W H I T E   P A P E R

VALIDATION OF VIRTUAL PROTOTYPES VIA A VIRTUAL TEST LABORATORY

Dr. Klaus Jörg Dittmann
DaimlerChrysler, Sindelfingen, Germany

F. Josef Albright, Dr. Christoph Leser
MTS Systems Corporation, Eden Prairie, MN, USA

Eden Prairie, MN, USA
July 29, 2002

Abstract:
Using validated dynamic models of physical test rigs a correlation study between virtual model and physical prototype was undertaken. The same load histories were applied to the model and the prototype and the responses were compared. Differences in the response gave indications to where model refinement was required to accurately predict the actual behavior.

Key words: Test, Analysis, Virtual, Multi-Body Simulation, Validation

1 Introduction

Due to the demands for shortened vehicle development cycles, reduction in development cost and the reduction of the physical prototypes built analytical numerical methods and physical tests of ever increasing complexity are being employed. The goal is to achieve a higher level product maturity at an earlier stage in the development process while using fewer physical prototypes. The previous goal of bringing the test track into the laboratory is considered to be achieved [1]. The future will require moving other development activities "upstream" from the physical into the virtual world. This is facilitated by increases in computing power by a factor of 10 in the last 5 years alone and simulation software with increasing predictive capabilities. Increased product maturity should be achieved during the early stages of development when physical prototypes are not yet available and one need to rely on analytical predictions only. This goal is referred to as "frontloading" of development activities. This study demonstrates the use of a "Virtual Test Laboratory" (VTL) to improve the confidence in the predictive capability of the virtual analysis. The figure below illustrates the phases of a typical development process in which VTL can be employed.

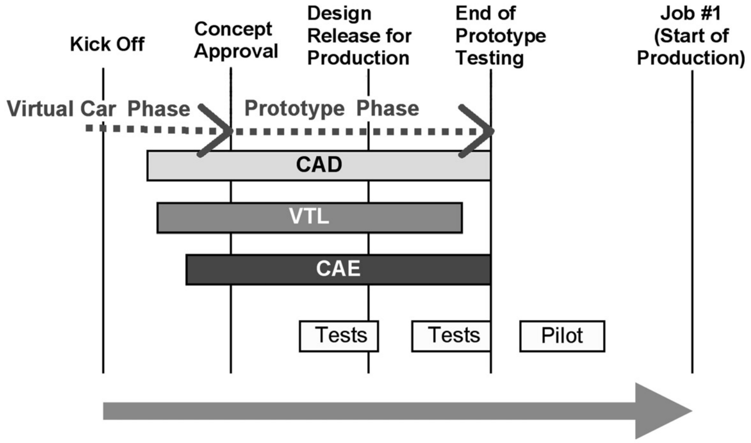


Figure 1 Phases of the Development Process

2 Motivation for Using a Virtual Test Laboratory (VTL) in the Vehicle Development Process

In order to achieve the goal of frontloading it is required to have a model or “Digital Mock Up” (DMU) of the product with high predictive capability. In addition to an accurate model of the vehicle and its components it is also required to have the “right” boundary conditions, cross sectional loads, and load time histories for all local and global components, sub systems and the full vehicle. In the past most efforts were spent on optimizing the full vehicle model, especially the body in white was modeled via FEM. Unit load cases were used for static and dynamic FEM analysis due to the fact that actual load time histories were not known. This gap can be closed when functional virtual prototypes and multi body simulation for vehicle and test equipment are used (e.g. [2]). The challenge is to find an appropriate forcing function and boundary condition for the virtual prototype of the vehicle under study. One possible solution is being demonstrated here using VTL tools for a dynamic simulation test of a full vehicle. The goal is to develop the load time histories for a subsequent FEM analysis of certain components, e.g. a shock absorber bracket. The results from this analysis can be used to estimate the fatigue life of the component in question. The following figure illustrates the domains in which data are generated and analyzed and the corresponding paths of data exchange.

