A Reconfigurable Vehicle Powertrain HIL Testing Facility

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ABSTRACT

Full vehicle Hardware-in-the-Loop (HIL) testing provides a virtual platform on which to accurately assess the performance of the powertrain, before the vehicle is built. Furthermore, it allows for seamless integration of components in a modeling and simulation environment with actual hardware to analyze hardware component performance. This paper presents the challenges of creating a rapidly deployable HIL test facility and compares and contrasts the test results of a conventional and parallel powertrain to modeling and simulation.

Introduction

The increasing complexity of conventional and hybrid driveline topologies has created a need to test one or several powertrain components within a virtual environment to verify the performance and design of the individual powertrain components. In addition, testing the performance of a component in a virtual vehicle presents a more cost effective alternative compared to full scale in-vehicle testing. Virtual vehicle testing of powertrain components is also referred to as Hardware-in-the-loop (HIL) testing. Specifically, this paper discusses the challenges associated with the creation of a rapidly deployable HIL testing facility and its use to develop, test and validate hardware powertrain components as well as advanced control strategies for hybrid powertrains. The reconfigurable HIL test facility offers the ability to test specific powertrain components as if they were operating in a vehicle driving over a user provided driving cycle. The challenges of seamless merging of hardware components with software models is discussed and presented. The results of the HIL testing are used to assess the fidelity of computer models of VPSET (**V**ehicle **P**owertrain **S**ystems **E**valuation **T**ool) [1], which is a vehicle modeling and simulation software. A comparison of the HIL test results with the VPSET computer model predictions is presented. Finally, the strengths of a reconfigurable vehicle powertrain HIL testing capability are demonstrated using several examples.

Description

The main hardware components of the HIL test facility are a DC dynamometer, dyno controller, and a bi-directional DC power supply (**Figure 1**). The dynamometer provides loading and motoring capabilities for any rotating components within the driveline. The bi-directional DC

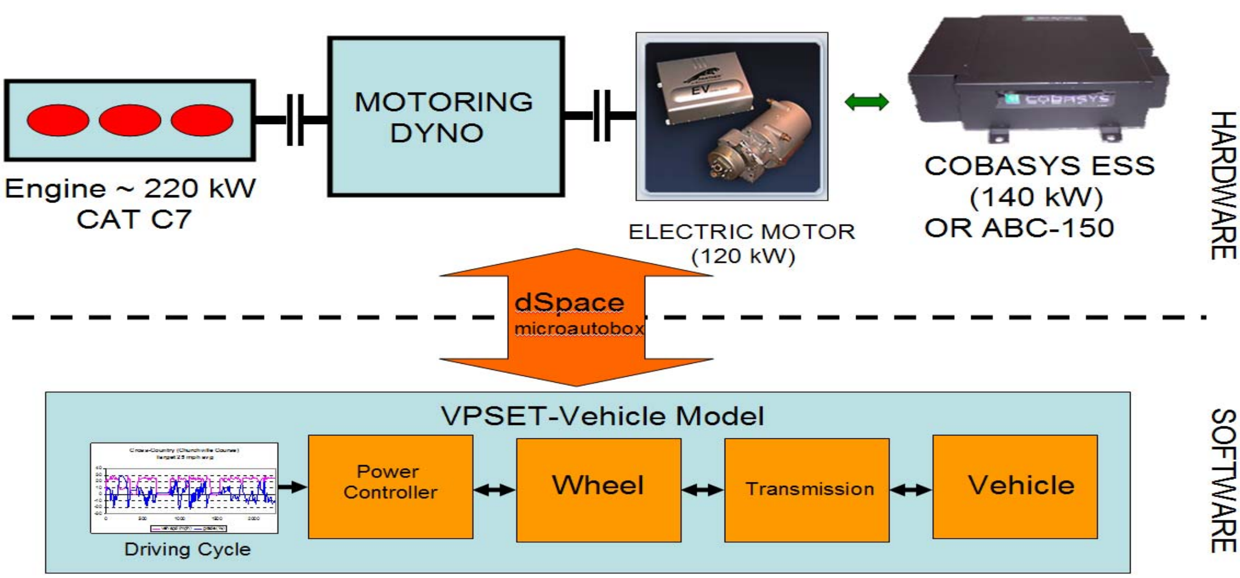

Figure 1 - HyVeTS Layout

power supply is an AV-900 from Aerovironment, which is used to emulate the energy storage system of a hybrid powertrain. In addition to the aforementioned hardware components, a data acquisition and real time control hardware is needed to integrate the hardware components to the virtual vehicle. A Micro Autobox from dSPACE serves as the primary data acquisition system and real-time interface between hardware components and the virtual vehicle. In addition to the Micro Autobox, there are several signal conditioning modules which are used to scale the I/O (Inputs/Outputs) of the Micro Autobox to the appropriate signal levels. The user interface for the DAQ system is provided by a standard PC connected to the Micro Autobox via a PCMCIA card. The PC provides an interface for the user to control the test stand, a platform from which to load the compiled model to the Micro Autobox, and a visual dashboard to monitor the performance of the test cell. In addition to the digital and analog I/Os, the Micro Autobox has several CAN ports that interface with various test components.

