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A Modular System for Energy Efficiency Study of Hydraulic Applications

Dr. Alamgir A. Choudhury, Western Michigan University

Alamgir A. Choudhury is an Associate 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 interest includes computer applications in curriculum, MCAE, mechanics, fluid power, and instrumentation & control. He is a Registered Professional Engineer in the State of Ohio and affiliated with ASME, ASEE, SME and TAP.

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

Faculty member 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 President's University-wide Sustainability Committee at WMU. Received his Ph.D. in Mechanical Engineering-Design from University of Wisconsin-Madison and received an MBA from Rutgers University. His B.S. degree was in Mechanical and Electrical Engineering at Monterrey Tech (ITESM-Monterrey Campus). Teaches courses in CAD/CAE, Mechanical Design, Finite Element Method and Optimization. His interest are in the area of product development, topology optimization, additive manufacturing, sustainable design, and biomechanics.

A modular system energy efficiency study of hydraulic applications

Due to the growing demand for energy efficient products on the market, the investigation of energy usage in product lifecycles is becoming an important factor in design processes. Often, this problem is addressed by the analysis of energy efficiency of a product already designed along with its subsequent design improvement. The consideration of energy efficiency at an earlier stage adds to the complexity of the design process, but payoff may be significant in terms of market dominance. In this paper, the design of a manually powered hydraulic bicycle using energy efficiency as a primary design objective is presented. A laboratory setup is developed to test performance of the hydraulic system components. Experimental analysis of component behavior of a functional prototype of the hydraulic system is performed. The analysis result is used to select components for optimum performance of the system in its desired operational conditions. The methodology can be utilized in design of similar systems where energy efficiency is a primary design objective.

1. Introduction

Worldwide, the vast majority of energy is produced from fossil-based fuels resulting in the increase of carbon dioxide in the atmosphere [1]. In the area of fluid power, the United States consumes about 2 Quads of energy per year with an average of 22% system efficiency [2]. The design of industrial products and processes requiring less energy will significantly impact the demand of fossil fuel-based energy and its impact on the climate. Production of 2 Quads energy costs about $60B, in process emits 360 million metric tons (MMT) of CO_2 to the atmosphere each year. Since the energy crisis of the 1970s, energy efficiency improvement in most industrial systems is noticeable, but very little has changed in the fluid power system. Improving this efficiency by a mere 5% would save fluid power industry about $10B per year, reducing CO_2 emissions by 65 MMT. A 10% improvement will bring the energy efficiency of fluid power systems comparable to that of the internal combustion engine, saving the industry $20B per year and reducing yearly CO_2 emissions by 110 MMT. Considering this benefit, industries are looking for methods to reduce overall energy consumption and maximize the sustainability of products and processes. Achieving this goal is a complex and gradual process and will require a different design methodology. Both industry and government bodies have made energy saving and energy efficiency a priority in all future operations. In academia, this awareness is leading to various curriculum reform. The National Science Foundation funded various projects to update engineering curricula for the comprehensive teaching of energy in different undergraduate programs. The NSF funded accelerated testing methodology projects [3] utilizing statistical methods to determine the interrelationship between various stress loadings and total energy use in a mechanical system. This established a framework to facilitate the optimum experimental design and energy reduction in the process. The US Department of Energy promotes best practices in energy efficiency, reusable energy, waste reduction, and productivity improvement through the integration of activities. While energy efficiency and conservation is a novel objective on its own merit, many consider this essential for the long term sustainability of an industrial society [4, 5, 6]. Generally, engineering design classes in undergraduate programs follow a structured problem- solving approaches for solutions of open ended design problems. Besides achieving mechanical integrity of the product and intended product functions, additional analysis tools are utilized to achieve other design goals, typically referred to as design for X [7]. This includes a variety of design objectives to ensure the long term sustainability of products and processes. Design for Environment (DfE), or ecodesign [8, 9] aims to reduce the environmental impact in the life cycle of a product by enhancing its design objectives. It may also aim to reduce resource consumption in terms of material, energy, and pollution prevention. Other concepts, such as Design for Disassembly (DfD) and Design for Recycling (DfR) practices [10, 11, 12], would also allow the product designer to have a substantial positive impact on the environmental aspects of a product’s lifecycle.

