Design Application: A Product to meet the need

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1 Introduction

He was fluent in mechanics and could calculate the stresses on the components of an assembly, but he had no confidence in applying his knowledge to a functioning machine. She knew how to draw using CAD, but she was overwhelmed by the complexity of selecting components to work together in a system. He was familiar with basic manufacturing processes, but he had no experience in assembling them into a production process with only product specifications to guide him. She understood tolerances but didn't have the experience needed to place tolerances on a blueprint in a manner that permitted cost-effective manufacturing. The faculty of the Purdue University Mechanical Engineering Technology Department determined that they could do a better job of providing practical application of organization, synthesis, and analysis skills to engineering technology graduates.

A Mechanical Design course was therefore introduced into the Mechanical Engineering Technology curriculum at Purdue University and taught for the first time in the Fall of 1997. It represents a cross-disciplinary approach to capstone application of the principles taught in the design, materials, mechanics, fluid power, and manufacturing undergraduate course sequences. The course utilized a student teamwork-oriented approach to accomplish three design projects and employed additional faculty to discuss such topics as inventiveness, concurrent engineering, teamwork & supervision, life cycle design, manufacturing cost, product safety, and professional ethics.

2 Course Objectives

Several primary objectives were established, following faculty recommendations from curriculum and mechanics subcommittees and from members of the Industrial Advisory Committee. The first was to **emphasize the fundamental elements of the design process**. Faculty members with expertise in selected topics offered to give supplemental lectures that included their personal experiences. Students received an introduction to each topic that included class exercises as well as assigned readings. Most, although not all, topics were further reinforced through team activities associated with the student design projects.

Secondly, **provide multiple open-ended design experiences** that reinforce prerequisite course work. Three projects were chosen to emphasize mechanical design, fluid power design, and manufacturing process. Students were assigned into three-member design teams[1] to encourage team effort and to discourage being perceived as slacking off. Student selection for these teams was based upon a leadership profile questionnaire[2] administered during the initial class session. The projects included lectures, lab activities, original investigations, personal logbook maintenance, computer aided drafting, and finite element analysis.

Thirdly, **provide interactive associations with regional industries.** During the initial course offering, spokespersons from the manufacturing sector supplemented class lectures and a plant trip was also conducted. Longer-term objectives include having design projects whereby industrial leaders can participate as mentors for students fulfilling a business need.

3 Project 1 - Line shaft Design

The project required students to design a solid, steel line shaft that delivered 40 hp each to a simple gear train and a V-belt drive at 1750 rpm. Although the project was an academic exercise in shafting, it served to refresh concepts taught to students in Strength of Materials, Machine Design, and Metallurgy. Each of the three-member teams was required to complete their design with documentation that included assembly and detail CAD drawings, parts list, sample calculations, and narrative descriptions that provided reasons for each portion of their design. The students were then able to apply their design to the subsequent manufacturing-process design project. The intent is to use the experience of this coordinated effort to plan for students to additionally manufacture, assemble, and test a "real" shaft from their design in follow-on semesters.

Design teams first selected the spur gears and sheaves from vendors' catalogs that met specified driven speeds, center distances, and duty requirements. The applied torques and lateral loads on the shaft due to these machine elements were then used to size the shaft based on stress analyses using maximum shear-stress and maximum distortion-energy theories. In order to account for the stress concentration at the keyseat locations of the pinion and gear, the Rule of Thumb of "reducing the allowable stress by 25% at keyseats" was utilized. A finite-element analysis (FEA) of keyseat stresses was demonstrated during a lab session, and students were assigned a similar FEA homework problem.

Students then did a "design by stiffness" based on torsional deflection, and this design produced larger required diameters along the shaft than did the "design by strength" which used the stress analyses. A brief review of some fundamental concepts of metallurgy reminded students that stiffness depends on the moduli of elasticity (Young's Modulus) and rigidity (Shear Modulus) as well as on shaft geometry, whereas a strength design depends on shaft geometry and the strength properties of yield and/or tensile strength with suitable factors of safety. Since the moduli of elasticity and rigidity do not change significantly between steels or between the same steel with different heat treatments whereas strength properties do, the design teams concluded that a material choice for the shaft could be a less expensive 1020 or 1040 steel rather than a high-hardenability 4140 or 4340 steel.

Next, the design teams were required to select the bearing assemblies from vendor catalogs. A 5-year B_{10} life was required for the bearings. Due to the brief time remaining in the first 5-week project, bearing selection was limited to pillow blocks that used deep-groove ball bearings. The design teams soon discovered that the 5-year bearing life required larger bore diameters at the trunion locations than the minimum shaft diameters previously determined in their strength and stiffness designs.

A guest lecturer from Alro Steel in Indianapolis gave the final lab presentation on some practical guides for shaft design.

Up to this point, the students were "guided" towards the expected conclusion. Then each design team was required to make the final decisions for their shaft configuration and to write their final reports. The instructor was available during office hours to answer questions such as:
1) how close should the pillow blocks be mounted next to the pinion gear and the V-belt sheave?
2) which tolerances need to be specified on the assembly and detail drawings?
3) what final process needs to be specified for the 1020 or 1040 steel?