The software that is used to model & simulate the non-hardware portion of the vehicle is VPSET. VPSET is an extensible, forward looking, parametric, Simulink based modeling package that was developed by Southwest Research Institute, and is used to predict vehicle fuel economy and performance. VPSET can model conventional, electric and hydraulic hybrids in series and parallel powertrain topologies.

The HIL test facility is setup to test the powertrain for a medium duty military vehicle. The **Hy**brid **Ve**hicle HIL **T**est **S**tand (HyVeTS), shown in **Figure 2** can be configured to test the performance of a given engine and electric motor combination (engine-electric motor-in-the-loop) in a real-time vehicle simulation to ascertain real-word performance and fuel economy of the given powertrain. Similarly, the HIL test facility can be reconfigured to analyze an engine-in-the-loop (conventional powertrain) or an electric motor -in-the-loop (electric powertrain) or an engine-generator-in-the-loop (series hybrid powertrain). In the present configuration of HyVeTS, the hardware components of the driveline that are included in the HIL setup are: (a) a diesel engine (b) an AC induction motor; and (c) an energy storage device, along with associated power controllers for each of the hardware components. The rest of the vehicle including the torque converter, transmission, energy storage system, fuel storage system, high level vehicle controller, accessory loads, vehicle, and driver are simulated in the VPSET software. As shown in **Figure 2**, the diesel engine and AC induction motor are connected to opposite ends of the DC dynamometer. The AV-900 is used to emulate a NiMH battery. Two HBM inline torque meters are used to measure the torque output of the engine and the torque output of the AC induction machine.

Capabilities

The current hardware configuration of the HIL test facility, allows the testing of the hardware components in conventional, parallel, and series vehicle configurations. In the conventional powertrain configuration, the engine and

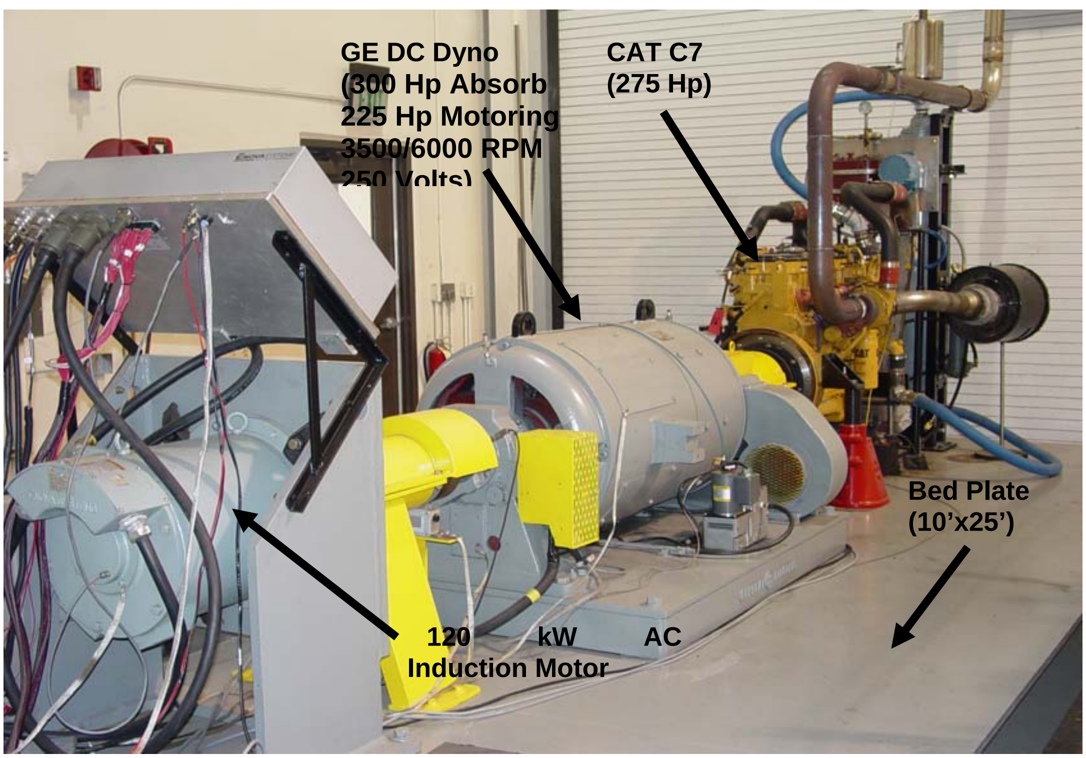

Figure 2. HyVeTS Hardware Layout

dynamometer are operational, and the electric machine is turned off. In the parallel configuration, both the AC induction motor, AV-900, engine and dynamometer are operational. In the series configuration the dynamometer is turned off and the engine coupled with the AC induction generator emulates an APU (Auxiliary Power Unit), with the propulsion drive motors simulated in the VPSET software.

