A Complementary Sequence in Thermal/Fluids and Mechanical Systems for Senior Capstone Design

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Abstract

The mechanical engineering program at Union College has developed two senior level design courses, Design of Thermal/Fluid Systems (DTFS) and Design of Mechanical Systems (DMS) aimed at diversifying the senior capstone design experience. These required courses are project-based design courses which complement each other so as to ensure coverage of design in both thermal/fluid systems and mechanical systems, and a wide range of teaming experiences. The thermal/fluids course utilizes multiple projects with relatively small teams, in which each student takes a turn as team leader. The mechanical design course typically has one major term project with the entire class working as a single large team on an industrial project solicited from a local company. There is one team leader with the rest of the team organized into functional groups. This paper describes each of these courses and goes into the details of how they serve to complement each other.

Curricular Background

The ME program at Union College has had in its curriculum for many years a two trimester course sequence titled Senior Project. This involves students working independently on a project and advised by ME faculty. The flexibility in the scope of this course sequence was well suited to the interests and goals of the different students. Some students were interested in design and build-type projects while others, mainly those considering going on to graduate school, preferred more research-oriented projects.

In the mid 1990's, new standards for the accreditation of engineering programs were developed. Criterion 4 of ABET Engineering Criteria 2000 calls for students to be prepared for engineering practice through the curriculum culminating in a major design experience based on the knowledge and skills acquired in earlier course work. The design experience should incorporate engineering standards and realistic constraints that include most of the following considerations: economic; environmental; sustainability; manufacturability; ethical; health and safety; social; and political. Further, Criterion 8 of the ASME Program Criteria calls for graduates of ME programs to have the ability to work professionally in both thermal and mechanical systems areas including the design and realization of such systems.

It became clear that changes in the ME curriculum would be necessary to ensure that all students met these criteria. Assessment results from alumni surveys indicated that the senior project, in its current form, was highly regarded by alumni. As a result, the faculty decided not to modify the senior project but rather to supplement it with required capstone design courses in thermal/fluid systems and mechanical systems. These courses preserve the many good points of the Senior

Project, provide the students with a significant capstone design experience in both stems of the curriculum, and provide the opportunity to address other program objectives such as teamwork.

This paper describes the senior capstone design sequence in mechanical engineering at Union College. In the sections that follow, we discuss the courses, project selection, complementary features of the course sequence and results of course assessment.

The Courses

Design of Thermal/Fluid Systems (DTFS) is a capstone, project-oriented course in the thermal/fluid area of mechanical engineering that applies design optimization techniques to the thermal and fluid sciences. Students work in teams (typically 5 students per team) on design projects that involve the design of piping systems, heat exchangers, thermodynamic cycles, and other thermal/fluid systems. The primary objectives of this course are to teach students to work in teams, lead projects, communicate effectively, apply design principles to the design of thermal/fluids systems and to apply principles of engineering economic analysis.

Design of Mechanical Systems (DMS) is a capstone, project-based course in machine design. The course is designed to give students: (1) experience in solving challenging open-ended problems in mechanical design (2) a practical working knowledge of basic machine elements such as motors, gears, belts, bearings, shafts, flywheels, and fasteners and (3) experience working on a large team (16 students per team). The term *working knowledge* in this context implies: an intuitive understanding of how the machine elements work, the ability to select parts from the catalogues and analyze them, and the ability to integrate those parts into the design of a complex mechanical system. In light of the multiple objectives, not all of the machine elements can be covered in lecture. This is as much by design as it is out of necessity. Periodically, students were intentionally confronted with the need to employ machine components not explained in lecture in an effort to encourage them to learn how to learn on their own.

The Projects

Thermal/Fluid Design Projects

The DTFS course is organized into 5 two-week projects. Table 1 summarizes each of the projects, lists pre-requisite topics, lecture topics and the assigned team roles. The instructor serves as both "manager" and "advisor" to the projects by assigning each project and then mentoring the students through the project. The first lecture of each two-week period is used to introduce the project, assign team roles and begin an initial warm-up assignment designed to re-familiarize the students with relevant thermal/fluids material. The final meeting of the two-week period is used for design presentations and project wrap-up. During the two weeks the instructor lectures on engineering economics, teamwork, and special topics related to the project. In addition the instructor meets with team leaders to discuss schedules, progress, problems, and review material on team management. Class time is also set aside for team meetings.

