HARDWARE-IN-THE-LOOP SIMULATION OF COMPLEX HYBRID HYDROMECHANICAL TRANSMISISONS

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ABSTRACT

Fuel efficiency and environmental concerns are factors that drive the development of complex solutions for propulsion in heavy working machines. Although these solutions, such as power-split hydromechanical transmissions and hydraulic hybrids, indeed are promising in terms of energy efficiency, they also tend to increase the dependency on accurate, stable control. The realization of this aspect, in turn, relies on continuous testing throughout the development process, usually carried out on expensive, time-consuming prototypes. To lower the development costs and time, hardware-in-the-loop (HWIL) simulations may be introduced as a middle-way between pure prototyping and computer-based simulations. In this concept, some parts of the transmission are represented as hardware while others are included as mathematical models running in real-time in a data acquisition system. This mix of hardware and software allows for high versatility while maintaining a high level of reliability of the results. This paper reports on parts of a study on HWIL simulations of heavy complex hybrid hydromechanical transmissions. Control algorithms for the hardware/model interface in a test rig are derived and their performance are evaluated in HWIL simulations of a mid-sized wheel loader. The results show the importance of fast rig controllers to capture the fast dynamics of the software simulations. It was also found that an important aspect of HWIL simulations is that they are well aligned with their purpose. If so, the simulation yields more reliable knowledge, which is of higher use in the design process of these complex systems. To summarize, HWIL simulations may, if implemented properly, be an important asset in the development of heavy complex hybrid hydromechanical transmissions.

Keywords: hardware-in-the-loop-simulations, hydromechanical transmissions, heavy hydraulic hybrid vehicles

INTRODUCTION

In the strive for energy efficient propulsion of heavy construction machinery, such as wheel loaders, hydromechanical transmissions (HMTs) are competitive alternatives to the hydrodynamic (torque converter) transmissions often used in this application today. Commonly mentioned advantages with HMTs are high power transmission efficiency as well as an ability to decouple the transmission input and output speeds, thereby enabling optimal control of the prime mover [1]. For heavy wheel loaders, so called power-split HMTs with planetary gear trains are typically required to ensure wide operating range with maintained acceptable efficiency of the transmission [2]. To further improve the fuel efficiency, hydraulic hybridisation may be realised by including a hydraulic accumulator in the transmission circuit [3], thereby enabling energy recuperation and thus further fuel savings [4]. Heavy Hybrid HMTs is the focus of this paper.

The high level of complexity of the considered systems implies an increased dependency on control. In the context of developing these transmissions, this increase, in turn, results in a greater need for testing control strategies throughout the development process. Tests of control algorithms are usually carried out in computer-based simulations followed by some sort of validation in a prototype machine. Prototypes are, however, expensive and time-consuming, especially if there are many candidates available for evaluation. As a middle-way alternative, HardWare-In-the-Loop (HWIL) simulations may be introduced as a compromise between computer-based simulations and pure prototyping. In this concept, parts of the system are included as hardware and the surroundings are represented by models executed in real-time. This approach has been common in academia for research on HMTs for some time, see e.g. [5], and the use in the automotive industry has increased as well [6]. The following sections briefly describes a test rig used at Linköping University for HWIL-simulations of complex hybrid HMTs, the control of it and some preliminary results of HWIL-simulations of a mid-sized wheel loader.

