Virtual Testing with a Virtual Spindle Coupled Road Simulator and Remote Parameter Control

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ABSTRACT

At the present time, multi-body simulation is capable of modeling most vehicle components with sufficient accuracy and reasonable effort to estimate realistic component load histories except for the tires. This paper describes an approach to derive component loads using a physical and virtual full vehicle spindle coupled test system. The advantage of using the test system as the load input device vs. a road profile is that the influence of the tire is eliminated. The effects of the tires need to be accounted for on both the physical and the virtual test rig and this is accomplished by driving them with command files that were obtained when simulating the road response on a similar vehicle using sensors mounted between the spindle and the wheel, so called wheel force transducers. The reproduction of field-measured loads in the laboratory is typically achieved via a process called Remote Parameter Control (RPC). In this study, the reproduction of measured spindle loads was achieved on a virtual model of a vehicle and test system. By using RPC technology in the virtual world, analysts have a new method to understand the virtual model by reproducing field-measured signals. This method can be used for virtual durability evaluation of vehicles and components. The tools and process improvements developed in this project will aid both test and analysis engineers to work closer together and contribute to solving each other's problems.

INTRODUCTION

A trend towards the integration of analytical investigations and testing hardware prototypes has emerged due to the increasing pressures of shortened development cycles and the desire to save costs. The combination of physical and virtual testing can accelerate the design process due to the identification and subsequent elimination of physical and virtual prototype deficiencies, such as transducer related errors and model parameter inaccuracies.

Many vehicle manufacturers are moving towards a laboratory test instead of a road test prior to production release due to the known advantages of time savings, the opportunity to observe the specimen and the overall controlled environment of a laboratory setting leading to repeatable results. To further accelerate development it is believed that it would be valuable to replicate this final laboratory test in the analytical world. The methodology introduced herein addresses the following issues commonly encountered in multi body simulations and durability assessment:

> Boundary Condition Mismatch:
> Utilizing the test rig as a part of the validation process [1] provides the test lab and the vehicle designer a direct method of comparing results, without introducing the errors, uncertainties and other limitations associated with comparing to proving ground data.
>
> Drift:
> Noise in physical measurements and computational inaccuracies lead to unrealistic gross motions for long simulation runs. An appropriate restraint of the vehicle and band pass filtering will eliminate this behavior.

Remote response measurement under non-linear system behavior:
For the simulation of system responses that are remote from the motion inputs no direct procedure exists to determine the appropriate input. This issue is exacerbated when the input-output relationship of the system is non-linear. The iterative approach described in this paper can provide the appropriate inputs.

VIRTUAL TEST LAB MODEL

The multi body dynamics model of the test system originated from the CAD model with replication of key features such as geometry, mass properties, and global stiffness properties. All of the appropriate communicators were set up so that the test rig model would couple directly to a multi body dynamics model of the vehicle. For this initial study, the test stand model was kept as simple as possible. All of the test rig components were modeled as rigid bodies. The flexibility of these components was taken into account by modifying the bushing properties of the test rig. While this is a simplification of the existing physical test rig, it was believed that all relevant static and dynamic properties required for a comparison of responses from physical and virtual prototypes were retained. In most test cases, this can be assumed, in that the Eigen-frequencies of the fixture are typically above 50 Hz. The full vehicle MSC.ADAMS/CAR model was assembled with the tuned test rig model (Figure 1).

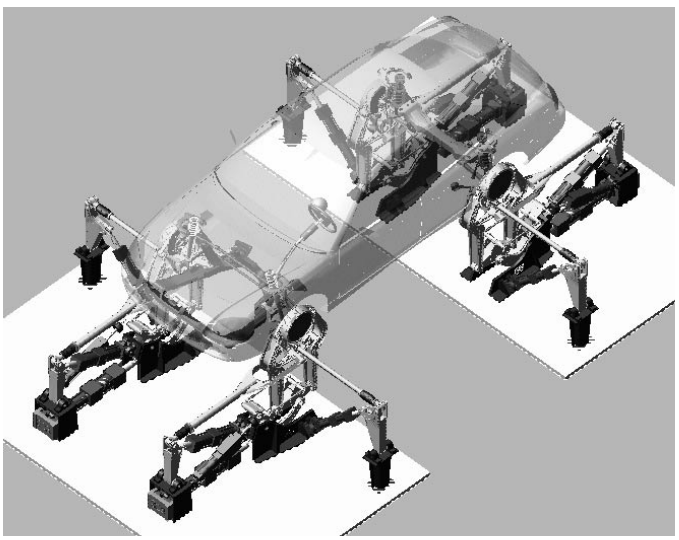
Figure 1. Full vehicle model on a 329 test rig model

