

Implementation and Validation of Active Aerodynamic Force Control During Race Vehicle 7-Post Testing

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ABSTRACT

The typical approach for body load simulation during 7-Post testing has been to match body motion and forces for a known suspension setup condition, and then to maintain the applied body loads for subsequent tests with different setups. However, in order for the test to remain valid across a wide range of vehicle setups, the applied body loads may need to be varied to match the specific test car. A significant component of the body load comes from aerodynamic downforce, which can be calculated during a 7-Post test based on vehicle body position and previously recorded wind tunnel test data. This paper discusses a method to generalize the 7-Post inputs by updating the aerodynamic force content automatically during each test run.

The paper begins by discussing validation of an active aerodynamic force control scheme on a MTS 320 7-Post road simulator with a NASCAR Sprint Cup vehicle. Testing included comparing loads on the rig with wind tunnel loads, verifying the ability of the simulator to input the desired loads, and measuring the response to vehicle setup changes.

The paper concludes that the active aerodynamic control method accurately replicates the relationship between vehicle body position and aerodynamic loads during 7-Post testing. The simulator control scheme correctly adapts to changes in body position by adjusting the aerodynamic loads to match previously measured static wind tunnel data. This method for 7-Post testing is expected to allow more accurate prediction of vehicle response due to suspension setup change, as well as more accurate overall prediction of track performance. The

new 7-Post control scheme has been found to be an improvement in testing methodology by more capably replicating expected on-track vehicle response.

INTRODUCTION

Race vehicle engineers have become accustomed to using MTS 320 7-Poster road simulators to aid in optimizing vehicle suspension setup conditions for on-track performance. The typical goal of 7-Poster testing is to evaluate the suspension forces and motions that occur for a given configuration when “driven” around a virtual test track. Evaluation can lead to selecting the best configuration for the specified track on race day.

A typical 7-Poster drive file consists of four vertical displacement inputs applied to the tires and three vertical force inputs applied to the chassis. The tire inputs are representative of the road surface disturbance and the chassis loading inputs are a combination of all additional forces applied to the chassis during a lap around the track. The two main sources of additional chassis loading are body accelerations and aerodynamic forces. These supplemental chassis loads are input via downforce actuators, which are positioned to introduce body lift, as well as pitch and roll moments.

The test approach for body load simulation has traditionally been to match body motion for a known suspension setup condition, and then to maintain the applied body loads for subsequent tests with different setups. Acceleration loads (lateral and longitudinal) are a function of the vehicle inertia and the driving profile, and are typically not modified after

the initial drive file has been generated. Aerodynamic loads, however, are a direct function of body position and attitude, which can be greatly affected by the suspension setup.

In order to avoid incorrect application of aerodynamic body loads, a method was required to regulate the aerodynamic body load component of the downforce system automatically during each test run. This could be accomplished by incorporating a functional relationship between body position and aerodynamic loading into the downforce control system.

The relationship between body position and aerodynamic loading is known as an “AeroMap”, and is obtained during independent wind-tunnel testing on the race vehicle. An aero-mapping test procedure adjusts body attitude and position in the wind-tunnel relative to the ground plane, and measures the forces acting on the body in that position. Body position is typically varied in heave, pitch, roll, and yaw angles during the test. The resulting data can be used to generate an AeroMap that defines forces based on body position and speed relative to the tested wind speed, or it can be used to generate a map relating body position to dimensionless aerodynamic coefficients for lift, roll moment, pitch moment, etc..

The AeroMap data can also be fit to a continuous function to make it suitable for dynamic control. The order and dimension of the function can be optimized based upon the desired conformance to the measured data. The AeroMap function can then be used as part of the downforce control system of the 7-Poster. The “AeroMap-in-the-Loop” control of the downforce actuators allows the applied force to adjust automatically for any position change of the body change during 7-Poster testing.

AERODYNAMIC FORCE & MOMENT CALCULATION

CONVENTIONS

Wind tunnel facilities worldwide often use different nomenclature and reference axes. To provide a common nomenclature for aerodynamic data and reports, the SAE Road Vehicle Aerodynamics Committee has published J1594 “Vehicle Aerodynamics Terminology” [1] which defines a standard vehicle coordinate system. This coordinate system has been utilized for referencing body clearance measurement and attachment force locations, as well as for establishing polarity for all calculated body forces and motions.