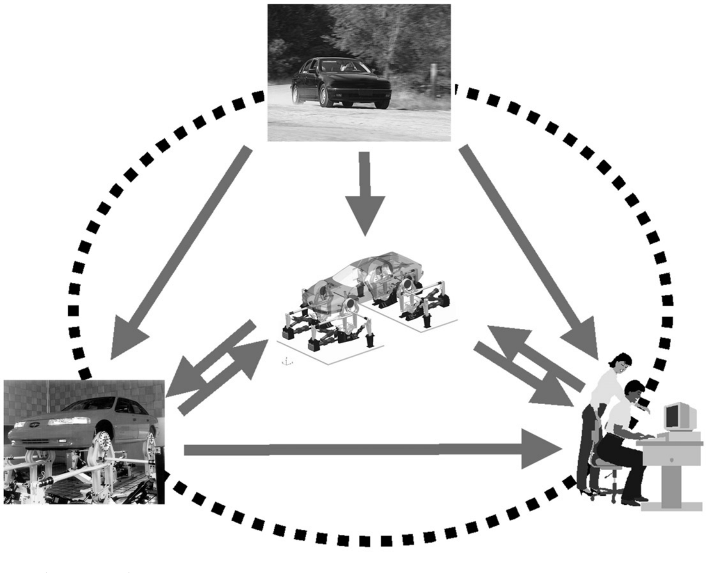


Figure 2 Data flow when using VTL

Realistic boundary conditions are achieved when a multi body dynamics model of the test rig is used. The virtual test stand must exhibit the same dynamic behavior as the in reality existing test stand used in the laboratory. The forcing functions are induced by using actuator displacement time histories from a previous physical test of a vehicle from the same class. This load assumption is only valid with restrictions and must be replaced during the development process with loads that are measured on representative prototypes.

The load time histories obtained from the above simulation can be used for FEM analysis or for physical tests of prototype subsystems. These fatigue tests can be used to validate the fatigue life estimation of the virtual model. This method can compensate for the weakness inherent in fatigue life estimation for predicting the absolute value of the life.

The advantages of using the VTL method become apparent when it is applied during the development process of a vehicle. The predictive capability of the virtual model can be improved through the incorporation of measurements that are taken during the phase when physical prototypes are available. The opportunity is then given by using VTL to evaluate the influence on the fatigue life due to changes in the design of respective components. Such changes can be in different styles of bodies in white, suspension tuning parameters or displacement of the center of gravity due to changed mass distribution.

To evaluate this concept's feasibility, the accuracy of an existing analytical model was evaluated. This evaluation process is being described in more detail below.

3 Basic Approach in Using VTL

The virtual test laboratory (VTL) is the virtual reproduction of a physical test stand with all its hardware and software components. It assures that the analytical tests are directly linked to the physical tests and therefore allows one to correlate and ultimately lead to a validation of the analytical models. This allows the user to work with models of higher confidence.

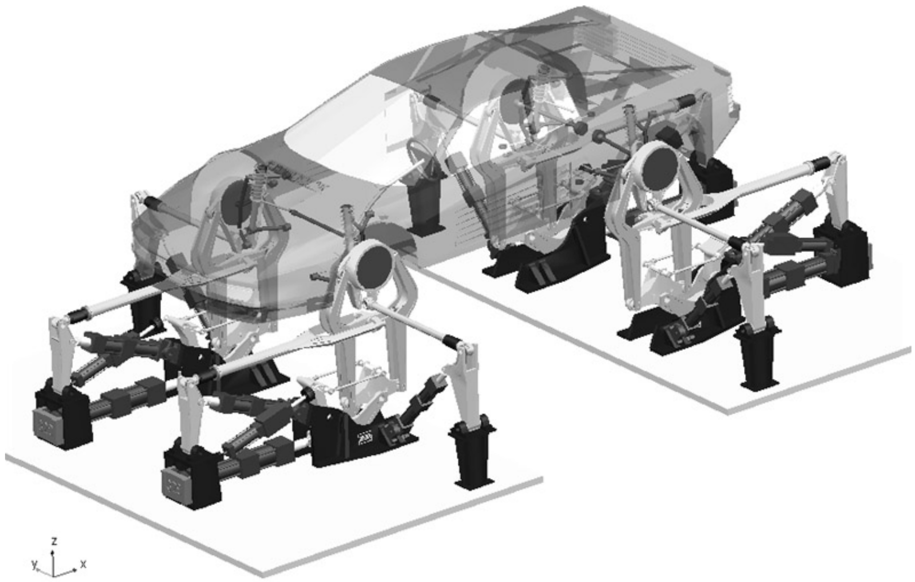


Figure 3 Virtual models of functional vehicle prototype and full vehicle simulator

In particular, analysis can be performed to benefit the following:

Validation

- Comparison of analytical and test results for vehicle parameters (stiffness, strength, durability) via correlation and validation studies
- Correlation and validation studies to compare predicted and achieved response from physical and analytical model for durability, performance and other evaluations. The aspect of gaining confidence in modeling accuracy via validating a virtual model is the key aspect of this study.
- Identification of unrealistic test conditions (e.g. study of fixture mass influence).

