AC 2009-2467: AN EXPERIMENTAL SET UP FOR OPTIMAL DESIGN OF A HUMAN-POWERED HYDRAULIC BICYCLE

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Experimental Setup for Optimal Design of a Human-Powered Hydraulic Bicycle

Abstract

Product development competitions through capstone design courses pose both, opportunities and challenges for graduating seniors in engineering and engineering technology programs. Faculties of relevant programs recognize the value of industry-sponsored projects for involvement of students in genuine practice of the design process, and for participation in major competitions. This can result in supportive sponsors, substantial resources, and enhanced motivation for the students. However, such competitions may also impose process, materials, fabrication, time, and performance constraints that are not usually encountered in a typical capstone design project.

This paper discusses senior design projects that have been based on a national hydraulic bicycle design competition sponsored by a major corporation. Incorporating long-term performance criteria of a product/system at an early stage of the design cycle was beneficial, and this experience is discussed. However, the team encountered a variety of challenges in working through the many constraints of the competition. Because such competitions typically work from a industry rather than an academic timeline, tasks such as prototyping, design refinement, fabrication, and a performance-based competition may be overwhelming for a two-semester project. Similarly, variability of the design team, integration of multiple design concepts in the final design, selection of available industrial components in lieu of specified components in the design are faced and also discussed in this paper. All of these specific conditions affect the implementation method of a traditional engineering design process and must be addressed by faculty. Thus, while industry-sponsored competitions offer exciting potential for capstone design projects, it is important that faculty, students, and sponsors recognize and respond to the constraints and challenges they are likely to face in successful completion of these projects.

Introduction

Prior to graduation, in most four-year technical programs, seniors are required to demonstrate ability to apply their academic learning and skills through a design and development project in a multi-semester capstone design course. There, a group of students are supervised by faculty to undertake a project which leads them through the general design process. Students solve the design problem from concept to finished product, going through design specification, analysis, improvement, and finally demonstrate successful performance of their design using a prototype or even the actual product. It might be an open-ended multidisciplinary team project involving design, analysis, or application with results presented in a written report in specified format. In many programs students also present their projects in public forum. In this type of project, students must be able to apply technical tools and skills to develop a solution for the chosen problem. To plan and track their progress, the students often use project management tools. Beyond the stated objective of the project, in the process the students also learn the importance of professional behavior, engineering ethics, role of a team member, need for lifelong learning and effective communication of project objectives, analysis and recommendations.

Recognizing the value for students in responding to real-life needs, expectations, and constraints[1], engineering and engineering technology faculty increasingly seeks corporate sponsorship and involvement in senior projects. Motivation for students is enhanced when they see themselves solving a practical problem for a industry client[2,3], and interaction with sponsors exposes students to demands and requirements not typically encountered in academic settings. This motivation and the rigor of project requirements can be heightened when the industry-based senior project is part of a larger competition[4].

At this institution students generally are offered a choice of industry-sponsored design, development, and/or analysis projects or grant-supported research projects with specific objectives that can be achieved within a time period of two semesters. Each student indicates its preference for first, second and third option. Using a bidding process, eventually a group of three or four students is assigned to each of the selected projects, since team-based design work reflects industry practice, where teamwork has become the prevalent mode[5]. In the case where the project has a sponsor, be that for commercial or non-for-profit organization, students seek additional information about sponsor's expectations, timelines, and specific design constraints. At times, those conditions may be too challenging for the students and may lead to frustration, but learning to ask the right questions is also essential to assimilate with the industry culture[6].

The project presented exemplifies how industry sponsored projects with objectives beyond capstone design courses may lead to frustration, unless participating institutions create a mechanism to achieve the objectives of both parties in a timely manner.

Initial Projects

The Parker-Hannifin hydraulic bicycle design[7] competition ("Chainless Challenge") started in the fall semester of 2004 among ten different universities across the nation that are part of Parker's hydraulic education initiative. The purpose of the competition is to challenge undergraduate engineering and engineering technology students for innovative design and development of a bicycle that would transfer a rider's manual power to the driving wheel through a hydraulic media without using any chain or direct drive mechanism. In a period of one year, students at participating universities would complete the design and development of the bike. Parker provided monetary and material grant to each university to offset part of the cost of design and fabrication of the bike. In the following summer, all university teams would meet at Parker's HQ to participate in the competition. Parker would evaluate each team based on novelty in design, reliability and safety, cost, manufacturability, marketability, workmanship, and design report. Finally, each team would compete in a 100-yard sprint race (new for 2008), and a 12-mile endurance race in a hilly terrain. A composite score including all listed areas and performance in the races would be used to determine the winner and rank each team.