The incorporation of energy efficiency in a design project will require additional analysis tools and proven design methodology. Because of the analytical complexity of the subject, experimental methods are more feasible to understand the source and nature of energy loss in fluid power system. This paper presents an initiative to incorporate energy efficiency in a fluid powered transportation system design project. Though the methodology is used in the capstone design project, it can be beneficial for the design of a mechanical system in general.

2. Experimental analysis of energy efficiency

The formulation of accurate analytical model of all energy losses system and its utilization in design of an energy efficient fluid power system is not expected to be within the reach of most undergraduate students. It is more viable to study the behavior of a prototype system in the laboratory and utilize the experimental result to improve the energy efficiency of the system. The prototype would be developed according to system specification in a conventional design process. It would be scaled to fit the laboratory limitations if such scaling does not affect the characteristics of the system significantly. Additional sensors and process instrumentation would be added to monitor the prototype behavior. In most hydraulic systems, major sources of energy loss are known. After the function of the prototype is verified, energy losses in the system would be measured and tabulated. Often, common sense practices can be quickly adapted in the system to enhance its energy efficiency without formal design changes. Actual experimental process starts with operation of the system under variety of conditions and acquiring of process data. A nonlinear regression modeling method is utilized to fit the process behavior with their expected analytical nature. Upon the performance of a sensitivity analysis of the process data, parameters mostly effecting the energy efficiency of the overall system are identified. In general, optimization of the energy efficiency model would specify optimal design parameters of the system. The study of the process parameters also leads a designer towards specific and innovative solutions of the design problem.

The design process presented in this paper is practiced in a conventional capstone design project, where a group of students are assigned a two semester design project. In the past, student groups were asked to design a human powered hydraulic system to transport a single person. Without using any direct drive mechanism, the system would transfer the rider’s power to the driving wheel through the use of a fluid power system. The goal of the design was its functionality, safety, reliability, manufacturability and cost effectiveness. It was implemented as a routine step by step process of the problem’s definition, concept generation, design analysis, design specification, component selection and fabrication, prototype development, performance testing, and validation of the design process. Later additional design criteria was added to address the issue of energy usage. This includes capture energy lost due to braking or downhill motion and energy efficiency of the overall system. This required a new design process with energy efficiency as primary design objective. The most significant sources of energy loss in a hydraulic system are the pump, motor, control valves and in fluid throttling process. The design of fluid power circuit without the throttling of fluid and the use of most efficient control valve were easily added to the design process. The challenge was the selection of the pump and motor for the most energy efficient operation of the system. Manufacturers of the components provide performance characteristics tested in their normal range of operating conditions. In this hydraulic system, pump and motor operate in a broader range of operating conditions. Therefore, their performance beyond normal operating conditions need to be determined experimentally. Meaningful analysis of the test data requires sophisticated measurement, data acquisition, and analysis system in the laboratory. Therefore, a new laboratory is being developed to assist student groups with such experiments.

In the following, example of an experimental analysis in design of an energy efficient human powered hydraulic transportation system is presented.

3. Energy efficiency testing laboratory

A laboratory (Figure 1) is developed to test performance of the prototype, variety of system configuration, and a fluid power system in general. For a hands-on study of the process and the designed system, one can assemble the components, create the desired application, and study its performance. The laboratory is composed of six modules. Using quick connect coupling and a flexible hose, these modules can be connected to create the system under investigation.

