SIMULATION BASED DESIGN FOR ACTIVELY CONTROLLED SUSPENSION SYSTEMS

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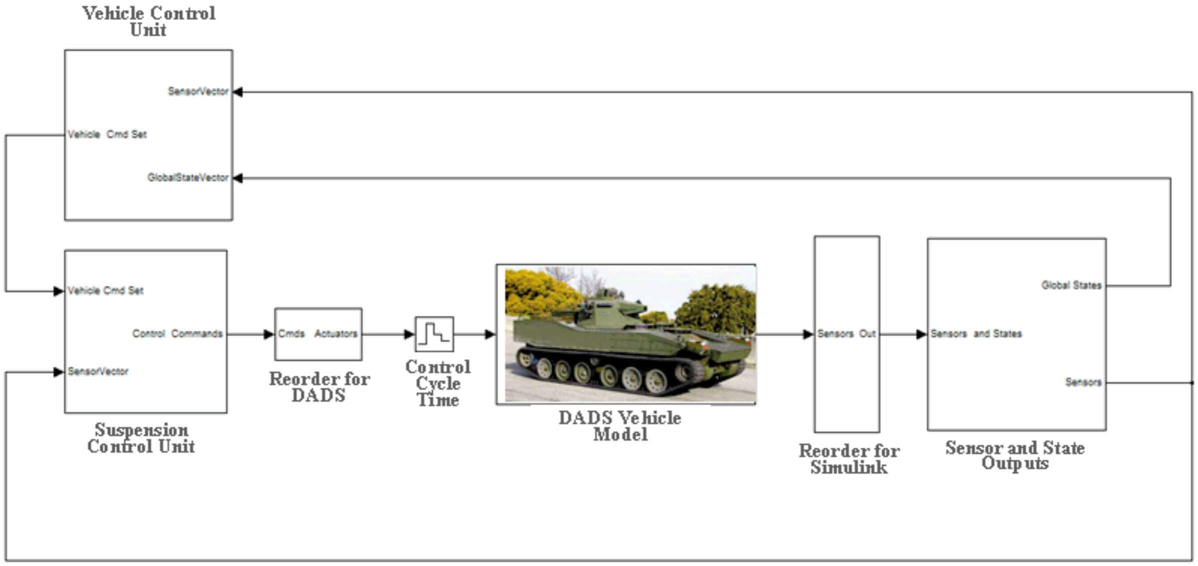
Abstract

Active and semi-active suspension systems are mechatronic systems that require a disciplined approach to synergistically combine the traditional engineering fields of mechanical, electronic, controls, power, systems, automotive, and suspension. Integrating suspension design is particularly challenging because it strongly interfaces with safety issues and driver perceptions, which are not easily optimized. Since 1993, the University of Texas Center for Electromechanics (UT-CEM) has successfully developed high performance active suspension technology and systems for a wide range of military vehicles, including small tactical trucks (e.g., HMMWV), medium tactical trucks (e.g., LMTV), and hybrid electric tanks (e.g., BAE's Lancer prototype). In addition to developing active suspension technology, UT-CEM has developed, refined, and validated an integrated simulation based design approach for controlled suspension systems that is the topic of this paper.

Modeling Environment

UT-CEM's design approach is centered on the MATLAB-Simulink environment, coupled with a dynamic vehicle simulation platform, such as DADS or ADAMS. The controls are modeled in Simulink, with full inclusion of all sensor processing/filtering, in a manner that allows direct transition to intended vehicle platform through autocode generation. Consequently, simulated control systems are identical to vehicle platform control systems. Over time, this improves simulation accuracy, expands usefulness of simulation results in the design and specification process, and allows relatively successful tuning and debugging prior to vehicle integration. The approach also tracks power and energy flow, allowing full understanding of trade-offs between component characteristics and power consumption in the design process. An example of the benefits of this tool was an early realization that active suspension control objectives directly impact power consumption and that active suspension systems can be designed to consume less vehicle power than passive dampers for vigorous off-road terrain (a concept that has been verified in recent HMMWV active suspension system durability testing).