VIRTUAL DURABILITY TEST

There are several approaches to conduct the analysis required to ensure durability. One method is to model (typically based on road profile measurements) the road surfaces and create a virtual proving ground. The virtual vehicle model then travels over the virtual proving ground to obtain the vehicle responses. This method requires modeling of the road surfaces accurately, which is difficult for surfaces like Belgian Block and Cobble Stone. Another difficulty is that this method requires accurate tire models. Although a number of commercial tire models are available, all of them make compromises with respect to computational efficiency and accuracy. This is due to the fact that tires are highly non-linear elements with multiple degrees of freedom.

Another approach is to collect the spindle loads or accelerations from a proving ground with an existing vehicle and apply the road loads or accelerations directly at the spindles of the virtual vehicle to obtain the vehicle response. The advantage of this method is that there is no need to model the proving ground surfaces and the tires. The disadvantage is that the road load data usually contains unrealistic signals such as noise. This noise can cause the virtual vehicle to “drift” in space, i.e. gross unrealistic motions will be predicted not representative of the actual response. Another disadvantage is that either load or acceleration can be applied for each degree of freedom. However, to model the vehicle dynamics accurately, both spindle load and acceleration need to be controlled at times.

The method proposed herein is to conduct a virtual durability test that mirrors the processes used when testing physical prototypes. Initially, road load data is collected with a physical prototype. The vehicle and a spindle coupled full vehicle simulation system are modeled. The road data is reproduced by the virtual system through an iterative deconvolution technique (RPC, MTS Systems Corporation) [2].

Remote Parameter Control (RPC) is an advanced simulation technique used to repeatedly replicate and analyze "in service" vibrations and motions of a specimen using a dynamic mechanical system in a controlled laboratory environment. The six steps for the RPC simulation process are shown below.

Using this approach, there is no need to model the road surfaces and the tires. Because the test rig is modeled, the vehicle is properly constrained and all drift issues are eliminated. Using RPC iterations one can reproduce a set of response signals that can be larger than the number of channels used for active input. This allows finding the optimal inputs for both spindle load and acceleration response in each degree of freedom. Finally, the virtual test results can easily be validated when using an equivalent physical test rig. Moreover, the virtual tests can help to prepare the final physical validation tests.

To illustrate the virtual test method, a Sonata vehicle model and a model of an MTS 329 spindle coupled full vehicle road simulator test system with four actively controlled degrees of freedom at each spindle (i.e. vertical, lateral, longitudinal and brake) were employed. RPC iteration was conducted to reproduce spindle loads of Belgian Block surface.

PROVING GROUND DATA COLLECTION

The instrumented vehicle is driven over selected proving ground events to measure the response-time history. Typically, several passes of each road surface are collected to ensure a statistically valid and representative sample of data. Time history data contains amplitude vs. time information for each channel and information about phasing between channels. The time history data can also be easily converted to the frequency domain using FFT techniques. Low-pass analog filters, designed to roll off before the Nyquist frequency (1/2 of the sample rate), are applied to the data prior to digitizing to prevent aliasing on each recorded channel. Simulation sample rates of 4-5 times the highest frequency of interest are common. Most of the road induced data on a vehicle relevant to durability effects is less than 50 Hz, so a typical sample rates would be 204.8 or 256 Hz. Data polarity and amplitude are documented for future reference.