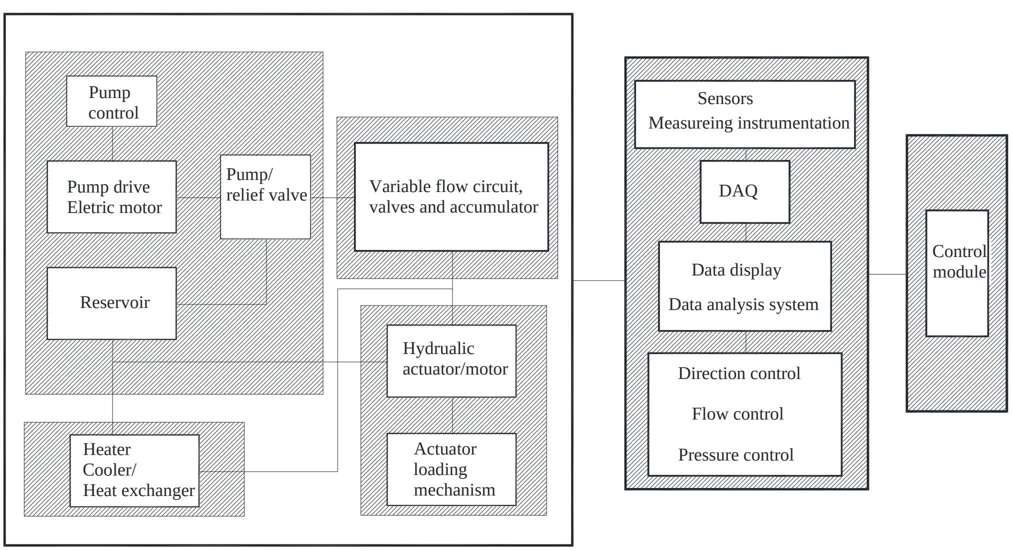

Figure 1. Layout of the test laboratory

Pump module: This module (Figure 2) has a series of variable displacement pumps to supply a fluid power system in general. The pumps are driven by 7.5, 2 and 0.5 HP electric motors with their own control (ABB ACS 500) to vary flow rate. A 30 gallon reservoir is used to supply fluid to these pumps

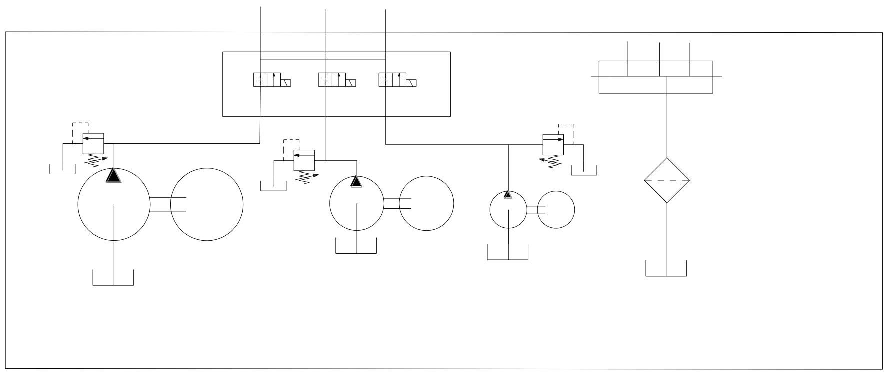

Figure 2. Pump module circuit

and other components of the module. A flexible pump mounting fixture is added to allow the installation of other pumps in a test system. A solenoid valve operated supply manifold is used to provide power from individual or combination of pumps. Flow from a hydraulic system returns to the reservoir through another manifold and cartridge filter. The whole module is mounted on a portable frame and quick connect couplings are used to integrate with other modules as necessary.

Flow and conditioning module: This module (Figure 3) will be used to create any flow circuit necessary for a specific system under consideration. It consists of a bank of stainless steel tubes in layers which can be connected in a series or parallel using two way direction control valves. One would be able to create different types of flow circuit utilizing the tubes, hoses, and direction control valves installed in the module. To ensure the maintenance of physical properties and chemical stability, hydraulic fluid from the actuator is conditioned prior to the return to the reservoir. Hydraulic fluid will be conditioned using a panel filtration unit, a heating unit and a heat exchanger in this module. This allows for testing the performance of a hydraulic system in a desired operating temperature, irrespective of ambient temperature.

Actuation module: Hydraulic motors and cylinders required in a system under investigation are installed in this module. The module (Figure 4) has flexible mountings to allow for the installation of different hydraulic motor or cylinder. A hydraulic motor is used to drive the pump with desired torque and rpm. Motor power is supplied by the flow from the pump module. The load on the pump is created by controlling the pressure and flow at the pump exit. To test characteristics of a linear actuator, the motor/pump setup can be replace with appropriate hydraulic cylinders and force sensors.

