Design of Energy-efficient Products Based on Experimental Analysis

Jorge Rodriguez and Alamgir Choudhury
Department of Industrial and Manufacturing Engineering
Western Michigan University
Kalamazoo, MI 49008-5336
jorge.rodriguez@wmich.edu

Abstract

Product design is an activity that needs to take into account many different engineering and non-engineering factors and issues during its various phases. There are factors that are directly related to the specified functions for which a design is being generated, and there are some factors that might not be directly related to the function of the design but they are important in the overall lifecycle of the product being designed. Among them, a design evaluation factor that has again come to prominence in the last decade is energy efficiency. Even though energy efficiency is most likely reflected in some direct evaluation factors, a specific evaluation is nowadays when a sustainability requirement is considered.

Including energy efficiency at an early stage may add to the complexity of the design process, but payoff may be significant in terms of market dominance and energy cost. In this manuscript a design process using energy efficiency as one of the primary criteria is presented. Experimental testing and analysis of component performance in functional prototype of a hydraulic system is used to select components for optimum operation. A laboratory setup is developed to test performance of hydraulic system components at a range of operational conditions. The availability of such data allows the designer to include parameters related to energy efficiency during the initial steps, and as more specific operational conditions are defined, performance parameters are extracted from the experimental data.

This methodology has been applied to standard pump-valves-motor hydraulic systems. It is expected that this methodology can be utilized in design of similar system where energy efficiency is a primary design criterion.

Introduction

The design of industrial products and processes requiring less energy will significantly impact the demand and production of energy in general. This is an important consideration because currently the vast majority of energy is produced from fossil-based fuels resulting in the increase of carbon dioxide in the atmosphere[1]. 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 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] is a project funded by NSF that utilizes 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 reborn 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], where “X” can refer to topics like Environment, Recycling, Disassembly[7,8,9].

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.

Energy efficiency in capstone design

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. An ongoing project is the design of a human-powered hydraulic vehicle 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.

In this type of project, after design and analysis are performed, the team selects standard components available commercially, and fabricates all nonstandard components. The system is 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 teams. An alternative, the performance of a designed 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 the performance requirement, 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 different set of operating conditions, and therefore, their performance at such operating conditions is not known but it is essential in determining overall system efficiency.

Energy efficiency testing laboratory

Performance testing of main hydraulic components is a topic that has been incorporated in the curriculum and in the undertaking of corresponding capstone design projects. Meaningful analysis of the test data requires accurate measurement, data acquisition, and analysis system in the laboratory. Therefore, a new laboratory setup is being developed to assist student groups with such experiments. 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. The modules are:

1. **Pump module:** This module has a permanent variable displacement pump, which is driven by a 5 HP electric motor and has its own controller to vary flow rate. An adjustable mounting fixture allows the testing of various components.
2. **Flow module:** This module allows the configuration of different types of flow circuit utilizing the tubes, hoses, and valves. The frame and basic components of this module is similar to a typical fluid mechanic undergraduate experiment.
3. **Actuation module:** This module has a hydraulic motor and hydraulic actuator to be used for a specific study or design project where electro-hydraulic load is required. It has as well adjustable mounting.
4. **Conditioning module:** This module allows for the control of the temperature in the fluid being used, in order to have stable physical properties and chemical stability. It allows the study of temperature as a parameter.
5. **Instrumentation module:** This module has sensors, data acquisition, data processing, and a display and control instrumentation. A combined NI's SCXI and PXI chassis is utilized. LabVIEW program is utilized to integrate the process sensors with the analysis and control system.
6. **Control module:** This is an external control module, and provides the ability to use mainly microcontrollers and programmable logic controllers (PLCs) in fluid power process. This module deals with hardware-based control systems.

Experimental analysis of pump-motor

A specific experimental analysis for a hydraulic system at low power and low rpms is presented. This case is part of the ongoing efforts for human-powered hydraulic bicycle. The design goal is to have an energy efficiency system, which implies selection of appropriate components that have combined efficient performance at operating conditions. In the considered hydraulic system, the pump and the motor are the source of most energy losses; therefore, the test focused on performance of candidate pumps and motors. Figure 1 shows the schematic of the testing cell setup, and Figure 2 shows a picture of the actual testing.