DATA EDITING AND ANALYSIS

The data collected from the proving ground usually is analyzed to determine the most significant and fatigue relevant inputs for the vehicle. A visual display panel, capable of displaying multiple channels at a time, allows the user to mark deletions regions and to create a file, which is a subset of channels or time sections without significantly affecting the original data with respect to fatigue damage. In the deletion file, sections of time are removed from each channel of data so that important phase information between channels is retained.

Proving ground tests, which normally take months to complete, may be completed in a few weeks as a result of data editing. This is the time compression referred to by the term "test acceleration." Sections of time which are joined after editing are smoothed on either side of the deletion region to remove any discontinuity. For non-breaking events, the brake torque is set to zero, otherwise the noise of the break torque could cause large brake actuator motion in the virtual simulation. This is not an issue in physical simulation tests as there usually is a small amount of friction between the brake disks and the calipers, locking in the system. As an example, a portion of Belgian Block spindle load signals are considered to be the desired response. RPC iterations were conducted to reproduce the desired signals.

LINEAR SYSTEM MODEL – FREQUENCY RESPONSE FUNCTION (FRF)

For this virtual 329 Test System, the drive signals are the actuator displacements. The response channels are spindle loads in three directions and the brake torque at each corner. The excitation for the measurement of the frequency response function FRF (the linear input-output relationship between drive and response) is a shaped random excitation for each actuator. Random noise data with repeats are used to average out the noise effect in the lab. However, on the virtual side, the system is perfectly repeatable and no repeats are required, therefore, to save solving time, one average with one repeat is recommended.

The excitation for FRF measurement can be applied one channel at a time or with multiple channels simultaneously. In this application, multi-channel excitation is recommended. All contributors to system behavior, e.g. test rig kinematics, hydraulic performance, controller algorithm, etc. will be encapsulated in the frequency domain system model FRF. Both the amplitude and phase information are included in the FRF to fully characterize the test system. Figure 2 shows the FRF of the 329 test system with the Sonata vehicle model.

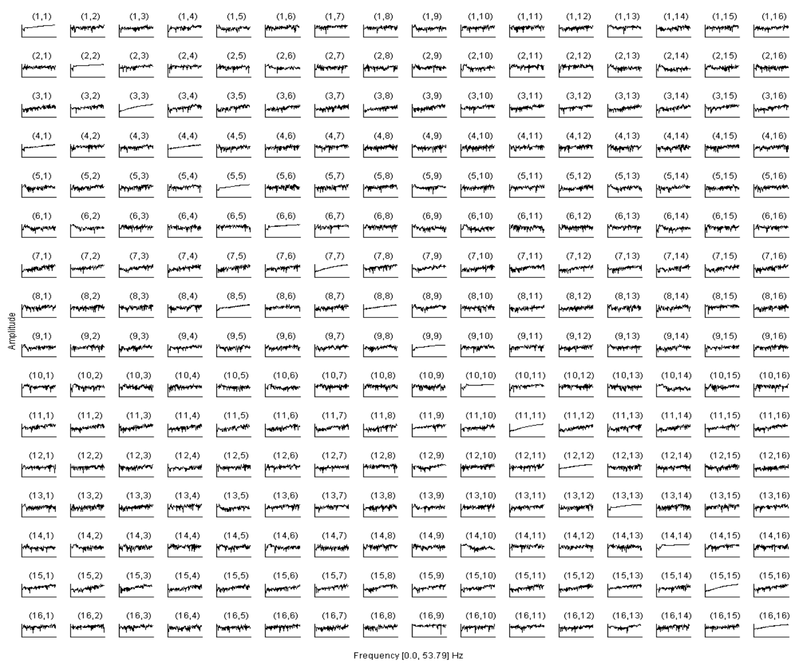

Figure 2. FRF of the 329 model with a Sonata vehicle model

ITERATION PROCESS – “DRIVE FILES” DEVELOPMENT

If the input to the system and the FRF are both known, the output can be predicted. In this application, the wheel force transducer load signals are the desired measurements that are to be reproduced. Therefore, if the FRF is inverted and the filtered road data (output) is known, the actuator displacement commands which drive the system (input) can be predicted. The process of back calculating the actuator displacements from the inverse FRF and system output is the core function of the RPC software.

