Improving the Content of a Freshman Design Course through Computer Modeling, Experimentation, and Error Analysis

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Introduction

Several years ago a new design course was added to the freshman engineering curriculum at the University of Tennessee at Martin. Its goals were to introduce the student to the use of the personal computer, and to introduce the engineering design method using team design project competitions[1]. Recent modifications and enhancements have been added to the course to more realistically reflect a real-life design project. These enhancements include a number of features, all of which attempt to show the relationship between analysis and design. The students employed spreadsheet based mathematical models to optimize key parameters in their design projects. Experiments were carried out to empirically determine energy-related parameters that may affect their design. Finally, limited application of error analysis was introduced by encouraging the students to examine expected performance when key parameters were varied. This paper discusses the success of this modified project approach, and possible improvements that might be incorporated in the future.

Original Structure of the Design Course

The freshman engineering students at UT Martin take a design course in their first semester. This course was developed in response to several factors. In recent years engineering education has come under increasing criticism from the industrial community, and our Industrial Advisory Board, concerning the lack of preparation for teamwork on design projects. In reaction the School of Engineering at UTM has undertaken an extensive revision of its curriculum[2], with increased emphasis being placed on communications skills and experience in working as a member of a team. Ideas from Koen[3] and a March, 1995 workshop titled "Integrating Design into the Engineering Curriculum"[4] have been incorporated into this new course, which is the first of several that will utilize team design projects, written technical reports, and oral presentations. The new program at UTM follows the recommendations contained in the 1994 ASEE report "Engineering Education for a Changing World"[5]. A textbook was compiled using four modules from the Benjamin / Cummings Engineers Toolkit[6, 7, 8, 9]. Lecture notes supplement this textbook.

A common complaint from first and second year engineering students is, "I'm studying all this math and science: when do I get to do some engineering?" This design course immediately introduces the student to engineering by means of a team design project, which culminates with a group competition. The students seem to be strongly motivated by the competition. The goals of this course have been:

- To introduce the personal computer as an engineering tool

- To differentiate between engineering analysis and design
- To help students develop the teamwork approach process
  - for the solution of engineering design projects
  - for developing report preparation skills
  - for developing report presentation skills
- To heighten student interest in engineering as a profession

The faculty members who teach the various sections of the course have specified a single design project. Thus all student groups are working on a common project, and specific guidelines are presented to all sections of the class early in the semester. Within each section, randomly appointed three to four student teams are formed. Each group is required to design, fabricate, and test their prototype design prior to a final competitive demonstration. Each of the teams from each of the class sections participate together in the final competition. About a week after the competition, each team submits a formal written report and makes a formal oral presentation on its work to the class.

This one semester-hour credit course meets for one three-hour period each week. Typically, the instructor uses the first hour for lecture and discussion. The students then use the remaining time working on computer assignments and/or team project work, with the instructor basically serving as a consultant.

Throughout the semester the following 5-step design process is introduced, explained, reiterated, and its use strongly encouraged:

1. Define the problem
2. Gather pertinent information
3. Generate multiple solutions
4. Analyze each solution and select one
5. Test, refine, and implement the solution selected

Each team is graded, with all of its members receiving the same grade. The team project grade was comprised of a score from each of these components: application of the design process, performance of the device, the written report, and the oral presentation.

Overview of Improvements and Modifications

The faculty teaching the freshman design course at UT Martin recognized that there is a great difference between empirical, experiential based design and true engineering design which incorporates mathematical modeling, analysis, prototype development, modifications, and final product delivery. When the typical freshman student is asked, “How would you design a launcher?” the answer is quite often “I will build one and see how it works”. More often than not, the typical student will be satisfied with the final design, and will not be inclined to modify it to gain improved performance. After all, it is a class project, and there are many other demands placed on engineering students. It is rare indeed for the freshman student to even consider using mathematics or physics as part of the design process. His or her education has rarely associated the study of mathematics and physics principles to any concrete applications. A cursory examination of high school mathematics and science texts supports this unfortunate fact. Thus when given the task of designing, for example, a launcher to propel golf balls, the team will tend to rely on the combined past experience of the members, unless encouraged and shown how to do something different. Thus, the first additional goal in the freshman design course has been the introduction of mathematical models, which exposes the student to the merging of mathematics and physics early in their engineering careers. There are many attendant difficulties associated with this goal, and these will be discussed in a subsequent section.

