The Future of Engineering Education
2024 Annual Conference & Exposition
Oregon Convention Center
Portland, OR . June 23 - 26, 2024
ASEE
Paper ID #43988

Real-Time Evaluation of Energy Efficiency of Hydraulic Systems

Dr. Alamgir A. Choudhury, Western Michigan University

Alamgir A. Choudhury is a Professor of Engineering Design, Manufacturing and Management Systems at Western Michigan University, Kalamazoo, Michigan. His MS and PhD are in mechanical engineering from NMSU (Las Cruces) and BS in mechanical engineering from BUET (Dhaka). His area of interest is engineering education, engineering design, fluid power, instrumentation and control

Dr. Jorge Rodriguez P.E., Western Michigan University

Professor in the Department of Engineering Design, Manufacturing, and Management Systems (EDMMS) at Western Michigan University's (WMU). Co-Director of the Center for Integrated Design (CID), and currently the college representative to the Presidentâ€™s U

Real-Time Evaluation of Energy Efficiency of Hydraulic Systems

Abstract

The importance of real-time monitoring and evaluation of any system has become increasingly significant due to the trend towards full automation of systems, which is part of the Industry 4.0 concepts. A real-time data analysis system was developed as part of a class project on the energy efficiency of an industrial hydraulic system. Using a system-level experimental methodology, this system implements automation for the hydraulic systems to improve energy efficiency in real-time. The system contains hydraulic actuators, shock absorbers, electronic flow control valves, and electronic sensors. This prototype is used to experiment with different operating conditions to characterize the behavior of the hydraulic system. A real-time data analysis system was developed using LabVIEW and an Open Platform Communication (OPC) server on a limited scale. Using the Math Script node, the data analysis system can conduct correlation coefficient analysis among different operating parameters. At the end of a task, the system automatically generates the actions needed to improve the system's efficiency. The implemented system, along with the experimental setup and procedure, will be presented, along with the data collected from monitoring the system. The specific analysis conducted on the collected data, and the resulting actions and effects on system performance, are also presented. Results indicate that improvement in efficiency has been accomplished. This project illustrates the use of senior project groups to develop lab experiments that can eventually be included in courses dealing with particular topics, such as hydraulic systems and efficiency of components. The goal is to include this system in the undergraduate fluid mechanics lab for real-time system evaluation.

Introduction

The widespread use of hydraulic systems in industry can be attributed to their ability to handle significant loads in a simple and cost-effective manner, owing to their energy density. An important characteristic of hydraulic systems is their ability to multiply force, offering a wide range of speed and torque. This feature makes hydraulics pioneers in the field of heavy load handling. Handling large loads would otherwise require an extensive number of mechanical components (e.g., gears, sprockets) arranged with heavy-duty control systems to perform the required tasks. A hydraulic circuit comprises several major components, including an electric motor, pump, fluid conductor (i.e., hose, tubing, pipe), reservoir, control valves, and hydraulic actuators (e.g., cylinder, hydraulic motor). It also includes additional support components such as pressure relief valves, filters, and pressure gauges. The prime mover (e.g., electric motor) converts electrical energy into mechanical energy to rotate the hydraulic pump. The pump circulates hydraulic fluid throughout the system, converting mechanical energy into hydraulic energy. Pressurized fluid operates the hydraulic cylinder, converting hydraulic energy into a usable form of mechanical energy. Figure 1 illustrates a basic hydraulic circuit and its components.

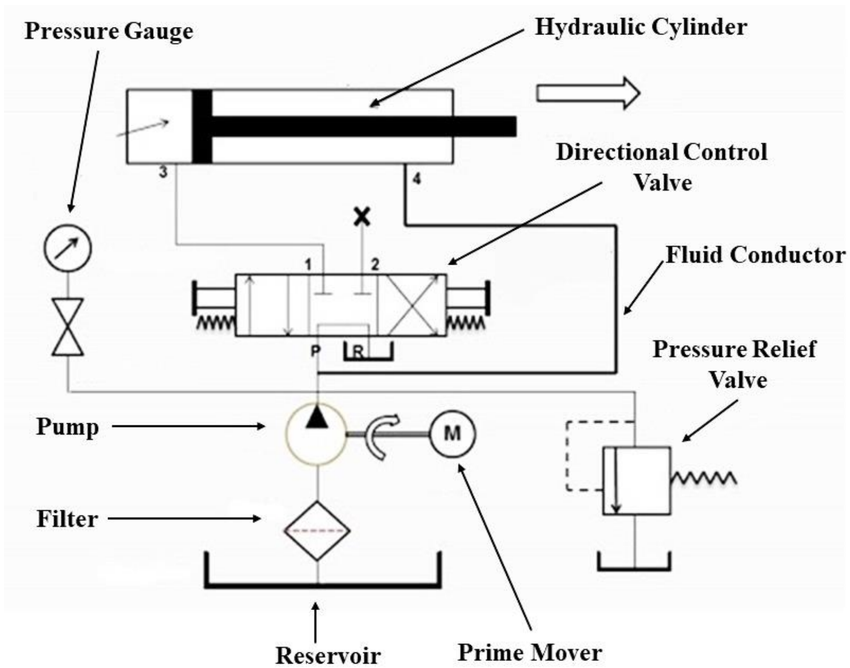

Figure 1. Basic Hydraulic Circuit and its Components [1].

