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Finite Element Analysis and Design as a Degree Requirement in Undergraduate Mechanical Engineering Curriculum

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Finite Element Analysis and Design as a Degree Requirement in Undergraduate Mechanical Engineering Curriculum

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Abstract

It is debatable whether or not the subject of finite element analysis should be included as a required course in an undergraduate mechanical engineering program. In the past couple of decades, commercial finite element software packages have dramatically increased their capabilities by improving their calculation power, merging and integrating other computer tools into the packages, and creating many user-friendly features. The design and manufacturing industries embrace the powerful finite element tool and require their engineers to use the tool for product development and design refinement. Academia supplies entry-level engineers to the design and manufacturing industries. It is time to reconsider adding a finite element course in the undergraduate required mechanical engineering curriculum if a program has not done so. The benefits of having this required course include extending the students' knowledge in using a powerful tool to solve a variety of complex engineering problems, applying the computer tool for the capstone design project and other course projects, and bridging the gap between academic education and industrial work.

Introduction

In early human history, parents or elderly assumed the role of teacher to the youngsters for life skills. In later human history, teaching became a profession of educated people. Teaching scope has evolved in conjunction with the changes of the tools used in various durations. If we were technical teachers 200,000 years ago, we would teach the students the skills of making stone tools. If we were technical teachers 5,000 years ago, we would teach the students the skills of making mostly agriculture related tools. If we were engineering professors in year 1960's, we would include a class to teach the students using a slider ruler to calculate the solutions of engineering problems. If we were engineering professors in year 1980, we would ask the students solving engineering problems with Fortran on a mainframe computer. If we were engineering professors in year 2000, we would ask the students solving engineering problems on a personal computer.

We are now in year 2022, the main computing tool is still personal computer. However, the capability of a personal computer with the advanced software makes it very convenient and very powerful to solve many complex engineering problems in much shorter time than before. The design and manufacturing industries have made it a standard of using computer tools in planning, conceptual design, virtual test, and refinement process. It is evident when we view the job descriptions of mechanical design engineer on many company's advertisements[1,2,3]. When the companies hire

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graduates from an engineering school, they expect the graduates having the fundamental knowledge of computer tools, for instance, the knowledge of a finite element analysis commercial package for a mechanical design engineer position.

Many undergraduate mechanical engineering (UGME) programs do not require their majors to take a finite element analysis course[4,5]. These programs generally list a finite element analysis course as a technical elective course rather than a requirement. However, the author has noticed, a major institution in Texas revised its UGME program requirements in the recent years from not including a finite element analysis course[6] to requiring the finite element analysis course[7] in the UGME degree. It could be a trend for other institutions to follow.

Finite Element Taught at Prairie View A&M

A Finite Element Analysis and Design class has been taught as a required subject in the UGME program at Prairie View A&M University in the past thirty years[8]. The prerequisite of the Finite Element Analysis and Design class at Prairie View A&M is mechanics of materials; another subject, heat transfer, is coded as a prerequisite with concurrency, i.e., if the students have not taken heat transfer before, they can register for heat transfer and finite element classes in the same semester. The required textbook in year 2021 was Finite Element Modeling and Simulation with ANSYS Workbench[9]. The instructor added a Chapter 0 to the class before teaching the textbook materials. Chapter 0 was a summary of mathematic topics that helped the students gain the mathematics background in solving finite element problems. Since Linear Algebra is not a required subject in the UGME program at Prairie View A&M, it is important for the students to know matrix operations, such as adding, subtraction, multiplication, inverse of matrixes, etc. In the Chapter 0 assignments, the students were required to calculate matrix operations on paper, as well as to use a computer tool, MATLAB, to do more elaborate calculations.

The beginning three chapters in the textbook contain the main derivation of equations in finite element formulation in one-dimensional elements, two-dimensional elements, and a brief illustration of three-dimensional elements. Structure elements including spring, bar, truss, and beam are used in formulating the stiffness matrixes. Each element has its own derived stiffness matrix along its local coordinate. Local coordinates of the individual elements must be converted through coordinate transformation into the reference coordinate before the combining process to obtain a global stiffness matrix of the system. Force equilibrium equations are formed by the global stiffness matrixes, displacement variables, and the external loads. Boundary conditions and given values of external loads are applied in the equilibrium equations before the solution phase. Matrix algebra is used to solve these displacement variables of a structure, or so-called direct solutions. The secondary solutions, such as reaction forces, and stresses, can be solved after the displacement variables are obtained.

The sizes of the global stiffness matrixes can be very large. Considering the limitation of writing the matrixes on paper, or printing on paper, the exercise problems used in this class are limited under 12x12 matrix size. Going through the finite element formulation of a structure problem, variable definition, coordinate transformation, identification of boundary conditions, and matrix solving processes, the students learn the fundamental concepts of finite element formulation. When they use

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the commercial finite element analysis package, they still need define boundary conditions and external loads. However, the students do not have to perform the complex calculations for very large matrix sizes by themselves; they can appreciate the powerful calculations behind the scene by the software package. Besides, since the students gain the knowledge of solving the finite element problem on paper, they can use the knowledge to verify computer results by solving a simplified model from the actual problem and to compare the "simplified estimate" with the computer solutions.

