

Toward Real-time Energy Efficiency Analysis of a Hydraulic System

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Abstract

This manuscript describes a project undertaken at the university that aims to develop a real-time data analysis system. This which will be part of labs in a current fluid power and hydraulics course. The intention is to provide information on the various factors that play a role in defining the energy efficiency of an industrial system. This reports on the work done, using a system-level experimental methodology, towards implementing automation for an hydraulic systems where adjustments and changes can be performed to accomplish energy efficiency in real-time. The hydraulic system implemented for this endeavor is a linear push system, which includes hydraulic actuator, shock absorber, electronic flow control valve, and electronic sensor. A data analysis system is programmed using LabVIEW and an Open Platform Communication (OPC) server with limited scale. Using the Math Script node, the data analysis system can conduct correlation coefficient analysis among different operating parameters. At the end of an analysis the system automatically generates an analysis report in the specified format. This linear push systems has been used to experiment with different operating conditions for characterization of the hydraulic system behavior, which are provided here.

Background

Hydraulics are used in modern industries for handling large loads because of simple and cost-effective methods due to its energy density. It offers a vast range of speed and torque. An important characteristic of a hydraulic system is the multiplication of force. Because of this feature, hydraulics are pioneers in the field of heavy load handling. Large load handling would require sophisticated electronic control and extensive mechanical arrangements with lots of gears and pulleys if tried to execute without hydraulics. A hydraulic circuit consists of some major components such as prime mover, pump, fluid conductor (hose, tubing, pipe), reservoir, directional control valve, and hydraulic actuator (cylinder and motor). It also consists of additional support components such as pressure relief valve, filter, and pressure gauge. Figure 1 shows a basic hydraulic circuit and its components.

The prime mover or the motor converts electrical energy into mechanical energy to rotate the pump. The pump circulates hydraulic fluid into the system and converts mechanical energy into hydraulic energy. Pressurized fluid operates the hydraulic cylinder, and hydraulic energy is converted into a usable form of mechanical energy.

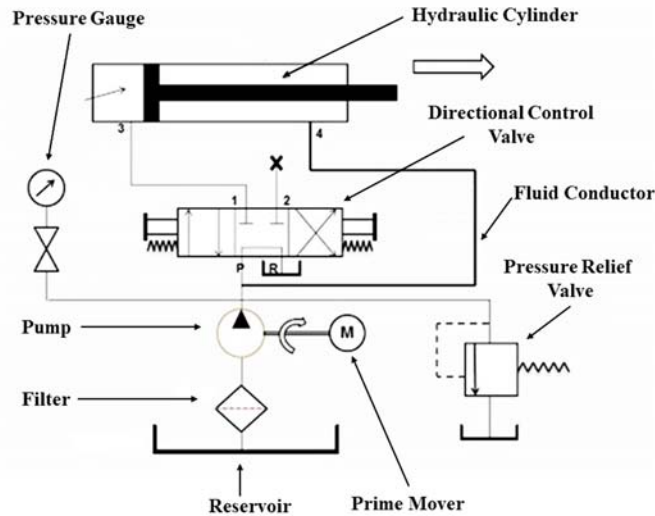


Figure 1. Basic Hydraulic Circuit and its Components [1].

In each stage of energy conversion, some energy loss occurs as none of the components run at full efficiency [2, 3]. Each component loses some energy during energy conversion. Besides that, during fluid circulation, friction occurs, and energy is lost in the form of heat. Friction increases when flow deflection occurs due to bends and restrictions in the fluid conductor. Friction also results in a pressure drop by creating turbulence in the flow, and additional energy is required to overcome this pressure difference [4]. Pressure drops also occur due to leaks in different components and seals, which result in loss of pumping energy [5]. Leaks are more common in systems having rotary actuators and in old equipment which are not adequately maintained. Throttling is another reason for pressure loss, and it occurs due to flow resistance. In a constant pressure system, loss due to throttling is higher.

Approaches to Improving Energy Efficiency of Hydraulic Systems

Recent research in the field of hydraulic systems is focused on improving energy efficiency. These approaches can be divided into three major categories: component level approach, system level approach, and control system approach. Some recent development examples through these approaches are described below.

Component Level Approach

The component level approach focuses on increasing the efficiency of different components of a hydraulic circuit. It emphasizes the electromechanical operation and design philosophy of various components to efficiently develop the required fluid pressure and flow for the circuit. It tries to reduce leaks, friction, and throttling. Use of a fixed displacement piston pump is a good example of this approach. These pumps can be up to 98% energy efficient [6]. An excellent hydraulic circuit design is also required with a piston pump to be efficient overall.