Conventional Powertrain Results

The current hardware configuration was tested for all three powertrain topologies (conventional, parallel, and series). The virtual vehicle model was executed over three different driving cycles: (i) urban dynamometer driving schedule (UDDS), (ii) highway dynamometer driving schedule (HUDDS) and (iii) a custom trapezoidal cycle with a maximum speed of 25 meters per second. The fuel economy data from the HyVeTS was recorded and is compared to the fuel economy results from the VPSET vehicle simulation software, as shown in **Table 1**.

Table 1 – Conventional Vehicle FE

Conventional Fuel Economy (MPG)			
Cycle	HyVeTS	VPSET Model	HIL vs Model
UDDS	11.35	10.61	-6.9%
HUDDS	15.29	17.31	11.7%
Trapezoid 25m/s	14.23	16.71	14.8%

The variability between the results of the HyVeTS and the VPSET model is due to the use of quasi-steady state component data to populate the component data of VPSET. The quasi-steady state maps assume immediate responses from the hardware components when a step input is commanded. In reality, there is a lag between the time a request is made and the time that the request is honored. This is especially true in the case of the diesel engine. This lag is not modeled within the components of VPSET. The correlation of engine torque and speed throughout the driving cycle, between the HyVeTS and VPSET was very good, and a portion is presented graphically in **Figure 3** and **Figure 4**. In **Figure 3** the mean error for the torque over the given time period is -3.74 Newton-meters with a standard deviation of 56.17 N-m.

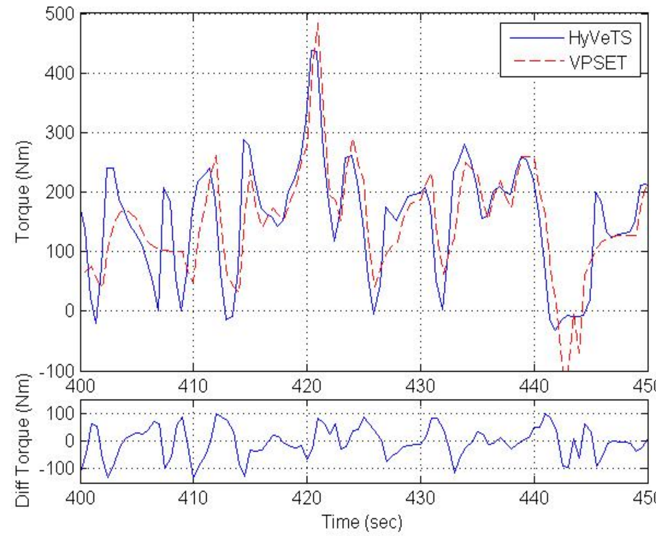

Figure 3 - Engine torque test cell vs simulation

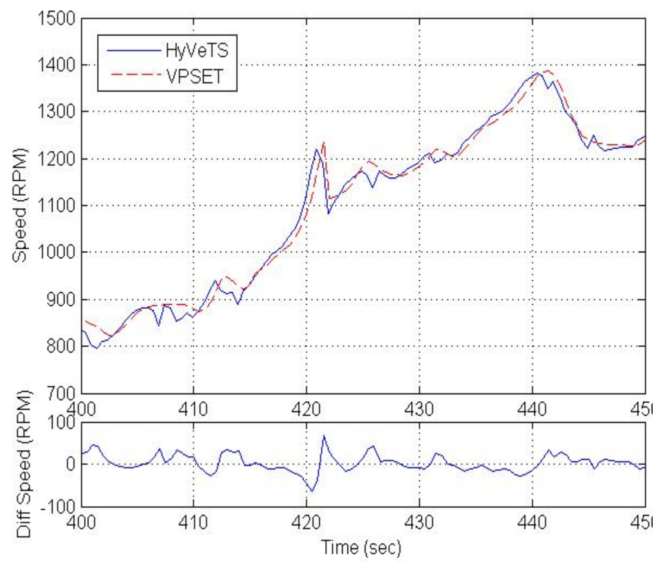

Figure 4 - Engine speed test cell vs simulation

In **Figure 3** it is notable that the differences in torque between HyVeTS and VPSET are negligible during quasi-steady state operation, and only depart from each other during transients. During large positive transients, an overshoot is observed. Similarly, during large negative transients, an undershoot is observed. The error observed in **Figure 3** is largely due to the aforementioned time lag in the real hardware engine. This error between the HyVeTS and VPSET could be decreased through use of a higher fidelity dynamic engine model.