The final project 1 reports from the design teams were very good, but the design project needs to be improved along with an additional allocation of time so that the following investigations can be included:

1) stiffness investigation involving lateral deflection over the length of the shaft and at the gear-train location in order to prevent excessive mating-teeth separation,
2) stiffness investigation involving excessive slope changes at the bearing locations in order to prevent shaft binding,
3) inclusion of fatigue and fracture investigations in the strength design,
4) calculation of critical shaft speeds instead of relying on a short shaft with bearing mounts close to the power take-off's to "probably" produce sufficiently high critical speeds,
5) selection options for bearing mounts and housings that would include shaft shoulders and interference fits.

4 Project 2 - Lawn Tractor Conversion

Hydraulics are used extensively in large mobile equipment and off-road vehicles of all types. In this project, students used a small mechanically powered lawn tractor to investigate the use of hydraulics for propulsion, motor rotors, lifts/actuators, steering, and other functions not currently feasible because of the mechanical system limitations. The nature of this project is such that a detailed design or actual construction of the modifications to the tractor could not be accomplished in the available time frame. It was concludued that a conceptual design, coupled with the evaluation of marketing applications and the feasibility study of manufacturing methods applicable to key elements of the system would be of maximum educational value to the graduating MET students taking this course.

The project emphasizes the systems aspects of design, how components are selected and how they function together. Converting the design to hydraulics requires the students to become familiar with the advantages of the high force capability of hydraulic actuators and the extensive variability of hydraulic propulsion. They also need to be aware of potential disadvantages in hydraulics, i.e., higher cost and decreased power efficiency which must be offset by added or new capabilities. The complexity of the new system required structuring the teams so that each major function of the tractor would be separately engineered and integrated into a total working system.

Each of the three-member design teams was assigned one of the following five principal phases:

1. Power conversion and distribution system
2. Vehicle Propulsion
3. Mower Drive and position
4. Vehicle steering and blade actuation
5. Hydraulically powered accessories

The coordination of various subsystem interfaces on the vehicle was essential in order for all systems to operate efficiently and safely. In the photo Fig. 1, a typical systems coordination took place in a laboratory session. The responsibilities of each of the teams included, but were not restricted to, the functional tasks implied by the title of the team.

All teams have at their disposal the computer-based electronic catalogs of Vickers and Parker Hannifin and a variety of industrial and mobile fluid power catalogs in the Fluid Power Lab. A guest lecturer representing Kraft Fluid Power, a prominent mobile Fluid Power equipment supply house, was invited to speak to the class.

Figure 1. Hydraulic Circuit Diagrams are matched to form working system

The tractor was on display in the Lab at all times and copies of the available service and maintenance literature was given to each team. Manufacturers' performance data on the 12 HP Briggs and Stratton engine was made available. The Lab computers carry a program called Hydroworks which facilitates the design and drafting of hydraulic circuitry. Also, a 2-dimensional CAD package called VISIO is available that permits the use of limited hydraulic and mechanical sketching in the Fluid Power Lab. Autocad is also installed on the computers. Team members used their Fluid Power texts and handbooks for reference and referred to the course instructor for guidance about information that is not readily available.

Each team was responsible to generate a weekly progress report. This progress report consisted of 1) the summary report for the week's activity by the selected team coordinator and 2) individual reports by team members. The individual reports included details, sketches, computations, and data in order to validate the summary report. The progress reports were graded using a procedure outlined in Stern[3]. These progress reports were instrumental in keeping track of the progress each team was making towards the integrated goal of the project. They afforded the instructor a ready means of redirecting effort whenever a student strayed from a productive path of investigation. It is for that reason that lateness in reporting was not tolerated. The individual reports were critiqued and returned to the students before the following laboratory session so that each student had the opportunity to respond to the critique in the following week's report.

Final reports were then submitted wherein each team summarized its contribution to the total project design. Additionally, students gave oral presentations on individual areas of responsibility in their team's report.

5 Project 3 - Manufacturing Specifications

The manufacturing-process design project consisted of a practical exercise in developing processes to manufacture the line shaft and the lawn tractor conversion equipment. The faculty member played the mentor role by asking pointed questions when a group detoured down a non-feasible path, thereby keeping the project groups in the realm of practicality while requiring the students to generate their own ideas and direction.

The project began with students developing specifications for manufacturing in the form of product engineering drawings. The project required the design of the manufacturing process to occur concurrently with the development of the product design, and therefore cross-functional concurrent-engineering teams were formed. Each team was composed of a design advocate, a manufacturing advocate, and a cost (accounting and purchasing) advocate.

Students discovered that concurrent engineering complicated the product design process, and that the chosen manufacturing process had a profound effect upon the design details of the product. Tolerances, for the first time, had meaning as students considered the manufacturing precision dictated by tolerances, the effect of interchangeable manufacturing upon tolerance accumulation within an assembly, and the influence of tolerance upon feature location. They soon realized that the tight tolerances that were needed to defeat tolerance accumulation and position error were not feasible. Design for manufacturability would not permit them to design a feature without an accompanying manufacturing process, and each tolerance was required to comply with the precision capability of the machine which had been selected to manufacture that feature. Otherwise, the product could not realistically be produced. A simplified version of one team's experience follows.