Instrumentation module: This module has sensors, data acquisition, data processing, and a display and control instrumentation. A combined SCXI and PXI chassis based National Instrument hardware is utilized for this purpose. NI DAQ cards, such as NI PCI-7342, 6024E, GPIB ENET, NI CR10-9073, NI 9213, NI 9205, NI 9901, NI 9977, and other accessories are utilized for

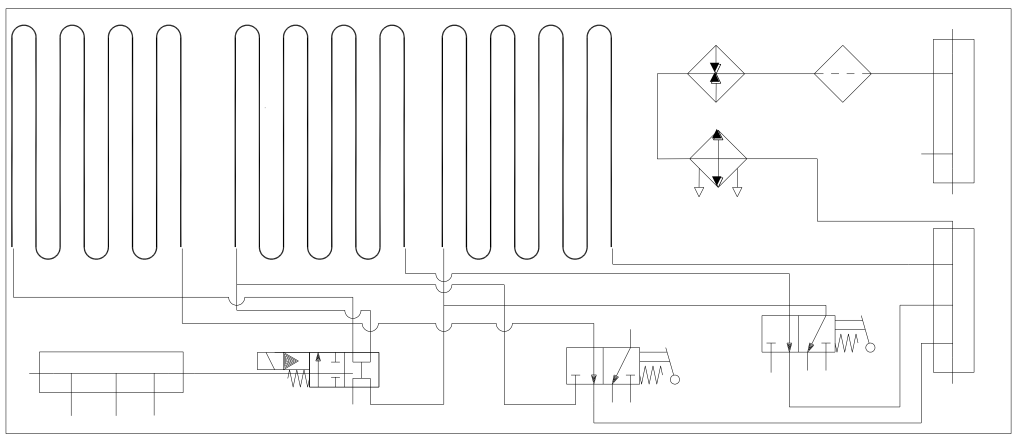

Figure 3. Flow and conditioning module

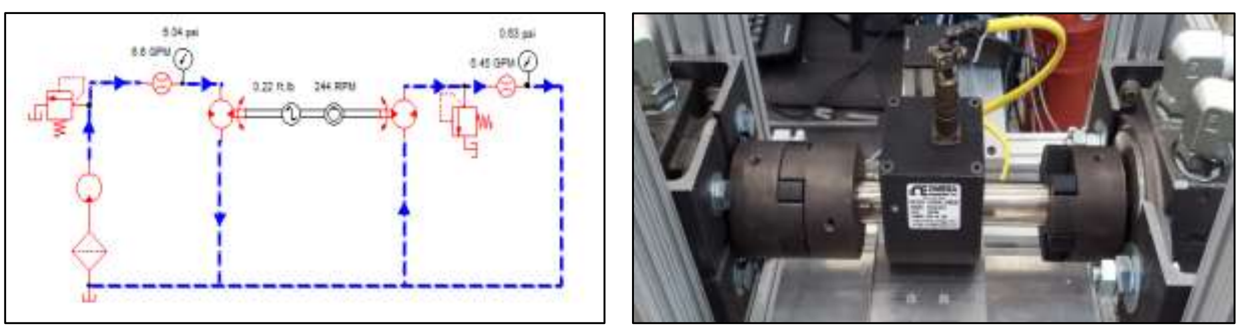

Figure 4. Actuator module and motor-pump coupling

collecting all process data (pressure, temperature, flow, torque, force, and rpm) in either analog or digital form. The sensors are configured by the DAQ modules for their excitation and output signals. The system also allows sending appropriate signals to process actuators (valves, pump drive and temperature controller). LabVIEW program is utilized to integrate the process sensors with the analysis and control system. Additionally, Matlab, Automation Studio, and other analysis tools are used for further study of process and component behavior based on the data acquired.

Control module: This is an external module that uses mainly microcontrollers and programmable logic controllers (PLCs) in the fluid power process. It replicates a hardware-based control systems, as opposed to the software-based controls included in the Instrumentation Module. It can be expanded to control other systems besides the fluid power modules, thus allowing for a wider range of possible projects.

