ANALYSIS OF NOVEL ZONAL TWO-CYLINDER ACTUATION SYSTEM FOR HEAVY LOADS

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ABSTRACT

Climate change and economic opportunities motivate investigating electric distributed power for working hydraulics in non-road mobile machinery (NRMM) instead of conventional hydraulics. This recent method allows significant energy savings in hydraulic systems, which was demonstrated previously by many independent studies. In this study, zonal hydraulics (as electrically distributed) are realized with direct driven hydraulics drive (DDH) units. Unlike conventional hydraulic drives the DDH units are disconnected from the engine (main prime mover) and distributed throughout the system. In a DDH unit, a single fixed displacement pump/motor with a speed-controlled electric servomotor directly controls the flow. The aim of this paper is to determine functionality of this new two-cylinder DDH-system in a lifting work cycle (or a swerve motion of the work machine). For this purpose, a model was created to investigate performance of the new test rig Dolores. The results of the simulation model will be utilized in future research to discover and compare other alternatives for working hydraulics architectures.

Keywords: direct driven hydraulics, zonal hydraulics

1. GENERAL INSTRUCTIONS

Many factors such as climate change and economic opportunities motivate investigating the electrification of heavy-duty non-road mobile machinery (NRMM). NRMM has been a field of extensive research due to various environmental concerns and enforced upcoming Tier V regulations for non-road engines [1].

According to [2], electric powertrains for NRMM are commercially viable in all power classes. However, according to [3] because of the heavy-load, low-speed and periodically operation mode, the authors stated that electric technology cannot be applied directly in construction machinery. This is why in order to decrease the fuel consumption in construction machinery, the usage of hybrid powertrain technology has increased. Manufacturers have made significant progress in recent years, examples of commercially available electrified excavators are Kobe Steel series-parallel hybrid excavator [4], Doosan [5] and Komatsu [6] series-parallel hybrid excavator, Hitachi [7] and New Holland [8] parallel hybrid excavator and Kobelco [9] parallel hybrid excavator.

Low powered electric vehicles (under 10kW) are most technologically feasible for electrification, as this category has the largest variety of products in the market. The electromechanical solutions perform better at higher power and higher speeds as compared to hydraulic solutions. However, reliability in these systems requires detailed investigation. Despite the shortcomings, prototype actuators with electromechanical solutions were recently released. For more details refer to Volvo [10] and Yanwar [11].

Electric powertrains are seen as a local emission-free solution that can increase overall system work efficiency but as it was demonstrated, developments are mostly concentrated on drivetrains. One solution that brings further improved efficiency is based on electric distributed power for working hydraulics in NRMM instead of conventional hydraulic ones. This concept is known as zonal or decentralized hydraulics.

This recent concept allows significant energy saving in hydraulic systems, which has been demonstrated by many studies previously. In [12, 13] the results manifested high energy efficiency for both stationary and mobile applications.

In this study, zonal hydraulics (as electrically distributed) are realized with a direct driven hydraulics drive (DDH) units. Compared to conventional systems the DDH units are disconnected from the engine (main prime mover) and distributed throughout the system. In a DDH unit, single fixed displacement pump/motors with a speed-controlled electric servomotor directly control the flow.

The aim of this paper is to determine functionality of this new two-cylinder DDH-system under in a lifting work cycle (or a swerve motion of the work machine). For this purpose, a model is created and initial investigations are performed in this study on new test rig Dolores.

2. DOLORES TEST RIG

Figure 1 illustrates the test rig Dolores. Dolores is a new full-scale test rig for zonal hydraulics in Aalto University for simulating high power applications.

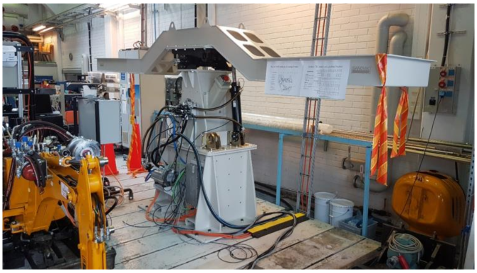

Figure 1: Test rig Dolores

The current setup is a two-cylinder DDH-solution, which represents one working hydraulic zone in a work machine, illustrated in **Figure 2**. This proposed architecture is new, but based on existing on market components (servomotor 80 kW, pump, and cylinders are manufactured by Parker).