Test systems and specimens all have non-linearities, but the inverse FRF was developed as a linear model to approximate the real test system. To compensate for these differences, an iterative process is used to achieve actuator displacements (inputs) that create very nearly the same response in the lab (outputs) as was measured in service. During each iteration, the command signal is modified so that it more closely reproduces the desired transducer signal on the test vehicle, even when the action causing the response is remote from the transducer. Consistent and repeatable loading inputs are achieved by maintaining crucial phase and amplitude relationships between multiple inputs – so the test track environment can be precisely duplicated.

Since the FRF is only an approximation of a non-linear system, for different excitation amplitudes, the FRF should be different. An in-adequate FRF will cause iterations to only slowly converge. To solve this problem, MTS developed a tool called TURBO. This tool modifies the inverse FRF based upon the response signals predicted by the existing FRF and the response signals measured by the physical system during each iteration. As a result, the inverse FRF can better represent the current state of the physical system and iterations will converge faster to the desired response.

In this study, sixteen actuator displacement signals are the drive channels (4 spindle inputs of vertical, lateral, longitudinal and brake). Sixteen wheel force transducer loads (FX, FY, FZ, MY (brake) at each corner) are the response channels. If there is no breaking event, the break torque should be zeroed. The control band for the wheel force transducer loads is from 0.6 Hz to 50 Hz. The reason for this selection is that the testing system is an inertially reacted system. It is difficult to achieve low frequency control without large actuator displacements, that could exceed the range of motion. On the other hand, from experience, beyond 50 Hz, there is very little road induced damaging content. Therefore, there is no need to reproduce the content beyond 50 Hz.

For a complicated MSC.ADAMS model, it usually takes a long time to obtain a simulation result. In this case, it took about 50 minutes for a 1 GHz, 1 GB RAM PC computer to obtain the solution for a sixteen second event. Therefore, the RPC iteration process with a virtual system could be quite lengthy especially when the system is quite nonlinear and a large number of iterations are needed to minimize the error.

MTS has developed a piece of software (Virtual Test Server, [3]), which enables the RPC software to exchange files with MSC.ADAMS models directly and allows multiple RPC iterations to be conducted automatically. This facilitates batch type execution of the iteration process without requiring user interaction and thereby saving time.

Iterations were conducted to reproduce the Belgian Block wheel force transducer signals. After eighteen iterations, the RMS error for all wheel force transducer load channels are below 30% with most of the channels below 20%, no significant further reduction could be achieved. This level of error is in agreement withat what would be observed under physical test conditions. Figure 3 and Table 1 show the RMS error for the Belgian Block surface iteration process.

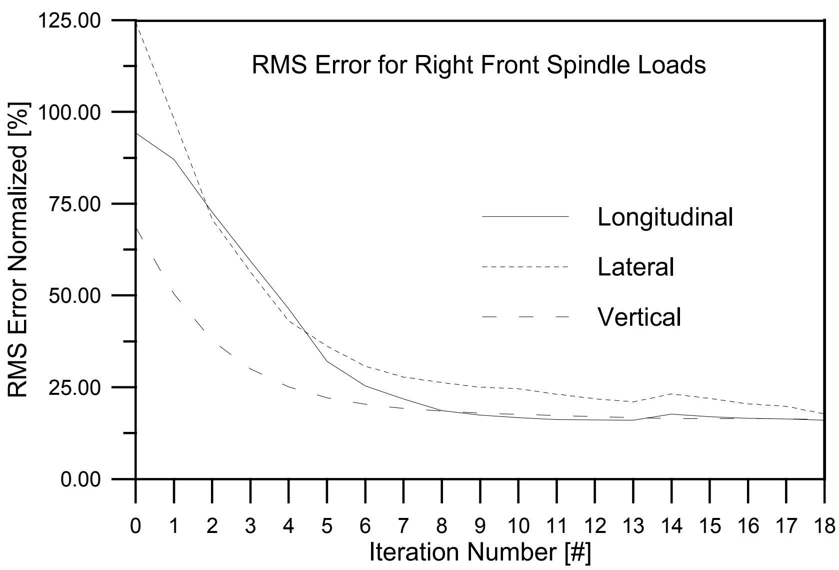

Figure 3. RMS error curves for right front spindle load of the Belgian Block surface iteration process

