

Development of a Full-Vehicle Hybrid-Simulation Test using Hybrid System Response Convergence (HSRC)

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ABSTRACT

Hybrid vehicle simulation methods combine physical test articles (vehicles, suspensions, etc) with complementary virtual vehicle components and virtual road and driver inputs to simulate the actual vehicle operating environment. Using appropriate components, hybrid simulation offers the possibility to develop more accurate physical tests earlier, and at lower cost, than possible with conventional test methods. MTS Systems has developed Hybrid System Response Convergence (HSRC), a hybrid simulation method that can utilize existing durability test systems and detailed non-realtime virtual component models to create an accurate full-vehicle simulation test without requiring road load data acquisition.

MTS Systems and Audi AG have recently completed a joint evaluation project for the HSRC hybrid simulation method using an MTS 329 road simulator at the Audi facility in Ingolstadt, Germany. The hybrid simulation consisted of an Audi A5 Coupé installed on laboratory road simulator, combined with virtual vehicle tires modeled using FTire™ and Audi digital roads running in the standard ADAMS simulation environment. The scope of the evaluation included the development of a complete set of 20-channel control signals for the 329 road simulator for 3 rough-road durability test profiles representing selected Audi proving ground roads.

The physical spindle loads developed by the A5 + FTire hybrid simulation were compared to vehicle spindle loads obtained from three other methods: 1) a road load measurement for the A5, 2) a road measurement for a different but similar vehicle, and 3) analytically-predicted loads from a complete virtual vehicle system model. The comparisons indicated that laboratory vehicle test loads created using accurate tire models and hybrid simulation closely correlate to fatigue critical loads from a physical road measurement, and in overall result in more appropriate loads for the test vehicle than analytically-predicted or “bookshelf” loads.

This paper describes the HSRC hybrid simulation method, and its potential advantages for the vehicle durability testing and development process compared to other laboratory simulation methods. The paper describes the application of HSRC to create a full-vehicle laboratory test, and presents detailed simulation results for rough-road test events, along with comparison of the results to 3 alternate sources of vehicle loads.

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INTRODUCTION

Hybrid System Response Convergence (HSRC) is a hybrid-simulation control process that allows physical and virtual simulation elements to be combined to form a comprehensive system simulation. It differs from most hybrid-simulation techniques in that it creates an accurate dynamic simulation without requiring all system components to be operated in real-time. This enables HSRC to use

standard laboratory test systems and more complex virtual models as components in a hybrid-simulation.

For laboratory durability testing, HSRC offers the possibility to develop prototype vehicle and subsystem tests without requiring a dedicated vehicle data acquisition program. HSRC allows the test specimen to be surrounded by a complementary virtual environment to create a complete vehicle system, and then “driven” over a digital test track. Eliminating the need for vehicle-specific data can speed

development, reduce costs, and/or avoid the compromise of using inappropriate data for testing.

In contrast to other common durability test methods, the loads applied to the physical test specimen using the HSRC method are not measured or predicted in advance. HSRC simulation loads develop as a result of the inputs to the hybrid system, and are purely a function of the dynamics of the coupled virtual and physical components of that system. This situation can make test accuracy assessment difficult for hybrid simulations, as compared to conventional methods where the expected response is known in advance.

To evaluate the capabilities of HSRC control, and to assess the quality of loads information that can be delivered by this method, MTS Systems & Audi cooperated on a hybrid-simulation pilot project during the first half of 2010. The scope of the project called for development of a set of full-vehicle hybrid-simulation test drive-files using the following components:

- Audi's MTS 329 LongStroke Road Simulator with FlexTest™ control system
- An Audi A5 measurement and test vehicle
- Audi digital road profiles
- An FTire dynamic durability tire model with Audi tire parameters
- MTS custom HSRC modeling and control software within a modified RPC Pro™ environment

HYBRID SIMULATION FOR DURABILITY

Hybrid vehicle simulation methods combine the physical test article (vehicle, suspension, etc) with complementary virtual vehicle components, and the virtual road and driver inputs required to simulate the actual driving environment. This combination enables durability tests to be created without requiring the interface forces or motions for the tested sub-system to be determined in advance. Some advantages for this method:

- Hybrid tests can usually be developed earlier and at less cost than methods which use measured loads. Hybrid simulation tests can be developed as soon as physical test hardware is available, and do not rely on the availability of drivable prototypes for data acquisition. Safety and security risks associated with operating prototypes on the track or public roads can also be avoided.
- Hybrid tests can often be more accurate than methods which use virtually adapted or predicted loads. Hybrid simulation tests do not require the critical behavior of the tested components to be modeled. Only components that are not included in the test are represented virtually, along with the road and driver inputs.
- Hybrid simulations allow the complete, accurate dynamic response of the test specimen to be reproduced. This is in

contrast to the use of purely synthetic test inputs (e.g. random noise excitation), which may not reproduce the required internal velocities and accelerations at the proper phase relationships to generate accurate component forces [1].