System-Level Approach

The system-level approach investigates the overall hydraulic circuit. Each year, the United States uses around 2 quads of energy with 22% system efficiency [7,8] in the area of fluid power systems [9]. However, as the world moves towards green energy and clean energy, there is an opportunity of improving the efficiency of the overall fluid power system through a system-level approach. For example, using this approach, a new type of synthetic hydraulic fluid [10] has been developed recently, which reduces the energy consumption of the hydraulic system by 8%.

System-level approaches are also being used by hydraulic hybrid propulsion systems [11] for automobiles. It works on the overall automation of the hydraulic circuit instead of a single component. It also works on improving the energy efficiency of the overall system by integrating energy efficient ways or implementing ways of capturing and reusing unused energy. One such approach is the use of a hydraulic accumulator, which stores hydraulic energy. It is a pressure storage device for an incompressible fluid. Hydraulic accumulators respond quickly to temporary demands, and they also reduce pulsations [12] by reducing pressure spikes which ultimately extend the lifecycle of components used in the system. Energy can be recovered through an accumulator while lowering or decelerating a load [13]. Hydraulic hybrid vehicles use regenerated energy using hydraulic accumulators [14, 15].

Control System Approach

Instead of implementing a control system for individual components, the whole system can be automated through a central control system that can operate according to load demand [16]. The control system approach works on the entire system, but it requires command signal receivable baseline components to be controlled centrally.

The position control of nonlinear hydraulic systems [17] is using this approach in gaining energy efficiency. It utilizes the Particle Swarm Optimization (PSO) algorithm to identify an improved Proportional Integral Derivative (PID) controller gain for the nonlinear hydraulic system.

Accumulator Motor Generator Energy Regeneration System (AMGERS) [18] based research is being conducted to increase energy efficiency for load-carrying vehicles such as cranes and excavators. This system utilizes the potential energy of the boom when it is lowered or decelerated. This captures the hydraulic fluid pressure in the accumulator and uses this pressure to run the hydraulic motor. The motor turns a coupled generator to create electrical energy, which is inverted and stored in batteries for further use.

Linear-push System

A hydraulic linear push system is developed for this project. The system has the capacity to exert a 1,000 pounds force, and allows for different configurations thus providing the capability to experiment with various operating conditions. To simulate the force and load environment, two parallelly connected hydraulic cylinders are used as hydraulic actuators, and two parallelly

installed gas spring shock absorbers are used as load. The prototype consists of a 0.5 hp external pump with a pressure rating of 1,000 psi and a maximum flow rate of 1.0 gpm that supplies hydraulic fluid into the system. Figure 2 shows the schematic diagram of the implemented system.

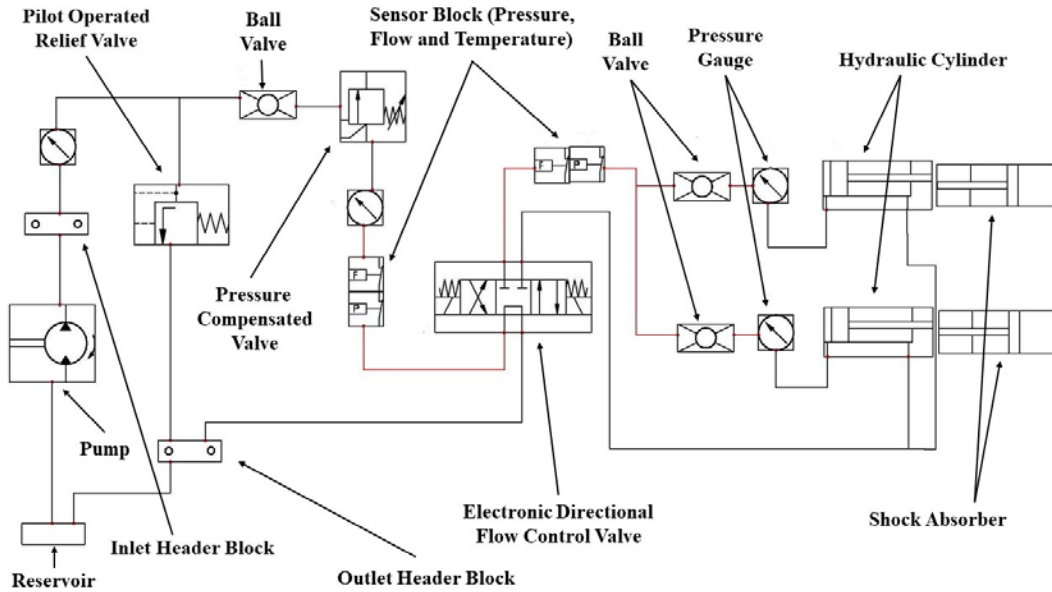


Figure 2. Schematic Diagram of the Hydraulic Circuit.

