VIRTUAL SIMULATOR TO TEST SUITABILITY OF INTEGRATED ELECTRO-HYDRAULIC ENERGY CONVERTER IN DIFFERENT TYPES OF WORKING MACHINES

Lauri O. LUOSTARINEN, Rafael ÅMAN and Heikki HANDROOS

Laboratory of Intelligent Machines, LUT Mechanical Engineering
Lappeenranta University of Technology
Skinnarilankatu 34, FI-53850 Lappeenranta, Finland
(E-mail: lauri.luostarinen@lut.fi)

ABSTRACT

A simulation model that describes an energy efficient hybrid log crane with energy recovery capability was developed. The lifting cylinder of the crane is operated by integrated electro-hydraulic energy converter (IEHEC). The system in question is a pump-controlled fluid power circuit. Pump-controlled fluid power circuits reduce energy losses in comparison to conventional valve controlled circuits. The model of the log crane is based on multibody dynamics. The model of the fluid power system is implemented in Simulink. The models are run synchronously on real-time. The developed simulation models enable to study the hybrid electro-hydraulic power transmission under varying conditions. With the setup described in this paper the suitability and profitability of IEHEC operated system can be tested virtually on any working machine. Due to the modularity of simulation models only the multibody model of the working machine must be regenerated to test IEHEC in different types of working machines.

KEY WORDS

Simulation, Working machine, Hybrid, Fluid power, Energy efficient

INTRODUCTION

Energy efficiency and environment friendliness of working machines is an important topic for machine developers and manufacturers. Working cycles of working machines typically consist of alternating periods...
in which energy is needed and then released. In such conditions hybrid technology has a great potential to increase the efficiency of power transmissions in several ways. Energy losses can be reduced [1] and kinetic or potential energy can be recovered [2]. As a case study a simulation model for an energy efficient hybrid log crane was developed (Figure 1). The lifting cylinder of the log crane is operated by an integrated electro-hydraulic energy converter (IEHEC) (Figure 2).

![Figure 1 Illustration of the log crane](image1.png)

The key component of IEHEC is a newly designed liquid cooled electrical machine in which hydraulic fluid can be used as a cooling media. The electrical machine is connected to a fixed-displacement bent-axis pump-motor. Suitable places for IEHEC in working vehicles are all actuators that carry out work cycle in which the kinetic and potential energy is available for recovery e.g. lifting cylinders in cranes, grippers that tend to open by the payload mass and gravity etc. [3].

![Figure 2 Prototype of LUT IEHEC [3](image2.png)

The circuit diagram of the electro-hydraulic hybrid actuator system is shown in Figure 3 in which an asymmetric differential cylinder is operated by IEHEC. In closed loop pump-controlled systems it is essential to maintain even volume flows in the input and output ports of the pump. The pump control of an asymmetric differential cylinder can cause problems due to the differential volumes in the cylinder chambers. The pilot operated check valves equalize the volume flows. [4]

![Figure 3 Electro-hydraulic hybrid actuator system](image3.png)

The directional control valve is for priorisation of the boost pump operation. Primarily the boost pump flow is directed to the pressure accumulator, otherwise the flow is directed through the electrical machine to cool down the windings. The cooling is not discussed in this study. [1]

The responses of the IEHEC and the auxiliary fluid power circuit have been simulated in Simulink environment with a simple mass loading case [3]. In this study the same Simulink model is used but the simple mass is replaced by a multibody model describing the mechanical construction of the log crane. The multibody model is simulated by a real-time simulation software optimized for simulation of working machines [5].

The simulated system responses show that the developed models are working correctly. The models are efficient tool to assess the suitability and the benefits of IEHEC in different working machines.

**SIMULATION MODELS**

The equations used for the fluid power system model are described below. Angular speed of electrical machine is calculated using first order dynamics Eq. (1)

\[
\dot{\omega} = \frac{\omega_m - \omega}{\tau}
\]

(1)

The pump volume flow is calculated using Eq. (2)

\[
Q_p = \omega \cdot V_p \cdot \eta_{vol}
\]

(2)

The cylinder flow is
\[ Q_{re} = \dot{x} \cdot A_{re} \] (3)

The pressure build up in volumes can be described by Eq. (4) [6].

\[ \dot{p} = \frac{B_e}{V} \Delta Q \] (4)

The compressional flow is described by Eq. (5).