The projects are chosen to build on the prerequisite courses of fluid mechanics, heat transfer and thermodynamics. Because of the two week time limit there is not much time to teach "new" material to the students. The new topics introduced for each project are listed in Table 1. In general the instructor lectures 2 to 3 times per project. Students are assigned a review problem at the start of each project and the instructor supplies handouts on new material. It is also important to choose projects that cover a range of thermal/fluid design issues, from the design of piping systems to the design of heat exchangers.

It is important to use projects with clearly defined roles. Each team has a team leader and engineering economist and the three remaining team members are assigned the role of "analyst". In the first project the analysts are differentiated by being given responsibility for different groups of refrigerants. In the second project one analyst is assigned responsibility for the water clock mechanism, the second has responsibility for the auto-refill system, and the third is assigned the task of historian (to perform background research on clepsydras) and draftsperson/prototyper. In the third and fifth projects analysts are assigned to (1) analyze the fluid mechanics (2) analyze the heat transfer (3) choose a flow meter and valve (project 3) and perform a fouling analysis (project 5). In the fourth project two analysts are assigned to run the experiments while the third is assigned responsibility for developing a finite element model of the electronic component.

Mechanical Design Projects

The DMS course is organized around 3 projects: an industrial project and two calculation-intensive machine design problems. The industrial project spans the entire semester and the class works on it as a single large team. The machine design problems are packaged as mid-term and final take-home exams, in which students work either in pairs or individually. Percentage of credit is assigned up front in proportion to the amount of time planned for each: 70% industrial project, 30% machine design projects.

The industrial project was selected from those available based on the heavy dose of machine elements applications implicit in the following problem statement from the company: "Develop a generic test facility to evaluate advanced bearings and control algorithms". Prior to selecting it, a functional decomposition of the design was prepared both to summarize the tasks at hand as well as to explore opportunities for self-organization by the team. The result is presented in Figure 1. A design that does not easily decompose into sub-functions of comparable importance and workload is probably not a good candidate for a large team format.

Intermediate goals in the form of design milestones were formulated to help guide the students through the design process. The milestones used with the DMS project are listed in Table 2. They are essential for keeping the students on schedule during a long project. The associated grades provide an effective tool for sending a strong motivational signal when one is needed.

Complementary Features

In an attempt to have the thermal/fluid and mechanical design courses complement each other to the highest degree, choices were made which served to diversify the combined set of experiences. Some of these choices and their implications are described below.

Teams

Prior to the senior year ME students have a variety of teaming experiences ranging from in-course design projects, beginning with the freshman engineering course, and cooperative learning exercises in the classroom, to laboratory courses, and participation in extra-curricular projects (mini-baja, formula car). One objective of our senior year curriculum is to offer more formalized teaming experiences in which the students utilize knowledge and experience gained in their first three years. When developing the two new capstone design courses we intentionally chose to use different teaming models.

A goal of the both design courses was to offer a multidisciplinary experience for the students. Miller and Olds,[1] and Lewis, Aldridge, and Swamidas,[2] discuss the use of multidisciplinary teams in the engineering design experience as one involving students from clearly distinct disciplines. We expand that definition to emphasize the importance of the role of team member interdependencies and define the teaming experience to be multidisciplinary if: (1) team members have different experiential backgrounds that create **interdependence** among team members in achieving the team's goals; (2) team members are assigned fundamentally different roles or areas of responsibility that create **interdependence** among the team members in achieving the team's goal; or (3) members of the team are from different academic disciplines and the expertise developed in that discipline results in **interdependence** among team members in achieving the team's goals.