4. Experimental analysis

This design project was part of a national design competition among fifteen different university teams. The success of the design would be determined by performance of the system in a series of competitive races. The objective was to design a hydraulic system that would minimize energy loss and optimize performance of the system in the races. In the design process, all pumps and motors meeting the operational requirement were assessed and two sets of pumps and motors identified as “Aerospace” and “H3” were selected for testing in the laboratory. A test system is developed in the laboratory that allows operation of the pumps and motors under variable flow rate, pressure, rpm, torque and power. This operational data was imported in Excel for detailed analysis.

Energy analysis and energy efficiency mapping: The goal of the analysis was to determine overall which pump and motor would operate at higher efficiency during the duration of the races. Based on the desired speed of the bike in race track, shaft rpm of pump and motor was determined as function of time. Table 1 shows the bike speed, corresponding track length, shaft rpm and its duration. The data is used to calculate a *Speed Factor* (S) at each pump and motor speed as fraction of total race time.

$$S_i = \frac{t_i}{T} \qquad \dots (1)$$

Where, S_i = Speed Factor

t_i = Duration of a specific speed

T= Completion time of race.

For each wheel velocity, the corresponding shaft speed is calculated based on wheel rpm and gear ratio. In the laboratory efficiency characteristics of the pumps and motors are mapped with respect to shaft rpm and pressure (Figures 5 and 6). Rotational speed and power are measured by utilizing an electric motor control system. Appropriate pressure and flow is maintained by using a pressure relief valve and a flow control valve.

Using the efficiency maps of the pump and motor, an overall *Efficiency Index* (E) is calculated for both sets of pump and motor. The Efficiency Index at each shaft speed is given by

$$E_i = S_i \eta_i \qquad \ldots (2)$$

Where, E_i = Efficiency Index

η_i = Efficiency at pressure i

Overall *Efficiency Index* is $E = \sum_{i-1,n} \sum_{j=1,m} E_{ij}$ … (3)

Where i and j are for each pressure and speed factor

For the overall calculation speed and efficiency data was used to create a regression model of efficiency characteristics and calculate efficiency index for any shaft speed and pressure in a specific design scenario. The result of the analysis are shown in Table 2 and 3. Based on this analysis, the highest efficiency index pump and motor were found to be 154.441 and 197.9571 for the Aerospace pump and motor respectively.

1 Lap												
	Start	Length 1	Turn 1	Length 2	Turn 2	Length 3	Turn 3	Length 4	Turn 4	Length 5	Turn 5	Total
Length(ft)	100	4400	100	2000	200	2800	150	1200	150	2400	942.4778	14442.48
Speed (mph)	Time(s)	Time(s)	Time(s)	Time(s)	Time(s)	Time(s)	Time(s)	Time(s)	Time(s)	Time(s)	Time(s)	Time(s)
5	2	0	1	0	6	0	4	0	4	0	4	21
10	2	0	3	0	5	0	3	0	3	0	24	40
15	2	14	4	6	4	9.5	3	4	3	8.2	8	65.7
20	2	84	0	36	0	57	0	24	0	49.2	4	256.2
25	0	28	0	12	0	19	0	8	0	16.4	0	83.4
30	0	14	0	6	0	9.5	0	4	0	8.2	0	41.7
T (s)	8	140	8	60	15	95	10	40	10	82	40	508
Time	8.46667	Min										
Speed (mph)	Factor	RPM @ Wheel										
5	0.0413	64.98242001										
10	0.0787	129.96484										
15	0.1293	194.94726										
20	0.5043	259.92968										
25	0.1642	324.9121001										
30	0.0821	389.8945201										

Table 1. Speed factor

Therefore, they were chosen in the final design. In a later stage of the design, the efficiency index formulation was modified by introducing factors due to size, weight and the cost of pumps and motors. Because of the low cost, an H3 pump and motor were deemed more suitable in final component selection.