TEST RIG

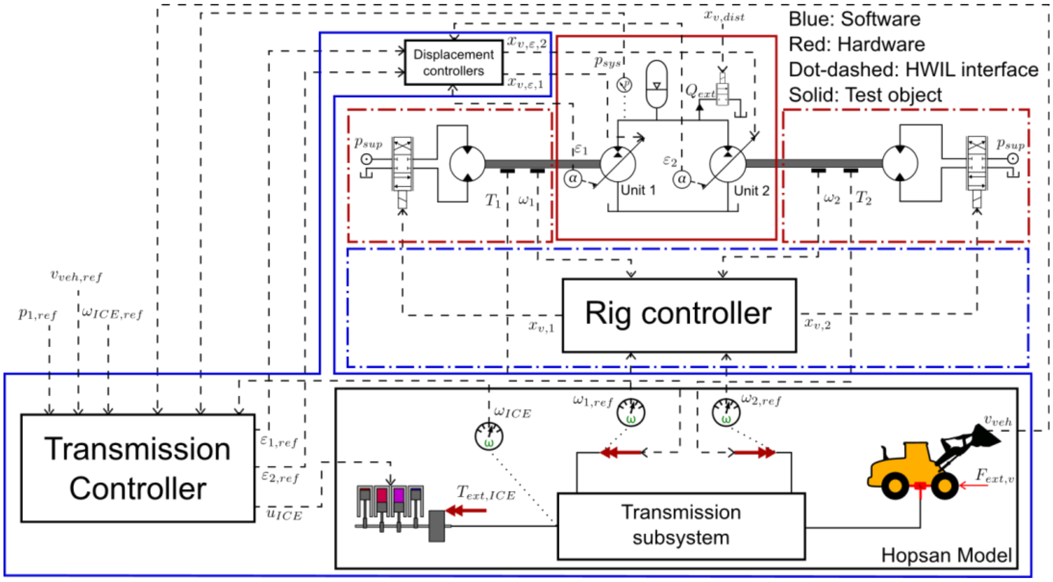

Figure 10 - Overview of the principle of operation of the HWIL simulation test rig used in the study.

Figure 10 shows a schematic overview of the HWIL simulation rig that is used in the study. The "cut" between the model and the hardware is made at the shafts of the two hydrostatic units. The shaft torques are measured and sent to a model of the rest of the transmission (transmission subsystem, engine and vehicle) which calculates the resulting shaft speeds and sends these values as references to the rig controllers. This causality (measure torque → control speed) is motivated primarily by the strong coupling between torque and relative displacement of the hybrid circuit [7]. The rig controllers (compiled Simulink-models) and the Hopsan [8] model are executed in real-time on a National Instruments PXI computer running with a sampling frequency of 1 kHz.

The basic idea of the setup is to validate a control strategy for a certain transmission concept. A Multiple Input Multiple Output (MIMO) control approach that is applicable to a high number of transmission configurations has been proposed earlier by the authors [9] and is used in this paper. The displacement actuators consist of hydraulic servo circuits in the two identical in-line axial piston transmission units (Bosch Rexroth A11, 110 cm3/rev) and the displacements are measured using Hall-effect sensors. The control loops for the displacement controllers have been analyzed and designed by the authors in previous studies [10]. A servo valve is installed in the transmission circuit to study the effects of flow leaving the circuit.

Rig Control

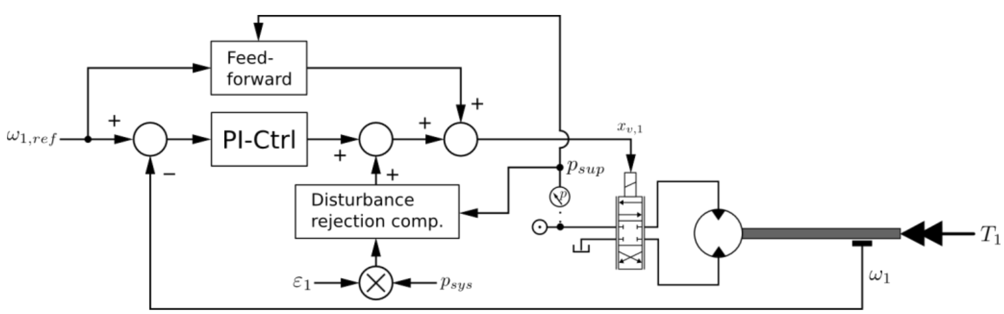

Figure 11 - Principal strategy for the speed control of unit 1.