Faculty of each participating university Chainless Challenge has the liberty to decide how to manage their design project. Most universities with large Hydraulics program form a dedicated team to work on the project from beginning to end. Other faculties involved in the project have realized that the task involved in design, development and eventually winning such competition are far beyond the scope of a typical capstone design project. Therefore, some have decided that initial design of the hydraulic bike would be completed as one senior design project. Since the design group would graduate at the end of the spring semester, a new group of students would be carry on with the implementation based on that design.

As the overall design project and design competition criteria is presented to senior students, class discussions showed that students think that this project is very intriguing and exciting, but students are also cautious about the possibility of being involved in a national competition. Since building the bike and participating in the competition have been separated from the objective of the senior project, it has been a capstone design project with high degree of interest in the class. Among the interested students opting for the project, a team of four with both design and manufacturing background are typically chosen for the hydraulic bicycle design project. A typical senior design project requires defining the design problem, researching necessary background information, articulating a plan to solve the problem, writing an official proposal, undertaking the appropriate tasks, testing, evaluating, refining, and finally, reporting findings and making recommendations.

Because of importance of the design for the competition, the student teams, working under the specific needs of the competition, have encountered and ultimately worked through a number of constraints and expectations most of their classmates have not experience. At that time it was decided that the scope of the senior design project would be limited to concept generation, analysis, detail design, design specification and prototype for proof of concept. Accordingly, the senior design teams complete their design according to the requirement, produced the design specification, and usually develop a prototype as proof of their concept. A formal design report is produced in specified format and the project is presented in an open public forum. At the end of the spring semester the groups graduate and a new group of students are recruited to continue on with the project. This new group, not necessarily a senior design team, is responsible for fabrication of the race bike based on the design specification provided by the senior design group. During the summer this new group fabricates the complete system, tests its performance and eventually the team participates in the competition. The hydraulic bike design project has continued each of the following years. The emphasis has been improvement of the previous design based on its performance rather than creating a brand new design. Consequently, focus of the senior design teams has been to analyze previous model's performance, identify area of design improvement, and define and specify them for the new bike. This approach has produced better performances in the competition in each of the subsequent years. It is similar to design of a production model based on actual performance and customer feedback of a newly designed product in industry.

New Design Objective

The overall objective of the senior design project presented here is to lead a group of four students to optimize the design of a recumbent style hydraulic bicycle based on established design and performance criteria. If the hydraulic bicycle design is considered as a long-term design process, each year a senior design project team achieved specific short-term goals which contribute to continuous design improvement, thus leading to better performance in the competition. In this project, although students are guided through the overall design process, the students initially study the performance of previous designs and identify the areas of improvement in the design. Specifically the goal of the project was to:

1. Identification of areas of design improvement based on performance of previous designs and criteria specified
2. Development of methodology for optimizing the overall design

3. Implementation of the design process
4. Development of prototype for proof-of-concept
5. Design documentation and presentation of design in a public forum.

Design Process

The design team field-tested the performance of previous hydraulic bicycle and identified the following areas of improvement:

a) Reduction of weight both frame and components
b) Efficiency of the hydraulic drive system
c) Drive-train performance.

Reduction of weight frame and components: For the first area of improvement, the student team planned the details of the design process, individual responsibility, timeline, logistics, material requirement, budget and assessment and feedback procedure. The main features of the process are briefly presented here. After study of earlier designs, the criteria of performance of the new system, and space constraints in the assembly of the components, it was decided that a three-wheeled recumbent frame would be most suitable for the new system. A dropped frame with lower center of gravity in single-body frame style was deemed ideal for maintaining stability in sharp turn in a hilly terrain. It accommodates riders from 5'2" to 6'2" comfortably with minimum adjustment of the pedal location and steering handle. An adjustable support bar connected to the rear of the frame ensured ergonomic seating position of all riders. The frame was incorporated with larger wheel to accommodate with the new drive train. Based on material characteristics[8], both carbon fiber with aluminum parts and all aluminum frames were considered. Finite element analysis was performed to evaluate stresses and deformations of the designed components to ensure their safe performance in 5,000 miles of continuous operation. This achieved a primary design objective by reducing the frame weight by 49% compared to previous design.