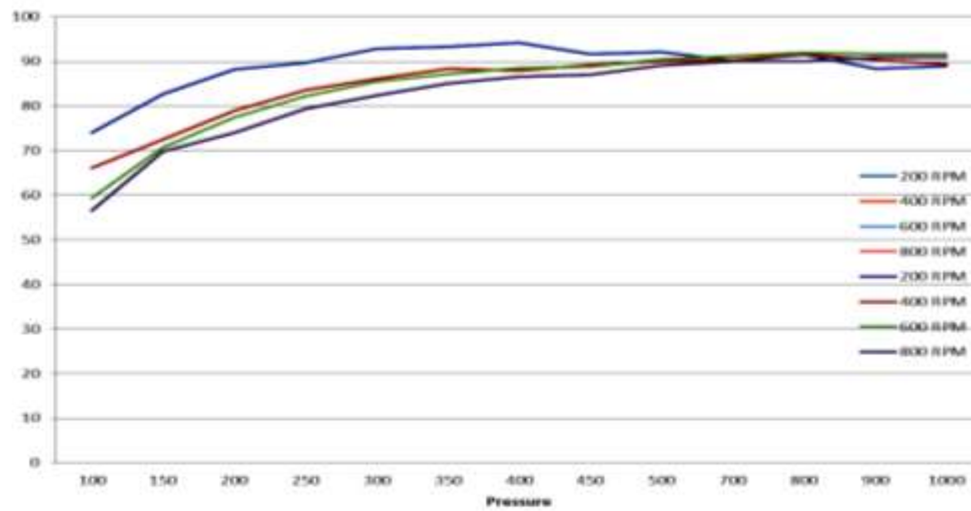

Figure 5 Hydraulic motor overall efficiency versus pressure

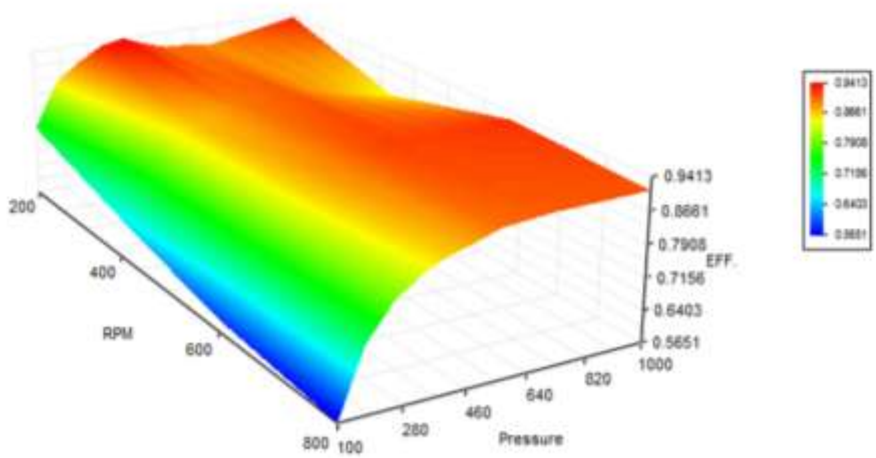

Figure 6. Efficiency mapping of a hydraulic motor

5. Design assessment

Effectiveness of this design process is assessed by the success of the design in the competitive races among twelve participating university teams. Prior to use of this design process, our system met the competition criteria but was not the winner in the races. This design did, however, earn first place in the design report as assessed by industry professionals. In terms of its actual performance, it earned the overall championship in the competition. Performance testing of student design in the laboratory and effectiveness of such design is shown as an example in the departmental senior design project class.

