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Hardware-in-the-Loop simulation applied to roadheader cutting head speed control system testing

This paper presents a description of the test stand and results of the Hardware-in-the--Loop simulation for the angular speed control system of roadheader cutting heads. The system has been implemented in the LabView package using National Instruments cRIO and cDAQ devices. The system uses a discrete PI controller implemented with a cRIO FPGA module. Some results of simulation tests undernormal operating conditions and in emergency conditions have been presented.

Key words: *roadheader, angular speed control, Hardware-in-the-Loop simulation*

1. INTRODUCTION

The cutting head load of aroadheader during mining operation is a complex phenomenon dependent on a number of factors. The optimization of this process with respect topower consumption reduction and dynamic load reduction requires the identification ofindividual factors and their influence on the roadheader's performance. The most-influencing factor is cutting thickness; this depends on the location of the individual knives on the cutting head,the angular speed of the head, and the horizontal and vertical tilts. In the currently used roadheaders, the cutting head angular speed is not adjustableand the tilt is controlled manually. Automation of this process requires the use of appropriate closed-loop control systems. Selection of the structures and parameters of these systems can be made by analytical or simulation methods, but the practical implementation of such a control system using a suitable controller with specialized control software requires previous verification of its correct operation. One method of this verification may be the Hardware-in-the-Loop (HIL) simulation.

2. THE ROLE OF HARDWARE-IN-THE-LOOP SIMULATION IN DESIGN PROCESS OF CONVERTER-FED DRIVE SYSTEMS

The functional properties of today's electromechanical drive systems with digitally controlled power electronics are largely determined by their control software [1]. The development and testing of this control software plays a vital role in the design of adrive system. However, simulation studies that do not take into account the specific properties of the target digital system implementing the control algorithmare not able to detect certain phenomena that may play a negative role in the later functioning of the entire system. The discrepancy between the performance of the algorithm at the computer simulation level and its real-time performance (e.g., related to the speed limits of control program execution, limited signal transfer rate, memory capacity constraints, or range and precision constraints of the variables used by control algorithms) may lead to damage or destruction of the controlled machinein extreme cases (e.g., caused by instability of the control system). Disclosure of these phenomena only at the stage of testing the complete solution can involve considerable time and cost and even risk to health and human life [2]. Hence, Hardware-in-the-Loop techniques utilizing areal controller and computer-simulated model of the controlled object [3] are becoming increasingly important. This method can be considered as an intermediate solution between simulation studies in a uniform programming environment (e.g., Matlab/ Simulink or Scilab/Scicos) and experimental studies using real controller and real object [4, 5]. This relationship has been shown in Figure 1.

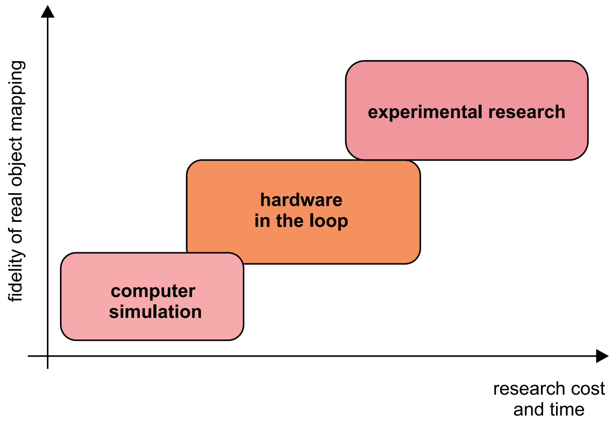


Fig. 1. Comparison of Hardware-in-the-Loop simulation with other converter-fed drive systems research methods (based on [1])

Both the controller algorithm and controlled object model are separately implemented in the form of periodically executed software loops. Between these loops, there is a continuous exchange of data. This data maps the internal state and output signal state of the controlled object as well asthe control signals generated by the controller algorithm [6]. This process has been shown schematically in Figure 2.