Design of Components

- Vehicle and component loading under realistic boundary conditions, i.e. the virtual test uses the same constraints as the physical test.
- Predicted spindle induced loads can be used to derive component loads, these component loads in turn can be used for:
    a) FEM calculations (sub systems) with subsequent fatigue life calculations.
    b) Component tests in the test laboratory to resolve uncertainties in the fatigue life predictions.
- Evaluations under extreme load and limit case situations.

Productivity in Test Execution

- Optimization of the physical test program prior to the start of a test (limit setting, event choices, number and order of events, superposition of events).

VTL allows for a more productive application of the analytical tools. It is particularly well suited at bringing together the physical and the virtual results for the fastest possible transition from unproven model to high fidelity correlated and possibly validated models. This helps to utilize previous generation vehicle data for the development of the new design prior to building hardware prototypes. This is accomplished by using the measured data from the previous design to confirm the validity of the new model. If the two designs are supposed to be similar, then the responses of the new virtual car should be close to the responses of the previous vehicle. VTL correlation tools expedite the process of gaining confidence that the new model is properly constructed. It will readily highlight areas of different response.

4 Application of the VTL Concept in a Current Vehicle Development Program

Measurements were taken in the development of a current vehicle platform in order to show that the proposed concept can yield valid data with appropriate predictive capability. Measurements where taken that formed a direct load path of from the suspension to the transducers as well as correlation transducers that where remote from this load path. All measurements were taken as a part of a full vehicle physical and virtual simulation.

Transducers in the direct load path are the wheel forces and the damper forces, correlation transducers are the engine mount loads.

In order to reach the goal of using the derived loads for a fatigue life evaluation (test or analytical prediction) a close agreement of virtually predicted and physically measured loads at given transducer locations must be achieved.

4.1 Model Creation for VTL Application

Functional Virtual Prototypes are based on three-dimensional component solid models and modal representations of component finite element models to accurately predict the operating performance of the product. Depending on the level of detail desired individual vehicle components will be modeled with a varying degree of complexity and resulting accuracy.

The multi body dynamics model of the test system originated from the CAD model. Care was taken to replicate 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 any multi body dynamics model generated in the ADAMS/Car platform of MSC.

Initially, the test stand model was as simple as possible. All of the test stand components were assumed to be rigid bodies. Bushings were modeled using measured bushing stiffness. 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 analytical and physical prototypes were retained. Model development always involves trade-offs between model accuracy and computational efficiency. The development of a validated model is elusive at best. A model is only valid over a specific range of applications.

In order to confirm that the virtual test stand itself would correlate closely to the physical test stand a validation study was undertaken. The first step was to compare a two-corner physical and virtual models of the MTS 329 Road Simulator. A dummy specimen (a simple beam) was attached between the two spindle housings and various inputs were given to the physical model to help characterize it. These same drive files were played into the virtual test stand and the responses were compared. Modifications of the virtual test stand were undertaken until the output of physical and virtual test agreed.

4.2 Vehicle Model Correlation

The objective of "correlating", i.e. the comparison of two types of results, was achieved by using a software tool that can read, display, adjust, and re-display signals that originated in two different domains, namely test response data from a physical test rig and analytical predictions from a multi body simulation. This tool, from hereon referred to as the "Correlation Tool" has the following features:

- Windows Operating System
- Graphical User Interface
- Scripting Language for customized analysis and reports
- Graphical Display Capabilities for X-Y and Contour Style Plots

The comparison of response wave forms and the quantification of differences from physical and analytical domain is achieved as follows:

1) Play out of the synthetic drives to both physical prototype and analytical model
2) Collect the responses from the physical and analytical test rig
3) Compare responses
4) Calculate the error between the two sets of responses