The team embarked upon the design of a simple locating bracket. The students' first concession to manufacturability was to save cost by selecting an inexpensive manufacturing process, punching, for creation of the holes, which would enable attachment of the bracket to its supporting surface. The size and location tolerances for these locating holes were assigned to be consistent with the precision capability of the punching process. For simplicity, the team referenced the position dimensions for each locating hole from the ends of the bracket. The students soon found that this design caused a match-up problem with the mating hole pattern in the supporting surface. Due to tolerance accumulation, the length of the bracket would have to be established and manufactured precisely to permit bolts to fit through both patterns, necessitating the addition of costly milling operations to the manufacturing process. This design was too costly to manufacture.

Therefore, the design was altered for the purpose of resolving the manufacturability problem, and the bracket locating holes were all dimensioned from one common end of the bracket. This resulted in a hole pattern which could more feasibly be manufactured to match the pattern in the supporting surface. However, another problem surfaced. Other machined features were required in the bracket which permitted the attachment of a hydraulic motor. These features required precise location with reference to the bracket locating holes to assure correct location of the motor. It was quickly determined that the position of these machined features must be referenced from the same common end used to locate the bracket-mounting holes. The unfinished end of the bracket, however, would not provide an accurate locating surface to ensure that the machined motor locators were precisely aligned with the bracket locating holes. One end of the bracket would have to be milled to provide a precise locating surface, which was too expensive.

Two design iterations later, the team finally determined that the bracket- locating holes and motor-locating features could all be punched in one operation, enabling the process to locate features more precisely. This permitted the team to manufacture the tighter location tolerance needed on the design drawing. The team calculated the force required to punch all of the features at the same time and compared their figure to the capacity (in tons) of the available punch press. Consequently, they determined that an economic justification for the purchase of a new punch press was not necessary. The team was also required to consider locating surfaces, cost, and feasibility for the complex die set which was required for the multiple punching operation.

The above process was far more complicated than the team anticipated for designing a simple bracket, but the elapsed time was short. With the design, manufacturing, and cost advocates working together as a team, four product/process design iterations were generated and evaluated in a matter of minutes, and the design was quickly ready for machine capacity and cost calculations which were tackled concurrently by the team members.

6 Student Opinions:

Near the end of the semester, students were asked to provide anonymous feedback regarding the course content, instructors, team-teaching approach, or any other course-related comments. The following categorized remarks reflect the dominant opinions expressed by the students:

Class Size: 15
Total Respondents: 13

TOPIC	COMMENTS	RESPONSE
Class Format	Liked course format-learning from numerous individuals.	77%
Schedule	Insufficient time to complete projects Too much material was included Felt rushed	92%
Atmosphere	Good overall concept for a class Liked group work/class atmosphere Provide donuts on Fridays!	54%
Textbook	Use an engineering handbook Do not use a textbook-guest instructors cover most topics. Adopt a new textbook	46%
Projects	Provide hands-on involvement of students Actually fabricate a design Combine designs within one integrated project.	46%

7 Conclusions:

The class format used was well accepted by most students. An integrated faculty team offered added depth and interest to lectures by drawing from personal areas of expertise. A major challenge to this form of instruction is the integration of subject matter within the course. This is an area that will be refined and carefully monitored in subsequent course offerings.

Both students and faculty concluded that two rather than three assigned projects during a semester would offer improved utilization of time within the overall schedule and permit the addition of a hands-on component.

Overall student attitude throughout the semester was very positive and the team approach worked well as originally defined. Student teams chosen on the basis of leadership qualities offered beneficial interpersonal association. Doubts concerning problems arising from personality differences or other factors proved to be inconsequential. Reassignment was an option after the first project was completed; however, students elected to keep the original three-man teams.

Some questions were raised concerning the textbook chosen for the course[1]. Student opinions were mixed and preferences were expressed favoring no textbook, changing texts, or adopting an engineering handbook as the principal reference. No conclusions were reached, and the same book will be used again but with added emphasis.

The Industrial Advisory Committee offered several recommendations for the new class. These ideas included: awareness of the soft skills of leadership or management styles, interacting with people, how to treat customers, and qualities of an effective subordinate as well as boss. Adoption of these recommendations within the new curriculum is in progress.

8 References

[1] Ullman, D. G. (1997). The mechanical design process. Boston, Massachusetts: McGraw-Hill.

[2] Excellence in engineering design education. A three day short course & workshop, Saint Louis University & Texas A&M University, Saint Louis, Missouri, Aug. 3-5, 1997.

[3] Stern, H. Team Projects can offer incentives. Proceeding of the ASEE 1989 Annual Conference.

9 Biographical Data

Each of the authors is an Associate Professor in the Department of Mechanical Engineering Technology at Purdue University, West Lafayette, Indiana.

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