The advantage of such a solution is the possibility of the relatively easy and rapid testing of the actual response of the control system to anticipated emergency situations, such as exceeding the range of allowable output values, disturbances in signal transmission, or some sensor malfunction. Verification of the real control system and developed software operation based on the mathematical model of the controlled object can significantly facilitate and shorten the entire system start-up process after the controller has been connected to the actual actuators, sensors, and controlled object [3].

Hardware-in-the-Loop tests can therefore be viewed as real-time validation of the results of the synthesis of the control algorithm developed at the Model-in-the-Loop (MIL) level. The MIL level coverstheimplementation of the control algorithm, mathematical model of the controlled object, and mathematical models of the actuators and sensor dynamics in a uniform hardware and software environment based on relationships developed through theoretical analysis or experimental identification.

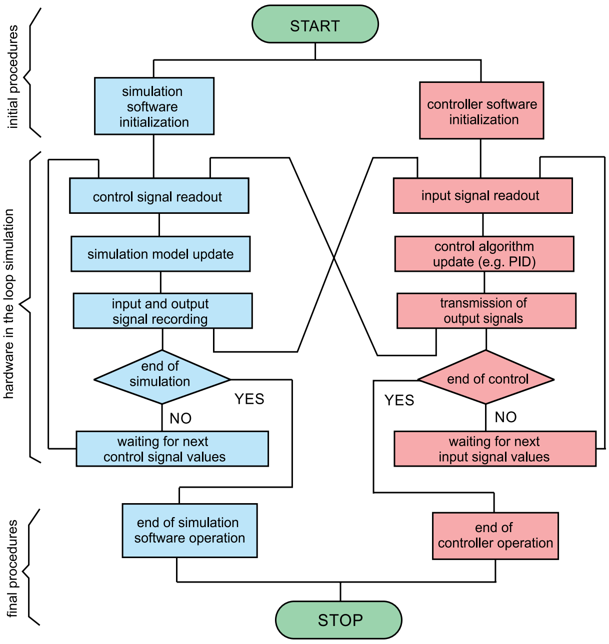


Fig. 2. Simulation process using Hardware-in-the-Loop method

3. LABORATORY STAND FOR TESTING CONTROL SYSTEM OF ROADHEADER CUTTING HEAD DRIVE SYSTEM USING HARDWARE-IN-THE-LOOP SIMULATION METHOD

3.1. Structure of test stand

A closer approximation of the realoperating conditions of acontrol system is possible with the HIL method and is based on the application of the target controller with the developed software, connected to the mathematical model of the controlled plant executed on a separate hardware platform. An important feature of this method is that the nature of the input and output signals and their changes are similar to the measurement and control signals occurring under real-time and real-operating-environment conditions. Based on previously developed and identified models of the converter-fed drive system dynamics used in pure simulation research of the cutting head angular velocity control system using themodel-in-the-loop (MIL) technique, a laboratory stand has been developed for the control circuits and software using the Hardware-in-the-Loop (HIL) technique. The purpose of developing such a system is related to the ability to test the implementation of the relevant real-time control algorithms with the target industrial controller and input and output signals close to reality. The developed concept of the HIL test stand is based on two main hardware components: a target real-time controller intended to be used in the final system, and a PC-based simulation model of the controlled object developed using LabView™ software. The controlled object model imitates a roadheader cutting head converter-fed drive system together with the model of the load process. The schematic diagram of the circuit is shown in Figure 3. As shown in Figure 3, the hardware interface between the controller and PC computer is the National Instruments cDAQ-9174 device [7] with the appropriate analog input and output cards. On the basis of the accepted conceptual assumptions described above, an automated test stand for the cutting head speed control system has been designed and completed for use of the HIL method.