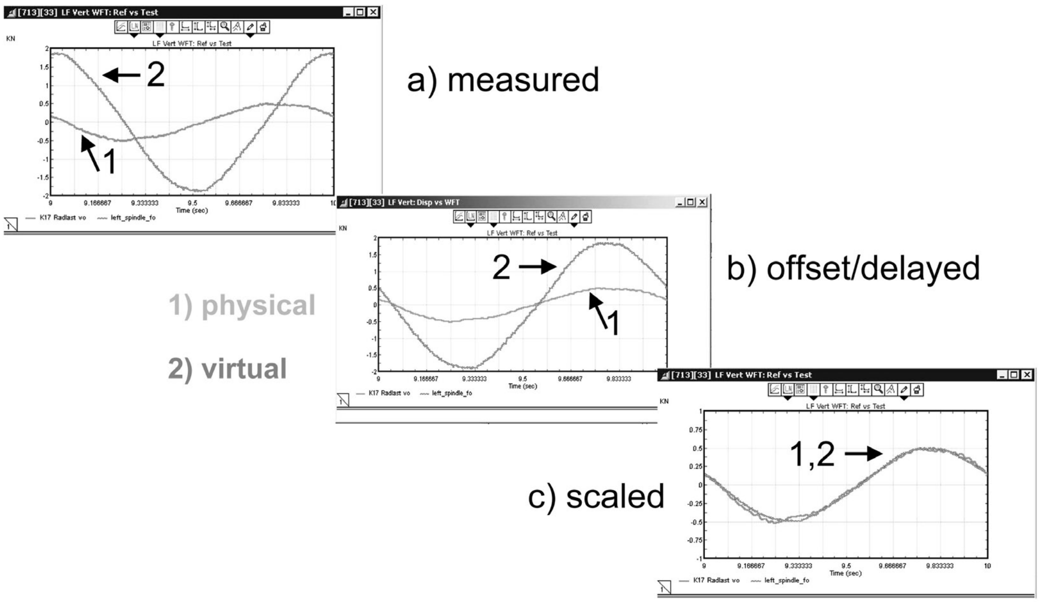
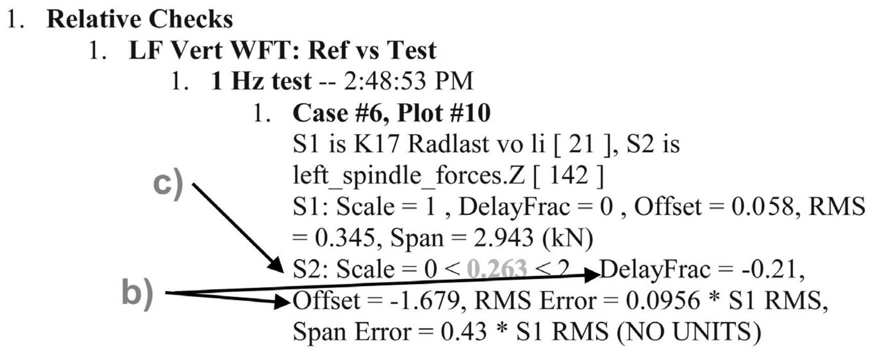


Figure 4 Initial correlation analysis and adjustment to signals



1. **Relative Checks**
    1. **LF Vert WFT: Ref vs Test**
        1. **1 Hz test** -- 2:48:53 PM
            1. **Case #6, Plot #10**
               S1 is K17 Radlast vo li [21], S2 is left_spindle_forces.Z [142]
               S1: Scale = 1 , DelayFrac = 0 , Offset = 0.058, RMS = 0.345, Span = 2.943 (kN)
               S2: Scale = 0 < 0.263 < 2 , DelayFrac = -0.21, Offset = -1.679, RMS Error = 0.0956 * S1 RMS, Span Error = 0.43 * S1 RMS (NO UNITS)

Figure 5 Report style output format for correlation analysis where b) and c) refer to the previous figure

4.3 Vehicle Model Improvement

The step of "improving" a specific multi body dynamics model requires knowledge of the level of correlation and then uses a methodical approach to adjust certain parameters of the model such that all transducers show close agreement between the virtual and the physical response. The following steps can be followed in an iterative manner:

5) Follow steps 1) through 4) above to identify differences in the response
6) Find sensitivity to change in vehicle specific parameter (e.g. spring rate and scale error) and error in response
7) Adjust the virtual vehicle model (e.g. change spring rate by the amount suggested by the sensitivity analysis to result in minimum error)
8) Play out synthetic drive again to the virtual model
9) Compare the responses
10) Calculate the error
11) Repeat steps 7) through 10) until the error is reduced to an acceptable level