At each stage of energy conversion, some energy loss occurs as none of the components operate at 100% efficiency [2, 3]. Additionally, during fluid circulation, friction occurs, leading to energy loss in the form of heat. Friction increases when flow deflection occurs due to bends and restrictions in the fluid conductor. It also results in pressure drop by creating turbulence in the flow, requiring additional energy to overcome this pressure difference [4]. Pressure drop further occurs due to leaks in different components and seals, resulting in the loss of pumping energy [5]. Leaks are more common in systems with rotary actuators and in older equipment that is not adequately maintained. Throttling, another reason for pressure loss, occurs due to flow resistance, with higher losses in a constant pressure system.

There are various approaches to improving the energy efficiency of hydraulic systems, which is currently a trending focus. These approaches can be divided into three major categories: the component-level approach, the system-level approach, and the control system approach. The component-level approach focuses on increasing the efficiency of different components of a hydraulic circuit. A good example of this approach is the use of fixed displacement piston pumps, which can achieve up to 98% energy efficiency [6]. The system-level approach investigates the overall hydraulic circuit. For instance, a new type of synthetic hydraulic fluid [7-10] has recently been developed using this approach, reducing the energy consumption of hydraulic systems by 8%. System-level approaches are also employed in hydraulic hybrid propulsion systems for automobiles, utilizing hydraulic accumulators [12-15].

The control system approach focuses on implementing a central control system for the entire system, which can operate according to load demand [16]. Although this approach works on the entire system, it requires baseline components capable of receiving command signals to be controlled centrally. Position control of nonlinear hydraulic systems [17-18] utilizes this approach to achieve energy efficiency through a PID controller.

Methodology - System to Study Energy Efficiency

A lab setup was designed and implemented with the goal of creating a hydraulic system for conducting various studies on energy efficiency. It features a hydraulic linear push system capable of exerting a force of 1,000 pounds and allows for different configurations, enabling experimentation with various operating conditions. To simulate the force and load environment, two hydraulic cylinders are connected in parallel as hydraulic actuators, while two gas spring shock absorbers are installed in parallel as loads. The prototype includes a 0.5 hp external pump with a pressure rating of 1,000 psi and a maximum flow rate of 1.0 gpm to supply hydraulic fluid to the system. Figure 2 depicts the schematic diagram of the implemented hydraulic system.

Control System: In terms of controls, the system is automated using 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 via the NIDAQ unit. LabVIEW is used for data acquisition and display, while the Math Script module of LabVIEW analyzes collected data. Hydraulic fluid first enters the inlet header block and is distributed throughout the system. The incoming fluid is controlled by a pressure-compensated valve. Additionally, the system is equipped with a pilot-operated relief valve set at 3,000 psi to protect against overpressure.

