

Terrain Profile Estimation for use in Suspension Simulation Testing

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ABSTRACT

Efforts by vehicle manufacturers to reduce road testing have resulted in an increased reliance on the simulation methods for loads measurement and validation, including increased emphasis on methods to characterize and digitally represent test road inputs. Accurate terrain models are especially important in the case of large dynamic road inputs, and for evaluation of vehicle suspension loads and durability. In contrast to direct terrain topology measurement, methods to estimate test road input using only vehicle suspension measurements and a tire dynamic model will be presented. Applications of terrain models for generic simulation and testing will also be discussed.

INTRODUCTION

The U.S. Army Aberdeen Test Center (ATC) and MTS are evaluating methods to perform generic terrain simulation control for test vehicles in ATC's vehicle durability simulation laboratory. With these control methods, test course measurement data and tire models are used to generate a generic terrain that is used in an iteration scheme for feedback control of a vehicle durability road simulator (see Figure 1).



Figure 1 -- Vehicle Spindle-Coupled Road Simulator

The terrain control method differs from the standard durability simulation because the standard method replicates vehicle specific test course measurements on the durability simulator. This method is often referred to as response simulation and commercial products for response simulation test control have been available for many years [1]. Drive files generated via response simulation methods are typically used throughout the entire subsequent vehicle durability test.

A limitation with the response simulation method is that if the vehicle configuration changes between response measurement and test completion, the test simulation may not accurately simulate the vehicle response in the field. The potential vehicle changes can include any combination of component design changes, vehicle setup changes, or vehicle structural degradation during testing. A generic terrain control method has been developed that can be used to help minimize this limitation of durability simulation [2] [3].

With generic terrain control, a tire vibration model and measured test course data are used to calculate a terrain time history that produced the measured responses. Vehicle spindle force and motion response data measured on the track are used with a model representing the vehicle's tire dynamics to determine the road input consistent with the measured vehicle response. The road input (or terrain time history) for the test course is then used in conjunction with the test vehicle mounted to the simulator and the tire model, to develop the actuator drive files for the simulation. During simulation, the vehicle response is measured and used to generate the effective terrain, which is then compared to the reference road input. The resulting terrain error can then be used in an adaptation of the standard response simulation method to compensate the actuator drive files. Since the feedback signal is computed from the generic tire/ground interface point and is independent of the specific vehicle, it will automatically compensate for changes in the vehicle dynamics producing a more accurate simulation.

Accurate identification of the tire dynamic characteristics is a critical component of generic terrain simulation control. Experimental tire characterization methods have been developed for application to the terrain profile control method. These methods provide the means to accurately characterize large-amplitude tire response via an efficient, invertible linear dynamic model [4].

The purpose of this paper is to report the experimental tire characterization and validation of a standard military light tactical vehicle (LTV). The paper is organized into two sections. In Section A, the experimental tire characterization procedure is presented, and the results of the characterization are reported. In Section B, the measured field data and the experimental tire model are used to estimate generic terrain profiles. The resulting profiles are compared to physically measured micro-profile (MP) data for the same surfaces.

The terrain profile estimation method utilizes a tire model and measured time history data to generate a road terrain time history. Since the current state-of-art in generic terrain simulator control only uses a radial vibration model and a longitudinal and vertical (two-dimensional (2-D)) generic terrain information, the tire characterization model and terrain calculations presented in this paper address only the radial dynamics of the tire and the predicted longitudinal and vertical terrain.

Additional vehicle and tire response data collected during this study will allow for terrain prediction in non-longitudinal/vertical directions (out-of-plane directions), but these topics will not be presented here.

SECTION A - TIRE CHARACTERIZATION TESTING

CHARACTERIZATION TEST PROCEDURE

The LTV tire, Goodyear Wrangler 37x12.5R16.5, was the candidate tire for the study. It is a standard radial ply military tire that incorporates a run-flat design and is mounted on a two-piece steel rim. An assembly drawing of the tire is presented in Figure 2.

The dynamic properties of the LTV tire were characterized using a multiple degree of freedom (MDOF) vibration table and a custom-fabricated tire support test fixture. The MDOF vibration system was an MTS 353.20 Multi-Axial Simulation Table (MAST), capable of generating independent 6DOF motion inputs over a frequency range of 0 to 100+ Hz.