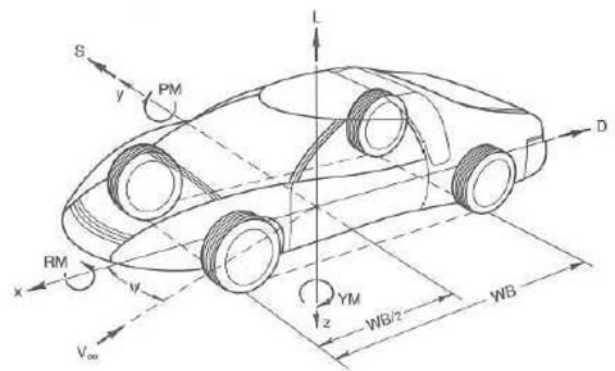


Figure 2. Aerodynamic vehicle coordinate system (Ref SAE J1594)

The axis system origin is located on the ground, at mid-wheelbase and mid-track as shown in [Figure 2](#). Polarities are:

- x is positive forward
- y is positive right
- z is positive downward

Exception: The calculated values for aerodynamic lift force follow the common convention of designating positive lift as an upward force. Therefore, positive vehicle lift forces act in the negative z direction.

AERO COEFFICIENTS AND FORCE CALCULATIONS

The AeroForce implementation uses an AeroMap function that generates aerodynamic coefficients based on body position. The aerodynamic coefficients generated are:

- Clf: Front Lift Coefficient
- Clr: Rear Lift Coefficient
- Crm: Roll Moment Coefficient

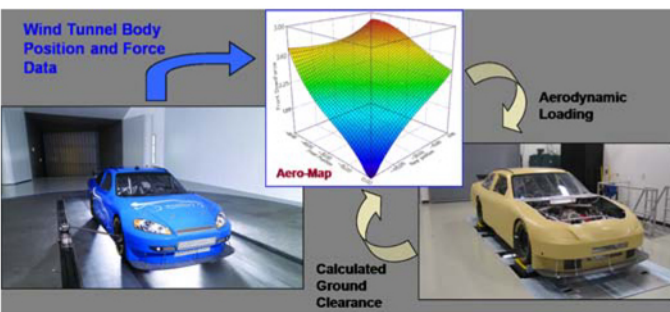


Figure 1. Aero-Mapping for AeroForce Downforce control (wind tunnel photo courtesy of Windshear, Inc.)

These coefficients (C_{xx}) are used for body force and moment calculations as follows:

$$\text{Front Lift Force (L}_f\text{)} = \text{Dynamic Air Pressure} * \text{Frontal Area} * C_{lf} \quad [1]$$

$$\text{Rear Lift Force (L}_r\text{)} = \text{Dynamic Air Pressure} * \text{Frontal Area} * C_{lr} \quad [2]$$

$$\text{Total Lift Force} = L_f + L_r \quad [3]$$

$$\text{Roll Moment} = \text{Dynamic Air Pressure} * \text{Frontal Area} * \text{Wheelbase} * C_{rm} \quad [4]$$

$$\text{Pitch Moment} = (L_f - L_r) * \text{Wheelbase} * \frac{1}{2} \quad [5]$$

Dynamic Air Pressure (q_∞) is defined as:

$$q_\infty = \frac{1}{2} * \text{Effective Air Density} * (\text{Wind Speed})^2 \quad [6]$$

AERO-MAPPING DATA AND FUNCTIONS

The form of the AeroMap function can be varied to suit user preferences and the nature of the available wind-tunnel mapping data. A continuous function that represents the wind-tunnel data characteristics has been derived for use in the AeroForce control loop.

The general implementation uses a mapping function which generates dimensionless aerodynamic coefficients (C_{lf} , C_{lr} , C_{rm}) from body position data. The function that has been implemented is an empirical 2nd-order function of 4 variables: body clearance at 3 positions (BC_1 , BC_2 , BC_3), and vehicle yaw angle. A 2nd-order function was used, although any function that results in a data fit error below the user's tolerance can be substituted. For the aero coefficient mapping function, the raw wind-tunnel mapping data had been converted from force response to equivalent aerodynamic coefficient values for the vehicle and test conditions. The function coefficients ($c_0 \rightarrow c_{14}$) have been identified by using a minimum-error fit of the processed wind-tunnel data. The form of the function is:

$C_{xx} =$

$$\begin{aligned} &c_0 + c_1*BC_1 + c_2*BC_2 + c_3*BC_3 + c_4*Yaw + \\ &c_5*BC_{12} + c_6*BC_{22} + c_7*BC_{32} + c_8*Yaw^2 + \\ &c_9*BC_1*BC_2 + c_{10}*BC_1*BC_3 + c_{11}*BC_1*Yaw + \\ &c_{12}*BC_2*BC_3 + c_{13}*BC_2*Yaw + c_{14}*BC_3*Yaw \end{aligned} \quad [7]$$

TEST RIG LAYOUT

The MTS FlexTest 200 7-Poster used in this experiment had three downforce actuators positioned in the layout shown in [Figure 3](#). When referencing individual actuators the names RF, RR, and LC will be used. 7-Poster tests involving racecars that run oval courses, such as the NASCAR Sprint Cup vehicle in this test, will typically have two actuators on the right side of the vehicle due to non-symmetric loading on the track.