Computational Education within Mechanical Engineering Programs

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Abstract

This paper describes the experience in the Mechanical Engineering Department at New Mexico State University in introducing a sophisticated solids modeling software package at the freshman level to replace the traditional computer aided mechanical drawing course. The package is then further utilized within the upper level undergraduate courses at increasing degrees of complexity and sophistication. The rationale for this is that employers of mechanical engineers expect them to have proficiency with this type of software, and there is a very steep learning curve in reaching a reasonable degree of proficiency. The results of several years of experience with developing this teaching approach are discussed. For example, students' performance in applying mathematics, from geometry through differential equations, to solving mechanical engineering problems is examined in order to determine if their mathematical abilities are enhanced or degraded. Other advantages and disadvantages of such an undergraduate program are discussed and suggestions and recommendations concerning future programs are made.

I. Introduction

A subject that has been discussed by engineering professors and practicing engineers since the advent of computer software used to solve engineering problems is this: should the user of this software understand the mathematics, the assumptions, and the algorithms which are utilized within the software? As the software evolves to higher and higher order, this question becomes more important. Within our undergraduate Mechanical Engineering curriculum it is certainly necessary that our students be introduced to such software and reach a certain degree of competency in its use because their future employers expect this. Further, such software allows the solution of more and more complex problems, such as non-linear problems, for example, which leads to more realistic, more accurate design of products and processes. Also, the speed and efficiency which computers bring to the design process is highly desirable.

But, is there a downside? The answer to this question may depend upon your point of view, but from the academic side of Mechanical Engineering we see several difficulties that need to be addressed in various areas of the curriculum. Most Mechanical Engineering curriculums are rather diverse in the science and engineering topics addressed. However, from the computational stand point most divide roughly into two categories: field theory courses, such as heat transfer, fluid mechanics, vibrations, etc. and mechanical design oriented courses, such as drafting, machine element design, etc. Of course, there obviously is cross over between these areas, since the field theory topics are also used within design. Nevertheless, this is a convenient designation because the ordinary and partial differential equations, linear or non-linear, which are solved computationally in field theory courses can be handled, for the most part, using packages like MATLAB, MATHCAD, MATHEMATICA, etc. These are software packages which we might classify as having a medium learning curve. Students can attain a reasonable degree of mastery of them within a semester or two of exposure. On the other hand, the design type software packages, such as CATIA, PRO/E, Unigraphics, etc. (Solids Modelers), which are currently in use to replace the hands-on drafting courses and to do many of the necessary design calculations, such as stress analysis, have a very steep learning curve that may take many semesters of exposure in a sequence of design courses before students can be said to be proficient with these packages.

Some of the problems and difficulties which students encounter are common to both types of software. These may include having a less than adequate grasp of mathematical principles in topics ranging from geometry through differential equations. Especially worrisome in the design area is an apparent difficulty with spatial visualization and orientation. In the paper that follows, we will examine the use of the solids modelers within the design sequence of Mechanical Engineering at New Mexico State University. In this paper we address the difficulties listed above, but we shall also discuss the successes of the program. Admittedly, much of this will be anecdotal in nature, but we hope it will bring insight to the difficulties we have encountered and eventually lead to a rational study of this area which will, in turn, help improve our teaching methods. Other members of our Mechanical Engineering Department at New Mexico State University (NMSU) will discuss their experiences with what we have called field theory software in a separate paper.

II. A Brief History of Computer Aided Design at NMSU

Computer aided design in the Mechanical Engineering Department at NMSU has its roots in the mid-1970's when the department received a gift of an Applicon computer drafting system from Sandia Laboratories. The Applicon was integrated into the freshman level drafting courses, but by the early 1980's it was replaced by more economic PC's using such software as AUTOCAD and CADKEY. Students were urged, but not required, to use these systems in ongoing design courses. In the 1990's it became evident that there needed to be more integration between the computational drafting and computational design calculations and the department began to introduce solids modeling software to eventually replace the traditional computer drafting software at the freshman level. This has now been accomplished and the department has several years of experience in teaching students to utilize solids modeling in courses from the freshman level through the senior level.