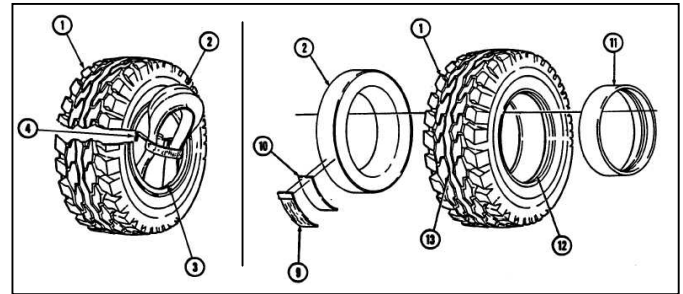


Figure 2 – LTV Tire with Rubber Run-Flat Insert

The tire, modified wheel, and SWIFT wheel-force transducer (WFT) assembly used for proving ground data acquisition were used for characterization tests. The test tire was rigidly fixed to a fabricated support fixture, with the tire cantilevered over the table surface. To measure reaction forces at the tire mounting location, an MTS SWIFT™ 40T WFT was installed with the tire. The test setup with the LTV tire installed is shown in Figure 3. The 353.20 MAST control system enables the X-Y motion-axis coordinate system to be rotated and the origin of the center-of-motion to be re-positioned to any spatial location. As such, the center-of-motion of the table could be relocated to the center of the tire contact patch, regardless of the tire/table contact point, allowing the tire to be located at the table's edge, which simplified the design of the tire support fixture.

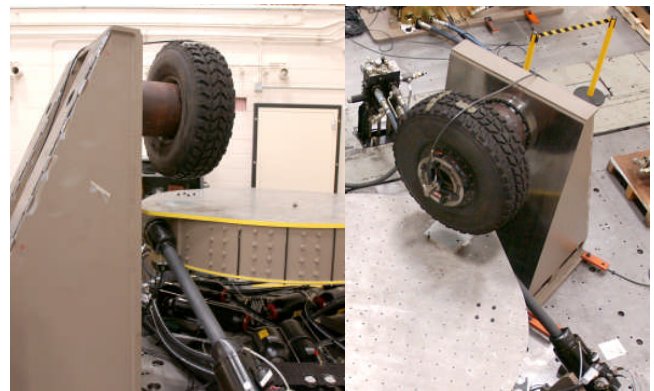


Figure 3 – MTS 353 MAST with LTV Tire

Although the primary objective was to identify parameters for the radial tire model, the 6DOF capabilities of the 353.20 MAST system provided the opportunity to measure the dynamic response of the tire to additional DOF inputs. A complete series of dynamic tests were performed at multiple tire pressures and static preload conditions, as shown in Table 1.

Tire Inputs	Vertical (radial)	Vertical (radial)	Vertical (radial)	Vertical (radial)	Lateral
Tire Pressure (bar)	2	2.75	3.45	2	2
Tire Preloads (kN)	14 17 19	14 17 19	14 17 19	14	14
Tire Contact	Lubed surface	Lubed surface	Lubed surface	Spike plate	Spike plate

Tire Inputs	Fore-Aft (torsional)	Yaw (steer)	Vertical Lateral Fore-Aft Yaw	Vertical Lateral Fore-Aft Yaw	Vertical Lateral Fore-Aft Yaw
Tire Pressure (bar)	2	2	2	2.75	3.45
Tire Preloads (kN)	14	14	14 17 19	14 17 19	14 17 19
Tire Contact	Spike plate	Spike plate	Spike plate	Spike plate	Spike plate

Table 1: LTV Tire Characterization Tests

For tests that required loading the tire contact patch in the horizontal plane (lateral, longitudinal, yaw), a special spike plate was fabricated to mount to the table surface. The spike plate, shown in Figure 4, had 360 4.75-mm track spikes to prevent tire slippage during the out-of-plane tire characterization. The non-radial characterization data were not used in the current analysis, but will be used to support future generic terrain simulation research at ATC.

