boundary layer removal system in front of the belts. For the 5-belt mode, a distributed suction replaces the side belts, apart from the WDU's.

Under Floor Balance and Dynamic Measurements

The aerodynamic balance is used for the static measurements of aerodynamic forces and moments acting on the test vehicle. An overall drawing of the balance is given in [figure 2](#). The balance upper frame is integrated with the RRS so that the forces, which act via the RPR's and WDU's in 5-belt mode or via the side-belts and VPR's in 3-belt mode, are measured by the balance. Additional components of

the RRS such as the turntable and center-belt do not touch the components connected to the vehicle so that only aerodynamic forces acting on the vehicle are measured.

The transducers are designed to be highly sensitive in the measured load directions while mechanically rejecting off axis loads to reduce cross talk. The system uses an all-bending beam construction. This maximizes the strain output for greatest sensitivity using the minimum number of strain sensing elements for greater reliability and long term stability while at the same time providing high system stiffness. Custom strain gauges with thermal and creep characteristics matched to the transducer material are utilized. Each transducer has a 0.01 % full-scale static error band over the load range. This is necessary to insure that balance as a system meets the quoted accuracy (see [figure 3](#)).

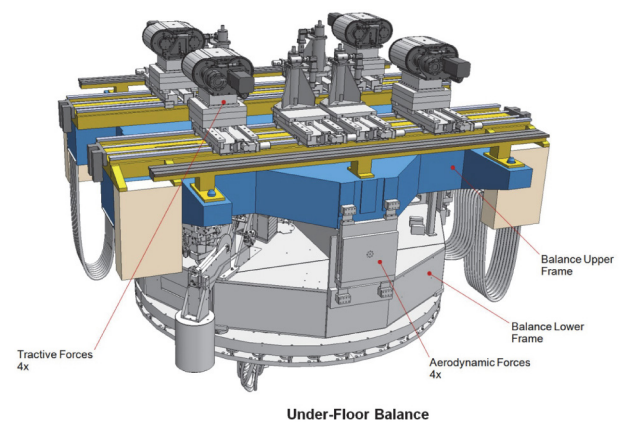


Figure 2. Drawing of the under-floor balance which has been installed in the full-scale aeroacoustic wind tunnel (source: MTS).

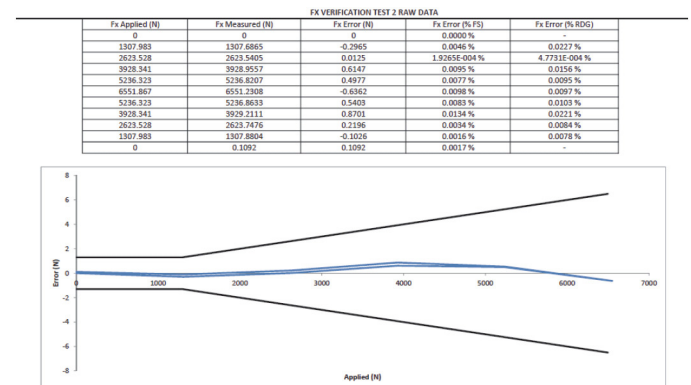


Figure 3. Performance of the under-floor balance. The achieved accuracy (blue lines) is of much higher quality than the originally specified values (black lines).

With respect to the unsteady aerodynamic effects that will be investigated, the balance system is suitable for dynamic measurements. For these investigations, a lock-out mechanism is activated in the balance. This lock-out increases the stiffness of the balance and the resonant frequency performance of the whole system including fixed vehicle to over 10 Hz, which is beyond the considered range for aerodynamic investigations.

For the dynamic force measurements, specialized load transducers are integrated to the RPR system. Adapters are mounted to the top of the RPR actuator bases to provide a stiff connection for the load cell. Short, stiff vehicle adapters are required to mount between the load transducer and the vehicle.

The four dynamic force measurement transducers are designed with the following features:

- Each load transducer is a piezoelectric tri-axial load transducer.
- Inherently low cross-talk transducer with high-stiffness, i.e. high eigenfrequency to allow for dynamic measurement.
- Each load transducer also includes an amplifier which converts the electrical signal of the sensor into high-level analog output voltage.

The data from each transducer is collected by an analog-to-digital conversion electronics at 1024 Hz. The real-time controller transforms the data force outputs for each transducer into the vehicle coordinate system. The data is broadcast to the data acquisition system via a user datagram protocol ethernet at 128 Hz and contain the AC as well as the DC components. The whole measurement procedure and first results will be described in a future paper.