III. The Design Sequence

The basic design sequence within the Mechanical Engineering Department at NMSU contains the following courses. Graphical Communication and Design: a freshman course which treats sketching and orthographic projects with PRO/E[1]. This course replaces the traditional freshman level computer aided drafting course. Instruction in the use of PRO/E is an integral part of the course. The second course, a sophomore level course, Introduction to Product Development, continues student instruction in PRO/E at a more advanced level. Manufacturing methods are also treated within the laboratory portion of this course. The third course, an elective senior level course called Finite Element Analysis and Design, continues the instruction in PRO/E to include stress analysis of the object under design. The purpose of this sequence of courses is to proceed from a design concept to a completed design of a mechanical part or a mechanical system. The sequence could be characterized as follows: Conceptualization, solids modeling, checking through animation of mechanisms, checking by stress analysis, checking manufacturability, production of all necessary engineering drawings and documentation. Students are expected to utilize PRO/E in all their design courses and especially in their senior level capstone design courses.

1. Experiences in 'Graphical Communications and Design'

Introduction of solids modeling software at the freshman level challenges both the instructor and the students. Three dimensional modeling software has become incredibly powerful and, therefore, complex. The fundamental tools and procedures available to the user are so broad that it makes learning the software a rigorous task. Procedures involved in performing even simple drawings require familiarity with as many as 10 different main menus, hundreds of menu items and several options within each function. Learning locations of menu items and their associated choices and options requires repeated daily exposure and usage of the software. Although today's entering freshmen are fairly computer literate, their experience is diverse. We have found that they must be given instruction and practice in developing basic computer and file management skills. These include understanding the file systems and directory structure organization, file types (ASCII, binary, etc.), file naming conventions (.doc, .txt, .pdf, .eps, etc.), editing, copying, renaming and moving of files, and basic computer networking (clients, servers, login, logoff, transfer of files, e-mail, WebCT, etc.).

Some of the entering freshman have difficulty with basic mathematics and problem solving skills and must be reminded of or even taught these concepts during the course. Another difficultly commonly encountered by freshman students in this course deals with the visualization of three-dimensional objects with respect to identification of ANSI standard views (TOP, FRONT, RIGHT, Isometric, Trimetric, etc.). Students must also be taught the relationships between the different orthogonal views, especially how views are projected to each other. Typically, students are given an isometric view of an object as shown in Figure 1 on the following page.

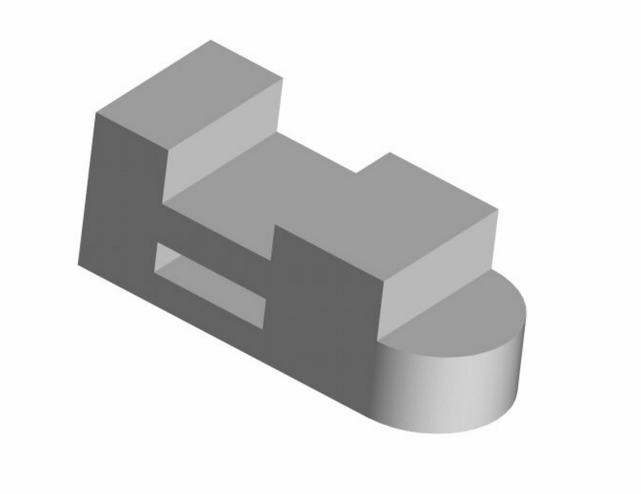

Figure 1 - Typical Isometric View in Pro/E

The student must then identify which faces of the object relate to the TOP, FRONT, and RIGHT views and then choose a datum on which to orient and "sketch" their design protrusion. Problems are often encountered with determining the view which best defines the objects overall geometry.

Many students seem to lack sufficient geometric and/or trigonometric relational skills which are essential when modeling even simple geometric objects. For example, they must be taught that in order to maintain a constant thickness of a part through a curve (notice the circled curved bracket in the student produced drawing of Figure 2), the center for the radii of both surfaces must coincide.

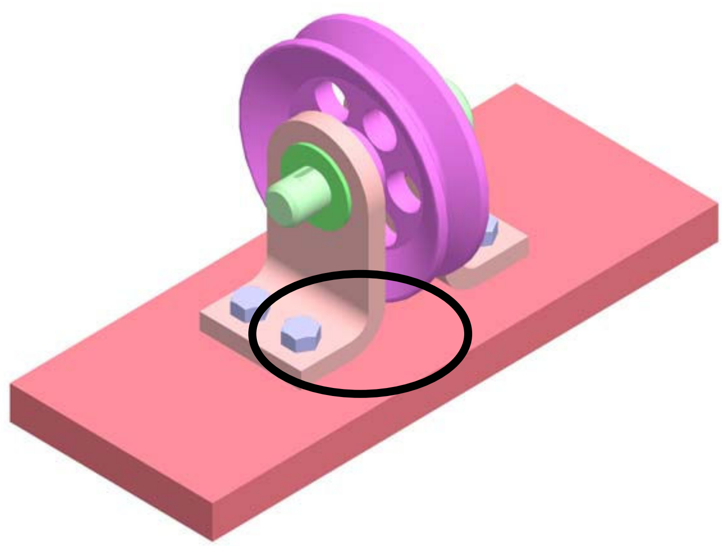

Figure 2 - Assembly with Curved Bracket

Similarly, many students have difficulty understanding which dimensions are necessary to define completely an object's parametric features.