For this class, we only focus the formulation and solving processes in structure problems. The formulas in other areas, such as fluid flow, heat transfer, vibrations, etc. were briefly illustrated without getting into the detailed finite element formulations. The physics of fluid flow, heat transfer, and vibration are very different from structure. However, the finite element mathematic processes of all these areas are similar. The structure area serves as a good representation for finite element formulation and solving process. Without getting into the detailed processes in fluid flow, heat transfer, and vibration, we save the time for the class to practicing the applications on a commercial finite element package.

The students are required to work on 8 to 10 case studies using the commercial finite element package, ANSYS in this class. The subjects of the case studies range from truss structure, surface structure, rotational solid, assembly of several solids, acoustic analysis from vibrational impact, static temperature analysis, transient temperature analysis, air dynamics, and design optimization. Toward the end of the semester, the students are required to design a product and perform finite element analysis to refine the product. Generally, it would take multiple iterations of the refinement processes to achieve a good design. The students are required to present their results and to convince the audience that they have achieved the "best" design through the finite element refinement process.

A challenge to many students is to concisely present the relevant finite element results and choose good strategies in the refinement process. Design is an interactive process. The students have to review the finite element analysis results of the initial design and decide what to change before the next simulation run on computer. After getting another set of computer solution, the students have to review the solutions again and decide what to change next; it could be the same strategy for further refinement, or a completely different strategy. In many situations, there are judgement calls by a mechanical designer. For instance, an assembly product with several parts targets a design goal of the minimum weight. There are numerous ways to reduce the weight within the constraint of satisfying the required functionality and allowable stresses in the materials under critical loading conditions. The mechanical designer's knowledge in materials, mechanics, manufacturing process, cost, product life cycle, application environment, aesthetics, etc. all contribute to his/her decision-making process. Classroom discussions can help develop a student's design refinement ability. When the students present their project, they explain the thought process of implementing their refinement strategies. The instructor and other students then comment on what they think on these strategies. The whole class can gain experience from each other in the design review process.

The knowledge and skills that the students learned in the finite element class benefit their learning in other subjects in the mechanical engineering curriculum, such as Machine Design, Heat Transfer, Mechanical Vibrations, Air Dynamics, etc. In the capstone senior design class, finite element analysis package is the most used computer tool for design analysis and refinement process. Many students

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also include graphical finite element analysis results in their portfolios that have assisted them in explaining what they have learned in the design and refinement process in job interviews.

Capability Expansion of Finite Element Commercial Packages

There are many commercial finite element analysis packages available on the market, such as ANSYS, COMSOL, Nastran, ABAQUS, etc. ANSYS is listed as the top software by Mechanicalbase.com that used by professionals among many commercial finite element analysis packages[10]. When I first used ANSYS finite element program in the late 1980, both software and computer hardware were very primitive. I had to type a series of line commands and submitted as a batch job on an IBM personal computer, the top personal computer back then. I would not run a finite element program during the day because it would normally take a few hours to run a case. Generally, I would submit a job at the end of my working day in my office and come back in the morning to view the solutions. Many times, I viewed a message of "syntax error" in my submitted line command program on the 2nd day. I had to correct the error and resubmit the program at the end of the 2nd day and hope to get a result on the 3rd day. Thirty some years later, IBM personal computer no longer exists; a personal computer now is thousand times faster than the 1st generation IBM personal computer. The commercial finite element packages have changed dramatically, not only improved its speed, but also expand its capabilities to many territories in multiple engineering disciplines.

As we glance the major subjects taught in an undergraduate mechanical engineering degree, one can find the usage of the current commercial finite element program in many of these subjects. The ANSYS program has evolved to menu driven, and with many user-friendly features. As shown in a free-downloaded ANSYS Workbench package, a "Static Structural" in the ANSYS program can solve many problems in Mechanics of Materials and Design of Machine Elements; a "Steady-State Thermal" and "Transient Thermal" can solve many problems in Thermodynamics and Heat Transfer, "Fluid Flow" can solve many problems in Fluid Mechanics and Air Dynamics; "Modal" and "Random Vibration" and solve many problems in Mechanical Vibrations. The Multiphysics capability can connect the solving process from one area to another. As an example, the solutions of a heat transfer analysis can be linked to the set-up conditions of a structural analysis to analyze the thermal stress in the structure. ANSYS has expanded its usage not only in many traditional subjects in mechanical engineering and civil engineering, its features such as "Electric," "Magnetostatic," "Acoustics," and "Thermal-Electic" extended the usage to other fields, such as electrical engineering, bioengineering, etc.