Until recently, hybrid simulation of complex mechanical systems typically required “real-time” operation, especially if the hybrid system components (physical or virtual) had significant inertial or damping properties which would affect the overall system dynamic response. Real-time operation places constraints on the design and configuration of the various hybrid system components. First, virtual components must be modeled efficiently enough to allow real-time simulation in the processing environment. Second, physical components must be exercised or loaded in real-time, which means that test rig control systems must have near-perfect tracking control performance over the simulation frequency bandwidth. Finally, the data transfer between the virtual and physical systems must occur with minimal latency to simulate real-time coupling of the two systems.

Unfortunately, the constraints of real-time hybrid system implementation are typically incompatible with many common vehicle simulation requirements, given the current state-of-the-art. Simplified vehicle and tire models have been developed to run in real-time on standard computing platforms for vehicle handling and stability analysis. However, these models are inadequate to represent the more complex vehicle responses needed for ride comfort and durability simulations. Similarly, the test systems required to exercise and load the physical hybrid components are generally too complex to easily deliver the “perfect” load and motion tracking control required. Multi-axis test rigs designed for high amplitude and frequency vehicle durability simulation typically rely on compensated programming that has been iteratively developed to generate the desired responses within the test components.

Within these limitations, it is not currently feasible to configure a real-time hybrid system that has the component detail and operating complexity to perform most vehicle comfort and durability simulations. However, in light of the current pressures on the vehicle development process, it has become necessary to consider new and alternative hybrid simulation methods for developing and evaluating attributes such as vehicle durability.

HYBRID SYSTEM RESPONSE CONVERGENCE (HSRC)

To address the limitations of real-time techniques, MTS Systems Corporation has developed an alternative approach to hybrid simulation for durability applications. The Hybrid System Response Convergence (HSRC) technique enables physical and virtual components with multi-degree-of-freedom (MDOF) dynamic behavior to be simulated as a coupled, hybrid system. The various physical and virtual components of the system are operated sequentially as an open-loop system rather than simultaneously, thus avoiding

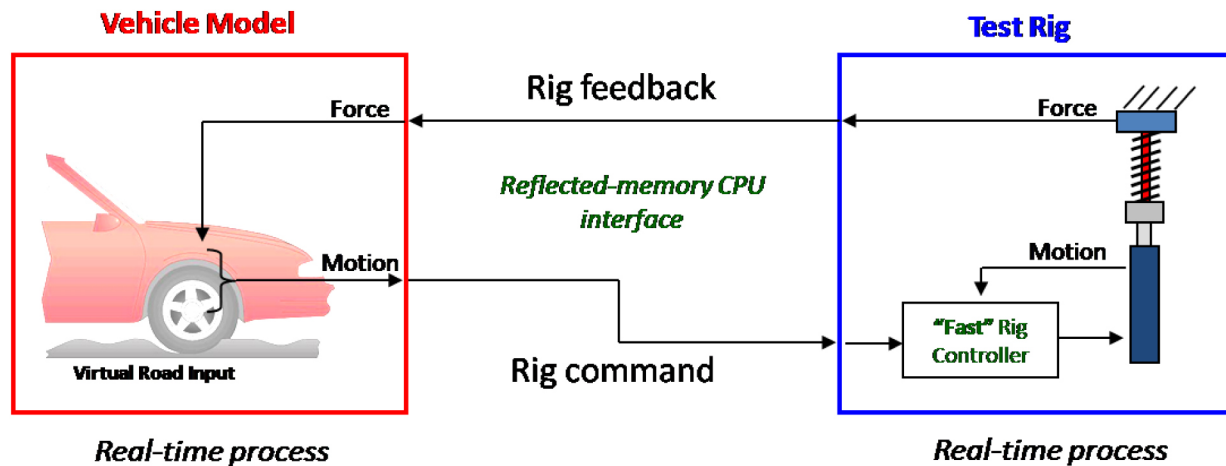


Figure 1. "Real-time" hybrid simulation system schematic

the requirement to run in real-time. The HSRC method uses an iterative approach to develop a solution that provides the equivalent behavior of a closed-loop hybrid system. The iterative HSRC method enables the open-loop process to converge on the correct solution by modifying the physical system inputs to move the physical and virtual system responses toward a compatible dynamic solution [2].