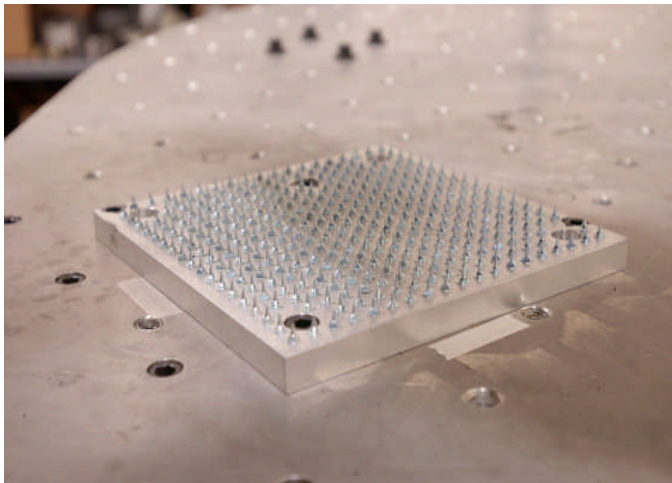


Figure 4 – Tire Contact Spike Plate on MAST Table

The signal used for tire excitation was a shaped white-noise time history designed to generate a random amplitude distribution. The RMS of the input amplitude decreased as a function of frequency at a rate of $1/f^3$ (see Figure 5). This frequency spectrum was chosen to approximate the distribution of the expected random road surface inputs (for reference, see Figure 28 in the Terrain Prediction section). Figure 6 shows the dynamic

range of the normally distributed excitation signal, which was designed to fully exercise the tire while maintaining a positive tire preload at all times.

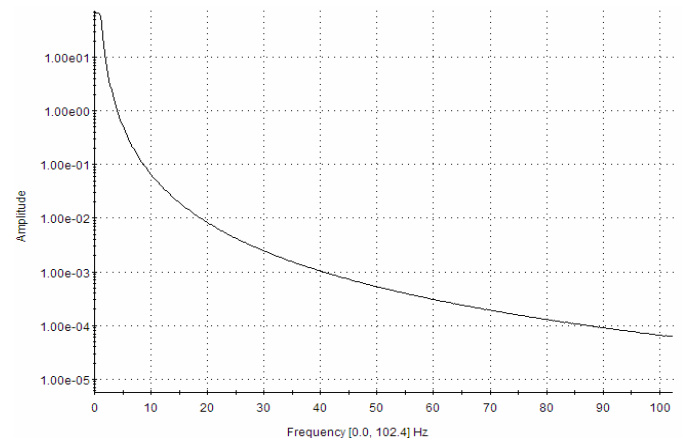


Figure 5 – Radial Tire Excitation PSD

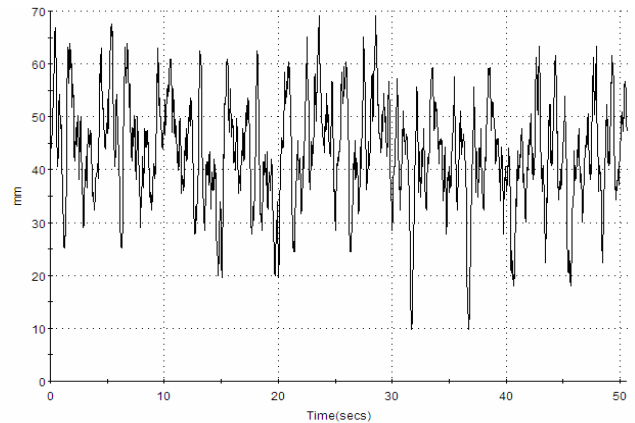


Figure 6 – Radial Tire Excitation Signal

TIRE TEST DATA ANALYSIS

The observed displacement input of the 353 MAST table was measured for each test, along with the SWIFT™ hub reaction forces and moments. The “observed” displacement for the MAST table is a combination of kinematically transformed displacement and acceleration feedback information, enabling accurate table motion control and measurements at both low and high test frequencies.

The MTS RPC Pro™ simulation software suite was used for characterization data analysis. Specific tools in the RPC Pro™ suite have been designed to analyze measured tire motion input and reaction force data, and to optimize the parameters of a general linear 2nd-order tire model to achieve the best correlation between the measured and modeled responses. The tire model form used for terrain profile estimation is shown in Figure 7.

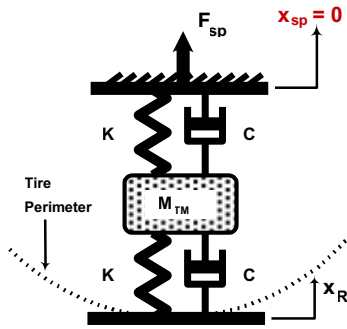


Figure 7 – 2nd-Order Linear Tire Dynamic Model

For tire characterization testing, the description of the model dynamics was simplified because the spindle attachment point was fixed. This simplification reduces the tire dynamic equation to a basic transfer function, easing the parameter identification effort. The dynamics of the spindle-constrained tire are described by the following general model:

$$DSM = \frac{F_{sp}(x_{sp}=0)}{x_R} = \frac{(K + sC)^2}{(2K + 2sC + s^2 M_{TM})}$$

where:

DSM = Dynamic Stiffness Model

F_{sp} = measured spindle force

x_{sp} = measured spindle displacement

x_R = measured tire input displacement

K, C, M_{TM} = dynamic tire parameters

The PRC Pro™ Tire Parameter Identification tool allows parameter optimization from measured test data in either the time or frequency domain, with additional capability to adjust the K parameter value based on the empirically measured static tire stiffness. The bandwidth over which the optimization was performed is also selectable.