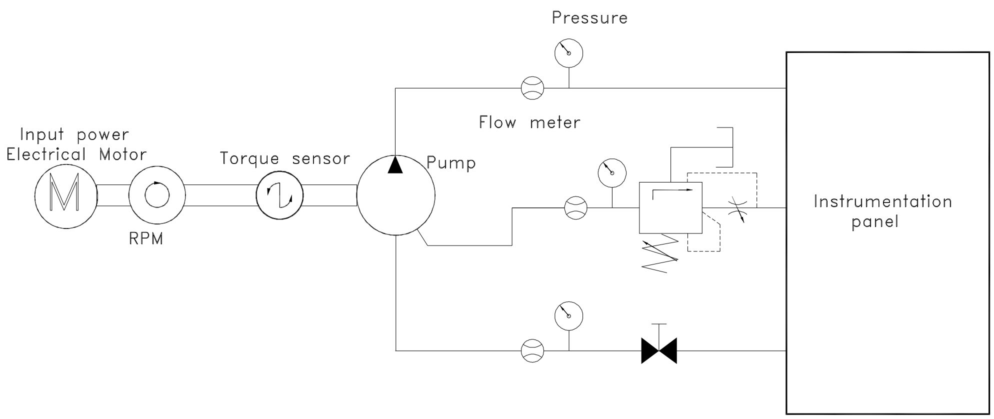

Figure 1. Schematic for test cell for hydraulic pump.

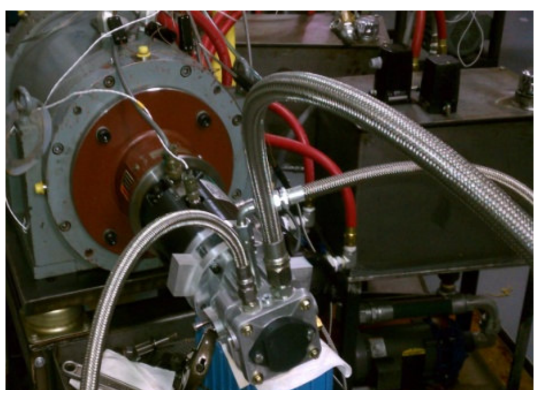

Figure 2. Picture of test cell for hydraulic pump.

Energy efficiency mapping

The purpose of the test was to determine which pump and motor would operate at higher efficiency during the whole range of operation. To determine the overall efficiency of the components, it was necessary to calculate operating conditions of the pumps and motors during various operation conditions. In related design calculations several desired speed of the vehicle at given operation conditions were converted to corresponding shaft rpm of pump and motor, based on tire diameter, gear ratios and hub settings. Table I shows the results for rear wheel rpms at given vehicle speeds, as it can be seen in the table the range of operation for the motor is very low (lower than 200 rpm for average vehicle velocity), further indicating the need for specific experimental performance data.

Table 1. Operating conditions

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

The testing cell was utilized to run the pump and motor at various rpm, pressures, and flow rates. Data is collected for these parameters as well as input parameters. Rotational speed and power are measured by utilizing an electric motor control system. Appropriate pressures and flows are maintained by using a pressure relief valve and a flow control valve. Two sets of pump/motor were evaluated, the "Aerospace" set and the "H3-piston" set. The collected data was used to generate efficiency 3D maps as function of shaft rpm and pressure (Figure 2), and specific efficiency 2D graphs (Figure 3).

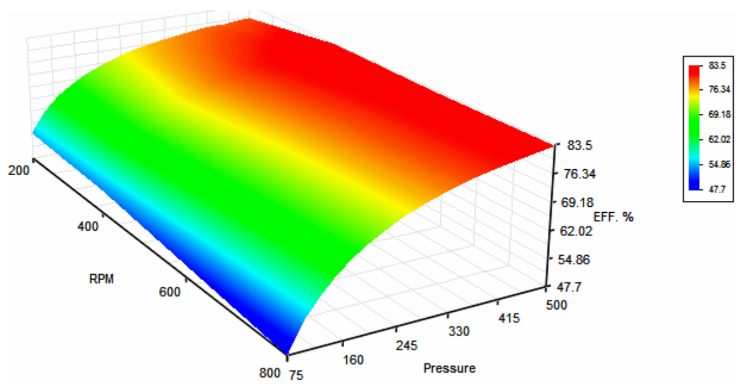

Figure 2. Efficiency 3D mapping for piston pump. .

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

$$E_i = S_i \eta_i$$

where, E_i = Efficiency Index i

S_i = Shaft velocity factor i

η_I = Efficiency at pressure I

And Overall *Efficiency Index* is

$$E = \sum_{i-1,n} \sum_{j=1,m} E_{ij}$$

where I and j are for each pressure and shaft velocity

These parameters were tabulated and the overall efficiency is defined for each combination of pump-motor. 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. The calculations for the pumps (Table 2) and motors (Table 3) are shown below. Based on this analysis highest efficiency index pump and motor were found to be 154.441 and 197.957 for the Aerospace pump and motor respectively. Therefore, they were chosen in the final design. It is important to mention that the design decision made here is solely function of the performance of the components, pump-motor in this case. In any design decision there are other factors that need to be taken into account, and the importance assigned to those factors might result in a different decision.