The control strategy is identical for the two units and Figure 11 shows the strategy of unit 1. The control problem may be described as a valve-controlled hydraulic motor with an inertial load and a disturbance torque. To ensure high reliability of the results, the control must be very stiff and fast, and exactly follow the output of the simulation model. To achieve a high bandwidth a feed-forward term from the reference speed is used. This uses the supply pressure to estimate the valve pressure drop and calculate the necessary valve displacement. Furthermore, the transmission pressure and the measured displacement setting of unit 1 are used to compensate for the torque disturbance. This compensation estimates the required additional valve displacement needed to account for the change in pressure drop over the valve caused by the change in shaft torque. The feedback part handles the modelling errors and consists of a PI-controller with an integrator window to avoid big overshoots of step responses.

RESULTS

Figure 12 shows the performance of the rig controller for a step response without torque load. As can be seen, the control loop is well-damped and fast. It is, however, not infinitely fast, which in turn sets the limit of how fast dynamics may be tested in the final HWIL-simulation.

Figure 13 shows the influence on shaft speed when a step in displacement setting is carried out, with and without disturbance compensation. Clearly, the compensation is needed to avoid too big deviations from the reference. Naturally, perfect rejection is not always possible to achieve in all operating points, which further emphasizes the limitations in what dynamics that may be tested in the final HWIL-simulation.

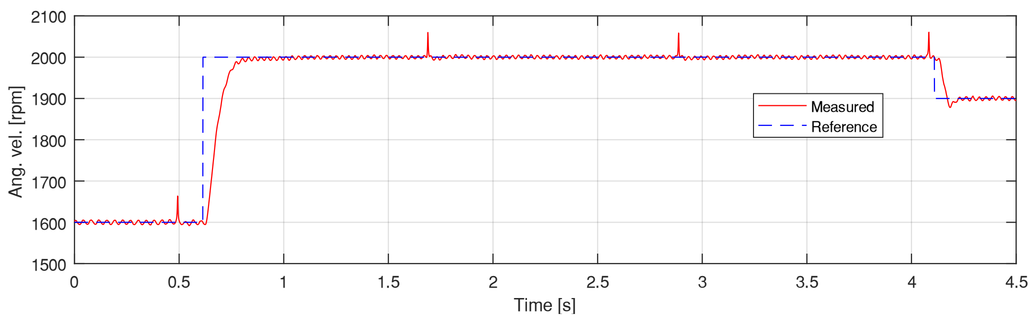

Figure 12 - Step response of the unit 1 shaft speed controller, with zero load.