Previous experiments have shown that the best optimization methods and test bandwidth will vary depending on the tire and test setup characteristics. A frequency-domain fit generally results in the best model for response correlation over the full frequency range. A logarithmic frequency fit provides for higher weighting of low-frequency response error, resulting in a better match of response for the lower frequency band, where tire stiffness characteristics are dominant. A time-domain fit will result in the best model for reproducing the largest amplitude dynamics (e.g., peak tire loading and unloading events). For best broadband tire response characterization, the frequency bandwidth should be set to include the first radial dynamic mode represented in the tire response data.

To apply this approach to tire characterization, the design of the tire support fixture must ensure that fixture-induced dynamics (i.e., fixture modal responses) are not included in the broadband measurements. Fixture modes will directly affect the identification of the tire parameters, producing a model that does not represent the tire. For this study, finite element models of the tire support fixture were analyzed prior to installation at the test site, and experimental tests were conducted on the tire support to evaluate and correlate the actual structural response. Based on the test results, a 65-Hz upper limit for tire parameter identification was selected.

For the series of LTV radial test results, the tire model parameters were optimized using a log-frequency fit over a bandwidth of 0.5 to 65 Hz. The frequency range was based on the calculation of dynamic stiffness FRFs from the raw measured data. The FRFs for multiple test conditions are compared in Figure 8 and Figure 9. Figure 8 illustrates the effect of changing tire preload for a given pressure condition. Figure 9 shows the relative effect due to pressure for a specific preload condition. The small changes in tire preload resulted in slight changes in low-frequency stiffness. The substantial changes in tire pressure resulted in a much larger tire stiffness changes, with noticeable effect on the first tire mode frequency.

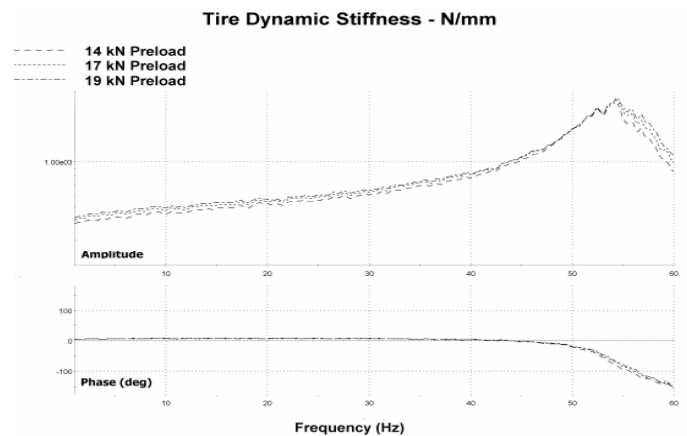


Figure 8 - Tire Dynamic Stiffness, 2-bar Inflation

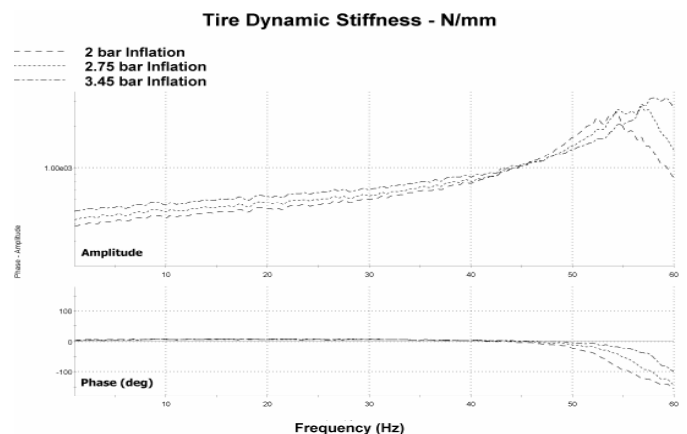


Figure 9 – Tire Dynamic Stiffness, 14-kN Preload