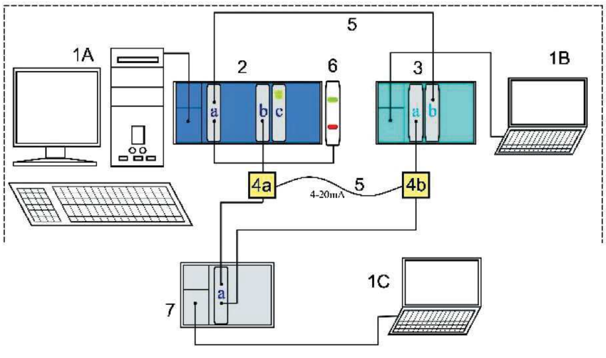


Fig. 3. Schematic diagram of laboratory standfor HIL testing of cutting head speed control system of roadheader

The basic elements of the developed HIL test stand shown in Figures 3 and 4 are as follows:

1) personal computers designed to work with National Instrument control and measurement devices: 1A connected toa cRIOreal-time PI controller; 1B connected to cDAQ, acting as an object simulator; 1C connected to cDAQ, designed for acquisition, recording, and visualization of measurement data;
2) NI cRIO-9074 controller (2) with analog input card (a), analog output card(b), and digital output card (c);
3) NI cDAQ-9174 (3) interface with analog input card (a) and analog output card (b);
4) voltage conversion circuit from 0–10 V to current standard 4–20 mA (4A) with an open-loop alarm and a simple current-voltage converter (4B);
5) shielded cables for transmission of control and measurement signals (5);
6) Fael LP322 switch (6) with normally closed unstable contact as an element designed to reset the protection against the effects of loss of control capability;
7) NI cDAQ-9174 (7) interface with an analog input card;
8) power supplies of the individual NI control and recording devices.

The NI cRIO-9074 (2) controller [8] has been intended for an operation in the final version of the angular speed control system of the roadheader cutting heads. The 32-channel 16-bit NI 9205 analog input module with a voltage range of ±10 V and a maximum sampling rate of 250 kS/s is used as the controller input [9]. The controller output has been implemented using an NI 9263 four-channel analog output module with a voltage range of ±10 V and maximum total sampling rate of 100 kS/s for all channels [10]. The cDAQ-9174 (3) 4-channel NI 9215 analog output module with a voltage range of ±10 V and a maximum total sampling rate of 150 kS/s divided by all channels and an identical analogue output module (as in the cRIO controller) have been used for the hardware modeling of the real controlled object. Additionally, the NI 9474 series digital output card has been used to signal a possible emergency condition. An overall view of the laboratory test stand is shown in Figure 4.

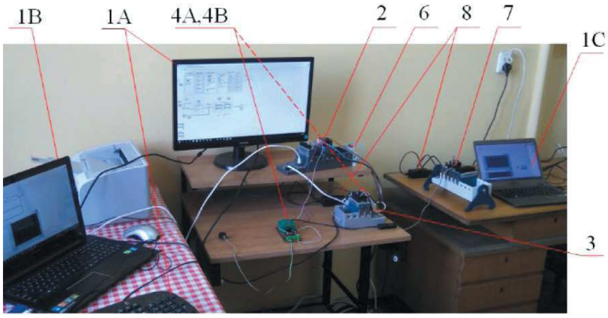


Fig. 4. Overall view of laboratory stand for HIL method control system testing

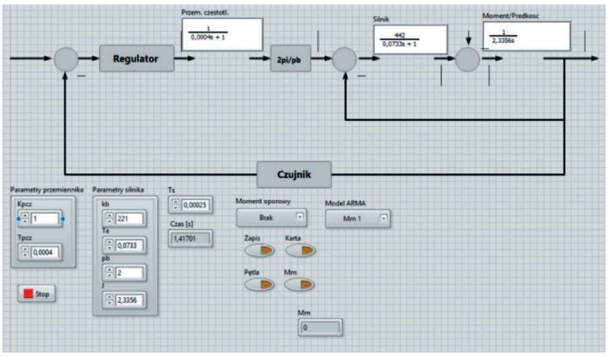
3.2. Transmission of control signal between controller and controlled object model