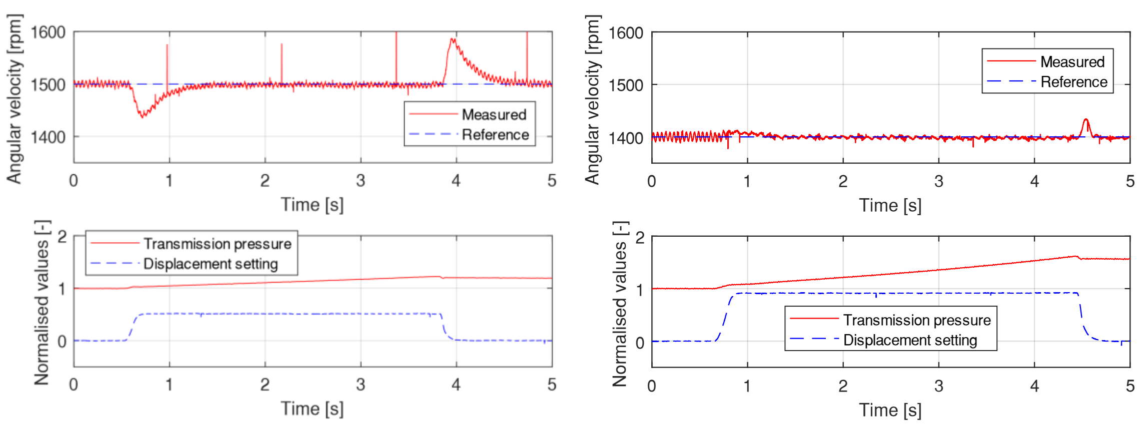

Figure 13 - Disturbance rejection (step in unit 1 displacement) of the unit 1 speed controller without (left) and with (right) compensation. Note that the transmission pressure curve has been normalized with a value of 100 bar. Note also the significantly bigger step magnitude in the right graph.

Figure 14 shows the results of a short HWIL-simulation of an example vehicle, a wheel loader with a mass of 5500 kg equipped with an Input-Coupled Power-Split (ICPS) hydraulic hybrid transmission (see [8] for more details). In this example, the engine speed is controlled at 1600 rpm and the transmission pressure is controlled at 100 bar. In an ICPS hydraulic hybrid, the unit 1 speed is determined by the engine speed and the unit 2 speed is a consequence of the vehicle speed and the engine speed. As can be seen, the rig controllers manage to follow the model outputs with acceptable response. The reference is ramped to ensure that too high response, and thus non-realizable HWIL-simulations, are required. In an ICPS hydraulic hybrid, the vehicle output torque is determined by the unit 2 displacement, which may be observed in the measurements. To maintain a constant pressure in the transmission circuit, the displacement of unit 1 compensates for the flow caused by unit 2. This may be observed as the curve for the unit 1 displacement mirrors that of unit 2 in the measurements.

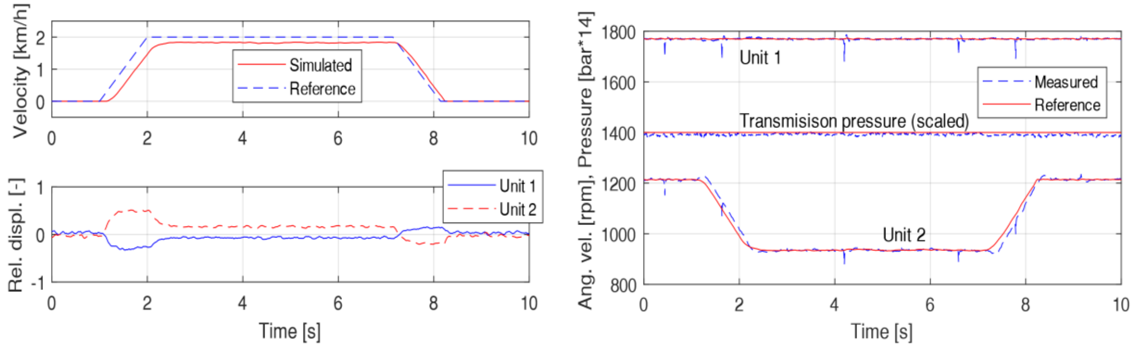

Figure 14 - Tentative HWIL-simulations of an example vehicle. Left: Vehicle speed and relative unit displacements. Right: Transmission units shaft speeds and transmission pressure (scaled).

CONCLUSION

This paper presents preliminary results of a study on HardWare-In-the-Loop simulations of heavy complex hydraulic hybrid transmissions. A test rig suitable for the topic is presented and a structure and control strategy for the HWIL-simulations are proposed. The results show the importance of decoupling the torque and speeds in the interface between the hardware and the software in the simulation, to maximise the reliability of the results. Furthermore, the bandwidth of the rig controllers cannot be ignored, as they set the limit of the testable system dynamics. For a simple test case of a mid-sized wheel loader equipped with an input-coupled power-split hydraulic hybrid transmission, the proposed set-up performed satisfactory results that may be used as validation of the transmission control strategy. Future work will primarily involve testing of more realistic drive cycles for the example vehicle.

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