Since many students appear to be deficient in the area of problem solving skills, their tendency is to look briefly at a modeling problem and then immediately jump into the computer software in hopes of a quick solution. Usually this leads to time consuming computer sessions which often yield poor or inadequate solutions to the problem.

Although the students seem to be mathematically immature, with appropriate instruction during the course they successfully complete several fairly sophisticated projects.

2. Experiences in 'Introduction to Product Development'

This sophomore course starts out where the freshman course ends, with advanced assembly modeling involving many parts as shown in Figures 3 and 4.

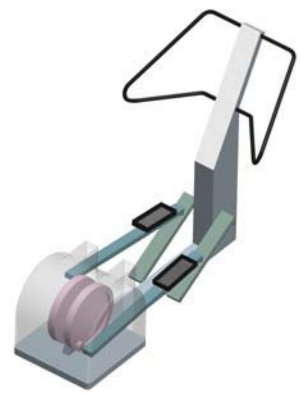

Figure 3 - Aerobic Stepper Mechanism

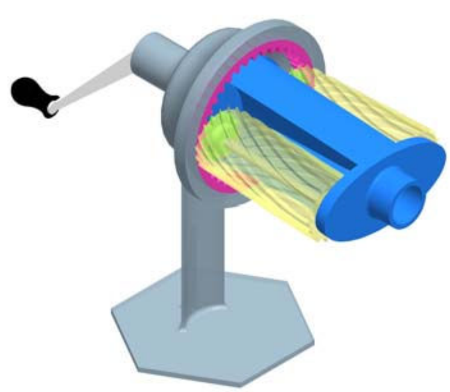

Figure 4 - Pencil Sharpener Mechanism

The students are assumed to know how to model individual parts and how to assemble simple collections of parts using the integrated design software Pro/E. The method of assembly to this point assumes that all degrees of freedom between parts are constrained to form a rigid assembly. This course builds on that knowledge and extends it to include methods used in large assemblies. A new assembly method is introduced to facilitate motion and animation of mechanism assemblies. In this assembly method, the student must leave certain degrees of freedom unconstrained to allow the desired motion. Servo motors are defined along with motion analyses utilizing these motors in order to model the behavior of the mechanisms. In general, the students become quite proficient and enjoy this material. These exercises provide vivid feedback on application of trigonometric relations and dynamic concepts of position, velocity, and acceleration. We don't attempt to introduce forces and resulting stresses in the mechanisms at this point since the students generally have not yet had a statics or dynamics course.

The next topic presented in the product development course is computer-aided manufacturing (CAM), again using Pro/E. An example illustrating milling of parts is shown in Figure 5.

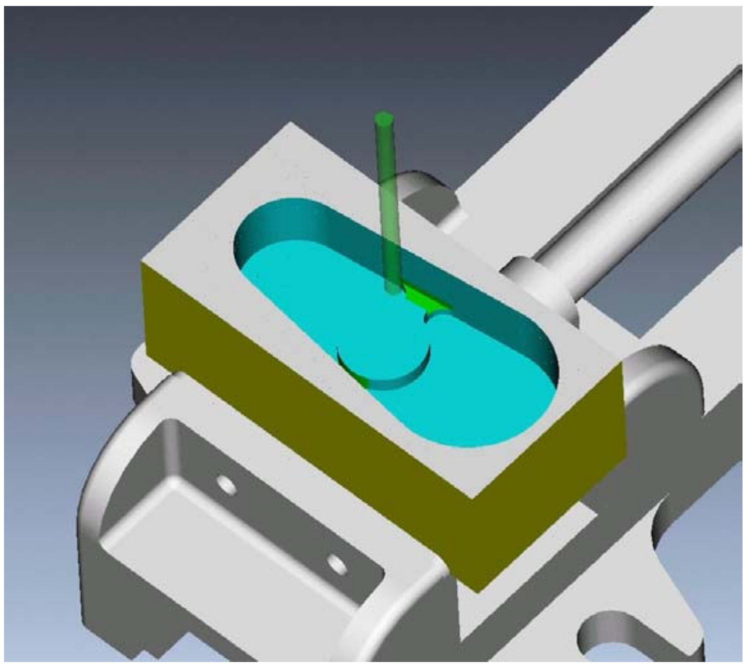

Figure 5 - CAM Model for a Simple Part

In this application the path of the milling cutter is calculated based on various characteristics of the machine, the cutting tool, the material, and the part. Again, the students enjoy this material and are particularly impressed to take their solutions into the shop and actually produce their parts. The main challenge is to reconcile the coordinate system and various offsets that they define in the software to those used by the machinist in the shop. They rely on simulation software to run their solutions on a "virtual" milling machine in the computer to assess problems they might encounter in the shop. If all goes well they should be able to take their program to the shop, load it into the machine tool, and run it directly.