The system is automated with the use of an Allen-Bradley CompactLogix Programmable Logic Controller (PLC). Data is collected from pressure and flow sensors through multiple 4 to 20 mA electrical devices connected by the NIDAQ unit. The system uses LabVIEW for data acquisition and display, and the Math Script module of LabVIEW analyzes collected data. Figure 3 shows a CAD rendering of the designed system.

Hydraulic fluid first enters the inlet header block and gets distributed into the system. Incoming fluid is controlled by a pressure compensated valve. The system is equipped with a pilot-operated relief valve set at 3,000 psi to protect the system from overpressure.

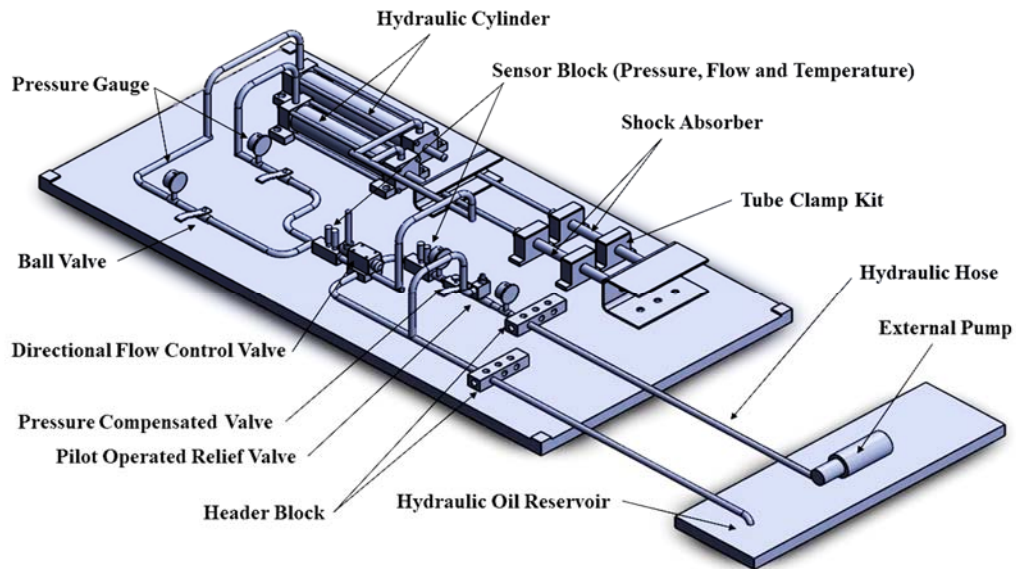


Figure 3. CAD Design for Hydraulic System Prototype.

Data Acquisition and Control System

The system's data acquisition and control system depend on integrating sensors and flow control valve with their compatible software. Key elements in this phase are the operation of LabVIEW, MATLAB, and STUDIO 5000 (PLC Programming Software) with the use of the NI OPC server. NI OPC server is used as both-way communication media between LabVIEW and STUDIO 5000.

Data acquisition requires electronic sensors to collect values of the needed parameters during operation or experimentation. In the designed system there are two pressure transducers with a range of 0 to 1,000 psi, two turbine type flow meters with a range of 0.4 to 7 gpm, and one temperature sensor with a range of -40 to 350° F. These sensors communicate (4 to 20 mA analog signal) via an NI (National Instruments) data collection module, which also communicates with the analysis program through the LabVIEW Human Machine Interface (HMI) program.

For converting the electrical signal of sensors into readable data, a National Instruments CompactDAQ chassis (NI cDAQ-9188) and voltage-current input module (NI-9207 with DSUB) are used. These devices are connected to LabVIEW. Continuous data collection and live graphical displays are available from LabVIEW. The analysis is programmed to be done online or offline, with data sent to the Math Script node of LabVIEW for online analysis and stored into an MS Excel file for offline analysis by MATLAB.