Data Acquisition System

The data acquisition system uses one general user interface (GUI) personal computer (PC) with Microsoft Windows 7 operating system. The GUI translates operator or wind tunnel control system inputs into subsystem commands. The demand upon the PC is low and real-time control processes do not depend upon the performance of the PC. The DAS can control both belt systems, all data measurement equipments, every subsystem which belongs to RRS and the side-wind and gust generator FKFS **swing**[®] (see below).

Elimination of Parasitic Forces

The WDU's used in a wind tunnel do more than rotate wheels. They are also connected to the wind tunnel balance, which measures the forces in the tire contact area as well as the forces that act on the vehicle laterally or longitudinally. When air flows around the vehicle, it causes a vacuum between the vehicle and the ground, which dynamically creates downforce on the underside of the vehicle. However, because the surface of the WDU's is larger than the tire contact area, the vacuum acts also on the uncovered part of the weighing elements. This alters the measurement results, because parasitic additional lift force is measured which does not exist in a real driving situation.

This phenomenon has been known for a long time. In older wind tunnels with board or roller systems, it was partially ignored. Sometimes correction factors were determined and integrated into the measurements. But neither of these approaches proved to be satisfactory. The situation was aggravated by the introduction of belt systems as WDU's, because they increase the impact surface for the vacuum. Many attempts were made to resolve this situation.

However, none of them solved the problem of measuring the pressure on the moving surfaces of the WDU's. Attempts by means of using similarity analogies to stationary points were unsuccessful.

Therefore a new method was developed at FKFS. On this, during a short correction measurement, the vehicle is locked directly to the wind tunnel floor by special means. In this way, all forces acting on the vehicle are no longer detected by the balance but intercepted by the floor. This configuration provides directly the sought lift forces of the pads (see [figure 4](#)). This patented process is called FKFS **pace**[®] which means pad correction procedure [9]. Extensive testing in the model-scale wind tunnel has verified the process, which has led to much more precise measurements of lift forces.

Suppression of Low-Frequency Pulsations

Open jet wind tunnels with a closed circuit are prone to low frequency fluctuations in pressure and velocity, especially at certain velocity ranges. These fluctuations can also modulate the flow noise in the duct and may influence the results of the aeroacoustic measurements. In the future unsteady measures like side forces or surface pressures will be of increasing importance in vehicle development. A necessary requirement for such investigations is a wind tunnel with as low pressure fluctuations as possible. Furthermore, pressure pulsations can damage the structure of the building. Low-frequency fluctuations should thus be minimized in automotive wind tunnels.

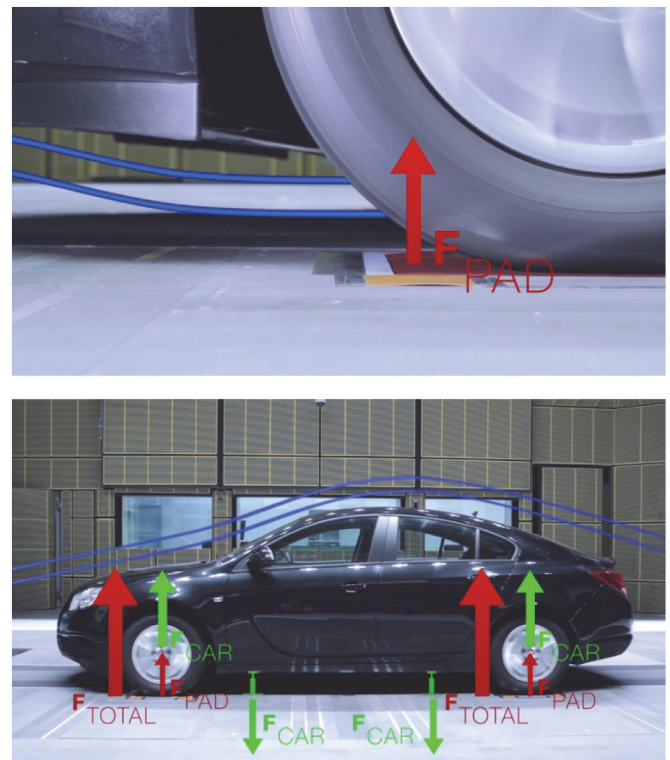


Figure 4. Sketch of the principle of pace.