Efficiency of hydraulic drive system: A key component of this design was to ensure optimal function of the hydraulic power transfer system. There are specific performance and safety criteria of bikes that would be participating in the competition. Due to limitations in time, cost and manufacturing methods available in a typical university laboratory, design of pump and hydraulic motor meeting the operating characteristics of the bicycle was deemed unrealistic. Instead, it would be prudent to identify available pump and motors which would perform most efficiently at the operating rotational speed and torque of the bicycle. Most hydraulic motors and pumps are designed for industrial use at relatively high velocity and pressure, transferring significantly large amount of power compared to a human-powered hydraulic bicycle. Power delivered by a typical rider of a recumbent bike is generally less than half a horsepower at pedal velocity varying from 0 to 100 rpm. Similarly, the hydraulic motor powered by the resulting fluid flow actuates the driving wheel at a relatively low speed. Experience of past hydraulic bicycle performance shows that overall efficiency of hydraulic motors and pumps is a critical in minimizing power loss in the overall drive system. Therefore, one needs to ensure that the pump and motor used in such a hydraulic system operate at their maximum possible efficiencies. In this design process, selection of pumps and motors were based on their efficiency at the operating conditions of the hydraulic system. Manufacturers of pumps and motors provide operating characteristics of each model at the normal range of their operating conditions, which are generally very high in power, torque and rotational velocity compared to the requirement of the new system. No commercial hydraulic pump and motor was available that is recommended for application at the low power, torque and velocity encountered in a bike. From the manufacturer's catalog, students identified a series of pumps and motors that most closely met the power, velocity and flow requirement of the hydraulic bicycle. But their efficiency at the bike's operating conditions is not available in the manufacturer's catalog. It was necessary to test characteristics of those pumps and motors in the laboratory. Therefore, development of a test bench and determination of pump and motor efficiency was incorporated in the design process. The test bench (Figure 1) utilizes a battery-powered DC electric motor driving the target pump by a synchronous belt and pulley system. A friction clutch system was developed to apply load to the hydraulic motor under various conditions. The system allows testing of hydraulic motors at different torques simulating operation of the bike in level as well as hilly terrain. A load is applied by hanging weights from a 26" lever arm which pushes the friction clutch against an aluminum drum. The frictional force of the clutch and leverage ratio of the arm is used to calculate torque applied on the motor shaft. The clutch was lubricated with oil to ensure identical frictional behavior at all test conditions. Testing was conducted using the static load required to propel the bike in level ground to the steepest hill of the competition course.

Figure 1
Hydraulic system test bench

Calculation of pump and motor efficiency at various operating conditions of the bike are based on power delivered to the pump, output power of the pump, power delivered to the motor and output power of the motor. The system is equipped with pressure gage and flow meter at the exit of the pump. Applied voltage and current are measured to calculate the input power to the electric motor. Pump input power is calculated by using the DC motor input power and its rated efficiency. At the beginning of testing, selected pump and motor were installed in the test circuit. Next desired load is applied to the hydraulic motor through the friction clutch. Before recoding any reading the system was run for several minutes until pressure and flow reading stabilized. From the pressure and flow rate, pump output power is calculated. Friction torque in the clutch is calculated based on applied load in the lever and friction coefficient of the wet clutch. Using the friction torque and motor velocity, output power of the motor is calculated. The calculated efficiency of each set of pump and hydraulic motor based on input and output power at various loading conditions of the pump and the hydraulic motor were recorded for further analysis. Efficiency characteristics of each pump and motor at various torque and velocity were plotted. These characteristics were supplemented to the measured characteristics provided by manufacturers of each device. Each hydraulic motor and pump was rated in terms of their efficiency at the range of operating conditions encountered in hydraulic system of the bike. This provided a clear rationale for selection of pump and motor for the hydraulic system. Since design and fabrication of special pump and motor for the hydraulic bike was not realistic, without such testing, a designer would be able to select the most suitable pump and motor only through a prolonged trial and error. Selection of pump and motor through such lab test allowed the design team to focus on the next crucial area of design improvement – drive trains for pump and driving wheel.

Drive-train performance: Once the hydraulic motor and pumps were selected, the team designed gear train required to drive the pump by the pedal and mounting bracket of the pump. This motor drive and gear train at the rear to actuate the driving wheel was composed of a reduction gear and internal hub in the rear wheel. Issues addressed during this part of the design process were, space constraint for the drive trains, weight, alignment of gears and drive shafts, appropriate manufacturing methods, system assembly, maintainability, reliability and their eventual performance.

Complete design specifications, along with performance simulation was documented and design report was presented in specified format. At the end of spring semester, a new group of student fabricated components and assembled the overall system (Figure 2). It was tested on campus for both performance and reliability prior to the competition.

Figure 2
Hydraulic bicycle

Conclusion

The objectives of industry-sponsored project and academic programs were achieved by matching the goals of the senior design course with that of the design competition. The mechanism used to integrate the work of a capstone design project with the hydraulic bicycle team was not seamless, but at the end all the set goals were achieved. Students were lead through a design process to optimize the performance of a previously designed system. Optimization of the design through feedback from product operation was achieved by laboratory testing of hydraulic system components before the improved system was fabricated. Based on this design, the new hydraulic bicycle was developed by the second group and successfully participated in the competition.

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