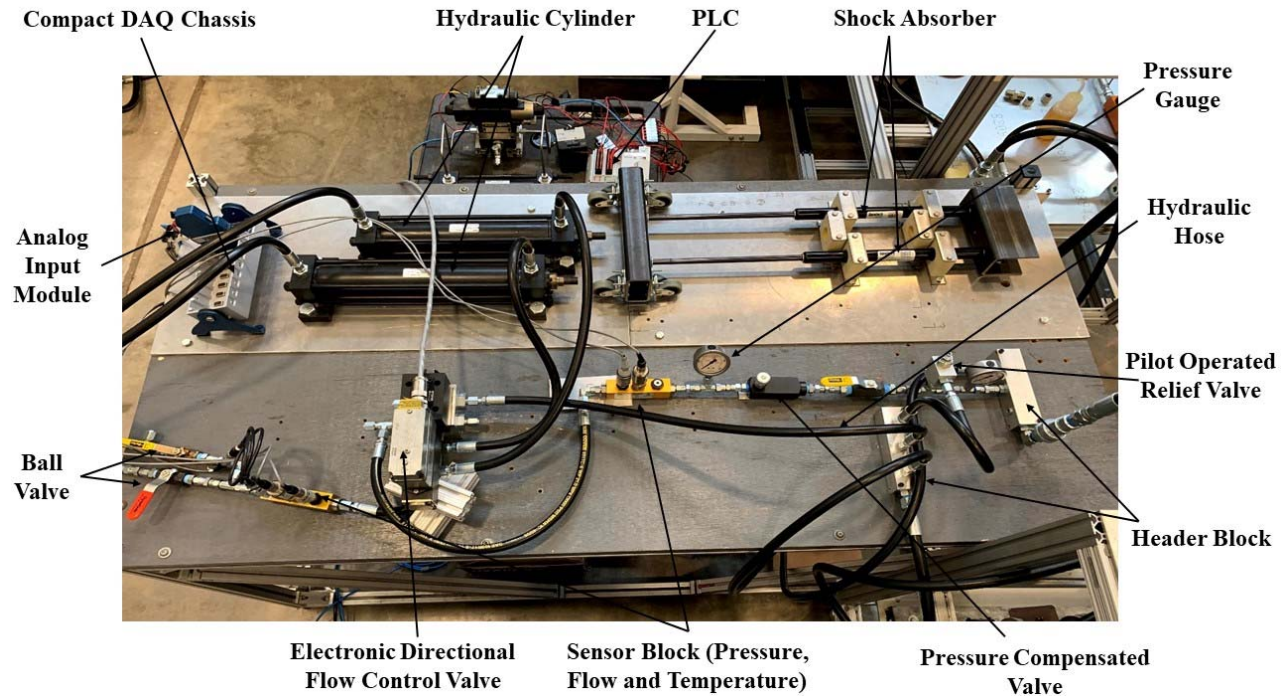


Figure 4. Prototype of Hydraulic System.

One set of flow meter and pressure transducer is installed upstream of the directional control valve to collect pressure and flow data of the fluid supplied by the pump. This data has been used to calculate energy supplied by the pump into the whole system. Another set of flow meter and pressure transducer is used upstream of the hydraulic cylinders to collect flow and pressure data for the fluid being used in the cylinders. This data has been used to calculate the energy consumed by the hydraulic cylinders to execute the task load. Figure 4 shows a photograph of the actual system in the lab.

Programming Requirement

Data collection and analysis require integration and communication among different hardware, software, and applications, thus requiring various levels of programming. The main sectors that were programmed are:

LabVIEW Programming: LabVIEW is a visual programming language from National Instruments. LabVIEW Professional Development Systems 2020 Version 20.0.0 (32 bit) has been used in this project. . The front panel of the developed program (Figure 5) shows real-time data and works as an HMI for controlling the system. In addition, the front panel provides a visual representation of

the sequence followed for analysis. The LabVIEW program shows data in the form of numeric indicators (Tags), which communicate with PLC through NI OPC Server.