The HSRC method uses frequency domain system identification techniques that are similar to those used by industry-standard "response simulation" test control software, such as MTS RPC Pro™. RPC Pro™ software identifies multi-channel, multi-DOF system behavior, and then uses an inverse model of the identified physical system to develop the correct control inputs necessary to generate a desired system response. The HSRC "response convergence" control method is based on similar techniques, except that HSRC tests have no "desired" system response. The HSRC control model contains information about the coupled dynamics of the complete physical and virtual system, and is able to iteratively identify a system response solution that is dynamically correct for the combined hybrid system components.

Figure 1 and Figure 2 describe the operational differences between a conventional real-time hybrid system and an HSRC hybrid system. Figure 1 is a schematic example of a real-time hybrid system. In this example, the virtual vehicle on the left is constructed without including suspension damper components in the model. Physical dampers intended for the vehicle system are installed in a damper test rig (right of figure). As the vehicle is driven over the test surface, the resulting virtual suspension motion is provided to the test rig as a control program. The damper forces developed on the rig are fed back to the virtual vehicle and applied to the suspension using virtual force generators. If the model execution, test control, and data transport can all be realized with insignificant delay, the hybrid system will behave dynamically as if the physical damper was installed in the virtual vehicle. Note that the selection of force as the

feedback and motion as the command for the physical system was based on achieving the best control conditions for both the physical and virtual systems. In other situations, the hybrid-system control requirements may best be satisfied by using motion as the physical feedback, and force as the command.

Figure 2 shows the same virtual and physical components from the damper simulation, now configured for HSRC control. In the HSRC implementation, the iterative control process begins by acquiring an initial force and motion response from the physical damper test rig. The initial response may be zero, or it may be an arbitrary response depending upon the initial test program selected. Next the virtual vehicle is driven over the test surface, while the measured physical damper force is simultaneously applying to the virtual suspension. The vehicle suspension motion is simultaneously recorded from the virtual driving event. The virtual suspension motion is then compared to the physical damper motion from the previous test response.

Using the difference in the motion response, the HSRC control model can calculate a program update for the damper test system. This update is applied to the physical system, and the process is iteratively repeated until the difference in the motion response between the physical and virtual systems is minimized to a specified tolerance. The HSRC control model, which is developed using a proprietary method, is based on an empirical identification of the behavior of the virtual and physical components of the hybrid system, and enables the control program for the physical test to be updated in a manner that will converge to the unique, correct solution for the specific set of hybrid system components.

Although the systems described in Figure 1 and Figure 2 are composed of the same basic elements, the use of the HSRC control technique creates several opportunities not possible with the real-time system:

- With HSRC, the simulation speed for the various system components can be different. This enables the use of more complex vehicle, suspension, tire, and road models designed

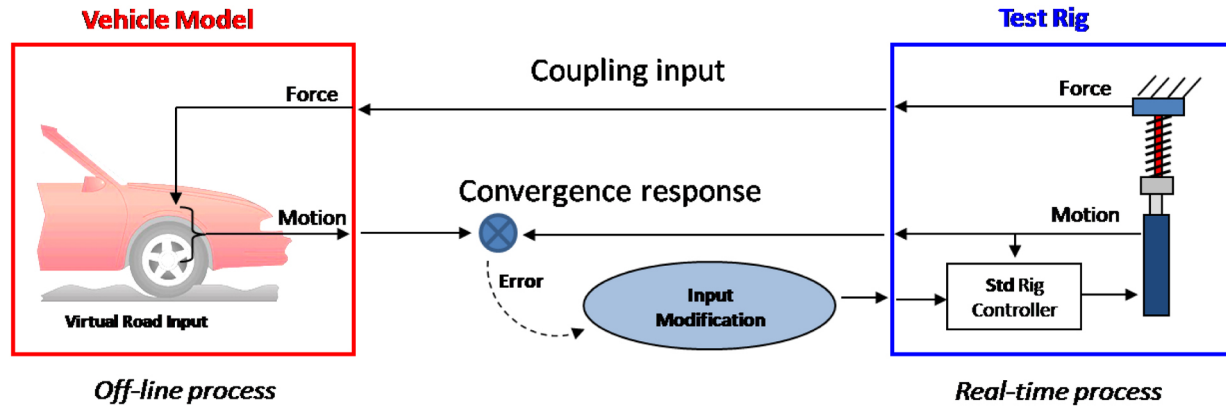


Figure 2. Hybrid System Response Convergence (HSRC) simulation system schematic

specifically for durability evaluation, and allows these models to be operated in their native environments at processor-dependent speeds.