One of the important factors determining the correct operation of the control system is the transmission of the control signal from the controller to the actuator. This transmission must be performed in a reliable manner (i.e., insensitive to disturbances) and must be adapted to the structure of the regulation system in terms of dynamics (frequency and periodicity of signal transmission) and to the distance between the controller and actuator. This method must also be adapted to the controller's ability to generate the output signal and signal the input capabilities of the actuator – in this case, the frequency inverter (equipped with an analog control input). Therefore, for transmission of the control signal, the 4–20 mA current loop standard has been chosen because – due to the higher output impedance of the signal transmitter and the lower input impedance of the receiver – it is much more immune to electromagnetic interference than the transmission of the voltage signal. Limiting the output signal domain to the 4–20 mA range makes it easy to detect a current loop break (i.e., loss of control signal) resulting in theloss of system controllability. In this case, the frequency inverter is quickly switched off,and the emergency event is properly signaled. The current loop interface has been implemented using the Analog Devices AD694 transmitter.Thisenables the conversion of a voltage signal from arange of 0–10 V (which corresponds to the output voltage level of the NI 9263 card) to a current signal of 4–20 mA with a nonlinearity lower than 0.002% [11]. This device features an open loop detection system and internal 2,000 V and 10,000 V reference voltage sources.

4. TEST RESULTS OF ROADHEADER CUTTING HEAD DRIVE SPEED CONTROL SYSTEM WITH HIL METHOD

4.1. Results of angular velocity control tests of cutting heads under load torque changes

The mounted and tested laboratory stand has been used for a number of real-time studies of the angular speed control system for roadheader cutting heads undercontrolled dynamic and static overload conditions, taking into account the real operating conditions of the machine and possible occurrence of emergency conditions. The target speed controller has been implemented in the NI cRIO-9074 controller using the FPGA module [12, 13]. The FPGA module has a unidirectional signal flow (without any software-based loops), so it complies with the requirements concerning the speed and reliability of the real-time system performance. The simulation model of the roadheader with the frequency inverter-fed drive system has been implemented using the NI cDAQ-9174. The Front Panel of this simulation model is shown in Figure 5.



Parametry przemiennika
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Fig. 5. Screenshot of Front Panel of road header drive simulation model

The input and output signal values have been recorded by a separate NI cDAQ device (pos. 7 in Figs. 3 and 4) programmed in LabView. The Front Panel of the recording program is shown in Figure 6.

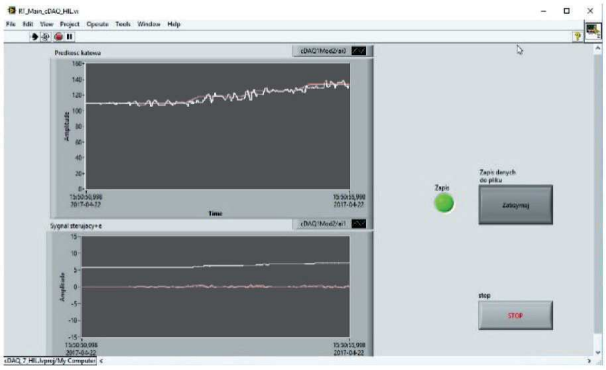

Fig. 6. Screenshot of Front Panel of recording software during example test of angular velocity control system with HIL method

Figure 7 shows the test results of a system with a load torque pattern programmed on the basis of data directly recorded during an operation of the real shearer (total load torque caused by friction and rock-cutting forces).

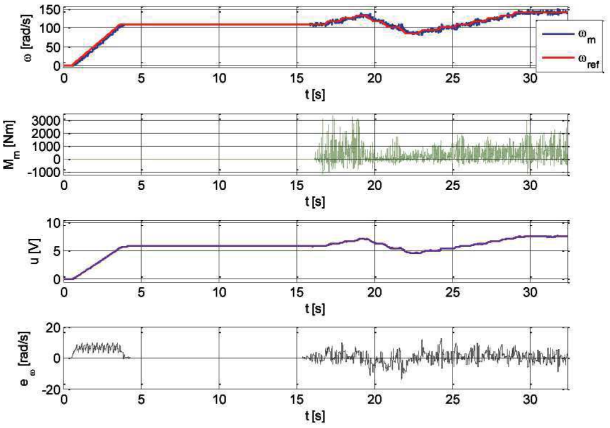

Fig. 7. HIL tested waveforms of reference and real angular velocity ofroadheader drive model loaded with torque restored from directly recorded load patterns

The next stage of the research involved the operation of the system with different load torque values generated by the ARMA model with coefficients identified from the experimental studies. The results of an example simulation are shown in Figure 8.