The basic modeling environment is shown below. This environment allows a medium fidelity model that runs quickly. In this particular example, our active suspension system demonstration on a hybrid electric 22 Ton tank is depicted. Vehicle dynamics are captured in DADS, a vehicle dynamic modeling environment (alternative environments, such as ADAMS, are also suitable). The objective of the model is to provide early estimates of suspension performance; provide a platform to develop optimal component specifications (e.g., active suspension actuator force, speed, and bandwidth capabilities based on performance goals); and to develop/tune the suspension control system.

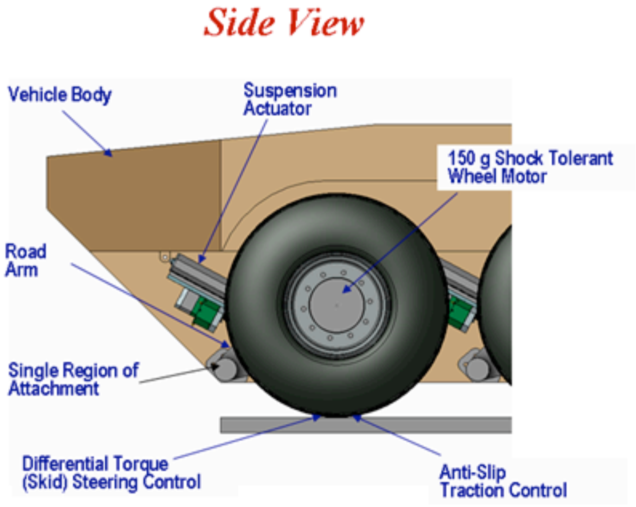


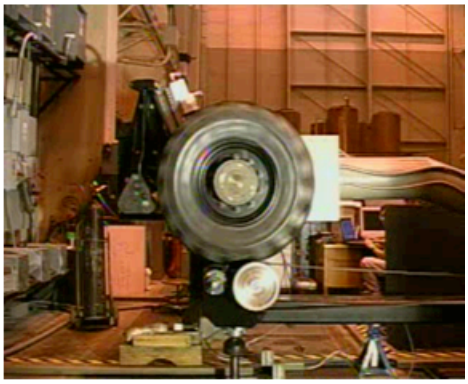
The interface between the Simulink and DADS model provides a natural separation between software and hardware that is eventually deployed on the vehicle. The mechanical system is primarily captured in the vehicle model, while the control software is conveniently segregated in the Simulink model. Output from the DADS model can represent information that can be physically sensed locally (i.e., on the vehicle, such as accelerometer output) and/or global variables that cannot be locally sensed on the vehicle (such as inertial velocity or direction of travel). Since one objective of the simulation is to develop the actual control system that is to be deployed on the vehicle, care is taken to ensure that only true sensor data is fed to the suspension controller. Global states are only fed to the simulated Vehicle Control Unit where it can be used to conveniently control vehicle speed and direction. The suspension controller contains all suspension control algorithms, all sensor filtering modules, and all other interfaces necessary for final vehicle implementation. The DADS vehicle model includes actual vehicle and suspension component dimension and mass properties, including suspension actuators and sensor locations. Of particular importance, in between the Simulink controller model and the DADS vehicle model, there is a sample and hold block (labeled Control Cycle Time on above figure) to properly enforce controller cycle time – actuator force commands are a held for a complete controller cycle time (typically 1-2 milliseconds) to enforce reality.