- With HSRC, “fast” test system controllers are not required. Standard durability test systems cannot typically be optimized for near-perfect tracking control, and require command compensation techniques such as RPC Pro™. Because the HSRC physical test control programs are developed iteratively, errors in tracking control can be iteratively reduced with RPC simultaneous with the HSRC hybrid system convergence process.
- With HSRC, hybrid system modeling and testing environments do not have to be co-located or linked for high-speed data transfer. HSRC iterations can be executed across standard network connections using any necessary file transfer protocol.

The above example is a very basic hybrid system configuration, involving a single degree-of-freedom component (i.e. a damper) removed from the vehicle, and requiring control between the physical and virtual systems at only one relative force and motion interface. The same HSRC control concepts, however, can be applied to multi-body systems (i.e. systems with inertial components) that are multi-axially constrained at several interface locations within the system. **The general requirement is that each control axis at each interface location must be able to be actuated, and that the corresponding force and motion information must be measurable.** This requirement, although relatively easy to implement on the virtual side of the interface, can be extremely complicated to implement at the corresponding physical system locations. It should be noted also that these interface measurement and actuation requirements pertain to all hybrid system implementations (i.e. HSRC or real-time).

FULL-VEHICLE TESTING USING HSRC

Full-vehicle road simulators typically utilize a structurally-complete vehicle as the test specimen. This means that the vehicle contains all of the representative suspension, chassis, and body components required to

develop proper internal dynamic loads when excited. What is typically absent for full-vehicle configurations is the wheel & tire combination. Instead of excitation using a road input through a physical tire, the specimen is excited via force and motion inputs directly at the vehicle spindles. For a hybrid simulation application, it is generally desired to drive the simulation starting from the digital road as input. Therefore, for full-vehicle hybrid simulation, the missing wheels and tires must be represented as virtual components. See Figure 3.

To apply the HSRC technique to full vehicle simulation applications, a suitable hybrid interface actuation and measurement location must be specified to satisfy the requirement stated above. For 329 full vehicle simulators, the obvious interface location between the rig and the physical vehicle is at the vehicle spindle. For spindle force and moment measurement on the pilot project, the interface was more specifically defined as being at the center of the Wheel Force Transducer (WFT) installed on the physical rig. This location was the most convenient point at which to define the MDOF physical-to-virtual interface, since the measured WFT forces and moments could be used directly in the HSRC control process. Corresponding motion measurements (displacements and angles) at this location would therefore also be required. For the pilot project, spindle motion measurement was accomplished primarily through the use of auxiliary accelerometers mounted on the 329 fixture spindle housings.

The next consideration for the full-vehicle application was to determine the appropriate control modes for the physical and virtual elements of the system at each interface axis (i.e. either force or position). By definition, the dimensions of the control modes for a given hybrid system interface axis must be of opposite dimensions for the physical and virtual components. This means that if the position of a specific axis of a physical system is being controlled, then force at the interface must be controlled for the corresponding axis on the virtual system.

In general, control mode selection will be influenced by the nature of the subsystem components. For HSRC, the fact