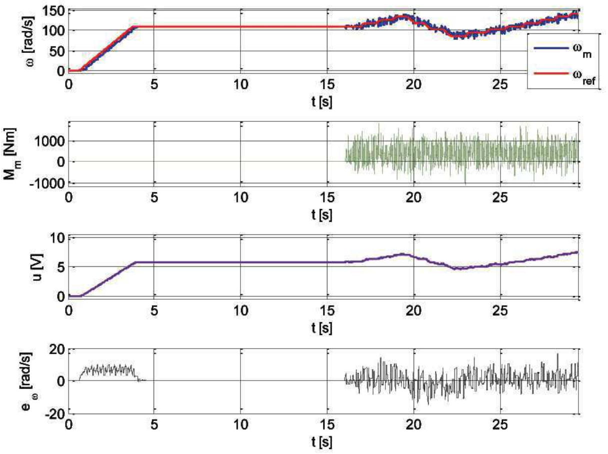

Fig. 8. HIL tests of reference value and angular velocity of roadheader drive model loaded with torque in form of time sequence generated using ARMA model

4.2. HIL test results of protection system against effects of emergency conditions

One of the important goals of the HIL simulation tests is to check the response of the software to possible emergency situations. These situations must be properly handled. Emergency conditions involve the loss of controllability; examples include the following situations:

- disappearing or interfering signals from the sensors (e.g., speed sensor),
- loss or disturbance of control signal transmission to actuators (e.g., frequency inverter),
- loss of system stability (i.e., oscillations of output values due to system divergence),
- operation of internal overcurrent protection in the actuator (frequency inverter).

Selected emergency states have been simulated on a test workbench. In the course of the test, the operation of the software safety module has been checked in case of an open loop break in the continuity of the control circuit, both in the control and feedback paths. The response of the protection system to the disappearance of the speed signal in the feedback loop is shown in Figure 9. A loss of system stability was achieved by incrementally increasing the value of the controller gain during system operation. The loss of system stability can be characterized by increasing high magnitude speed oscillations. As a criterion for detecting the fault state, exceeding the limit value of the deviation between the reference and actual speed value has been established. In each of the mentioned emergency states, the controller response should lead to zero control signal. It should also be possible to signal an emergency and exclude the possibility of direct reactivation of the control system in the event of an unrepaired failure. The response of the protection system to the loss of stability during system start-up is shown in Fig. 10, and the response of the control system to the loss of stability at the load torque is shown in Figures 11 and 12.

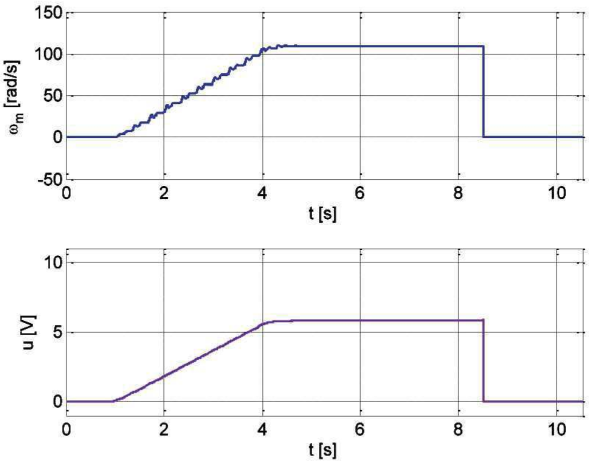

Fig. 9. Changes of angular speed ω_m and control signal u over time when feedback loop is broken (signal loss from speed sensor)