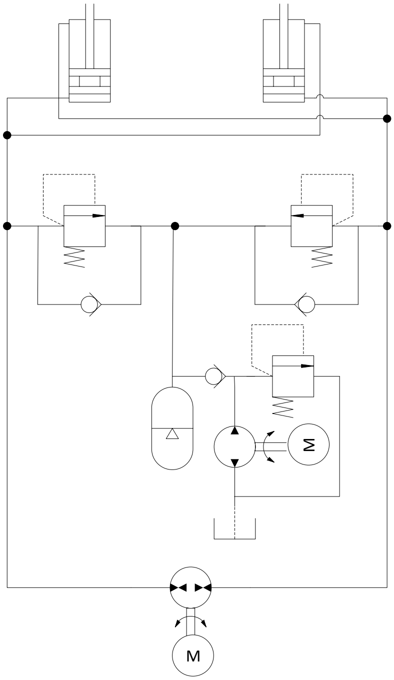

Figure 2: Simplified hydraulic schematics

Table 1 summarized utilized components in current version of Dolores test rig.

Table 1: Dolores Test rig components

Component	Manufacturer	Model
pump	Parker	PVD 3668_GB
Controller	Parker	IQAN-MC43FS
Display	Parker	IQAN-MD4
Electric Drive	Sevcon	Gen4 S10

The current version of the test rig is designed for testing of steering applications. Two cylinders steer the angle of the middle joint. The hydraulic cylinders are powered by a single fixed-displacement pump, which is run by an electric motor. The electric motor is controlled and powered by a SEVCON Gen4 Size 10 AC motor controller, which gets the DC power input from HVDC power supply. **Figure 3** demonstrates Dolores electrical circuit.

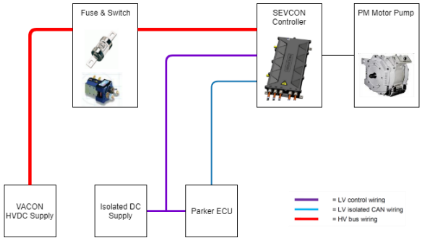

Figure 3: Electrical circuit of Dolores test rig

The test rig is currently controlled by a Parker ECU (Figure 3). It consists of a MC43 controller, MD4 display, wiring terminal, joystick, emergency switch, and fuses F2-F6. The Parker ECU communicates with the SEVCON controller via CANopen bus and with control valves using an analog signal.

There is a pre-charge system included in the test rig, which charges oil back to the system, provides cooling for SEVCON and electric motor, and also produces flushing flow for the pump casing.

3. MODELING

In order to investigate functionality of the new two-cylinder DDH-system, this study constructed a model in Matlab/Simulink, which integrated with hydraulic and electric systems of the test rig. The mathematical models of cylinder, pump/motors, pipes, and electric motor of DDH are built in the Matlab/Simulink environment utilizing Simscape blocks. A permanent Magnet Synchronous motor drive implemented with classic vector control with autotuning was utilized. The drive is powered from a three-phase voltage source with phase to phase voltage equal to 460 V.

Table 2 summarized parameters of cylinders.

Table 2: Parameters of the cylinder

Cylinder parameter	Value [unit]
Cap end area A_A	7.85×10^{-3} [m²]
Rod end area A_B	5.89×10^{-3} [m²]
length	0.45 [m]

Table 3 summarized parameters of system utilized during modeling.

Table 3: Parameters of the system

Parameter	Value [unit]
electric motor speed	2000 [rpm]
resistance	0.0315[ohm]
inductance	0.571×10^{-3} [H]
hydraulic motor displacement	19 [cm³/rev]

The following section presents simulation results of the proposed model based on simplified hydraulic schematics and includes initial analysis of them.

4. SIMULATION

The results of the simulation are presented in the figures in this section. For each simulation case, results are shown in terms of quality of the produced motion, as well as the cylinder chamber flows.

Figure 4 demonstrates the electric motor speed profile as a response to the step input reference.

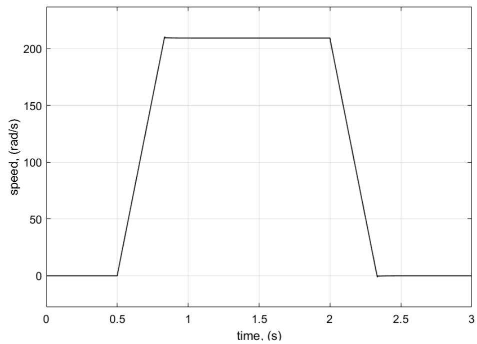

Figure 4: Utilized electric motor speed profile

Figure 5 illustrates electric motor torque requested by the hydraulic load.