An area which students typically tend to have difficulty with is the concept of energy. Students leaving high school will usually have heard of kinetic and potential energy, and will also have been exposed to energy concepts in other science courses. But the students are usually very weak in their understanding of what energy actually is. Our faculty's combined experience at the university level, gained from many different universities at both the undergraduate and graduate level, is that students view energy concepts as "separate", and that the very word usually causes a certain level of fear. Energy concept applications in various disciplines and subject areas are often treated in their respective textbooks in separate chapters, and are sometimes omitted due to time constraints. As our second goal, we have decided to emphasize the importance of energy in the freshman design course. Specifically we wanted to show the students how strain energy, stored in the form of stretched rubber bands, was converted to kinetic energy in the form of a flying golf ball. In addition, we hoped to show the students how to empirically calculate the amount of strain energy based on experimental observations. We then wanted them to understand how the stored strain energy is related to the mass and velocity of the ball. Finally the effect of air drag on the conservation of energy was addressed. We didn't want the students to leave thinking that there were no losses in the system. We hoped to do all of this with first semester freshman students, who in many cases had never taken physics at all, and often were taking pre-calculus due to poor mathematics preparation.

Finally, we wanted the students to be exposed to some limited applications of error analysis. We thought that the project was an excellent base from which to work, since in any real-life design there will be uncertainty in predicting the expected performance. If we were successful in having them identify an "optimal" design using the concepts introduced in our first two goals, then possibly we could have them examine the effect that variations had on that performance. Our initial goal was to require the students to examine variation in horizontal launch distance as a function of small changes in launch angle. We hoped that they would then use this as a tool to optimize their design to achieve the maximum score. This success is addressed in a subsequent section.

Description of an Example Design Project

For the fall semester, 1998, the students were required to design and build a golf ball launcher. The following design requirements were distributed to the students in all sections of the class at the beginning of the semester.

Group Design Project Description

Objective

The objective for this project is to design, fabricate, test, and report on a device used in the spring-armed ballistic launcher experiments (SABLE-3). These experiments will consist of launching a golf ball with a rubber band powered launcher. Specific objectives of this project are:

1. To maximize the horizontal distance traveled by the golf ball.
2. To maximize the accuracy of the launcher.
3. To maximize the repeatability and reliability of the launcher.
4. To control the cost of the launcher.
5. To fabricate a launcher which is safe and easy to operate.
6. To design a launcher with pleasant aesthetics.

General Requirements

Each design team shall design, fabricate and test a launcher which uses no more six #64 rubber bands as an energy source. The elastic material in these rubber bands will be the only energy source for the launcher. The rubber bands may be cut, tied, or modified in any manner as long as no additional elastic material is used in the launcher.

Each launcher shall employ a latch and release mechanism. This mechanism shall hold the launcher in the cocked position and the ball shall be launched with one external interaction with the release mechanism.

The total component cost of the final launcher shall not exceed $20.00. Safety must be considered at all times. A launcher that is deemed unsafe will be disqualified by the management and not allowed in the final launcher experiments.

Demonstration

Each launcher will be demonstrated in competition with the other design teams. For the demonstration, a fixed horizontal target will be provided at ground level. This target will consist of a shallow pan filled with sand. This pan will be approximately two feet in diameter. At the center of the two-foot diameter pan will be a smaller “Bulls-Eye” container that is approximately six-inch diameter.

A movable launch table will be provided for the design teams. The table will be at least two feet square and between two and four feet above the ground. C-clamps and other fasteners will be available to the teams to anchor their launcher to the launch platform. Detailed platform design information will be given to the design teams at least four weeks prior to the demonstration. Any special clamping requirements shall be given to management at least two weeks before the demonstration date.