Conclusions

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.

Table 2. Overall Efficiency Index for Pumps

Aerospace							
Speed (mph)	Factor	RPM	Point				
5	0.0413	64.98242	100 PSI	200 PSI	300 PSI	400 PSI	500 PSI
10	0.0787	129.9648	2.089	2.666	2.760	2.647	2.916
15	0.1293	194.9473	4.057	5.170	5.342	5.277	5.671
20	0.5043	259.9297	6.791	8.643	8.913	9.054	9.507
25	0.1642	324.9121	26.982	34.294	35.303	36.816	37.825
30	0.0821	389.8945	9.030	11.492	11.820	12.477	12.641
Weight factor	Cost		4.634	5.897	6.082	6.487	6.487
2	11					Total:	154.441

H3							
Speed (mph)	Factor	RPM	Point				
5	0.0413	64.98242	100 PSI	200 PSI	300 PSI	400 PSI	500 PSI
10	0.0787	129.9648	2.526	2.939	3.096	3.286	3.245
15	0.1293	194.9473	4.811	5.622	5.953	6.220	6.220
20	0.5043	259.9297	7.902	9.273	9.868	10.152	10.282
25	0.1642	324.9121	30.815	36.312	38.833	39.338	40.346
30	0.0821	389.8945	10.015	11.820	12.806	12.970	13.380
Weight factor	Cost		4.974	6.050	6.477	6.723	6.842
3	10					Total:	123.032

Table 3. Overall Efficiency Index for Motors

Aerospace			Point				
Speed (mph)	Factor	RPM @ motor	100 PSI	200 PSI	300 PSI	400 PSI	500 PSI
5	0.0413	64.98242001	3.2244	3.6585	3.9024	3.9148	3.8156
10	0.0787	129.96484	5.9843	6.9528	7.3701	7.4331	7.2598
15	0.1293	194.94726	9.5705	11.3940	12.0019	12.1700	11.9114
20	0.5043	259.92968	36.3118	44.3307	46.3984	47.3062	46.3984
25	0.1642	324.9121001	11.4921	14.3980	14.9726	15.3502	15.0875
30	0.0821	389.8945201	5.4259	6.4807	7.0594	6.5505	7.3796
Weight factor	Cost					Total:	197.9571
2	11						

H3			Point				
Speed (mph)	Factor	RPM @ motor	100 PSI	200 PSI	300 PSI	400 PSI	500 PSI
5	0.0413	64.98242001	2.3150	2.6457	2.7697	2.8524	2.8937
10	0.0787	129.96484	4.4882	5.1969	5.4331	5.5906	5.6693
15	0.1293	194.94726	7.5012	8.7945	9.1825	9.4411	9.5705
20	0.5043	259.92968	29.7555	35.3031	36.8161	37.8248	38.3291
25	0.1642	324.9121001	10.0146	11.8205	12.4772	12.8055	12.8055
30	0.0821	389.8945201	5.2125	6.1483	6.4766	6.6736	6.7229
Weight factor	Cost					Total:	117.8433
3	10						

Bibliography

1. Energy in the United States, Wikipedia, http://en.wikipedia.org/wiki/Energy in the United States
2. Liao, H.T. and Zhang, D.. "Statistically Precise and Energy Efficient Accelerated Life Testing," *SAE Int. J. Mater. Manuf.*, v.4, 2011, p. 992-998.
3. Foundation for Global Sustainability, *Do You Know What Sustainability Mean?*, http://www.kornet.org/fgs/edu/index.html
4. Robert A. Frosch, "Sustainability Engineering (editorial)", *The Bridge* 29:1, Spring 1999
5. UN Environment Program/Industry and Environment, *Ecodesign: A promising approach to sustainable production and consumption*. Tech. Rep. CP18, 1997
6. Timkor, S., Haapala, K. and Kumar, V.; *New Engineering Design Concepts for Sustainable Products*, Proceedings of ASEE Annual conference and Exhibition, 2006.
7. Design for Environment (DfE) or Ecodesign Definition, http://www.dantes.info/Projectinformation/Glossary/Glossary, 2006.
8. Burke, D., K. Beiter and K. Ishii, *Life cycle design for recyclability*, Proceedings of the ASME Design Theory and Methodology Conference, Scottsdale, AZ, 1992, DE-42, pp. 325– 332.
9. Gungor, A., Gupta, S. M., *Issues in environmentally conscious manufacturing and product recovery: a survey,* Computers & Industrial Engineering, 36, pp. 811-853, 1999.