

The Influence of Motion Aerodynamics on the Simulation of Vehicle Dynamics

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ABSTRACT

Race cars undergo very quick ride height changes on the track, which are induced by breaking, acceleration, cornering, as well as bumps on the track. It has recently been shown in wind tunnel tests that these quick changes in model attitude can lead to astonishingly large hysteresis effects on the aerodynamic coefficients. In order to verify whether such effects may be relevant to the overall performance of a car, aerodynamic data from wind tunnel tests with a moving model was fed into a vehicle dynamics simulation program. Relevant changes in estimated car performance on straight as well as on curved tracks are reported.

INTRODUCTION

Lap time or vehicle dynamics simulation is usually carried out assuming a fixed one-to-one relationship between aerodynamic coefficients and ride heights. The (static) aerodynamic characteristics are obtained from wind tunnel measurements or are calculated with CFD. In recent wind tunnel tests it has been shown that this approach is a significantly incomplete representation of the real transient situation. Indeed, large variations and hysteresis effects in time-resolved aerodynamic coefficients have been found for realistic ride height variations representative for normal race car driving ([1]-[4]).

Since the averaged aerodynamic load values from tests with a moving model correlate quite well with the values from traditional static wind tunnel tests, these findings could be rather irrelevant if the suspension / tyre system characteristics are such that the load variations are damped out. But, not only the magnitude of the load variation is critical: the transient aerodynamic effects may excite eigenfrequencies of the car, thus influencing the vehicles' handling and performance.

In the last few years, the interest in transient aerodynamic phenomena in the automotive industry has significantly increased, although tangible work is – in contrast to the aerospace field – scarce or not documented ([5], [6]). Car handling problems which potentially have their origin in transient aerodynamic effects triggered by ride height changes, have been described by drivers. But, until recently, there have not been any reports on tests aiming to reproduce these situations in the well controlled environment of a wind tunnel. If relevant handling issues, caused by transient aerodynamic phenomena, are in fact present on the road, they should also be observable in adequate lap time and vehicle dynamics simulations based on transient aerodynamic results from the wind tunnel tests. Such a testing environment with accordingly modified simulation tools may have a significant effect on future aerodynamic optimization processes, especially with respect to handling and stability as well as sensitivity studies with respect to the vehicles' setup not only in the field of racing.

Results from vehicle dynamics simulations obtained using aerodynamic data from dynamic as well as conventional static wind tunnel tests are compared and the influence of transient '*motion aerodynamics*' is documented for a virtual vehicle based on parameters of a representative race car model.

TRANSIENT AERODYNAMICS – MOTION AERODYNAMICS

The influence of quick ride height changes on the time-resolved aerodynamic coefficients – motion aerodynamics – is surprisingly large at least for the race cars tested in the wind tunnel up to now (figure 1). Traditional static tests can not yield the same information: the typical hysteresis effects shown later are only

observable in tests with a moving model and time-resolved measurement. The variations in lift, pitching moment and aerodynamic balance are in a significant order of magnitude with respect to aerodynamic stability and drivability of a car. In addition, the effects were found in a frequency range where interaction with the suspension, wheel, and chassis system must be anticipated. If ride height changes are induced, e.g. by breaking, acceleration, turning and bumps, with the chassis / suspension / wheel system responding substantially in this frequency range, it must be feared that the aerodynamic response could be unfavorable and destabilize the car. Or at least, that it would not damp sufficiently to allow quick recovery from the reduced stability state. This effect – the interaction of aerodynamics with the track / suspension / wheel / chassis / driver system - can have a relevant influence on the performance of the car and also on the difficulty of piloting it.

PROJECT SUMMARY

The development of the experimental capabilities in the wind tunnel to measure transient effects induced by motion has started a couple of years ago at RUAG Aerospace. From the beginning, the final objective was not only to provide wind tunnel experiments with freely programmable but pre-defined, forced motion but also with real-time simulations based on concurrent wind tunnel experiments and numerical simulations of the dynamic behavior of the car on a user definable virtual track.