The assignment of roles in the DTFS course follows the second approach. Each team member is assigned (by the instructor) to a different role as indicated in Table 1. This defined division of work effort is important because it forces the students to work in a true team environment with clear interdependencies among the members. Without the clear definition students tend to work together on the project instead of dividing up the work. Although each student has the same "nominal" mechanical engineering background, each team member was assigned a fundamentally different task. This forced interdependency among the team members such that, in accomplishing that task each member contributed something different and critical to the team's success in achieving its objective. The strongest interdependency arose between the economists and the analysts in each of the projects. Due to the nature of the projects this dependency often required several iterations (i.e. the analysts provided technical data to the economist who then provided cost estimates which required the analysts to iterate on a solution). Students were forced to develop good communication tools and tight schedules. Another example of an effective interdependency came when the tasks were divided between a heat transfer analyst and a fluids analyst as in the milk transport system project. In the electronics cooling project the experimentalist provided boundary condition data (in the form of a heat transfer coefficient) to the finite element analyst who was charged with then calculating the module junction temperature.

The entire class of 16 students in the DMS course was organized into a single large team to provide a teaming experience that was different from the 5-member teams of the thermal/fluids course. The assumption was that a large team would produce an entirely different group dynamic. Differences in team size also led to differences in team organizational structures and in levels of empowerment.

In the DMS course, the students organize themselves into functional groups, e.g. shaft, bearing, structure, shielding, controls, etc. The group structure is needed to simplify individual tasking and assessment as well as to heighten the sense of accountability among group members. In general, it is important that the functions be independent enough to allow each group some autonomy. If not, the strain of communication will be so great as to nullify any advantages of the group structure. The team is encouraged to reorganize as needed, especially after the completion of a major milestone. Flexible tasking along with the large team size has led to extraordinary levels of student empowerment in other areas as well, including design choices, deadlines, report formats, and even lecture topics. Without such empowerment, the large team lacks the freedom to succeed or fail by its own merits.

Whether it is a small team or a large team, a student (and not the instructor) must serve in the role of team leader. Any attempt by the instructor to do so would have corrupted the team decision-making process given that students have been programmed over the years to succeed by doing what the professor asks. In general, the team leader is responsible for coordinating and scheduling team activities, leading team meetings, representing the team in meetings with the instructor, overseeing technical activities and helping out as needed. Also, in DMS the team leader is attached to one or more functional groups; in DTFS the team leader is responsible for putting together the final report (written and oral).

Internal Projects and Industrial Projects

Design projects for the DTFS course are developed by the instructor. The advantage of this approach is that projects can be tailored to meet the objectives of the course. For example in DTFS, the need for finite elements and economics were designed into the project definitions. Also, projects were designed to be short in duration to provide all students with an opportunity to serve as team leader.

In DMS, some of these advantages were sacrificed in order that students could have the experience of working on an industrial project. Elucidation of customer requirements and enforcement of those requirements throughout the design process is a unique facet of such a project. Also, practical issues such as cost, detailed drawings, tolerancing, design for manufacture considerations, and safety tend to move to the forefront. Particular emphasis is placed on communication between the student team and the company representatives. For the project described in this paper, it began with a question and answer session at the company, the result of which was a highly detailed and quantitative list of design/customer requirements. Some design requirements were clarified later through email. In total, formalized submissions to the company included: (1) the aforementioned list of design requirements, (2) a concept report, (3) the final report and (4) a follow-up report. In each case but the last, the company responded with an extensive list of written comments largely aimed at making sure design requirements were met. The culminating event in the course was an oral presentation to engineers from the company.

Multiple Short Projects and Term Long Projects

The two-week project length of the DTFS course was chosen to maximize the number of projects and to ensure that there would be an opportunity for every student to be team leader and economist. It also exposes students to a larger range of project types. Projects are designed for the two-week timeframe by limiting the scope of the project or limiting the number of alternatives that students are to evaluate. The students quickly realize that they must focus on the most important design issues and make the best recommendation possible at the end of the two-week period. As a consequence of the short time frame, the projects tend to be “paper” designs because there is not enough time to build parts and perform testing. Teams are reassigned at the end of each project so that the students get a chance to work with different team members. Pike[3] discusses the advantages and disadvantages of multiple projects per term (or per terms) and concludes that the multiple project format works well because it provides opportunities for students to work in different teams. It also exposes students to a larger range of project types. Although the short time frame limits the project depth, this disadvantage is made up for in the term length DMS project (and by the Senior Project experience).