3. Experiences in 'Finite Element Analysis and Design'

This course is a senior elective course taken after the student has had courses in mechanics of materials and engineering mathematics (partial differential equations), but has not necessarily had a course in finite element numerical analysis. It is an applied course in computer-aided analysis again using the integrated design software Pro/E. The simulation modules of this software include structure, thermal, and motion modules, but the emphasis in the course is on structural analysis. Examples of results obtained in the course are shown in Figures 6 and 7.

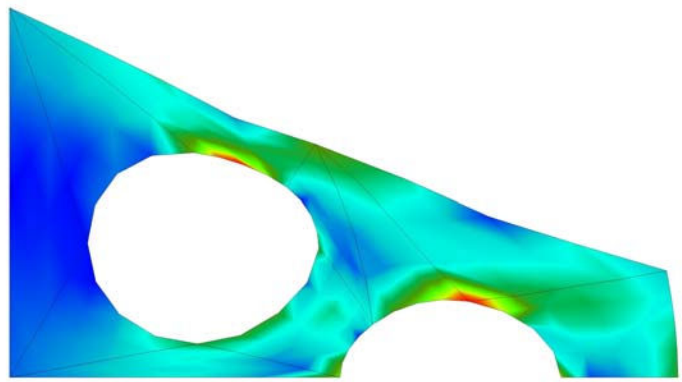

Figure 6 - Stress Results in a Part

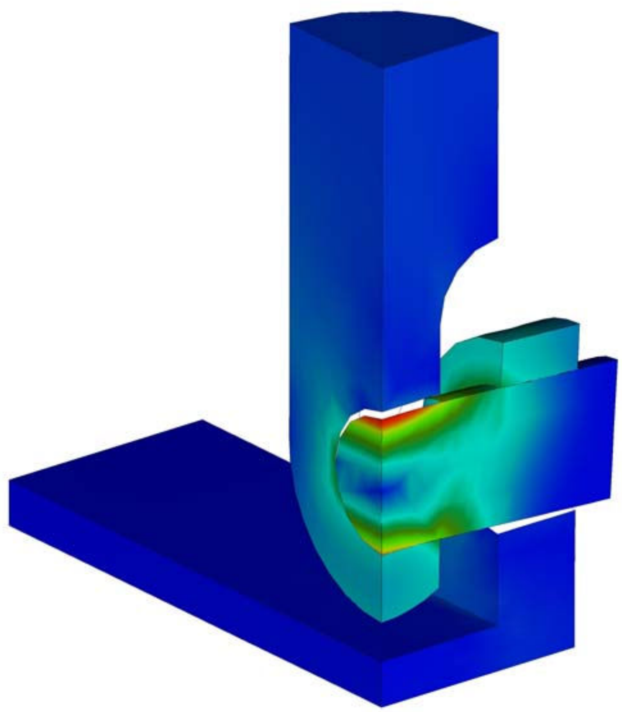

Figure 7 - Stress Results in an Assembly

Figure 6 shows the stress distribution in the top half of a bracket held rigidly on the left edge and pulled to the right on the right edge. The highest stress is seen to be at the edge of the holes (shown in red). Figure 7 shows the stress distribution in one fourth of an assembly of three parts held rigidly on the bottom and pulled vertically on the top. In this example, the highest stress is on the top surface of the pin (again shown in red).

The basic mathematical equations and boundary conditions for these problems are introduced and discussed, but due to time constraints no analytical or numerical methods are formally introduced – the software is treated like a black box. As a result, the students face challenges in getting the software to produce meaningful results in a reasonable amount of time. We try to expose the student to some of the pitfalls of this type of analysis and explain the mathematical reasoning, without getting into the details of the solutions.

IV. Mathematics Requirements within the Design Sequence

It has become obvious to us that introduction of solids modeling software at the freshman level in a design curriculum within Mechanical Engineering is certainly feasible. However, at all levels, freshman through senior, the mathematical maturity of the students has been a challenge and needs to be further addressed.