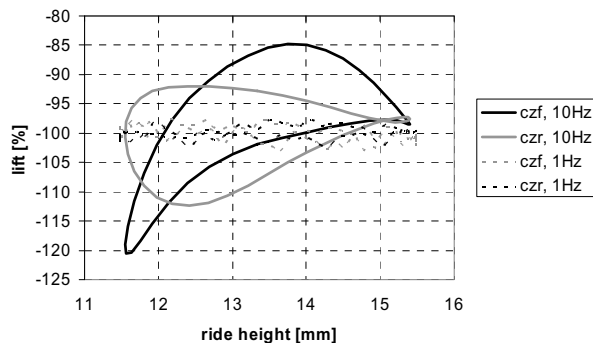


Figure 1: Typical curves for aerodynamic lift on front and rear axle for a simplified race car wind tunnel model as a function of ride height for pure vertical motion (heave) at 10Hz and 1Hz (quasi-static case) in percent of their respective mean value.

In a first step, a very powerful and compact two degrees of freedom in-model manipulator with integrated six-component balance was developed to allow particularly quick position control and precise measurement of loads (figure 2). Additional equipment such as a hollow sting through which the hydraulic power for the manipulator is routed or a balance that allows fully dynamic loads with an unusually large range-to-size ratio had to be developed as well. In a second step, the wind tunnel procedures and data analysis algorithms were

developed and tested; details of this can be found in references [1] and [2].

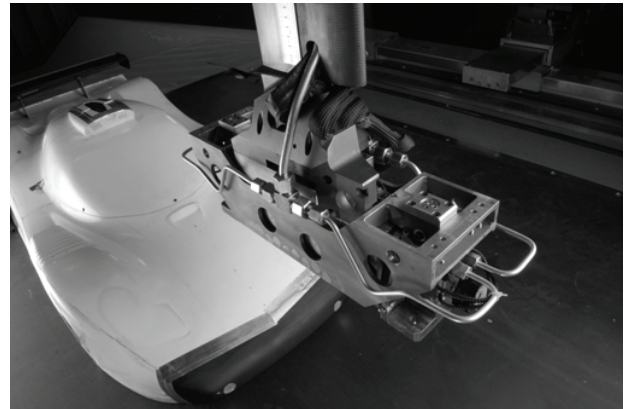


Figure 2: Two degrees of freedom in-model manipulator: 'shaker' (front and rear ride height).

The scope of the project phase herein reported was not yet to develop a fully functional simulation environment which takes into account the wind tunnel experiment with its transient results as well as the numerical simulations of the track, car and driver, but to reduce future development and operational risks by checking the feasibility and usefulness of such a system.

The final step in the undertaking – not described further here – is to concurrently measure the loads in the wind tunnel and to control the attitude of the model at the correctly scaled motion speed from the momentary aerodynamic wind tunnel loads and the results from the numerical real-time simulation of the vehicle on the virtual track (figure 3). The experimental and numerical simulations work hand in hand in (Strouhal number compensated) real-time in such a system.

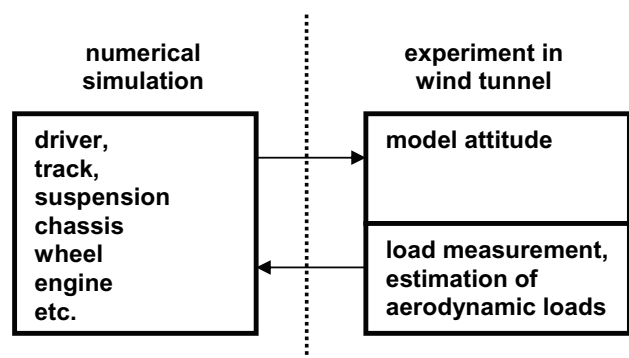


Figure 3: Overview of the envisioned system loop for concurrent experimental and numerical simulation.

Potential results of such an extensive simulation environment might be time-resolved aerodynamic loads (inertia effects removed), lap time, power consumption, aerodynamic work, handling characteristics, characterization of specific aerodynamic or non-aerodynamic configurations etc..