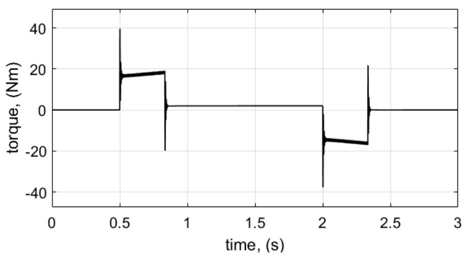

Figure 5: Electric motor torque

Figure 6 illustrates hydraulic motor out- and in-coming flow, this demonstrates that models work as expected.

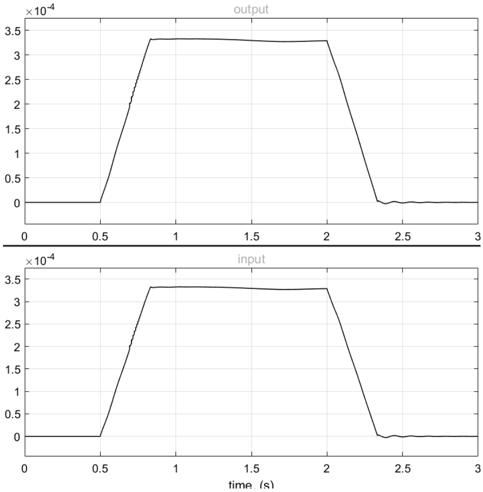

Figure 6: Pump outlet and inlet flows

Figure 7 shows the two cylinder positions as a response to the single utilized speed profile (see **Figure 4**). There is no motion until the electric motor starts; after 2.5 seconds, both cylinders are stopped.

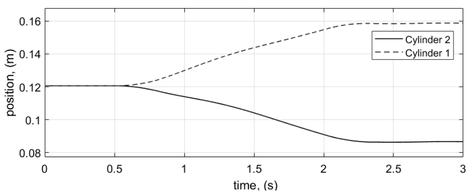

Figure 7: Cylinder positions

Figure 8 illustrates the flow variation during the performed cycle for the piston (A-side) and the rod (B-side) sides for cylinder 1 and 2, respectively. It can be seen in Figure 8 that the A-side in-flow cylinder 1 is equal to out-flow of A-side cylinder 2. Small difference in magnitude could be corrected with rigid cylinder connections to the joints and adjusting of pressure setting in valves.

5. DISCUSSION

Simulation demonstrated that effects of in- and out- coming flow to the system functionality is significant. Also, model functionality was sensitive to the tuning of electric motor control due to nature of direct control of the flow with speed-controlled electric servomotor.

This study is an initial investigation of a new two-cylinder DDH-system in a selected cycle with zonal hydraulics as a part of the EZE project. This paper evaluates functionality of the zonal hydraulics based on the simulation results from a Matlab/Simscape model as a function of parameters such as flow, position torque, and speed.

Coupling with multibody dynamics of the test rig was omitted in this stage of research. The developed electro-hydraulic model was tested a single cycle.

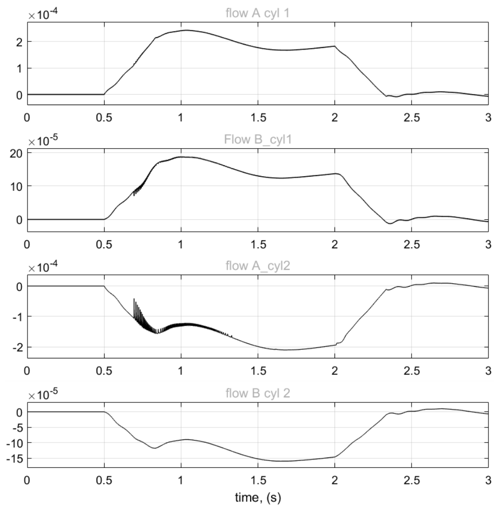

Figure 8: In- and out- flow from cylinders

The developed Matlab/Simscape model of the DDH will be validated against measurements under typical cycles. In future studies, empirical investigation with detailed energy balance is also needed as the generation mode (motoring mode for hydraulic motor) and near-zero speed operation was not investigated by the developed model.

Therefore, the aim of this work was to demonstrate functionality of the simulated architecture.

6. CONCLUSION AND OUTLOOK

The emissions of heavy-duty non-road mobile machinery are pushing towards more efficient solutions, hence fully electric powertrains are becoming a viable alternative to conventional diesel and valve-controlled systems. This paper analyses the functionality of a new two-cylinder DDH-system in a typical lifting-lowering work cycle. In this study, a model and initial simulation investigation was performed on the new test rig Dolores. The results of the simulation model demonstrated ability of the system to respond to the direct motor control.

Future research will discover and compare other alternatives for working hydraulic architectures with use of this new test rig Dolores.

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NOMENCLATURE

DDH Direct driven hydraulics
NRMM Non-road mobile machinery

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