Model Validation

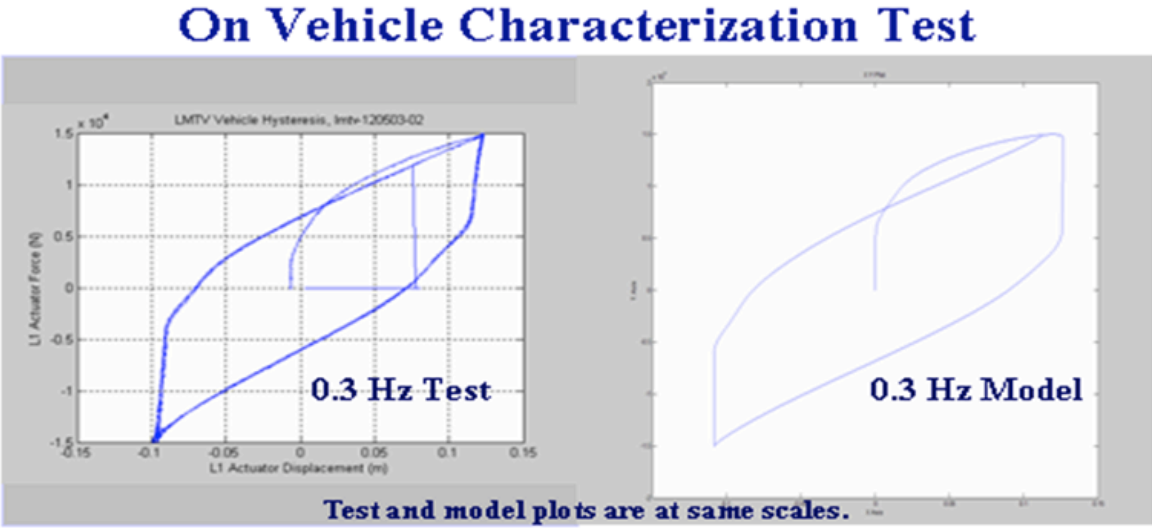
Model validation is a continuing activity. During the early design phase of a new suspension application, previous validated models are exploited to generate reliable simulation results. Typically, at this stage in the design process, identified trends are reliable and absolute numbers are within ~ 10-15%. Consequently, trade studies to evaluate design parameters like actuator force/power specifications vs. performance (e.g., driver average absorbed power on a particular test terrain) are dependable within ~10-15%.

After component hardware is built, detailed characterization results are used to refine models and performance estimates. The figure below shows a configurable single wheel test rig at UT-CEM, designed to replicate a single wheel station of a vehicle (in the example shown below, it was an 6x6 unmanned hybrid electric wheeled vehicle that employed skid steering and traction control). This test rig is also supported by test rigs (not shown) that isolate actuators to perform detailed actuator characterization. Component design refinements can be identified as a result of this coupled characterization-simulation activity with a high degree of confidence.





After the full compliment of hardware is fabricated and integrated on a vehicle, simple vehicle tests are used to further refine the simulation. Since actuator characterization has been completed, these on vehicle tests are particularly useful in identifying vehicle characteristics such as leaf-spring damping that were only estimated in previous design stages. As an example, the figure below shows actuator force (vertical axis) vs. actuator displacement (horizontal axis) on the front left wheel station of an Army LMTV (2.5 ton, leaf-spring, cargo truck), when a 0.3 Hz sinusoid actuator force is simultaneously applied to all four vehicle wheel stations. The step changes at the right and left edges of the plots are related to total suspension friction. Since the actuators are well characterized, adjusting vehicle friction characteristics until simulation matches test data, results in a reasonably good estimate of vehicle dynamic friction characteristics. It is noted, however, that these friction tests are performed at relatively slow suspension travel speeds, whereas high speed travel on vigorous off-road terrain results in high suspension travel speeds, a limitation in this method of estimated vehicle suspension characteristics.