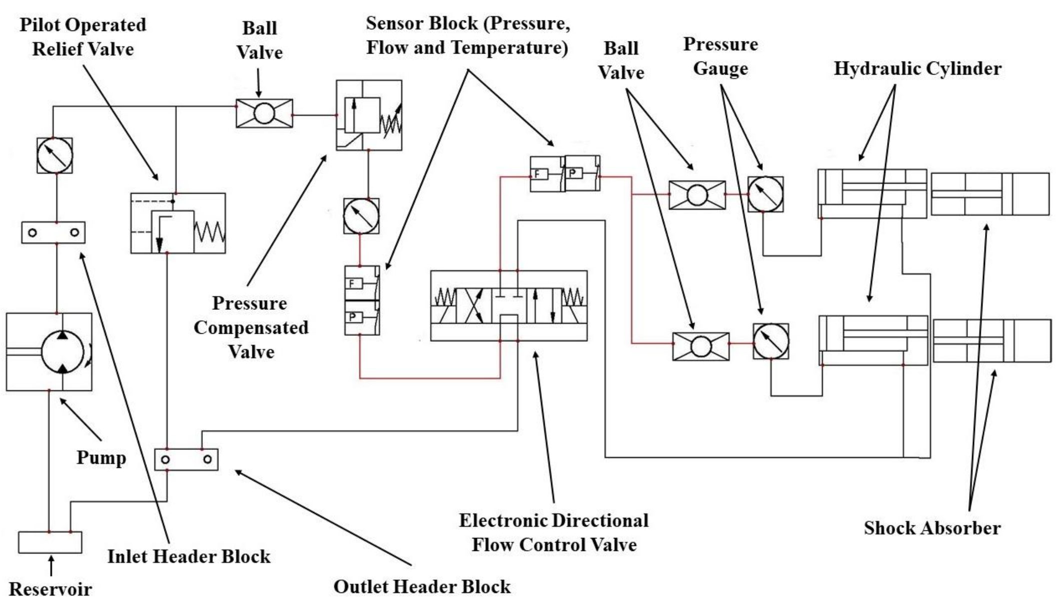

Figure 2. Schematic Diagram of the Hydraulic Circuit.

Implemented System

The actual implementation of the hydraulic linear-push system occurred after finalizing its design [19]. This phase involved properly connecting the hydraulic and control components to ensure they functioned together seamlessly. Extensive programming of LabVIEW, MATLAB, and PLC was necessary to integrate all components into a unified system. The system's data acquisition and control relied on integrating sensors and flow control valves with their respective software. Key elements in this phase included the operation of LabVIEW, MATLAB, and STUDIO 5000 (PLC Programming Software), facilitated by the use of the NI OPC server. The NI OPC server served as a bidirectional communication medium between LabVIEW and STUDIO 5000.

Data acquisition involves the use of electronic sensors to collect values of the required 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 via a 4 to 20 mA analog signal through an NI (National Instruments) data collection module, which also communicates with the analysis program through the LabVIEW Human Machine Interface (HMI) program.

To convert the electrical signals of the sensors into readable data, National Instruments CompactDAQ chassis (NI cDAQ-9188) and a voltage-current input module (NI-9207 with DSUB) are utilized. These devices are connected to LabVIEW. Continuous data collection and live graphical displays are available through LabVIEW. The analysis can be performed online or offline, with data sent to the Math Script node of LabVIEW for online analysis and stored in an MS Excel file for offline analysis using MATLAB.

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 the energy supplied by the pump into the whole system. Another set of flow meter and pressure transducer is installed 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 3 depicts a photograph of the actual system in the lab.