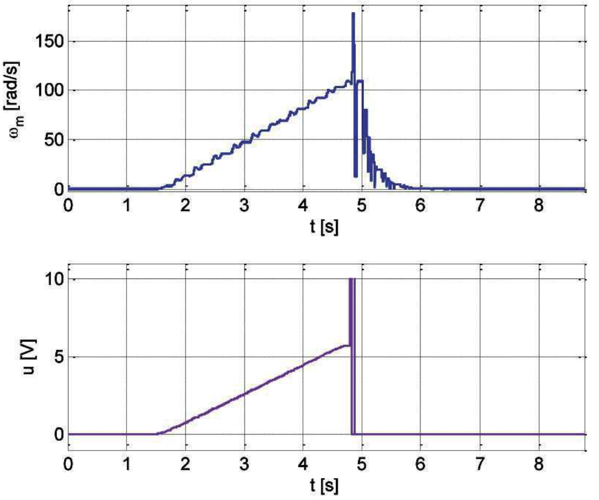

Fig. 10. Changes of angular speed ω_m and control signal u over time incase of detected speed oscillations due to loss of stability during start-up of drive

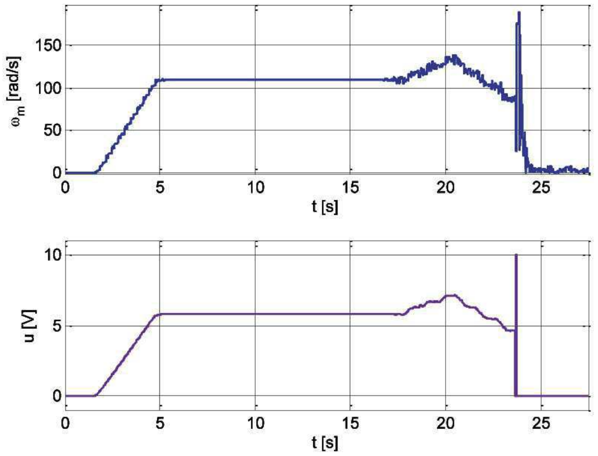

Fig. 11. Changes of angular speed ω_m and control signal u over time incase of detected speed oscillations due to loss of stability with decreasing load conditions

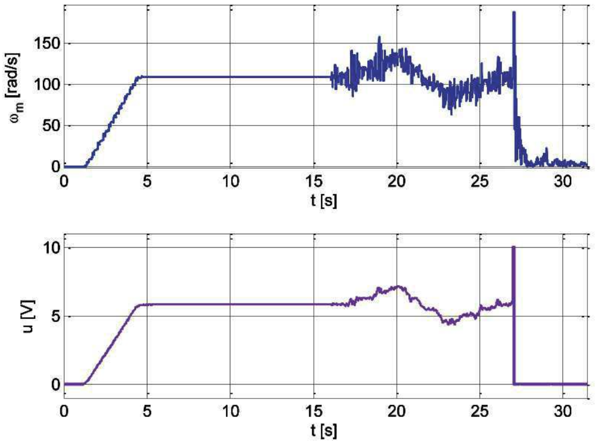

Fig. 12. Changes of angular speed ω_m and control signal u over time incase of detected speed oscillations due to loss of stability with increasing load conditions

5. CONCLUSIONS

The behavioral results of the discrete-PI controller (with gains tuned by an earlier MIL simulation method) implemented in the cRIO controller and interfacing with the digital simulation model of the roadheader cutting head drive system show a significant similarity toprevious MIL results. Also, the implemented protection algorithms against the effects of emergency conditions demonstrated their efficiency, responding quickly to the disruptions and breakdowns that can occur during the operation of aroadheader. This proved the correctness of the development of the adopted control algorithm and its software implementation, applied to acontroller intended for operation in areal system.

Acknowledgements

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