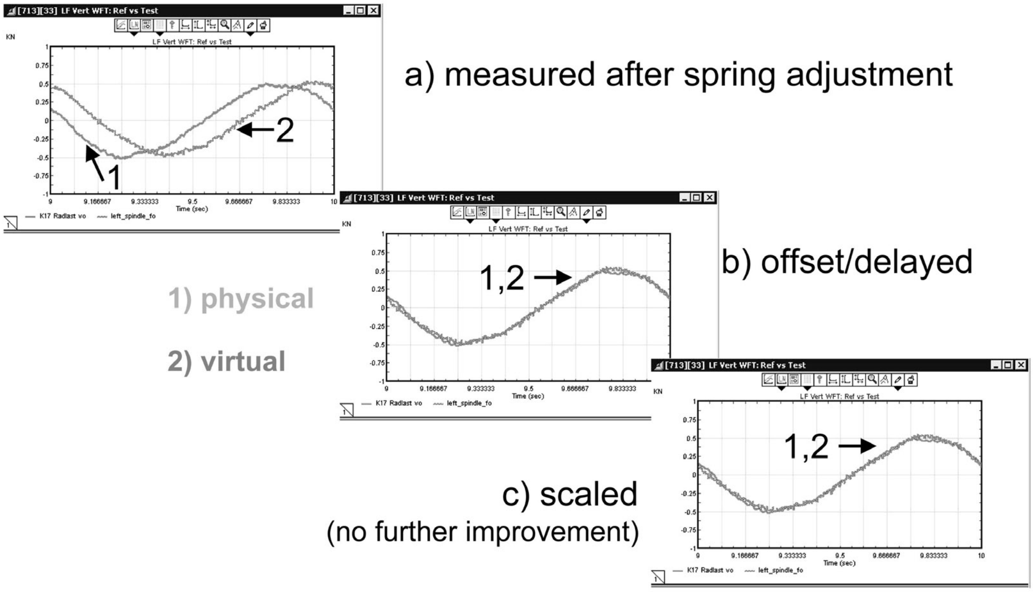
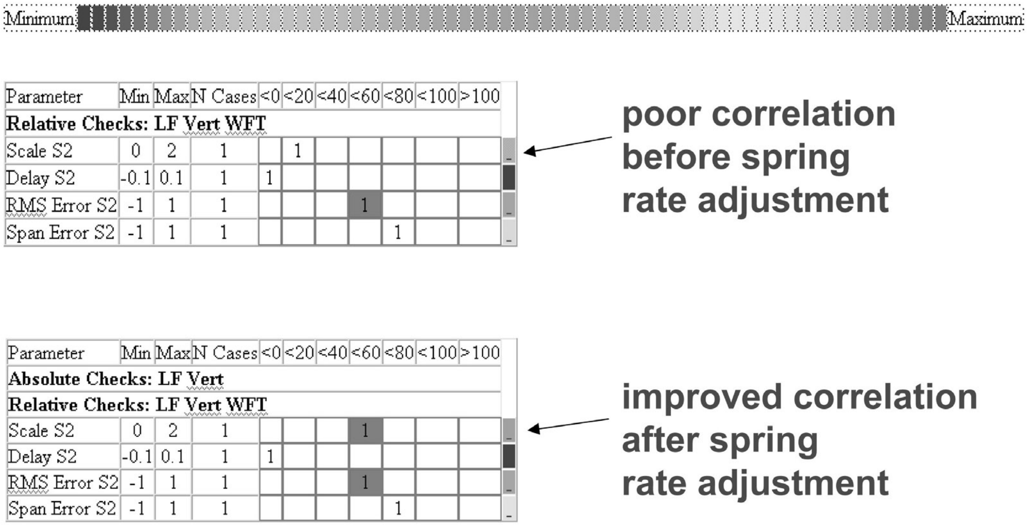


Figure 6 Final correlation analysis after changing the spring rate resulting in the removal of the correlation error with respect to scale.



Parameter	Min	Max	N Cases	<0	<20	<40	<60	<80	<100	>100
Relative Checks: LF Vert WFT										
Scale S2	0	2	1		1					
Delay S2	-0.1	0.1	1	1						
RMS Error S2	-1	1	1				1			
Span Error S2	-1	1	1					1		

poor correlation before spring rate adjustment

Parameter	Min	Max	N Cases	<0	<20	<40	<60	<80	<100	>100
Absolute Checks: LF Vert										
Relative Checks: LF Vert WFT										
Scale S2	0	2	1				1			
Delay S2	-0.1	0.1	1	1						
RMS Error S2	-1	1	1				1			
Span Error S2	-1	1	1					1		

improved correlation after spring rate adjustment

Figure 7 Contour plot demonstrating the removal of the correlation error with respect to scale. A scale of 0-100 is used where 50 means perfect correlation, a value of less than 50 means the virtual signal is too small and a value above 50 means the virtual signal is too large.