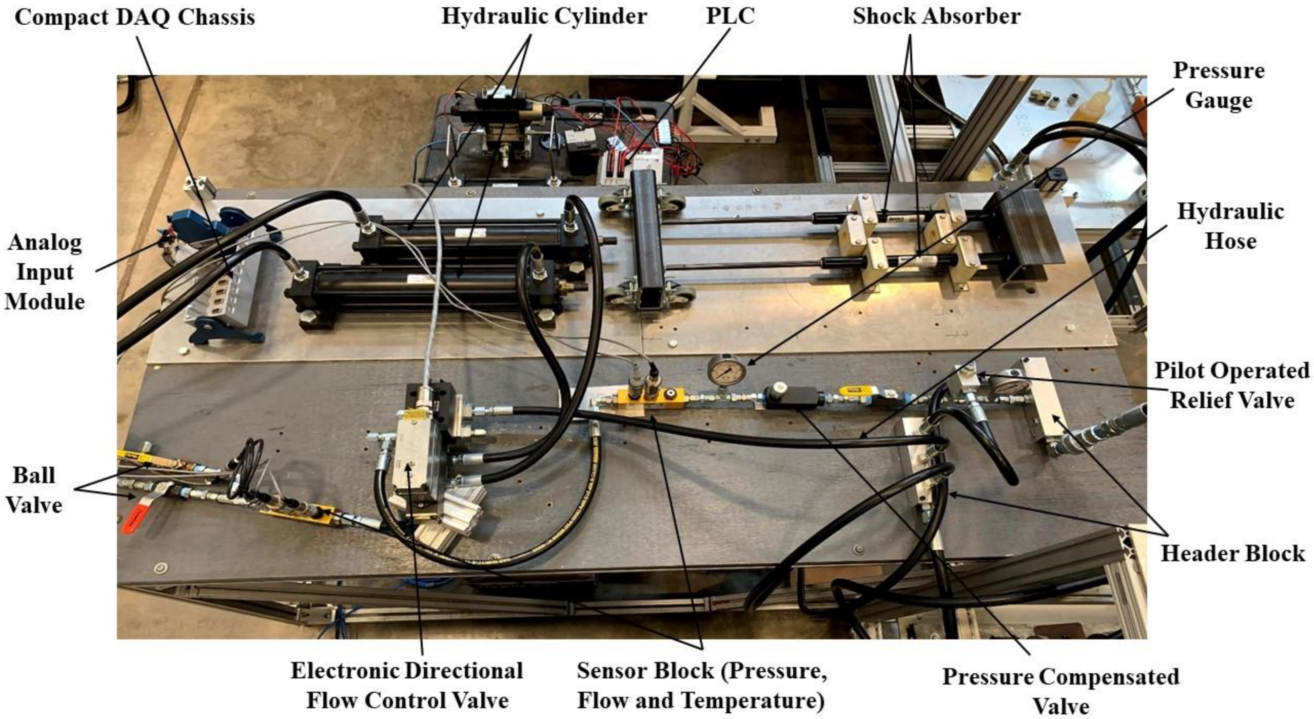

Figure 4. Prototype of Hydraulic System.

Initial Testing

After the initial integration of the system, a series of simple experiments were conducted to ensure that a functional hydraulic system with a valid control system had been implemented. Several adjustments were made to the system to achieve smoother operation, with most of the adjustments focusing on calibration and programming. One of the project goals is to establish an experimental setup capable of analyzing energy efficiency in a hydraulic linear push system. To accomplish this goal, the implemented system was operated under different conditions where the actuator compresses the shock absorber. Four different operating pressure conditions were tested using one actuator and one shock absorber, with system pressures set at 500, 600, 700, and 800 psi, adjusted using the pilot-operated relief valve.

Data was collected across the directional control valve (Sensor Blocks in Figure 2) to enable calculation of efficiency across this component. Data was collected using LabVIEW at a rate of 20 Hz, resulting in a total of 440 data points collected during the 22-second operation for each cycle. The PLC was utilized to run the experiment for 10 cycles at each pressure, with basic statistical analysis performed (see 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	*167.84222*	*0.6807755*	*162.12344*	*0.6416197*
Standard Deviation	*0.3381206*	*0.0042108*	*0.264359*	*0.0024472*

Results

For the Energy Efficiency Analysis, the experiment is conducted, and pressure and flow data are collected and stored in an MS Excel file using LabVIEW. This data is then analyzed to investigate the system's capabilities and performance. During the analysis, pressure (in psi) and flow (in gpm) data are collected at a rate of 20 Hz throughout the system's operation.

These data are then converted into power (HP). Subsequently, power in horsepower is further converted into energy (lb-ft/s) consumed per second. The total energy consumption (lb-ft/s) is calculated by summing up the energy consumed per second over the entire duration of the operation.

A summary of the calculated data is presented in Table 2. Experimental data is collected at 1-second intervals over the course of the task's cycles. The power at each second is utilized to calculate the energy consumed during that second's interval. The energy consumption for each second is then aggregated to obtain the total energy consumption.

Table 2. Energy Consumption at Different System Set Pressure

Operating Condition	**Total Incoming Energy**	**Total Outgoing Energy**	**Efficiency Across the Component**
1 Cylinder & 1 Absorber – 500lbs	*(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%

The experimental data indicates that energy consumption on both the incoming and outgoing sides is nearly identical across all operating conditions. Consequently, the efficiency also remains consistent, ranging between 90.08% and 90.50%. For instance, in the case of a system set pressure of 500 psi, 831.76 ft-lb of energy is supplied into the system, while 752.71 ft-lb of energy is available downstream of the directional control valve. Therefore, this particular component (the directional control valve) operates at an efficiency of 90.50%.

Discussion and Conclusion

This section of the project focuses on conducting an initial energy efficiency analysis of a hydraulic linear push system. The modular design of the implemented system enables users to experiment with different operating conditions based on load-actuator configurations and operating pressure set points. In this report (work in progress), we utilize the established test methodology to analyze the efficiency of a specific component, thereby demonstrating the overall capabilities of the implemented system.

By applying the established methodology, the prototype can be utilized to analyze various configurations of the hydraulic system. This system serves as the foundation for our ultimate goal of developing a real-time energy efficiency system for use in the undergraduate fluid mechanics course, which includes a lab component. Targeted at the junior level, this course covers topics ranging from basic fluid mechanics to hydraulic components and systems, with an emphasis on performance evaluation.

The utilization of this setup for real-time analysis implies the establishment of an efficiency goal based on the complete system under study. As data is collected and analyzed, adjustments will be made accordingly. The initial target efficiency can be determined either by previous data or by defining an estimate. This real-time implemented system will enable the evaluation of energy efficiency of components and systems, depending on the number of active sensors and actuators.

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 Rodriguez, Jorge. "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.

[19] Choudhury, Alamgir and Rodriguez, Jorge, "Towards Real-Time Energy Efficiency Analysis", 2023 ASEE Annual Conference and Exposition. 2023.