Figure 4 compares the HyVeTS engine speed and the VPSET simulation engine speed. The error in engine speeds is very small except during shift events were it can increase to up to 100 RPM. In **Figure 4** the mean error of the speed over the shown time period is 3.73 RPM with a standard deviation of 19.17 RPM. This error is caused by the limited transient response of the dynamometer due to inertia and torque limitations. This limitation can be overcome by using a lower inertia dynamometer with higher torque capacity.

Parallel Powertrain Results

Table 2 - Parallel hybrid FE

Parallel Hybrid Fuel Economy (MPG)			
Cycle	HyVeTS	VPSET Model	% Diff HIL vs Model
UDDS	11.85	12.55	5.6%
HUDDS	16.65	18.71	11.0%
Trapezoid 25m/s	16.07	17.30	7.1%

The fuel economy for the parallel hybrid electric vehicle is compared to the fuel economy of the VPSET simulation in **Table 2**. The fuel economy results for the parallel powertrain are slightly higher than the fuel economy results for the conventional model. The torque and speed comparisons between the HyVeTS and VPSET are presented in **Figure 5 and Figure 6**. The speed and torque in the parallel HyVeTS simulation match VPSET better then the conventional simulation. The mean error for the torque over the given time period is -4.15 Newton-meters with a standard deviation of 32.08 N-m. The mean error of the speed over the same time period is 4.96 RPM with a standard deviation of 15.19 RPM. The reason that the parallel HyVeTS test matches the VPSET simulation better then the conventional test is that the frequency of the motor response is an order of magnitude faster then the engine response.

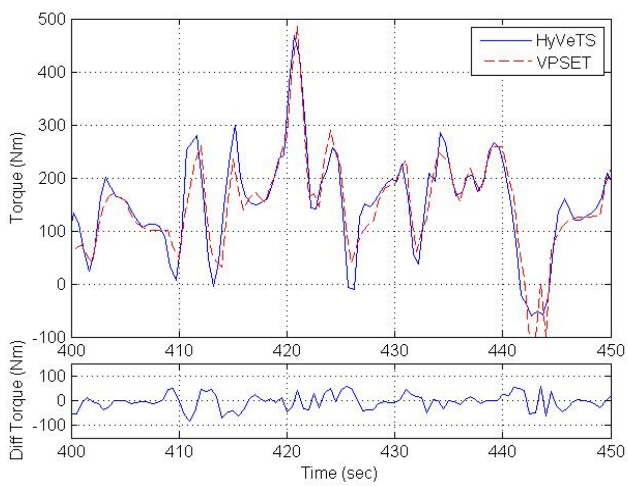

Figure 5 – Engine & motor torque, test cell vs simulation

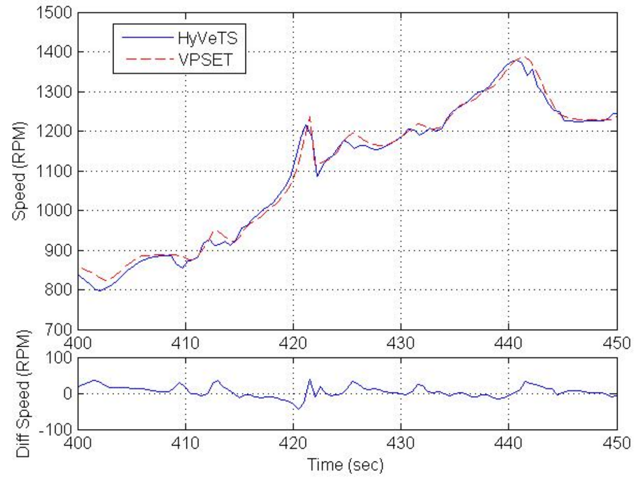

Figure 6 - Engine plus motor torque test cell vs simulation

CONCLUSIONS

This paper describes a rapidly configurable HIL testing facility with a multitude of capabilities. The HIL testing of the engine-in-the-loop provided valuable engine performance data as if the engine were operating in a virtual conventional vehicle powertrain. The data collected from the HIL testing was also used to validate the conventional module of the vehicle modeling and simulation software VPSET. Similarly, the engine-and-electric motor-in-the-loop HIL testing was used to validate the combined performance of the engine and electric motor in a virtual parallel hybrid vehicle powertrain. The data collected from the parallel hybrid HIL testing was used to validate the parallel hybrid modules of VPSET. Differences between the HIL test data and VPSET are discussed and improvements are proposed. Finally, the challenges of seamless merging between the hardware and software components of a typical HIL setup are discussed.

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