To conduct the demonstration, a team will attach the launcher to the launch platform and then position the platform at their desired location relative to the target. The projectile will be loaded into the launcher, the launcher cocked and then fired with a single external interaction from the team. This launch interaction must be done at a safe distance from the launch device. Each team will be given a total of ten minutes to practice fire their launcher and execute the ten shots. At the end of the practice time the launch table will be locked in position. The demonstration will consist of ten golf ball launches and the launch table may not be moved between shots. During the demonstration, each team will record data on the performance of their launcher. This data will be included in the final report.

The management will score the overall performance of the launcher. This score will include points for distance and points for accuracy. The overall score will then be normalized with a cost weighting function. The final scoring algorithm will be provided to the teams at least four weeks prior to the testing date.

The scoring algorithm is shown below.

$$SCORE = D\left(N_1 + 5N_2\right)\frac{(AOF)}{1.5}$$

where D is the distance in feet from the front of the launcher to the center of the target. N_1 is the number of balls which land in the two-foot diameter pan, and N_2 is the number of balls that land in the six-inch diameter "Bulls-Eye" container.

The quantity AOF is the appearance and originality factor. This factor will range between a low value of 1.0 and a high value of 2.0. The AOF will be judged by at least two people who are professors and/or members of the industrial community. This factor will be highest for those designs that exhibit good creativity and originality and for those launchers that are aesthetically pleasing.

Deliverables

Each design team will submit a final report that describes the launcher design, analysis, cost, and performance. The final report will be a formal typed document. Specific requirements for the final report will be given to the teams at least four weeks prior to the demonstrations.

Each design team will make an oral presentation summarizing their project. Presentation software such as Power Point shall be used for these presentations. Each member of the team will participate in this presentation. Specific requirements will be given to the teams at least three weeks prior to the presentation.

Incorporation of Analysis and Design

Having defined the group project, the course goal was to structure all lectures, course activities, and homework assignments so that they would support the analysis and design of the golf ball launcher. The preliminary portion of the course addressed the five-step design process, and introduced the students to the use of Microsoft Word and Excel. Very rapidly the students were required to use Excel to build tables, formulas, and to generate graphs. A significant disadvantage was that most students were poorly prepared in both mathematics and physics. To circumvent this problem, the classical equations of kinematics for the path of a projectile were provided. Specifically, the two equations for vertical and horizontal displacement as a function of time for a given initial velocity and launch angle were presented and discussed. The students were required to algebraically combine these equations to obtain vertical displacement as a function of horizontal displacement. Having completed these preliminary steps, they were required to perform several tasks.

- Graphically determine the variation in horizon distance versus launch angle for a given initial velocity, with the goal of determining the optimal launch angle.
- Graphically determine the variation in horizontal distance versus launch angle for several different initial velocities, with the goal of showing that the optimal angle is independent velocity.
- Investigate the effects of air drag on the results obtained for the no drag case. To perform this study, the students were required to run a computer model that required as input the initial velocity, drag coefficient, frontal projectile area, and the projectile mass.

Based on the results of this study, the groups were able to correctly identify the appropriate launch angle for their designs. More importantly, for perhaps the first time they were exposed to the relationship between a mathematical equation and a physical situation that it modeled. In the process they learned to use graphical tools to zero in on parameters of interest. Unfortunately, most of the students did not have the differential calculus background to obtain the same results analytically.

The next step was to discuss the relationship between the initial launch velocity and the rubber bands that would provide the energy. The students possessed a very basic understanding of energy. However, they clearly understood that the stretched rubber bands provided energy to the ball. The students knew from their high school education that work may be defined as force through a distance. Therefore, the concept of this work being equal to the strain energy in the rubber bands was a natural extension. To complete the discussion, a typical load-deformation curve was discussed, and the area under the curve was obtained in a straightforward manner. To tie this to their projects, a lab was dedicated to experimentally measuring the load-deformation response of the rubber bands to be used. Using a force meter and ruler, each team measured several rubber bands, and used Excel to plot the results. They calculated the stored energy using the trapezoidal integration rule and from the area under a best linear fit of the data. From these experiments they had a reasonable bound on the stored energy available in six #64 rubber bands.

The students did not have the kinetics background necessary to follow the analytical derivation of the relationship between the stored energy and the projectile velocity. However, they had been exposed to the concept of conservation of energy. We simply provided then with the kinetic energy equation for a projectile, and suggested that they equate this to their measured energy. We discussed that this equation provides a theoretical limit on maximum achievable velocity. We encouraged them to relate the final performance of their launcher to the analytical/experimental predictions, hoping that the effect of unavoidable losses would be appreciated.