4.4 Synthetic Drive

A commonly asked question is “Why model a test rig?”. Simply by modeling the physical fixturing (i.e. not the hydraulics and controls) it is then possible to easily and unambiguously input “identical motions” into the virtual and the physical vehicle.

Despite having many years of experience in real time simulation of broad band random type signals in both the physical and analytical domain it was decided that for a correlation study, deterministic signals are more suitable in identifying differences in the respective responses. Broadband random signals are well suited to gain an initial understanding of the response of the model. However, due to signal to noise ratio issues and the fact that broad band random excitation can not characterize amplitude non-linearity we used the following deterministic functions:

- quasi-static tests to measure stiffness and compliance characteristics

- sine waves at various frequencies and amplitudes to identify specific frequency response characteristics including non-linear responses
- step functions to generate transient behaviors

A variety of events was created consisting of uniaxial excitation of the vehicle (e.g. left front vertical displacement) as well as a combination of multiple channels that were simultaneously excited (e.g. left front and right rear move upward, while right front and left rear move downward, induces twist). With such a systematic approach it is possible to achieve the following:

- identify that all transducer are active, polarities and amplification settings are correct
- quantify effect (sensitivity) of various vehicle parameter settings on response
- detect resonances in the vehicle model

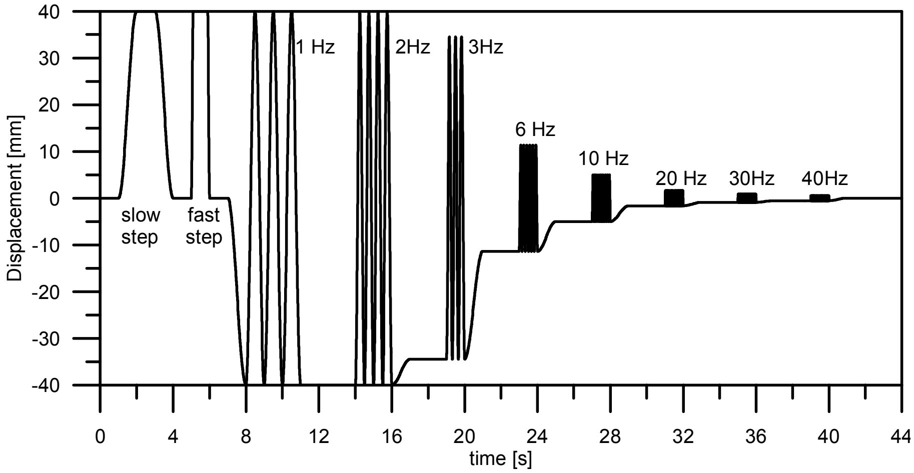


Figure 8 Synthetic Drive with step and sine excitation

4.5 Analysis of Results

The comparison of measured and predicted data for a given synthetic drive was performed using data obtained from a full vehicle test stand in the framework of a current development process.

The basic configuration of the specimen and test stand indicating transducer locations and load paths is illustrated below.