Aerospace												
Speed (mph)	Factor	RPM	Pump Efficiency Map					Point				
5	0.0413	64.98242	100 PSI	200 PSI	300 PSI	400 PSI	500 PSI	100 PSI	200 PSI	300 PSI	400 PSI	500 PSI
10	0.0787	129.9648	0.5053	0.6449	0.6676	0.6403	0.7053	2.089	2.666	2.760	2.647	2.916
15	0.1293	194.9473	0.5152	0.6566	0.6784	0.6702	0.7202	4.057	5.170	5.342	5.277	5.671
20	0.5043	259.9297	0.5251	0.6683	0.6892	0.7001	0.7351	6.791	8.643	8.913	9.054	9.507
25	0.1642	324.9121	0.535	0.68	0.7	0.73	0.75	26.982	34.294	35.303	36.816	37.825
30	0.0821	389.8945	0.55	0.7	0.72	0.76	0.77	9.030	11.492	11.820	12.477	12.641
Weight factor	Cost		0.5645	0.7184	0.7409	0.7903	0.7903	4.634	5.897	6.082	6.487	6.487
2	11										Total:	154.441
H3												
Speed (mph)	Factor	RPM	Pump Efficiency Map					Point				
5	0.0413	64.98242	100 PSI	200 PSI	300 PSI	400 PSI	500 PSI	100 PSI	200 PSI	300 PSI	400 PSI	500 PSI
10	0.0787	129.9648	0.611	0.711	0.749	0.795	0.785	2.526	2.939	3.096	3.286	3.245
15	0.1293	194.9473	0.611	0.714	0.756	0.79	0.79	4.811	5.622	5.953	6.220	6.220
20	0.5043	259.9297	0.611	0.717	0.763	0.785	0.795	7.902	9.273	9.868	10.152	10.282
25	0.1642	324.9121	0.611	0.72	0.77	0.78	0.8	30.815	36.312	38.833	39.338	40.346
30	0.0821	389.8945	0.61	0.72	0.78	0.79	0.815	10.015	11.820	12.806	12.970	13.380
Weight factor	Cost		0.606	0.737	0.789	0.819	0.8335	4.974	6.050	6.477	6.723	6.842
3	10										Total:	123.032

Table 2. Pump Efficiency Index

Aerospace			Motor Efficiency Map					Point				
Speed (mph)	Factor	RPM @ motor	100 PSI	200 PSI	300 PSI	400 PSI	500 PSI	100 PSI	200 PSI	300 PSI	400 PSI	500 PSI
5	0.0413	64.98242001	0.78	0.885	0.944	0.947	0.923	3.2244	3.6585	3.9024	3.9148	3.8156
10	0.0787	129.96484	0.76	0.883	0.936	0.944	0.922	5.9843	6.9528	7.3701	7.4331	7.2598
15	0.1293	194.94726	0.74	0.881	0.928	0.941	0.921	9.5705	11.3940	12.0019	12.1700	11.9114
20	0.5043	259.92968	0.72	0.879	0.92	0.938	0.92	36.3118	44.3307	46.3984	47.3062	46.3984
25	0.1642	324.9121001	0.7	0.877	0.912	0.935	0.919	11.4921	14.3980	14.9726	15.3502	15.0875
30	0.0821	389.8945201	0.661	0.7895	0.86	0.798	0.899	5.4259	6.4807	7.0594	6.5505	7.3796
Weight factor	Cost										Total:	197.9571
2	11											
H3			Motor Efficiency Map					Point				
Speed (mph)	Factor	RPM @ motor	100 PSI	200 PSI	300 PSI	400 PSI	500 PSI	100 PSI	200 PSI	300 PSI	400 PSI	500 PSI
5	0.0413	64.98242001	0.56	0.64	0.67	0.69	0.7	2.3150	2.6457	2.7697	2.8524	2.8937
10	0.0787	129.96484	0.57	0.66	0.69	0.71	0.72	4.4882	5.1969	5.4331	5.5906	5.6693
15	0.1293	194.94726	0.58	0.68	0.71	0.73	0.74	7.5012	8.7945	9.1825	9.4411	9.5705
20	0.5043	259.92968	0.59	0.7	0.73	0.75	0.76	29.7555	35.3031	36.8161	37.8248	38.3291
25	0.1642	324.9121001	0.61	0.72	0.76	0.78	0.78	10.0146	11.8205	12.4772	12.8055	12.8055
30	0.0821	389.8945201	0.635	0.749	0.789	0.813	0.819	5.2125	6.1483	6.4766	6.6736	6.7229
Weight factor	Cost										Total:	117.8433
3	10				Gear at back 1:1							

Table 3. Motor Efficiency Index

6. Conclusion

A modular form of laboratory for experimental analysis of energy efficiency of a hydraulic system is developed. The experimental method, type of analysis, and design process is discussed in general terms. An example of a hydraulic transportation system, analysis method adapted, and design process is presented. The result was a superior design and better realization of design objectives. The methodology can be applied in principle to achieving energy efficiency in system design.

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