A laboratory for energy efficient product design

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Abstract

Traditionally, energy consideration has been secondary in standard design methodology taught in typical undergraduate engineering curriculum. Most design analysis is focused on performance of a product or a system in terms of function, structural integrity or realization of other design goals. In the later stages of the design process, performance simulation and theoretical analysis is utilized to justify design refinement. In absence of accurate mathematical model, experimental understanding of energy conservation and losses in a functional prototype of a product is a priori for a design process with emphasis on energy efficiency. To study the energy efficiency of designed product, a multipurpose laboratory equipped with thermo-fluid process components, sensors, data acquisition and analysis tools is being developed. It will allow installation and operation of the prototypes, and experimental study of performance of the components. Analysis of the experimental data will lead to optimization of geometry, materials and other design details of the components. The methodology will be practiced in undergraduate design projects and eventually incorporated in the product design curriculum.

1. Introduction

Presently, 82% energy used in the world is produced from fossil based fuel. Over 80% of the energy used in USA originates in coal, oil or natural gas [2]. Environmental concern, global warming, finite reserve and cost of fossil fuel have changed the nature of products sought by consumers. Demand for energy efficient products, from a simple hand held gadgets to a complex transportation system, have brought the issue of energy efficiency at the fore front of all engineering practices. Industries are also looking forward to reduce overall energy consumption, minimize environmental impact and maximize sustainability of products and processes. Governments and legislative bodies are moving forward to mandate necessary changes in industrial practice to slow down the depletion of energy resources and subsequent environmental impacts. Achieving these goals would be a complex gradual process and requires a paradigm shift in product and process design. In the academia, this awareness underscores need for reforming curriculum so that graduates of programs are ready to lead these changes in real life practices. National Science Foundation funds projects to update engineering curriculum for comprehensive teaching of energy utilization in different undergraduate programs. Among them, the process intensification project [3] integrated energy efficiency and safety in several engineering courses. US Department of Energy promotes best practices in energy efficiency, reusable energy, waste reduction and productivity improvement through integration of activities. In 2007, University of Missouri, the state agencies, MU

Extension, and major utilities in Missouri partnered [4] to achieve such goals. While energy efficiency and conservation is a novel objective on its own merit, many consider this essential for long term sustainability of any industrial society [5,6,7]. Generally, engineering design classes in undergraduate programs follow a structured problems solving approach to solve the open ended design problems. Besides realizing the function and mechanical integrity of the design, additional tools are provided for further analysis to achieve other goals, typically referred as design for X [8]. Design for Environment (DfE), or ecodesign [9,10] aims to reduce the life cycle environmental impact of a product by enhancing its design features. It may also include objectives to reduce resource consumption, in terms of material and energy as well as pollution prevention. Other concepts, e.g. Design for Disassembly (DfD) and Design for Recycling (DfR) practices [11,12,13] would also have substantial positive impact on the environment in a product's life cycle. This paper presents in integrated approach in engineering technology programs to use energy efficiency and innovative product design sequentially in freshman, sophomore, junior and senior level curriculum, capstone design project and undergraduate research.

2. Curriculum reform

In Michigan, clean & renewable energy, and energy efficiency practices has been adapted as a principal strategy to regain its predominance in the manufacturing sector. A spectrum of curriculum in sustainability, renewable energy, green manufacturing and energy efficiency has been introduced in universities. Western Michigan University (WMU) has adapted energy efficiency and sustainability as a cornerstone of the university policies and guidelines. It promotes education, research and innovation in energy conservation, renewable energy, environmental safety and green practices. All operational and developmental projects of the university are required to adapt these principles. Within the Department of Industrial and Manufacturing Engineering, teaching fundamentals of energy efficiency will be mainly through the thermodynamics and fluid mechanics courses. For a more comprehensive practice of the subject from freshman thru senior level, a new freshman level product design fundamentals is introduced. The thermodynamics and fluid mechanics courses are reformed as a lecture and lab classes, and a new advanced product design course is introduced. Prior to graduation, students would utilize this knowledge in their capstone design project for design of innovative energy efficient products.

