Experimental analysis for an energy efficient product design

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Due to growing demand for energy efficient products in the market, the investigation of energy usage in product lifecycles is becoming an important factor in the design process. Often, this problem is addressed by the analysis of energy efficiency of a product already designed and its subsequent design improvement. 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, 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]. The design of industrial products and processes requiring less energy will significantly impact the demand and production of fossil fuel-based energy. Moreover, these fossil-based fuels are finite in nature and someday the abundant supply fueling civilization will become scarce. Therefore, energy efficiency of products and processes are an important design consideration in engineering practices. Industries are looking for methods to reduce overall energy consumption and maximize sustainability of products and processes. Governments and legislative bodies are moving forward to mandate necessary changes in industrial practices to slow down depletion of energy resources and environmental impacts. Achieving these goals is a complex gradual process and requires a paradigm shift in product and process design. In academia, this awareness underscores the need for reforming curriculum so that graduates of programs are ready to lead these changes in practices. The National Science Foundation funds projects to update engineering curriculum for the comprehensive teaching of energy in different undergraduate programs. Accelerated testing methodology [2] project funded by NSF utilized statistical method to determine the interrelationship between various stress loadings and total energy use in a mechanical system and

establish a framework to facilitate the optimum experimental design and energy reduction 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 long term sustainability of an industrial society [3,4,5]. Generally, engineering design classes in undergraduate programs follow a structured problem- solving approach for solutions of open ended design problems. Besides achieving intended product functions and mechanical integrity of the product, additional analysis tools are utilized to achieve other design goals, typically referred to as design for X [6]. This may include a variety of design objectives to ensure long term sustainability of products and processes. Design for Environment (DfE), or ecodesign [7,8] 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 [9,10,11], would also allow the product designer to have a substantial positive impact on the environmental aspects of a product's lifecycle.

This paper presents an approach to the use of energy efficiency in product design in junior and senior level curriculums and capstone design projects. Because of the analytical complexity of the subject, an experimental method is utilized to improve the energy efficiency of the product in its normal operational conditions. Though the methodology is developed for a typical capstone design project, its use can be beneficial for design of a mechanical system in general.

2. Energy efficiency in design process

In a conventional capstone design project, a group of students are assigned a two semester design project. They go through a step by step process of problem definition, concept generation, design analysis, design specification, component selection and fabrication, prototype development, performance testing, and validation of the design process. In such a typical project, a student group is assigned to design a human powered hydraulic system capable of transporting a single person. Without using any direct drive mechanism, the system should be able to transfer the rider's power to the driving wheel through the use of a hydraulic system. The system should also be able to capture energy lost due to braking or downhill motion and store it for later use. In this

type of project, after design analysis students would select standard components available commercially and fabricate all nonstandard components. The system would be assembled and tested for its performance. The most challenging part of this design has been optimizing the energy efficiency of the system. Analytical formulation of overall energy efficiency is complex and detail analysis within the time frame of the design project is not expected from most undergraduate level student groups. Instead, the behavior of a developed system can be tested in the laboratory and the result can be utilized to maximize the energy efficiency of the final system. The most important components in this design project are the hydraulic pumps and motors. Based on their performance requirement, all commercially available models are selected. Manufacturers of the components provide performance characteristics tested in their normal range of operating conditions. In this design project, components operate in a much broader range of operating conditions, and therefore, their performance beyond normal operating conditions is essential in determining overall system efficiency. Design process incorporated development of this test process and performance testing of all major components as a routine part of the design process. Meaningful analysis of the test data requires sophisticated measurement, data acquisition, and an analysis system in the laboratory. Therefore, a new laboratory is being developed to assist student groups with such experiments.

3. Energy efficiency testing laboratory

A laboratory 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, students 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.

Pump module: This module has a permanent variable displacement pump to supply a fluid power system in general. The pump is driven by a 5 HP electric motor and has its own control (ABB ACS 500) to vary flow rate, a pressure controller (Dennison R1E), and a relief valve. A 15 gallon reservoir is used to supply fluid to this pump and other components of the module. A flexible pump mounting fixture is added to allow the installation of other pumps in a test system. The whole module is mounted on a portable frame and quick connect couplings are used to integrate with other modules as necessary.

Flow module: This module 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 series or parallel using two way direction control valves. Students would be able to create different types of flow circuit utilizing the tubes, hoses, and valves installed in the module.

Actuation module: A hydraulic motors and cylinders required in a specific design project are installed in this module. The module has flexible mountings to allow for the installation of different hydraulic motor or cylinder. An electro-hydraulic loading device (ABB/Bonitron) is used to apply a desired load on a hydraulic actuator. To supplement the electro-hydraulic loading system, another gravity based loading mechanism has been designed and will be added to this module.

Conditioning module: The temperature aspect is a neglected issue in most fluid power applications. To ensure the maintenance of physical properties and chemical stability, hydraulic fluid from the actuator is conditioned prior to the return to the reservoir. Prior to return to the reservoir, hydraulic fluid will be conditioned using a panel filtration unit, a heat exchanger and a heating unit in this module. This allows for testing the performance of a hydraulic system in a desired operating temperature, irrespective of ambient temperature.

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 collecting all process data (pressure, temperature, flow, torque, force, and rpm) in either analog or digital form. The sensors will be configured properly 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 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 the fluid power modules, thus allowing for a wider range of possible projects.

4. Experimental analysis

In this section an experimental analysis for design of a human powered hydraulic bicycle is presented. The objective was to design a hydraulic system that would minimize energy loss and optimize performance of the system in a series of competitive races meeting specified performance criteria. This required the overall system is developed using the most energy efficient components available at the operating conditions of the races. In the system, efficiency of the hydraulic pumps and hydraulic motors were the most important factors. A test cell (Figure 1) was developed and performance data of the pumps and motors were acquired using a LabVIEW program. The data was imported in Excel for detailed analysis.

Figure 1. Test cell for efficiency mapping of a hydraulic pump.

Energy efficiency mapping

In the design process, two sets of pumps and motors were selected and are identified as “Aerospace” and “H3” in all test results. The purpose of the test was to determine 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 I shows the bike speed, corresponding track length, shaft rpm and its duration. The data is used to calculate *Speed Factor* at each pump and motor shaft speed as fraction of total race time.

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

Where, S_i = Speed Factor

t_i = Duration of speed and

T = Duration of the race.

Corresponding shaft speed is calculated based on wheel rpm and gear ratio.

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

In the laboratory efficiency characteristics of the pumps and motors are mapped with respect to shaft rpm and pressure (Figures 2 and 3). 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.

Figure 2. Efficiency mapping of an axial piston pump.

Figure 3. Efficiency mapping of two hydraulic motors.

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

$$E_i = S_i \eta_i \quad \dots (2)$$

Where, E_i = Efficiency Index

η_i = Efficiency at pressure i

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

Where i and j are for each pressure and speed factor

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

For overall calculation speed and efficiency data was used to create regression model of efficiency characteristics and calculate efficiency index for any shaft speed and pressure in a specific design scenario. Based on this analysis highest efficiency index pump and motor were found to be 154.441 and 197.9571 for the Aerospace pump and motor respectively. Therefore, they were chosen in the final design. In a later stage of the design, efficiency index formulation was modified introducing factors due to size, weight and cost of pumps and motors. Because of low cost, H3 pump and motor were deemed more suitable in final component selection.

5. Conclusion

An experimental analysis to design an energy efficient hydraulic transportation system is presented. Gathering of the experimental data and its analysis is integrated with the design process. The result was better design and realization of design objectives. The methodology can be applied in achieving energy efficiency in design process in general.

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