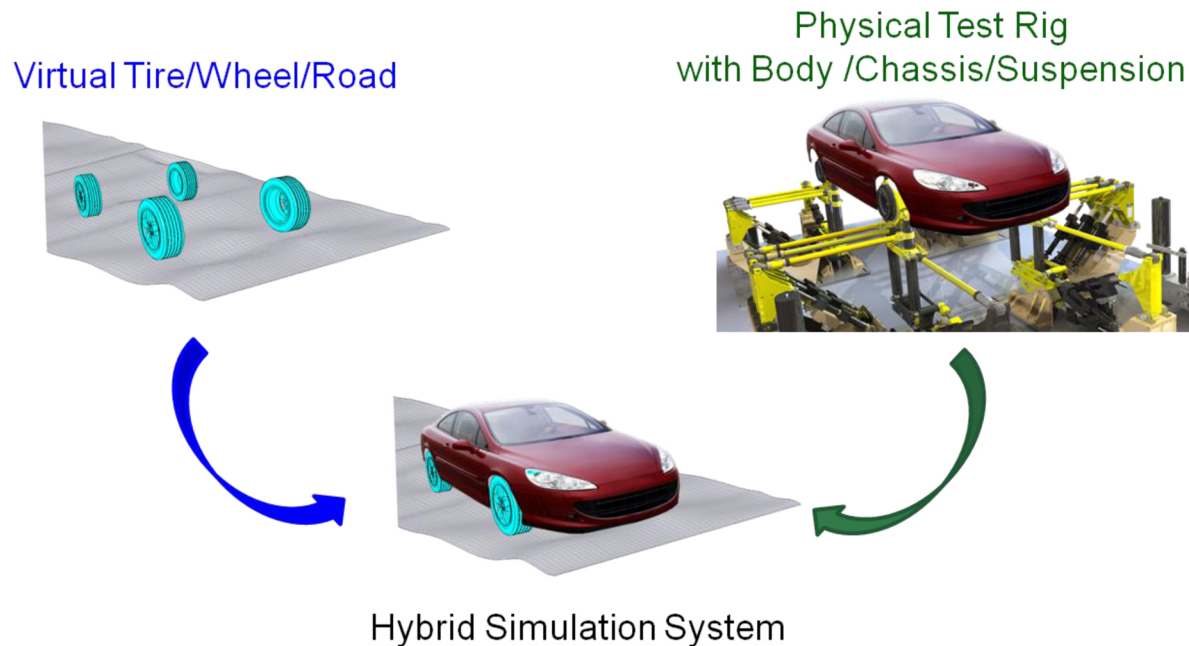


Figure 3. HSRC Full-vehicle Test Application

that the components of the hybrid system will be operated in an “open-loop” fashion during solution iteration is also a consideration. In the absence of the constraint imposed by a real-time coupled feedback, the virtual simulation may not initially be stable during the iterative process if inappropriate control modes are chosen. [Table 1](#) describes the virtual and physical control modes selected for DOFs control at each wheel interface for the full-vehicle test application.

Table 1. HSRC Interface Axis Control Modes - Full-vehicle Simulation

Interface Control Axis	Virtual Control (Coupling Input)	Physical Control (Convergence Response)
Spindle Longitudinal (x)	Displacement	Force
Spindle Lateral (y)	Displacement	Force
Spindle Vertical (z)	Force	Displacement
Spindle Camber(@x)	Angle	Moment
Spindle Steer (@z)	Angle	Moment

To reproduce the desired hybrid simulation vehicle response, it is required to “drive” the vehicle over the test event. For the full-vehicle HSRC application, this means driving the 4 virtual tires over the digital road surface, at the desired course and speed, while simultaneously applying the force inputs and position constraints measured from the physical vehicle on the road simulator.

The large, lower-frequency X- and Y-axis displacements associated with driving the virtual test event cannot be generated by the 329 road simulator, and therefore must be generated entirely within the virtual simulation. Similarly, there are other non-simulated vehicle inputs (e.g. powertrain)

that develop loads into the tires which might affect the simulation response. These must also be added to the virtual simulation. To accomplish this, a Driving Profile time history is provided to the virtual simulation in parallel with the physical test coupling response. The Driving Profile contains seven channels of information required to “drive” the virtual tires over the event. See [Figure 4](#). The additional inputs applied to the virtual simulation, such as powertrain torque, etc. can improve the loading conditions for the virtual elements (e.g. the tires) only. The absence of these inputs may still affect the response of the physical system components if not also applied by the laboratory test rig.

HSRC SIMULATION CONTROL

HSRC uses a Frequency Response Function (FRF) to identify the relationship between physical test rig control inputs and the response differences between the physical system and a complimentary virtual system. The HSRC FRF is then used to iteratively reduce the response differences between the systems by adjusting the physical system inputs until compatible dynamic behavior is reproduced. When this has been accomplished, the HSRC simulation represents the correct dynamic behavior for the coupled hybrid system, and the physical test inputs can be used for subsequent durability testing, etc.

[Figure 5](#) shows the HSRC control diagram for a full-vehicle simulation application. As discussed previously, this HSRC application contains two compatible systems: a physical vehicle system, and a virtual wheel & tire system. The hybrid interface for the systems is located at each vehicle spindle, and it is at these locations where compatible dynamic behavior in each controlled axis must be achieved. For every