The term-long timeline of the DMS course, creates opportunities for prototyping (if applicable) and provides the time needed for production of machinist-ready detailed drawings. Assembly drawings such as the one for the test rig shown in Figure 2 require extensive communication between contributing groups and involve multiple iterations. A longer timeline is also needed to accommodate the communication delays that occur between student team and company in an industrial project.

Evaluation Of Student Performance

To evaluate student performance in the DTFS course, the instructor graded the final project reports (group) and the individual design notebooks. The instructor also relied on peer evaluation forms which students filled out at the end of each project. The evaluation form requested ratings of team member performance in the areas of Organization, Initiative, Attitude, Quantity of Work, Quality of Work, and Overall. Students were to be rated in one of 8 categories from “excellent” to “no show”. In addition they were asked to rate the team’s ability to work together and the team’s progress toward meeting its objectives and achieving its goals. The students were required to include written comments to support their assessments. A student’s grade for each project was based on the group written report (20%); the group oral report (20%); faculty assessment of the students contribution based on role assignment (10%); completeness of design notebook (30%); evaluation of work by team members based on the peer evaluation forms (15%); and quality of peer evaluation review of team members (5%).

In the DMS course, each of the design milestones in Table 2 was evaluated using some combination of individual, group, and team grades. In the case of the concept report, a part of the grade was assigned by the company. A team grade was included in the formula whenever cooperation between groups was needed to achieve the goal. The following additional information was collected from the students in order to establish individual grades: a log of individual activities, a teaming survey, and input from the team leader. In the teaming survey, students were asked to (1) cite instances in which they performed activities which went beyond the normal responsibilities of the group, (2) rate their group members and (3) name the 5 most outstanding contributors to the team. The latter was particularly insightful when correlated with personal observation. The resulting individual grade constituted 23% of the overall project grade. In general, evaluation of the milestones tended to be somewhat subjective.

Results Of Course Assessment

Students assessed the DTFS on a project by project basis by completing a project evaluation form at the end of each project. The form was used to assess the level of challenge in the project, the suitability of the course prerequisites, the applicability of the warm-up homework exercise, the appropriateness of the team roles and the number of hours spent on each project. Results were used as feedback to assist the professor in making project assignments. In addition, at the end of the course, students were required to complete a 3 to 4 page paper assessing how well the course met the objectives.

The most challenging aspect of the DTFS course, to both instructor and student, was the two-week deadline. It limits the amount of hands on building opportunities and the depth of the projects. However, it is very effective at keeping the pace of the course going and it exposes the students to a larger variety of design projects and to more teaming experiences. The analytical nature of thermal/fluid design, which is reinforced in the course, also detracts from the “build” opportunities. However, it presents a nice opportunity to reinforce the importance of analysis in design. In our experience, many students like to jump straight to the build phase and minimize the analysis. This was not possible in the DTFS course. Students quickly learned the importance of careful analysis. One modification that we will incorporate next time is to change one of the two-week projects to a ten-week project that students work on in parallel with the 4 two-week projects. This will deepen the hands on aspect and also give the students an opportunity to multi-task projects.

On the whole, the teaming in DMS for the bearing test rig project went quite smoothly. There were no personality conflicts. Final documentation was of very high quality and included a complete set of machinist-ready detailed drawings. There were many examples of unselfish devotion to team goals. The team leader, on his own initiative, constructed a web site with a message board and email addresses. Many hours were volunteered to assimilate the various contributions to the design reports into uniform, self-consistent documents. Some teaming inefficiencies were identified. For example, distribution of work among the students appeared to be bimodal. Though there was the freedom to balance workloads through reassignment, the organizational structure generally remained static even when small fires arose, e.g. difficulties with an analysis or failure of some heavily burdened groups to meet deadlines. Instead, volunteers were relied upon to fill the gaps, and if none stepped forward, due dates had to be renegotiated.

Course assessment via student survey revealed three strategies for improving the DMS course. First, 87% of students favored replacing the 16-member team by two or three smaller teams when doing an industrial project. These teams could either compete against each other on the same problem or be assigned different projects. Besides making the teaming a little more manageable for the students, competing teams could serve to heighten the level of motivation as well as provide a more objective basis for evaluation of student work. Second, 63% of students called for introducing a hands-on component into the course. A significant hands-on experience is currently missing from the two-course sequence and, with the DMS project spanning the entire term, the DMS course is the logical place for it. Finally, some students proposed a weekly appearance by one of the company's engineers to answer detailed questions about design requirements. Although the quality of written communication between the team and the company was quite extraordinary (in the author's opinion), personal contact between them took place on only two occasions – at the initial interview and at the final design presentation. The same effect might be achieved by making the communication links between team and company more direct; under the present format, phone calls and emails are filtered through the instructor.