A goal that developed during the course was to have the students examine the sensitivity of their predicted model performance to small variations in key parameters. First, we required that they investigate the sensitivity of horizontal distance to small initial velocity variations, for several different launch angles. Secondly, we wanted them to examine sensitivity of horizontal distance to small angle variations, for several different launch angles. We hoped that this information would impact their final designs, and help them to maximize their score since distance and accuracy were both important in the scoring equation. Understandably, few teams were prepared for this level of sophistication.

Discussion of Competition Results

Each of the sixteen teams worked on their designs for a period of four to six weeks. They were required to demonstrate their launcher performance to the professor at least two weeks prior to the main competition. In many cases recommendations were made to the teams which might improve their performance. It was very clear that the students were rapidly beginning to appreciate that the "devil's in the details". They spent the last weeks addressing the appearance and originality factor, recognizing that this could have a significant effect on their overall score. Some of the teams recognized that the repeatability was greatly affected by the length of time the bands remained stretched before each successive launch, introducing the concept of hysteresis and relaxation. Almost all teams addressed issues such as reducing friction effects, perfecting the required trigger mechanism, and improving repeatability.

The competition was held one evening late in the semester, with the order of testing selected by random draw. Each team had a total of ten minutes to mount their launcher, adjust the target using practice shots, and record their ten required launches. Meanwhile, three independent judges scored the AOF factor for each team. Two of these judges were engineering professors, and the third was a professor in the department of Fine Arts. The total scores were tallied, and all teams were ranked. The results were impressive. The first place team placed seven shots in the bulls-eye, and the other three in the larger target, all at a distance of over 53 feet. This team also recorded the highest AOF factor at 1.8 of a possible 2.0. All sixteen teams placed at least one hit in the target area, and four teams placed all ten launches in the targets. The distances for these launches ranged from 50 to 60 feet. In at least one case, a poor AOF factor caused a team to be placed lower in the overall standings than they would have if their design had been more aesthetically pleasing.

Discussion of Successes and Disappointments

Although individual teams approached some of the course goals, we were disappointed in the performance of the class as a whole. We realized as we sat through their final presentations, and read their written reports, that the goals were a bit lofty for entering freshman-engineering students. For the most part, it seemed that few students appreciated the value of determining optimal design parameters using Excel as a design tool. This was particularly evident in our failure to meet goal three, having them examine the sensitivity to small variations in critical parameters. The introduction to energy concepts was less than successful. This is not surprising considering their lack of physical and analytical sophistication.

On a positive note, having the students actively involved in a project in which they wanted to do well produced excellent performance results. They spent countless hours testing their launchers, in several instances spending entire Saturdays refining their design. They learned that not all of the stored energy in the rubber bands necessarily went into the golf ball, but that there were many sources of wasted energy. Based on this realization, they attempted to minimize friction between moving parts, and to reduce the weights of the moving members. Based on the AOF factor, they also learned to appreciate the fact that a design often has more than a functional value. Finally, they learned to work within groups, often discussing at length the advantages and disadvantages of a possible design change.

Summary

This course provided the freshmen with a good introduction to an engineering design methodology and laid a good foundation for the use of computers and software as engineering tools. These projects also provided a good starting point to develop student skills in teamwork and oral and written communication. Enthusiasm shown by the students is viewed as an indicator that their interest in the engineering field has been increased. The goals of more fully incorporating analysis and design at the freshman level were largely unmet. However, we believe that exposing the students to the relationship between analysis and design at an early stage in their education is worth the effort.

Two additional, and unexpected, benefits were observed. First, camaraderie developed within this group of students. It started within the individual teams and spread through the entire group. These students now apparently feel that they belong here and they are interacting with the faculty and other students in ways that are not normally seen until the junior or senior year. Second, the projects seem to have sparked an interest in engineering science. Questions starting with, “When are we going to learn about…?” are becoming common. Perhaps the greatest success in this course will be keeping the students in the engineering program.

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