With the previous model verification steps complete, full vehicle tests on harsh off-road terrain can provide additional model validation. The plots below compare test and simulation results on the UT-CEM 2 inch rms test track for the LMTV vehicle described above. For this validation exercise it is important that accurate terrain displacement information is input into the simulation. It is also important that test drivers maintain accurate vehicle speed because vehicle response to dynamic terrain is highly dependant on speed. Of course, drivers are less perfect than simulations in this respect, resulting in differences between simulated and actual test data. The left plot shows suspension travel for the left front wheel station as a function of time for this terrain. Note that the simulated and test data are in very close agreement. There is a minor difference in time location of some travel peaks, indicating differences between test and simulated vehicle speeds as a function of time. Additionally, there are some minor differences in the magnitude of some peaks, although agreement is generally excellent. Some of the differences are due to speed variations between the model and actual vehicle, some are likely due to inaccuracies in suspension friction models,[1] and some are due to tire parameters.[2] The right plot compares average driver absorbed power for the LMTV on the UT-CEM 2 inch rms test track. Since the absorbed power metric is a time average, the value changes over time as additional data is included in

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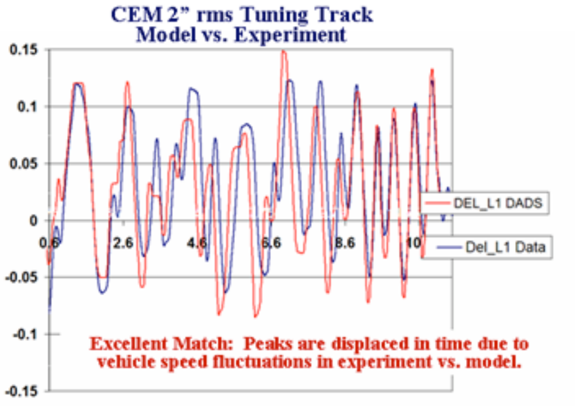
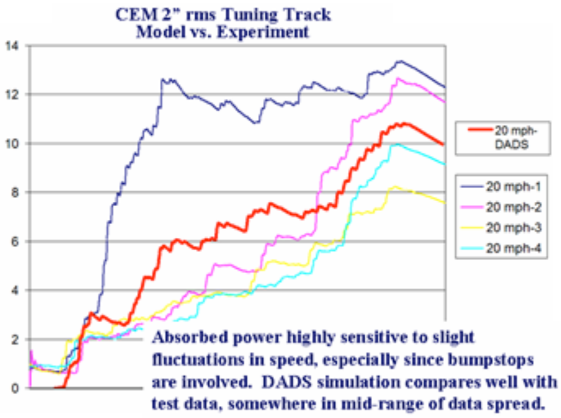
[1] Vehicle suspension friction estimates were accomplished at relatively low speeds, which is more significant for leaf-spring vehicles which exhibit complex friction characteristics.

[2] Vehicle simulation packages such as DADS and ADAMS contain highly developed tire models that rely on input parameters that often not readily available and must be estimated.

the average. Driver average absorbed power is a processed (filtered) result from an accelerometer at the driver's seat and is highly dependant on minor changes in vehicle speeds. The right plot compares the simulation with four different tests. The tests indicate a spread, with one test (20 mph-1) looking different than the others (highlighting the sensitivity of the average absorbed power result). Note that simulation results compare well with actual data, somewhere in the middle of the various test runs.





Software Transition from Simulation to Vehicle

Developing active suspension controls in the simulation environment described above greatly facilitates transition to the final vehicle using the dSpace product. dSpace offers an autocode generation product customized for Simulink and controller hardware suitable for prototype testing. Various products exist to continue this autocode transition process to controller hardware suitable for production vehicles. Consequently, discipline in developing the initial control algorithms in simulation (e.g., only using realizable sensor input in the simulation) greatly facilities successful transition. Our experience has shown that control gains tuned in simulation serve as very good initial set points during vehicle debugging and tuning. In the end, driver sensation guides final tuning parameter selection.

Conclusion and Observations

The simulation tools and processes described above have proven highly effective in seven different active suspension demonstration programs, ranging form HMMWV's to tracked vehicles, and also in transition to production ready systems. Over this time, a few keys to success have emerged:

- Use every new application to continually upgrade/improve simulation tools.
- Remain focused on model validation.
- Friction remains the largest model uncertainty; continually improve friction models at every opportunity.
- Enforce discipline in control algorithm simulation to facilitate transition to prototype and production vehicles systems.