\[ \Delta Q = \sum Q_{in} - \sum Q_{out} + \sum V \] (5)

where \( \dot{V} \) is externally supplied volume flow into and out of the volume (e.g. accumulator or actuator flow). The volume flows in and out of each volume through the orifices can be described by the conventional equation of the volume flow in turbulent orifice by Merritt [6].

\[ Q = C_d A \sqrt{\frac{2 \Delta p}{\rho}} \] (6)

For every volume in the system the volume flows are approximated using Eq. (2), (3), and (6), respectively. Appropriate conditional statements have been used to describe the function of valves. Also, the smoothening function has been used to avoid numerical problems in simulations.

The oil volume \( V_{oil} \) of the pressure accumulator is described using Eq. (7)

\[ V_{oil} = \int Q_{accu} dt + V_{oil0} \] (7)

The volume of the gas \( V_{gas} \) is then the differential of maximum volume of pressure vessel \( V_{max} \) and oil volume.

\[ V_{gas} = V_{max} - V_{oil} \] (8)

The gas pressure is solved using energy balance equation [7]. \( \kappa = 1.4 \) (adiabatic change of the gas state)

\[ p_{gas} V_{gas}^\kappa = p_{gas0} V_{gas0}^\kappa \] (9)

The multibody dynamic model of the log crane is simulated by a real-time simulation software which has been under development since 2002. The software has been optimised for simulation of working machines. In the core of the dynamic solver, the formulations are based on the Newton–Euler equations. The description of the dynamics of mechanical parts is based on Eq. (10).[5]

\[ M \ddot{q} + \dot{Q} = \dot{Q}^r + Q^r \] (10)

where \( q \) is the vector of \( n \) generalized coordinates which define the position and orientation of each body in the system, \( M \) is the mass matrix, \( \dot{Q} \) is the vector of generalized forces, \( Q^r \) is the quadratic velocity vector that includes velocity-dependent inertia forces, and \( Q^r \) is the vector of constraint forces related to a chosen set of generalized coordinates [5, 8].

The simulation model of the fluid power system and the multibody model are run synchronously. The force calculated in the fluid power simulation model is sent to the multibody model at each time step. The position and velocity are returned from the multibody model (Figure 4). The system is controlled by the speed reference signal of IEHEC.

Figure 4 Interface between the simulation models

RESULTS

Damping of hydraulic cylinders with direct pump control is typically low. A smooth piston motion was ensured using a ramped speed reference signal. The acceleration ramp is 1500rpm / 0.5s and the deceleration ramp is 1500rpm / 0.6s. To enable higher accelerations, the system damping must be increased by the means of control engineering. The speed reference signal is shown in Figure 5. System responses are described by the following figures.

Figure 5 Speed reference signal
The piston position (Figure 6) and the piston velocity (Figure 7) graphs illustrate the motion of the actuator operated by IEHEC. Small vibrations exist in the velocity. The level of the vibrations is not significant because the piston position seems smooth.

Pressures in both chambers of the cylinder are presented in Figure 8. The pressure of the chamber A is higher during the whole working cycle. This results in negative cylinder force (Figure 9) during the whole working cycle. The sign of the cylinder force is constant due to the high gravitational load at the end of the boom and due to relatively small accelerations.

The IEHEC power is shown in Figure 10. During lifting the load a power from IEHEC is required (negative sign). The sign of the power is changed and energy is released when the load is lowered. Thus, an energy recovery would be possible using IEHEC in the application in question.

CONCLUSION

A virtual simulator was developed to test suitability and benefits of IEHEC in different types of working machines. The results obtained from the simulations are at the correct level and they are behaving reasonably. Model verification is required to make the model as accurate as possible.
accurate as possible. The virtual simulator is an efficient and low-cost research tool because expensive real working machines are not needed. Various working cycles and environmental conditions can be defined easily in virtual reality (VR). Due to the modularity of the models, only the multibody model needs to be regenerated when the type of the working machine is changed (also parameter tuning of the fluid power model may be necessary). After careful virtual simulations, the next step in development of a novel energy efficient working machine will be hardware-in-the-loop (HIL) simulations. In HIL simulation a physical hardware is connected to run as a part of the simulation loop. That enables more accurate studying of the system and is less expensive than constructing a full prototype of the machine. The last step would be the construction of a complete physical prototype.

REFERENCES