Conclusions

A required two-course sequence covering design of thermal/fluid systems and design of mechanical systems has been developed in order to fulfill both the senior capstone design requirement in the ABET Engineering Criteria 2000 as well as the two stem approach called for in the ASME Program Criteria. The courses have been designed to provide a diverse array of project and teaming experiences. They are also an effective vehicle for teaching supplementary information on design of thermal/fluid and mechanical systems. Complementary features of the two courses include: a combination of small and large team experiences, industrial and academic project experiences, as well as a balance of short and term long projects.

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Project	**Pre Req**	**Lecture topics**	**Team Roles**
Refrigeration Cycle Optimization Design a cost optimized system to cool a process stream in a chemical plant from 1 to –5 ^{o}C.	T	Teamwork Eng Economics Environmental Issues	Team Leader Eng Economist Analyst (refrigerants 1-4) Analyst (refrigerants 5-8) Analyst (refrigerants 9-12)
Clepsydra Development Design and build a prototype of a water clock with auto-refill system for the consumer market.	FM	Sizing Pumps Teamwork Eng Economics	Team Leader Eng Economist Prototype/Draftsperson Analyst (refill) Analyst (clock mechanism)
Milk Transport System Design a cost optimized pump and piping system (with a valve and flow meter) to transport pasteurized milk from a pasteurization tank to a UHT (ultra high temperature) tank. .	HT FM T	Flow Meas Devices Flow Valves Sizing Pumps, Fans	Team Leader Eng Economist Analyst (flow valve/meter) Analyst (pipe/pump) Analyst (thermal)
Electronics Cooling Design a cost optimized cooling system for an electronics ///?? package using one of four available cooling schemes (free convection or one of 3 fan types) and consider the cost of a fan failure. To complete the project students were required to carry out lab testing and develop a thermal finite element model of the package.	HT FM T	Electronics Packaging Teamwork	Team Leader Eng Economist FE modeller Experimentalist Experimentalist
Heat Recovery System Design a heat recovery system for a commercial building using a counter flow heat exchanger and optimize the design by finding the most cost effective combination of: (a) coolant flow rate, (b) number of tubes high, (c) number of tubes deep in flow direction, and (d) tube geometry (i.e. staggered or aligned).	HT FM T	Heat Exchanger Design	Team Leader Eng Economist Analyst 1 (flow/pressure) Analyst 1 (thermal) Analyst 1 (fouling)

Table 1. Summary of Thermal/Fluids Projects. (H = Heat Transfer, FM = Fluid Mechanics, T = Thermodynamics)

Design Milestones	Main Tasks
Preliminary Research	-research company and technologies cited in project description (G) -present results to the team (T)
List of Specifications	-interview company engineers (T) -compose list of design requirements (G,T) -incorporate comments from company (T)
Generation of subfunction alternatives	-brainstorm alternatives (G) -research available technologies (G) -present results to the team (T) -combine best of subfunction alternatives to form overall design concept (T)
Concept Report	-produce interim report documenting alternatives and overall design concept (T)
Detailed Design	-incorporate comments from company (G) -analyze critical components (G) -CAD drawings of components (G) -CAD drawing of assembly (T) -produce final report (T)
Oral Design Defense	-oral presentation to company engineers (T)
Follow-up Report	-incorporate comments from company (G) -produce addendum report with revised CAD drawings (T)

Table 2. Design milestones used with the industrial project in the design of mechanical systems course. Each task is characterized according to whether it was performed mainly on the functional group level (G) or on the team level (T).