3. Energy efficiency testing

In recent years students of engineering technology programs of WMU have been offered capstone design projects for innovative design of energy efficient products. In 2004 students were challenged to design and develop a human powered hydraulic bike that can transfer a rider's manual power to the driving wheel using a hydraulic media. Subsequently, every year new design teams addressed this problem and attempted to improve the system design. Initially the challenge was to design a competitive system using mostly commercially available components. Later, improving the energy efficiency of the overall system became the primary goal of the design project. In this process students first identify the sources of energy loss and their nature. Using the conventional problem solving approach, they attempt to optimize the overall energy efficiency of the system under consideration. Specifications of components are derived from detail performance analysis of the system. It became evident that the traditional problem solving approach taught in machine design classes is not the best approach for design an energy efficient system in a capstone design project. As a result, a new design methodology was established to determine efficiency characteristics of standard components to be used in an application. This method required experimental measurement of performance characteristics and efficiency of all important system components at variety of operating conditions. Though manufacturers of the components provide typical performance data around recommended operating conditions, our design project required energy efficiency of system components at completely different operating conditions. Therefore, experimental determination of the performance characteristics of the components at all operating conditions became essential part of the design process. Students had to allocate significant time blocks to develop the test setup, gather performance data and utilize them for design optimization. Meaningful analysis of the test data requires sophisticated measurement, data acquisition and analysis tools. Due to lack of such facility on campus, students often had to use test and measurement system in local industrial sites. This underscores the importance of establishing an energy efficient product design laboratory on campus where students can routinely test performance of a designed system and its components as necessary.

3.1 Performance testing for product design

In Fall semester of 2011, in a standard two semester capstone design project, an interdisciplinary group of student were assigned an industry-sponsored project to design of a human powered vehicle. At the end of second semester, the group would participate in a design completion among twelve other universities. Due time constraint of this project, instead of detail design of each component of the system, the design team decided to adapt standard industrial components and focus on improving the initial design by optimizing performance of the overall system. Operating conditions of each component were established by simulating the competition race. Efficiency of components at these operating conditions was measured in a test cell (Figure 1) to optimize overall energy efficiency of the system.

3.2 Energy efficiency mapping

A critical feature of the human powered vehicle design project was to ensure optimal function of the hydraulic power train. Since design, fabrication and performance testing of all necessary components within the project time frame was unrealistic, it was decided to select the most suitable pumps and motors available in the market and adapt them in design of the overall system. These pumps and motors functions the best at significantly high power and rpm of industrial applications. In the human powered hydraulic vehicle, power delivered by the rider is generally less than half horse power and pedal speed varies in the range of 0-100 RPM.

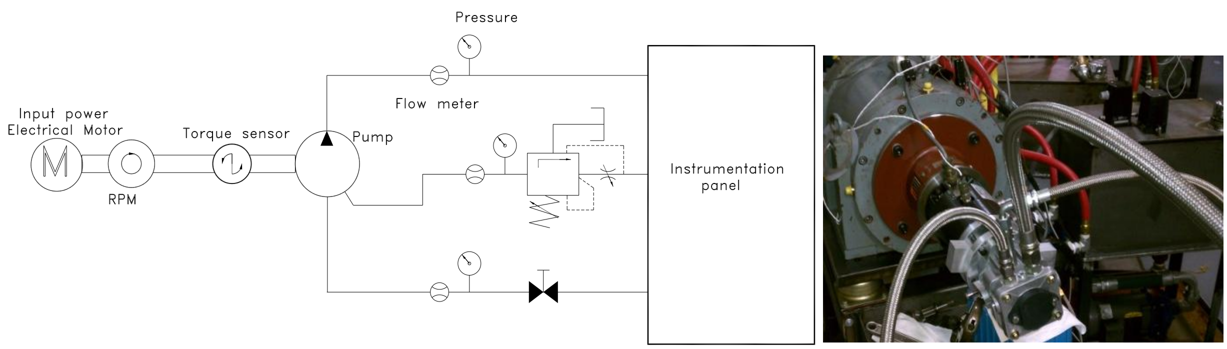

Figure 1. Instrumentation for efficiency mapping test cell.

Similarly RPM of the hydraulic motor that powers the driving wheel of the vehicle is significantly lower than most industrial applications. Therefore, the challenge is to ensure that the pump and motor used in such a hydraulic system can operate at the maximum possible efficiency. Equipment manufacturers provide operating characteristics of each model at their nominal operating conditions. Beyond those conditions, efficiency characteristics of the system are unknown. No commercial hydraulic pumps/motors matched the exact weight, power, torque and rpm conditions required in the vehicle. Among the pumps and motors meeting the system requirement of the vehicle most closely, efficiency characteristics at the operating pressure and rpm of the system was still unknown. Therefore, a special test stand is used to map overall efficiency of each pump and motor at diverse operating conditions. The system consists of a hydraulic system equipped with targeted pump and motor, sensors, data acquisition and analysis system. Pump's rotational speed and power are manipulated by using an electric motor control system. Desired system pressure and speed is maintained by using a pressure relief valve and a flow control mechanism. Two sets of axial piston type pumps and motors were initially selected and tested. In both types, it was found that the efficiency changes with system pressure and rpm (Figure 2). Efficiency of the pumps and motors were recorded from lowest to highest pressure and rpm deemed necessary in the simulated race. The highlighted (Figure 3) zones show the higher efficiency of one tested system over the other.