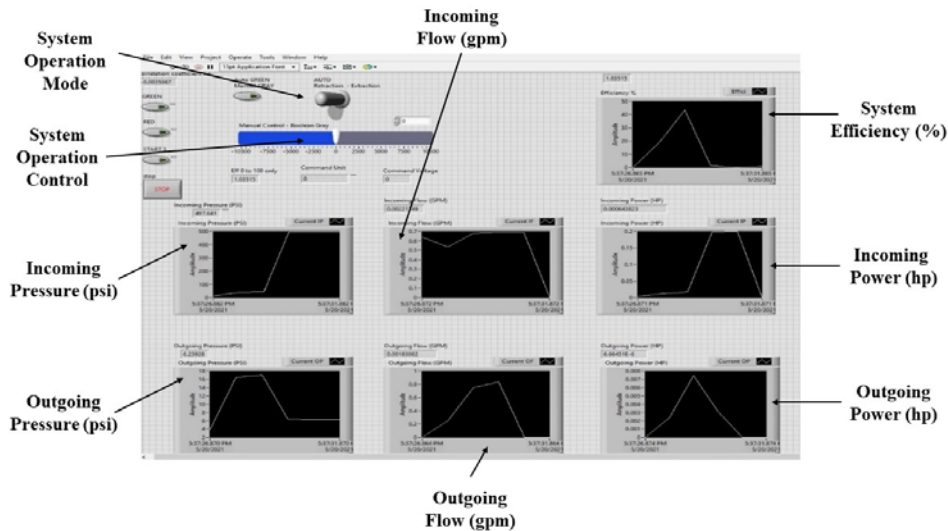


Figure 5. LabVIEW Front Panel Program and HMI.

MATLAB Programming: The Math Script function is a plugin of LabVIEW which utilizes the MATLAB workspace. The result can be displayed by MATLAB interface or can be used by LabVIEW for further automation of related decisions. In this project the Math Script node is programmed for statistical correlation analysis.

PLC Programming: PLC operates the electronic flow control valve. It controls the flow rate and direction of flow. The flow rate is proportional to the command voltage, and it has a range from 0.0 to 26.5 gpm, being represented in a 0.0 to 10.0 VDC voltage. This is done by the analog I/O module of the PLC.

Data Collection and Analysis

One goal in the project is to have an experimental setup that allows for analysis of energy efficiency in a system, a hydraulic linear push one. In order to accomplish that goal, the implemented system was run under different operating conditions where the actuator compresses the shock absorber. Four different operating pressure conditions using one actuator and one shock absorber, for system pressures of 500, 600, 700, and 800 psi, which were adjusted using the pilot-operated relief valve.

Data has been collected across the directional control valve (Sensor Blocks in Figure 2), allowing for calculation of the efficiency across this component. Data is collected using LabVIEW at a rate of 20 Hz for a total of 440 data points collected during the 22-seconds operation for each

cycle. The PLC is used to run the experiment for 10 cycles at each pressure, with basic statistical analysis performed (Table 1).

Table 1. Ten Cycle Sample Calculation for 500 psi at 10th Second

Cycle	Incoming Pressure (psi)	Incoming Flow (gpm)	Outgoing Pressure (psi)	Outgoing Flow (gpm)
1	168.45393	0.67998	162.46669	0.640244
2	167.5011	0.680278	161.7676	0.64264
3	167.77516	0.676714	161.98068	0.638042
4	167.73566	0.68512	162.14148	0.640877
5	167.89712	0.686635	162.27769	0.645387
6	168.00595	0.682769	162.26688	0.645391
7	168.35837	0.673786	162.59814	0.640521
8	167.83548	0.676258	161.77202	0.638145
9	167.41816	0.68647	161.97019	0.642003
10	167.44127	0.679745	161.99298	0.642947
Average	<i>167.84222</i>	<i>0.6807755</i>	<i>162.12344</i>	<i>0.6416197</i>
Standard Deviation	<i>0.3381206</i>	<i>0.0042108</i>	<i>0.264359</i>	<i>0.0024472</i>

For Energy Efficiency Analysis, the experiment is run and pressure and flow data are collected and stored in an MSExcel file with the use of LabVIEW, and this data is analyzed to investigate system capabilities and performance. In the analysis, pressure (psi) and flow (gpm) data have been collected at a rate of 20 Hz during the operation of the system. These data have been converted into power (hp). Power (hp) has been converted into energy (ft-lb/sec) consumed per second which is summed up for the whole operation duration to calculate total energy (ft-lb) consumption. A summary of the calculated data is shown in Table 2.

