Just like real racing: Wind tunnel measurements for simulating the dynamic behaviour of a ground vehicle

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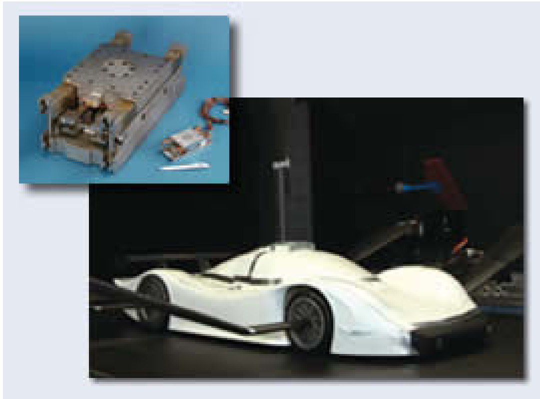

Most wind tunnel measurements with ground vehicles are performed with models that are kept stationary during the measurement. With a novel model manipulator, it is possible to simulate the dynamic behavior of the vehicle over the track with respect to height and pitch and at the same time measure its aerodynamic performance.

The results of such tests carried out with a race car model confirm that these transient aerodynamic effects must not be ignored during the optimization process of the aerodynamic design if best performance is needed.

The aerodynamics of new vehicles is often optimized in wind tunnels. Reduced-scale models are positioned in the wind on an aerodynamically shaped mounting. Sensors built into the model provide data on aerodynamic forces and moments, as well as pressure values on the surface of the model. Aerodynamicists use both measured and numerically derived characteristics to decide on necessary design changes. In wind tunnel testing, normally only mean values for aerodynamic characteristics such as lift/downforce and drag are determined, so that the estimate of test object properties is as reproducible as possible. But the latest investigations at the Center Aerodynamics of RUAG Aerospace in Emmen, Switzerland show that the use of aerodynamic mean values is not always correct.

Fig. 1: LeMans car model (30 %) in the automotive wind tunnel. At no time during this test do the wheels touch the model; they are held in the correct place by special wheel arms at the side.

Fluctuations caused by flow separation, natural air turbulence or the usually unavoidable natural motion of the test object relative to the wind, cause the instantaneous value to vary from the mean by unexpectedly large amounts. These instantaneous values are very useful for the development of highly optimized racing cars as well as more conservatively designed production cars, for keeping the distribution of force on the front and rear wheels in the safe range at every moment and to achieve good and reliable handling characteristics.

Just like running the car over the real track

To realistically simulate vehicle movements in the wind tunnel, vertical movements of several millimeters in amplitude are induced to the wheel axles, at frequencies up to more than 20 Hz. A hydraulic "shaker" with a control unit has been developed to produce such motions on the wind tunnel model. In the model, the shaker is located beneath the weighing sensor – the balance – that in turn is fixed at the vertically aligned model support protruding through the roof of the model. Separation of aerodynamic forces from the often considerably greater inertial forces caused by the above described movements poses a particular challenge in this measurement task, as the balance itself can only account for the sum of these forces and moments. To accomplish this partitioning with sufficient precision, the recording of about 100 measurement channels must be perfectly synchronized and analyzed. High-quality measurement data at sampling rates from 400 Hz upwards are the basis for this task.

A balance determines all the forces and moments acting on the model

The six aerodynamic forces and moments (drag, side force, lift/downforce, rolling moment, pitching moment and yawing moment) that act on the test object during the wind tunnel test are determined with a special six-component balance integrated into the shaker. Providing excellent quality of signal conditioning and amplifier, the balance meets stringent demands for accuracy at minimal dimensions and extreme stiffness.

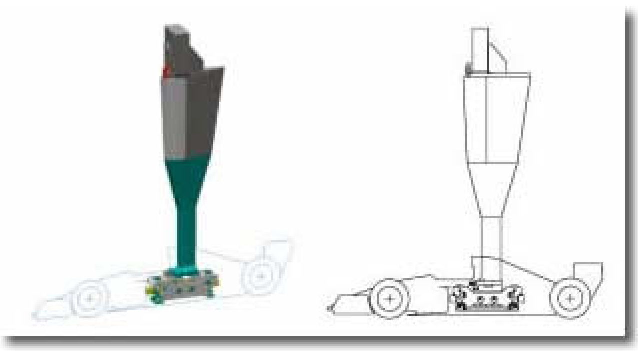

Fig. 2: The "shaker" model movement unit built into the vehicle model, with model mounting

Strain gages are applied as full Wheatstone bridges on the balance measuring beams. In order to cope with temperature variations the wiring is thermally compensated. The measuring beams under the action of the load only minimally deform in the elastic range and produce output signals in the strain gages proportional to the applied load. The correlation between these electrical signals and the actual load is determined by a balance calibration procedure carried out subsequent to fabrication. This procedure takes place with calibrated mass weights and a calibration device connected to the balance offering various pivot options.