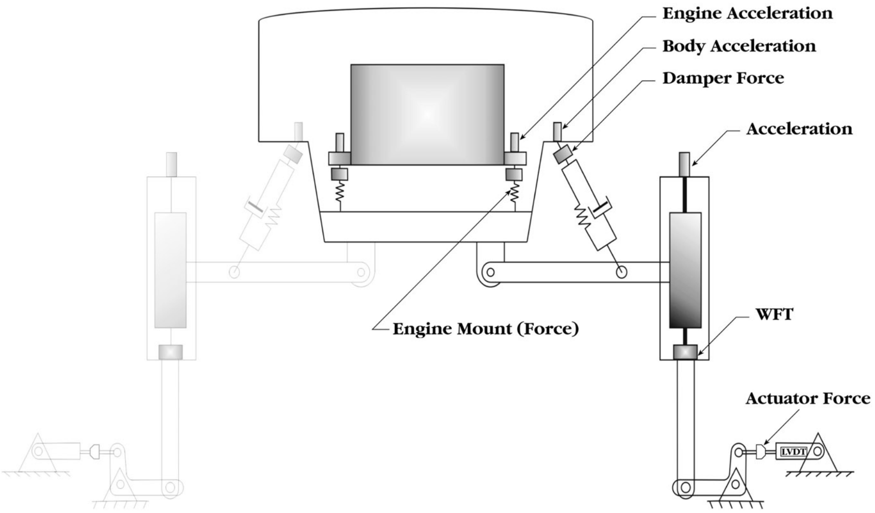


Figure 9 Transducer locations and load paths

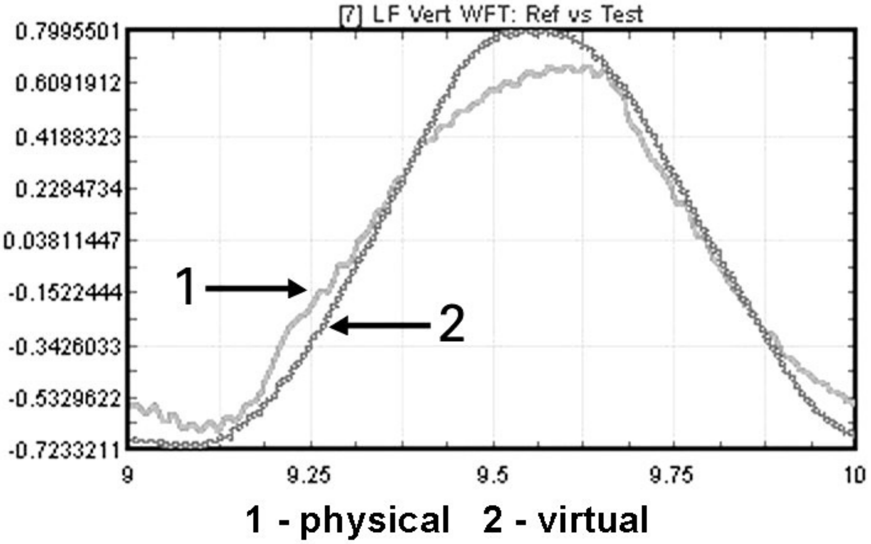


Figure 10 Correlation of the vertical left front wheel force

The result above shows a good agreement between physical test and virtual prediction. The force transducer was in the direct chassis to body load path.

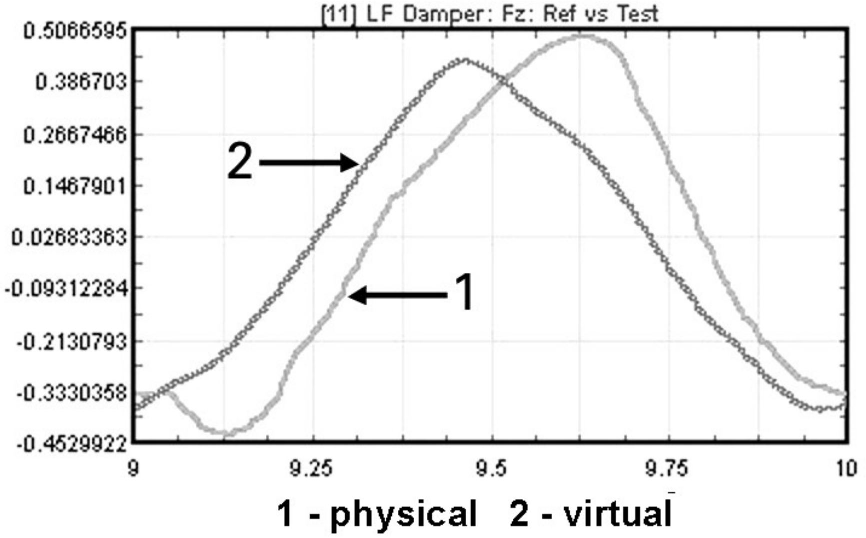


Figure 11 Correlation for the damper force transducer

The validation of the damper force above shows good agreement with respect to amplitude, but a phase shift between physical and virtual. The prediction by the virtual model requires, therefore, improvement to reduce the error in phase. Figure 9 indicates that this transducer is also in the load path of chassis to body, but due to the vicinity of the axle a kinematic influence of the axle will be noticeable