Transducer Location/Type	RMS Error %
Left Front Vertical Spindle Load	9.4
Right Front Vertical Spindle Load	15.7
Left Rear Vertical Spindle Load	13.0
Right Rear Vertical Spindle Load	8.0

Table 1. RMS error after eighteen iterations

Figures 4 to 6 show the time history comparison between desired and achieved right front spindle loads after 18 iterations. One can see that, by using RPC and VTL, measured spindle loads can be accurately reproduced.

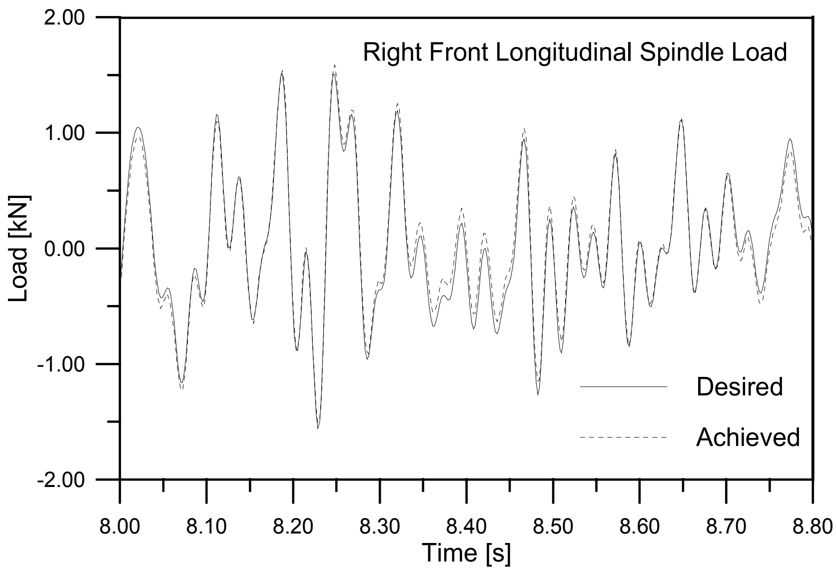

Figure 4. Desired versus achieved right front spindle load in longitudinal direction after 18 iterations

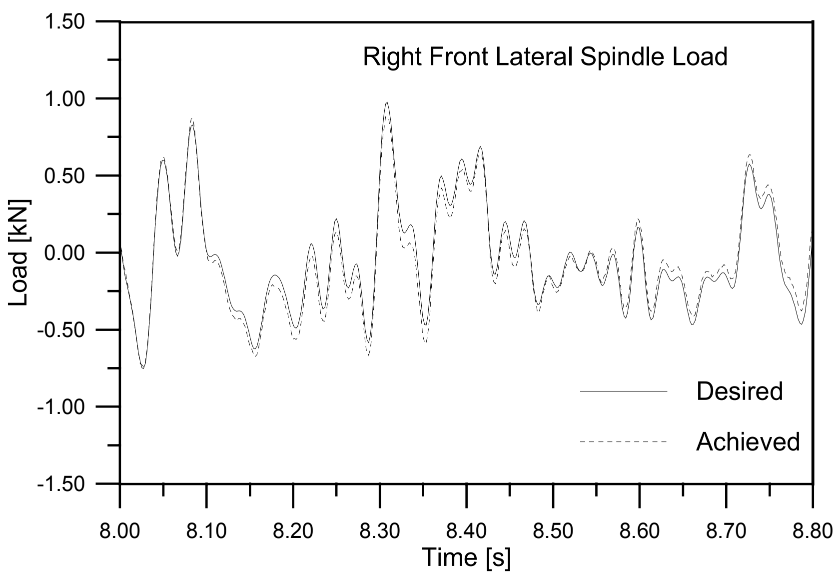

Figure 5. Desired versus achieved right front spindle load in lateral direction after 18 iterations