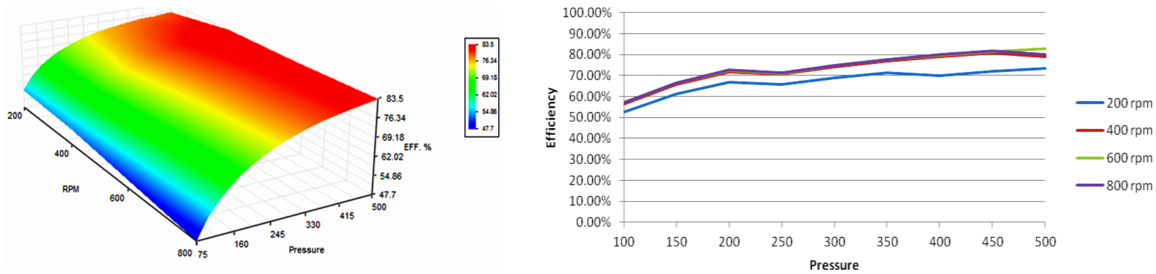

Figure 2. Efficiency mapping of an axial piston pump.

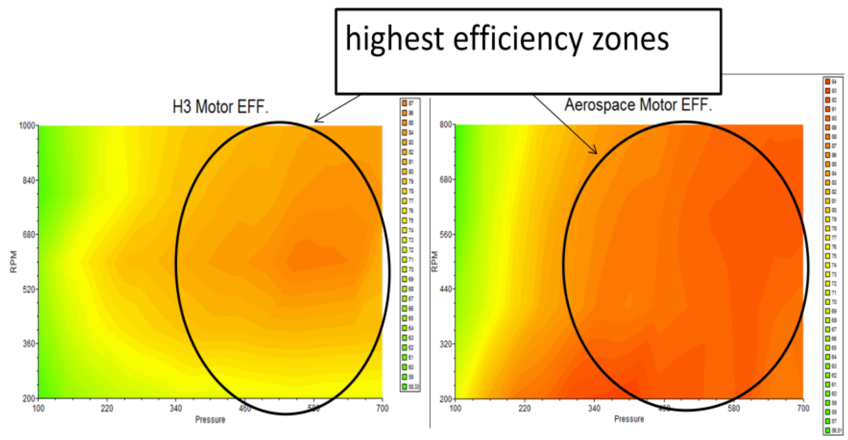

Figure 3. Efficiency mapping of a hydraulic motor.

An *Efficiency Index* of the system was calculated by using time multiple of efficiency of each components in the simulated race track, $E_I = \sum_{i=0}^{T} t_i e_i$, where t is duration of energy efficiency e of a device in total time of T of the race. Individual duration of efficiency was derived from the amount of time a component operates at each *RPM Index* in the entire course length shown in Table 1. Performance of pump and motor can be analyzed using an *Efficiency Index* value and the sum of the area of the map. Other factors that affected the *Efficiency Index* value were size, weight, and cost. Among the components deemed suitable for an application, the one with highest efficiency index is most suitable to maintain highest energy efficiency of the overall system. Table 2 shows the efficiency index of two sets of hydraulic motors operating at the simulated operating condition of the race. The Aerospace motor with efficiency index of 197.95 was the obvious choice compared to H3 motor with efficiency index of 117.83 under identical operating conditions.

Table 1. Course Factor

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 2. Motor 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						

4. Energy efficiency testing laboratory

A more detail energy efficiency laboratory is planned to test performance of a prototype, existing components with variety of system configuration, and fluid power system designed in general (Figure 4).