INTEGRATION OF MOTION AERODYNAMICS DATA INTO EXISTING VEHICLE DYNAMICS SIMULATION

General remarks

Normally, in lap time simulation, aerodynamics is simulated by using fixed lists of 'ride height – load correspondences' derived from traditional wind tunnel tests ([7]-[9]). The time-resolved history of model attitude is therefore not taken into account although it is undoubtedly present on the track and can have a large influence on the time-resolved aerodynamic loads.

As in this early stage of the project it was not possible to develop the full functionality of 'experimental (motion) aerodynamics – vehicle dynamics interaction', it was decided to first use already available components and data in a simulated off-line mode to prove the usefulness of the proposed concept. To allow this, a realistic scenario had to be defined that would give rise to the same vehicle motions on the virtual track as in the wind tunnel's experiments; e.g. small bumps in the virtual track were used to trigger the heave or pitch motions of the vehicle body, which then in turn gave rise to the load variation and hysteresis effects of a moving body in the airstream as depicted in figure 1.

In this way it was possible to run the simulation at its own pace by setting the correct vehicle speed on the virtual track and scan at the same time sequentially and off-line through the time-resolved aerodynamic results from earlier wind tunnel tests. Obviously, with such a procedure it is not possible to easily allow assessments of aerodynamic and other vehicle configurations for a development project. But it allowed – in comparison with standard simulations using traditional averaged wind tunnel data – to assess the influence of the transient effects on the virtual track.

All numbers given below are scaled to represent values for the real vehicle.

Although drag was simulated as well, its coefficient was kept constant for the complete duration of the simulation in order to focus solely on the influence of changing downforce levels.

SIMULATION PROCEDURES

Three different procedures to incorporate aerodynamics in the vehicle dynamics simulation were studied with the goal to show the relevance of *motion aerodynamics*. The following modeling approaches were considered:

1. Purely static aerodynamic coefficients are the simplest way to apply vertical forces on the front and rear axle. In this case, the resulting downforce is only dependent on the vehicle velocity. The coefficients for the simulations were adapted from a balanced setup of a real

race car with a high level of downforce and aerodynamic drag.

2. The downforce values depend only on the position of the car. This is the method traditionally used for vehicle dynamics simulations.
3. The static aerodynamic coefficients are combined with the hysteresis data measured in the wind tunnel for a simplified race car. This third approach takes into account the motion type, amplitude and frequency of the vehicle as well as the direction of rotation in the 'ride height-downforce map' (figure 4). A superposition of the static value with the properly scaled hysteresis measured in the wind tunnel delivers the new value of aerodynamic downforce for each axle. Figure 4 shows an example of a downforce hysteresis, which is added to the static value for a pure heave movement of 12 mm on the front and rear axle at 3.3 Hz (1:1).

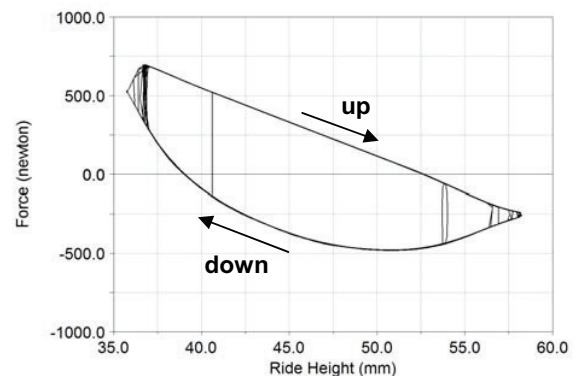


Figure 4: Hysteresis for downforce on front axle with simulation / discretization effects due to implementation as two unambiguous curves (heave).

The differences in the results from simulation modes 1 and 2 are small for the cases discussed in this paper. Therefore only the results from the simulation modes 1 and 3 are reported in the following.

IMPLEMENTATION

Since the hysteresis effects have been measured in the wind tunnel under very specific conditions, the vehicle in the simulation has to experience the same movement with respect to frequency and amplitude (compensated for Strouhal number).

The virtual vehicle is run over a sinusoidal road profile at a constant speed. As soon as the wheels hit these 'bumps', the simulated vehicle starts a vertical motion, the shape of which depends on various parameters: the period and amplitude of the sinusoidal track profile, the wheelbase, the vertical stiffness and the damping of the axles, the mass, the mass distribution and the moment