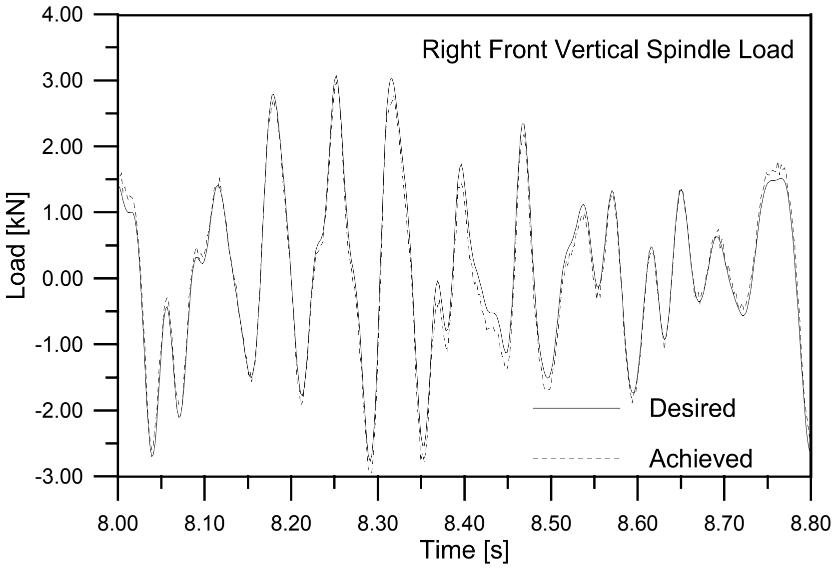

Figure 6. Desired versus achieved right front spindle load in vertical direction after 18 iterations

PSEUDO FATIGUE ANALYSIS

Analysis was performed to assess the fatigue relevant similarity of desired spindle load signals and the signals after 18 iterations. The spindle loads were assumed to be proportional to strains with a conversion factor chosen such that fatigue lives on the order of 1000 repetitions of the applied load history can be sustained. It was assumed that the material properties of 1005CD steel were representative of the vehicle components for comparison purposes. Strain life fatigue analysis was conducted. The Smith-Watson-Topper correction for mean stress was used. Table 2 shows that the lives of the achieved load signals are close to the ones for the desired signal. The differences between the fatigue life of desired and achieved spindle loads are all within 50 % (for the left front spindle all fatigue lives are within 35% error). This shows that by using RPC iteration, VTL is able to reproduce the fatigue sensitive content of the spindle load signals.

	Fatigue Life of desired loads	**Fatigue Life of achieved loads**	**Ratio between desired and achieved**
Longitudinal	1020	923	0.94
Lateral	1040	1180	1.13
Vertical	985	638	0.65

Table 2. Fatigue lives based upon desired and achieved left front spindle load signals

DURABILITY TEST

A durability test is composed of selected proving ground road surfaces for each of which drive files have been created to reproduce the filed measured loading. The drive files are nested together in a sequence considered to be representative of customer usage. The overall sequence is repeated for a certain number of times, equivalent to the target customers usage scenario. Fatigue software, such as FE Fatigue (nCode International), can predict the service life of the components by combining the information from loads obtained by the virtual test, stress distribution from a Finite Element analysis, material properties of the parts, and fatigue damage accumulation hypothesis. A physical durability test takes at least several weeks even for the accelerated test where all non-damaging events have already been removed (contrast this to several months of potential proving ground runs). However, the virtual durability test is only a fatigue analysis, which may be completed within hours. The savings in time and the possibility to “test” multiple configurations are the motivation for the virtual test.

SUMMARY

RPC iterations were conducted to reproduce the field measured spindle loads. The achieved spindle loads matched very well with the desired spindle loads in the time domain. The fatigue analysis indicates that the differences of fatigue lives calculated for the measured desired signals and simulated signals achieved after iterations were all within 50 %. This shows that the virtual test system model has the capability to conduct RPC iterations to accurately reproduce the spindle loads. This opens up the possibility to simulate complex cases (with respect to loads and geometry) where responses are remote from the inputs.

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