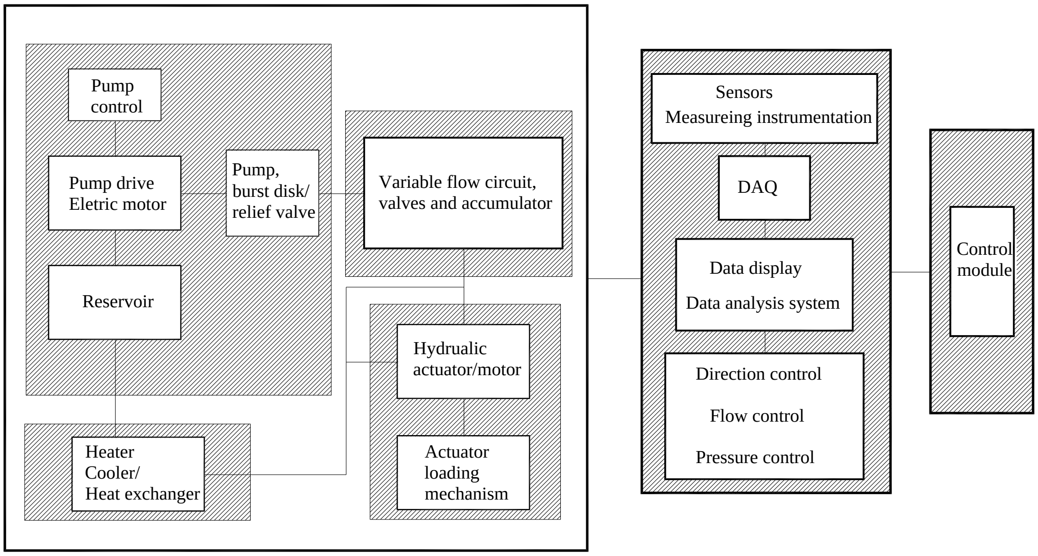

Figure 4. Layout of fluid power system laboratory.

In the design stage, students will use Matlab, Automation Studio, and other analysis tools to model and study behavior of a system and its components. For hands on study of the process and the system designed, students will assemble the components and study its performance characteristics. The laboratory is composed of following six modules. Using quick connect coupling and flexible hose, these modules will be connected as necessary.

Pump module: This module will have a permanent variable displacement pump to supply a fluid power system in general. The pump will be driven by a 5 HP electric motor and will have its own control to vary flow rate, a pressure controller and a relief valve. A reservoir sufficient to supply this pump and any other application will be part of this module. A flexible pump mounting fixture will be added to allow addition of other pumps in a test system. The whole module will be mounted on a portable frame and using quick connect couplings can be added to other modules as necessary.

Flow module: Students will be able to create different types of flow circuit utilizing the tubes, hoses, and valves located in this part. The frame and basic components of this module are already established and will be expanded further to allow creation of a hydraulic circuit necessary for a specific system under consideration. Additional components, accumulator and flow control valves will be necessary for this module.

Actuation module: Hydraulic motor and cylinder to be used for a specific study or design project will be installed in this module. The module will have flexible mountings to allow installation of a hydraulic motor or cylinder. An electro-hydraulic loading device will be used to apply a desired load on a hydraulic actuator.

Conditioning module: Temperature aspect is a neglected topic in most fluid power curriculum. In this laboratory, to ensure maintenance of physical properties and chemical stability, hydraulic fluid from actuator will be conditioned prior to return to the reservoir. A water cooled heat exchanger and a heating unit will be utilized for this purposed. This will allow testing performance of a hydraulic system in a desired operating temperature, irrespective of ambient temperature. Students of thermodynamics class will be able to practice measurement of thermal properties of a fluid, investigate energy balance and application of laws of thermodynamics in a realistic hydraulic system.

Instrumentation module: This module will have the sensors, data acquisition, data processing, and display and control instrumentation. A combined SCXI and PXI chassis based National Instrument hardware will be utilized for this purpose. NI DAQ cards, and other accessories will be utilized for collecting all process data (pressure, temperature, flow, torque, force, and rpm) in either in analog or digital form. The system will also allow sending appropriate signals to process actuators, e.g. valves, pump drive and temperature controller. LabVIEW program will be utilized to integrate the process sensors with the analysis and control system. Additionally, Matlab, Automation Studio, and other analysis tools will also be used for further study of process and component behavior.

Control module: This is an external control module, and will provide the ability to use mainly microcontrollers and programmable logic controllers in fluid power process. This module deals with hardware-based control systems, as opposed to the software-based controls included in the Instrumentation Module. The applicability will expand to other systems besides the ones in the fluid power modules, thus allowing for a wider range of possible projects.

5. Impact on Design and Performance

The initial implementation of a bench for testing of thermo/fluid components has resulted in a deeper understanding of the impact that energy efficiency considerations on the engineering design and overall performance of a mechanical system. 'Energy efficiency' typically is not given a high priority in the design process, thus resulting on great designs which are not so great in performance when the complete lifecycle evaluation is considered. At this point we have been successful to carry out our goal of including these philosophies across the curriculum in 2nd and 3rd year courses, with limited implementation at the senior level. The goal is to have design projects in the upper level systems-design course that emphasize energy efficiency from an early stage of the design process.

6. Conclusions

A laboratory is being developed to test performance and energy efficiency of fluid power applications. Thermodynamics, fluid mechanics and product design curricula are reformed to incorporate experimental testing and performance study of engineering applications. To design more energy efficient system, these experiments and test results will be utilized in class projects of product design classes and capstone design projects. Initial use of this integrated design philosophy has already produced an award winning design of a human powered hydraulic vehicle.

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