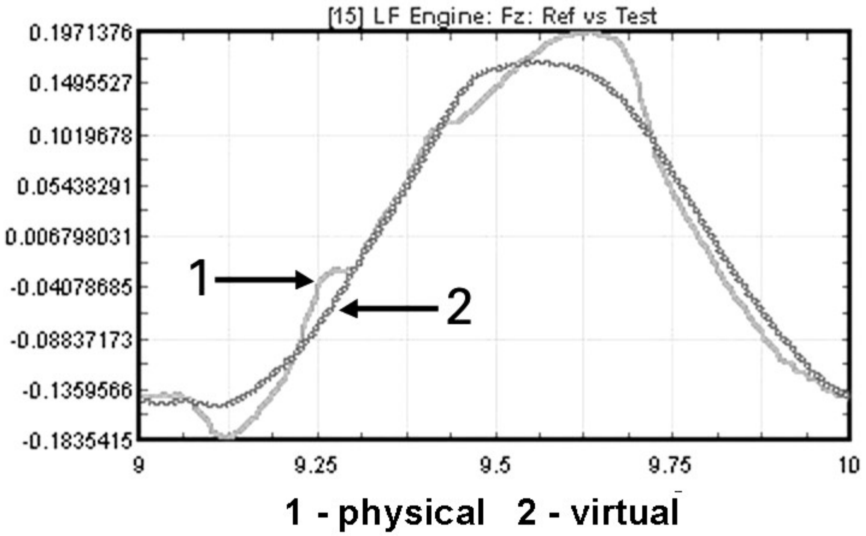


Figure 12 Correlation of the engine mount transducer

This transducer which does not lie in the direct load path of chassis to body and is dominated by the inertial reaction force of the engine shows good agreement between physical and virtual measurement with respect to both amplitude and phase.

Load spectra typically used in vehicle development have energy content up to about 40 Hz. The following analysis was performed for the engine mount load under a non-synthetic broad band random type excitation that was obtained from the response to road excitation. The correlation between predicted virtual and test stand measured response is sufficiently close (Figure 13). This transducer is not in the direct load path of the chassis to body and the dynamics are dominated by the inertial motions of the engine mass.

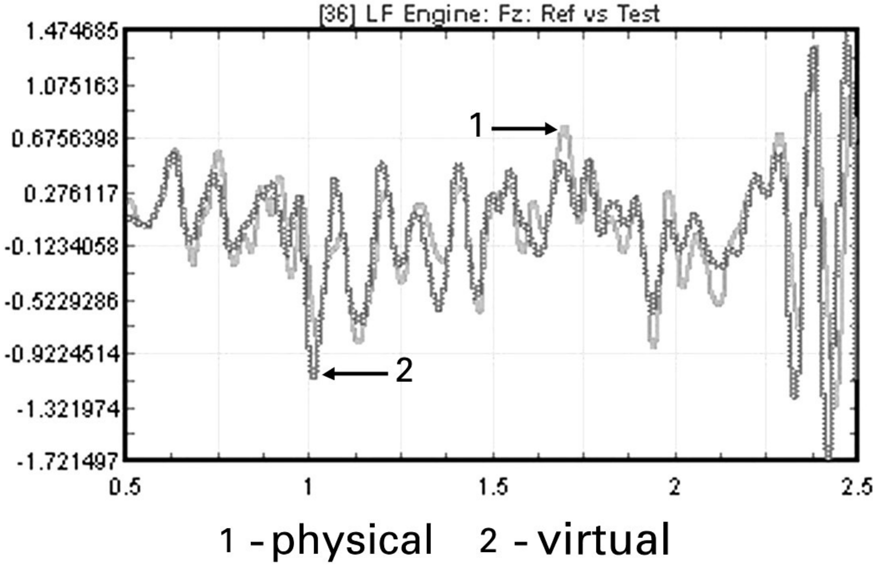


Figure 13 Correlation of the engine mount transducer under application of a non deterministic load sequence

4.4 Interdisciplinary Collaborative Engineering Approach

The use of virtual test laboratory tools will change the traditional distinction of test and analysis. Virtual test and physical test will be meshed activities in which a multidisciplinary team will work. With the increasing capabilities of multi body simulations it is envisioned that physical and virtual tests can be substitutes for each other where the test engineers see themselves as laboratory staff as well as analysts and will be able to functions in both domains.

The skills of the future test engineer working with VTL will exceed the current familiarity with measurement and control technology, data acquisition and analysis, test rig dynamics and include knowledge in numerical analysis and multi body simulation.

5 Conclusion

VTL offers a method to generate load sequences with the demonstrated correlation fidelity between measurements on the physical vehicle and the virtual results. The use of VTL in the early stages of vehicle development will facilitate the desired front loading of activities. In addition, due to the optimization of the test procedures it is expected that time intensive fatigue tests can be executed more efficiently. VTL now needs to prove itself in the actual environment of production development.

6 Acknowledgments

The authors want to thank the following individuals from DaimlerChrysler: Hubert Ebel, Dr. Malte Hahn, Erich Neuwirth, Stefan Weimer, MSC.Software: Guido Barati, Hans-Jürgen Büchler, Manfred Dienes and MTS Systems Corporation: Michael Moen, Gary Sandlass, Matthew Sauer, Raymond Schoenherr for support and assistance in generating this paper.

7 References

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