Experimental data shows that energy consumption in both the incoming and outgoing sides is almost similar for all the operating conditions. As a result, efficiency is also identical and varies between 90.08% to 90.50%. For example, for a 500 psi system set pressure, 831.76 ft-lb energy is supplied into the system, and 752.71 ft-lb energy is available downstream of the directional control valve, so this particular component (directional control valve) runs at 90.50% efficiency.

Table 2. Energy Consumption at Different System Set Pressure

Operating Condition	Total Incoming Energy	Total Outgoing Energy	Efficiency Across the Component
<i>1 Cylinder & 1 Absorber – 500lbs</i>	(ft-lb)	(ft-lb)	%
500 psi	831.76	752.71	90.50%
600 psi	829.71	747.39	90.08%
700 psi	839.12	756.66	90.17%
800 psi	867.32	783.46	90.33%

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Conclusion

Energy efficiency analysis of a hydraulic linear push system has been conducted in this section of the project. The modular design of the implemented system allows the user to experiment with different operating conditions based on load-actuator configurations and operating pressure set points. In this study, the developed methodology is used for the efficiency analysis across specific components, demonstrating the capabilities of the implemented system.

Applying the same methodology, the prototype can be used to analyze other configurations of the hydraulic system. This system provides the basis for the ultimate goal of having a real-time energy efficiency system.

REFERENCES

- [1] “How regenerative hydraulic circuit works - PART 3.” *YouTube*, Chinmayacademy, 2 November 2016, <https://www.youtube.com/watch?v=1KGVBwYEHIA>.
- [2] Cullen, Jonathan M., and Julian M. Allwood. “Theoretical efficiency limits for energy conversion devices.” *Energy* 35.5 (2010): 2059-2069.
- [3] Parasiliti, Francesco, and Paolo Bertoldi, eds. *Energy efficiency in motor driven systems*. Springer Science & Business Media, 2012.

- [4] Vogelesang, Hans. "Energy consumption in pumps–friction losses." *World Pumps* 2008.499 (2008): 20-24.
- [5] Latchoomun, L., et al. "Quantifying the Pumping Energy Loss Associated with Different Types of Leak in a Piping System." *International Conference on Emerging Trends in Electrical, Electronic and Communications Engineering*. Springer, Cham, 2016.
- [6] Parr, Andrew. "Hydraulic Pumps and Pressure Regulation." *Hydraulics and Pneumatics* (2011): 31-49.
- [7] Love, Lonnie J., Eric Lanke, and Pete Alles. "Estimating the impact (energy, emissions and economics) of the US fluid power industry." *Oak Ridge National Laboratory, Oak Ridge, TN* (2012).
- [8] Choudhury, Alamgir A., and Jorge Rodriguez. "A Modular System for Energy Efficiency Study of Hydraulic Applications." *2016 ASEE Annual Conference & Exposition*. 2016.
- [9] James, A. Sullivan. "Fluid power theory and applications." (1998).
- [10] Hitchcox, Alan. "Hydraulic Fluid Helps Improve System Efficiency." *Hydraulics and Pneumatics* 62.7 (2009): 14. Web.
- [11] Wu, Wei, et al. "Investigation of energy efficient hydraulic hybrid propulsion system for automobiles." *Energy* 73 (2014): 497-505.
- [12] Mikota, Josef. "A novel, compact pulsation compensator to reduce pressure pulsations in hydraulic systems." *World Scientific* 45 (2001): 69-78.
- [13] Rydberg, Karl-Erik. "Hydraulic accumulators as key components in energy efficient mobile systems." *6th International conference on fluid power transmission and control*. 2005.
- [14] Rydberg, Karl-Erik. "Energy efficient hydraulic hybrid drives." *11th Scandinavian International Conference on Fluid Power, SICFP'09*, June 2-4, Linköping, Sweden. 2009.
- [15] "How does a hydraulic accumulator work." *YouTube*, Гидравлика и пневматика, 17 February 2019, <https://www.youtube.com/watch?v=uMFVUukXfQA> .
- [16] Ho, Triet Hung, and Kyoung Kwan Ahn. "Design and control of a closed-loop hydraulic energy-regenerative system." *Automation in Construction* 22 (2012): 444-458.
- [17] Ye, Yi, et al. "Position control of nonlinear hydraulic system using an improved PSO based PID controller." *Mechanical Systems and Signal Processing* 83 (2017): 241-259.
- [18] Lin, Tianliang, et al. "Research on the energy regeneration systems for hybrid hydraulic excavators." *Automation in Construction* 19.8 (2010): 1016-1026.