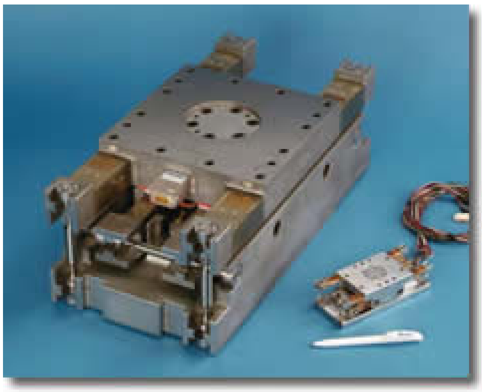

Fig. 3: A selection of multi-component balances, as used in wind tunnel testing. The smallest balance weighs 0.25 kg, the largest 112 kg.

By attaching the weights to these pivot points on the model side of the balance, pure forces or a combination of a force and up to two moments can be applied on the balance. The calibration matrix – defining the relationship between load values and electrical strain gage values – is derived by a regression algorithm that takes into account all the well defined load cases which that were applied during the calibration process. The inverted matrix – defining the relationship between electrical values and load values – allows the calculation of the applied forces and moments from the electrical measurement signals as is needed during measurement.

For some years, Ruag Aerospace has relied for data acquisition in its wind tunnels on HBM's MGCplus technology. By choosing different amplifier types and combining the amplifiers with the proper connection boards, it is possible to meet the demands for accuracy (divided into accuracy classes) as well as for a wide variety of possible sensor types. For each wind tunnel at the Center Aerodynamics, the hardware components have been integrated in a flexible and easily used complete system in a cabinet with various monitoring devices.

Fig. 4: Data acquisition system with MGCplus technology: Front (on the left) and back with connection boards (on the right)

For practical reasons, it was decided to use standard modular enclosure systems on rollers with five MGCplus housings, with the amplifier displays and control buttons at the front and standard connection boards with sockets for the power, measurement signal and data lines at the back. Drivers for communication between the hardware and the company's own master computer and data analysis software also had to be created and adapted to the specific measurement tasks. Finally, a special calibration system/procedure was developed for the measurement system, for flexible – and for the expensive wind tunnel test environment most important – quick on-site use that allowed to trace back all the different system components to national standards.

Motion greatly influences aerodynamics

In first wind tunnel test campaigns with the moving model, motion trajectories were initiated at frequencies up to 10 Hz, for 20 second periods, in order to search for transient aerodynamic phenomena. The movements took the front and rear axles of the vehicle model up to 4 mm out of the standard position, the front and rear axle being either fully in phase, 180° out of phase or the rear axle being kept still. A sampling rate of 400 Hz was specified for these tests by weighing up the timing resolution and the amount of data this would produce. Once data is available from a wind tunnel test with time-resolved measurement, there are many possible ways to evaluate it.

In the initial phase, non-linear filtering is applied, in order to reduce the noise component of the individual measurements. Then the inertial forces are calculated and subtracted from the total forces, for which signals from the acceleration transducers at selected model positions are consulted. With the calculated result a number of relevant stability problems caused by the interplay of aerodynamics with the chassis dynamics can be analyzed in detail and used to characterize the drivability or even the safety of the vehicle configuration at hand. This method of measurement allows the optimization of the vehicle not just to the lab-like conditions in the wind tunnel, but also, by simulating realistic vehicle movements, to real situations that occur on the track.

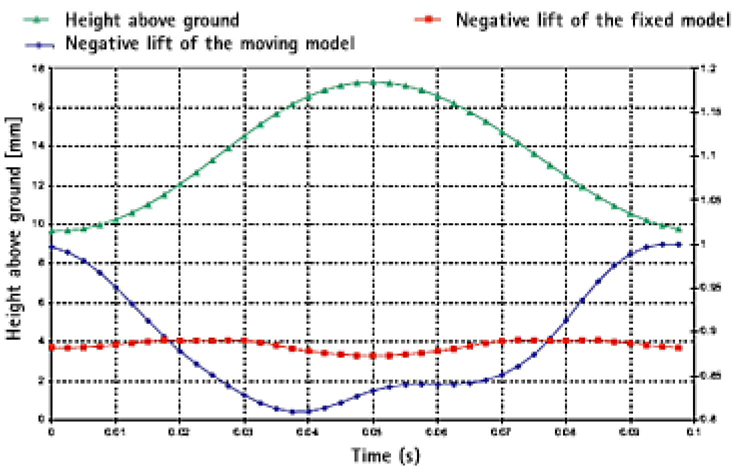

Fig. 5: Comparison of static and time-resolved measurements for a simplified a LeMans race car

Figure 5 shows the time varying downforce coefficient (negative lift) of a simplified model of a LeMans racing car moved at 10 Hz (Fig. 1) compared to static measurements. The green curve describes the movement when, in this case, the front and rear axles move up and down in phase at an amplitude of 4 mm. As is usual for race cars, there was very little ground clearance for this test, so that the nose of the model approached to within about 2 mm of the ground. The red curve describes the downforce measurements with a fixed model. To derive this curve, the model was taken to every one of the given positions, was fixed in position and the average downforce level was established; in the configuration shown, there proves to be only a slight dependency between the downforce coefficient and the height above ground. The situation is completely different when measurement and analysis are time-resolved and relate to the moving model (blue curve). The enormous differences from the mean value indicate that the movement causes vast fluctuations in aerodynamic force and moment, which under certain circumstances can greatly influence the stability of the vehicle.

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