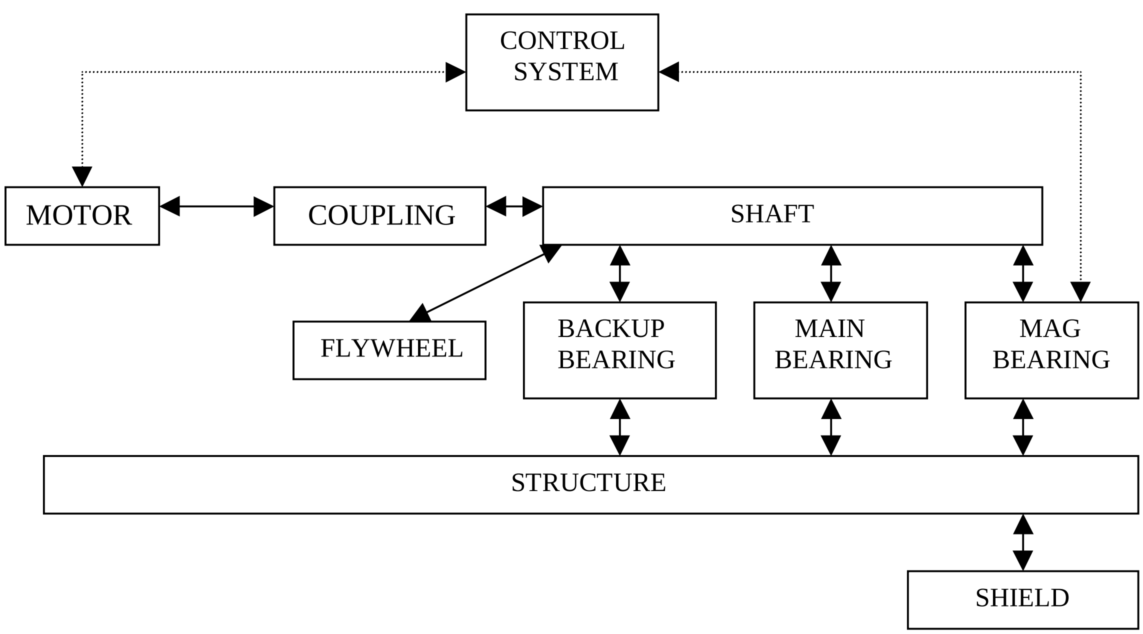

Figure 1. Functional decomposition for the advanced bearing test rig.

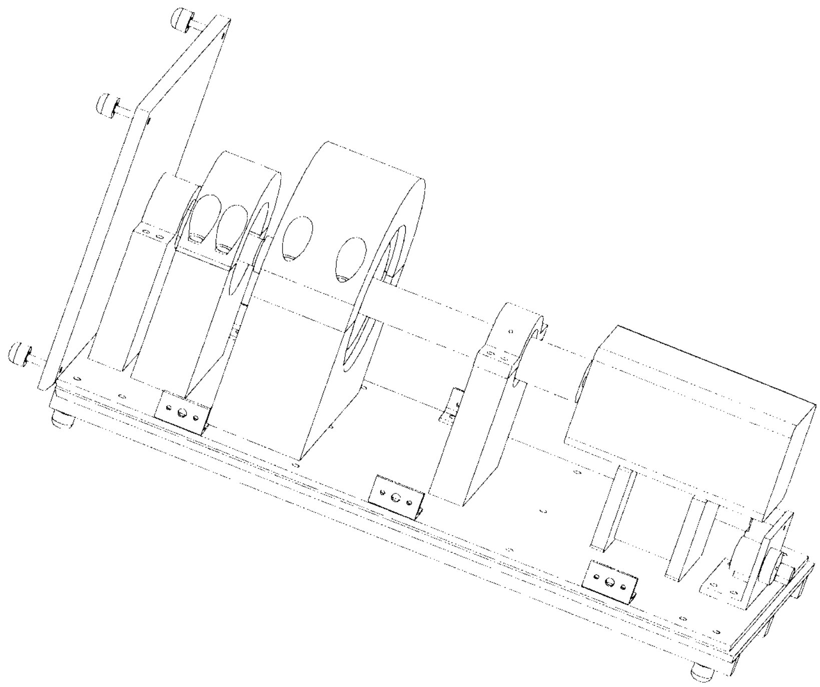

Figure 2. Student-produced assembly drawing of advanced bearing test rig.