Graphical Communication and Design, the freshman level design course, does not have a mathematics prerequisite. Unfortunately, entering freshmen from New Mexico high schools may not have taken algebra, geometry or trigonometry in secondary school. Hence, in their first year in Mechanical Engineering many students are taking remedial math courses concurrently with this design course. Furthermore, those students who do qualify to enter the calculus and analytic geometry sequence in the Mathematics Department also take these courses concurrently with the design course. Thus, many of the concepts, from basic mathematics through geometry and trigonometry, necessary for a sound understanding of the solids modeling software may not yet be familiar to many freshmen students.

One reason that motivated us to introduce solids modeling into the design curriculum at the freshman level involved retention. This course allows the students introduction to fairly sophisticated engineering problems and methods for solving them early in their career. It was felt that early successes by the students would encourage them to continue in an academic field which is known to be very rigorous and has, in the past, been plagued by a very high drop out rate. It is probably too soon since the institution of this program to tell if there has been a decrease in the drop out rate from Mechanical Engineering, but drop out and failure rates for the freshman design course are now significantly lower than ones observed before the solids modeling course was introduced. Although it might not appear appropriate to require a mathematics prerequisite for this course, our experiences in teaching the freshman graphical communication and design course convinces us that the addition of trigonometry as a co-requisite is necessary. In addition, cooperation with the Mathematics Department on a 'just-in-time' approach in offering the material in the remedial mathematics course and the freshman level calculus and analytic geometry courses also would seem to be appropriate.

In the sophomore design course, students still have some geometric difficulties, specifically in the area of coordinate systems. This is resolved within the course by spending extra time on this subject, but a more complete understanding would be desirable in future applications of PRO/E to more advanced problems. Perhaps just-in-time cooperation with the Mathematics Department on the sequencing of course content within the calculus and analytic geometry might be a viable fix in this area also.

The need within the senior level course, Finite Element Analysis and Design, for students to have an understanding of the theory of finite elements was discussed in an earlier section. A good approach here might be to introduce as a prerequisite to this design course an already existing junior level course in applied numerical analysis for engineers. Such a condition may be difficult to achieve because of the timing crunch juniors and seniors traditionally face in their course scheduling.

V. Discussion and Recommendations

We asked two questions in the Introduction section of this paper: (1) should the user of (solids modeling) software understand the mathematics, and the algorithms utilized within the software? and (2) is there a downside, i.e. do the disadvantages of introducing sophisticated solids modeling software at the freshman level out weigh the advantages? As to the first question, our experience in teaching the design sequence using PRO/E tells us that yes, the student must understand the mathematics used within the software, and they must be instructed in areas in which they are deficient. However, for the most part, understanding the algorithms used within the software does not appear critical. We can not come to any type of conclusion about whether computational packages are detrimental to the over all mathematical skills of our students. Further investigation of this question appears necessary.

The downside of question (2) appears to exist only for those formulating curriculum and teaching the design sequence courses. Here at NMSU we do not claim to have come to closure in this area. Much remains to be done to improve both the courses and the overall sequencing of the Mechanical Engineering courses within the computer aided design sequence. This may also be said of integration of the design sequence with outside the department courses, especially those within the Mathematics Department.

We are recommending to the Mechanical Engineering Department at NMSU that the current development of the computational design sequence be continued. In fact, because of the rapid development in both computer hardware and software, this effort must be continuous. Specific recommendations are: (1) to add a prerequisite of trigonometry to the freshman level graphical communication and design course, (2) to investigate just-in-time coordination with mathematical content within remedial mathematics courses and within the calculus and analytic geometry courses, (3) to investigate changing the senior level computational design course prerequisites to include a finite element engineering analysis course, and (4) to begin a study to document the effects of the current computer aided design sequence upon retention of students within the Mechanical Engineering Department and also upon the mathematical skills of its students.

Because of the success of introducing solids modeling software at the freshman, sophomore and senior levels in our design sequence, we make the following recommendations: (1) that use of the solids modeling software be required in all junior and senior level design courses, and (2) that the current elective senior level course, Finite Element Analysis and Design be made a required course.

VI. Conclusion

We are very pleased with the progress our Mechanical Engineering students have made since our introduction of solids modeling software in the freshman Graphical Communication and Design course and in other strategic upper level design courses. More importantly, our students seem to enjoy the courses and are proud of and excited about their abilities to handle sophisticated engineering design problems.

Bibliography

1.) *Pro/ENGINEER Wildfire Tutorial and MultiMedia CD*, R. Toogood and Zecher, SDC Publications, 2003.

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