Industry Embracement of Finite Element Packages

As mentioned earlier, the design and manufacturing industries have made it a standard of using computer tools in planning, conceptual design, virtual testing, and refinement process. Let's check on Internet or glance on technical magazines; we can see many recruitment advertisements for engineer positions. The advertisements typically list the following attributes for a mechanical design engineer position[1,2,3] as illustrated in Figure 1.

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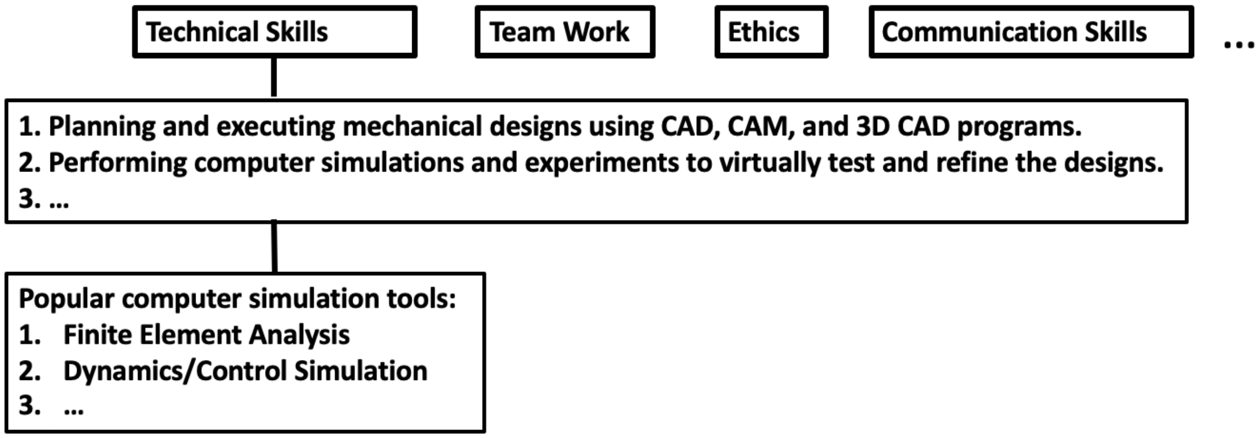

Figure 1. Typical Attributes of a Mechanical Design Engineer

An important duty of an engineering school is to produce entry-level engineers who are capable of meeting the need of current industries. To supply good entry-level mechanical design engineers, we shall train our students using computer simulation tools. Training on using computer tools involves much more than just skillful hand movements on a key board and mouse. We shall train the students to have a comprehensive ability of using the computer tools in broad scope of design and manufacturing processes.

Let's visit the 2nd bullet under Technical Skills of a mechanical design engineer in Figure 1. A required skill is to perform computer simulations and experiments to virtually test and refine the designs. In other words, the engineer must have the abilities to virtually test and refine the designs using computer tools. Under this tribute, I elaborate the required abilities for a mechanical design engineer and what we can do in a UGME program to develop the student's abilities in the following.

1. be familiar with the 3D modeling tool and be skillful to modify the models.
   What we can do in UGME program: Courses can be taught in UGME curriculum: 3D modeling (AutoCAD, NX, Solid Works, etc.) and finite element modeling (ANSYS, COMSOL, Nastran, ABAQUS, etc.)
2. be resourceful to gather parameters used in the computer simulation.
   What we can do in UGME program: Courses that prepare the students' ability in UGME curriculum include: chemistry, physics, mathematics, material science, thermodynamics, fluid mechanics, heat transfer, engineering mechanics, machine design, etc.
3. understand the physics and science behind the simulation so that properly apply the correct parameters in various simulation conditions.
   What we can do in UGME program: Courses taught in UGME curriculum will be depended on the particular problem being solving. For instance, if we use a computer tool to calculate top 10 natural frequencies of a solid body, a UGME mechanical vibration course can provide the background knowledge.
4. be familiar with the simulation process to obtain a broad range of test results.
   What we can do in UGME program: Course can be taught in UGME: finite element modeling.
5. have the ability to interpolate simulation results, make judgment based on sound engineering

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knowledge, manipulate simulation direction, and make a correct conclusion.
What we can do in UGME program:
It depends on the particular problem being solving. For instance, when we design a mechanical component for the minimum weight, we have to understand material properties, safety factor in this particular environment, force functions, and boundary conditions. A UGME machine design course can provide the knowledge for this particular problem.

6. have efficient technical writing and presentation skills to deliver the simulation results.
What we can do in UGME program: Technical writing and speech communication courses in the UGME degree can provide the knowledge.

As we can see, the knowledge and skills in respect to performing computer simulations link to many standard courses currently required in most UGME curricula. However, the use of the computer simulation tool itself, such as finite element modeling, is not a required course in many mechanical engineering programs around the country. Some programs integrate computer simulation tool in their capstone design courses. In those capstone design classes, the students have to learn the computer tool by themselves and implement it in their design projects. This project driven approach can lead the students only learn a particular functionality in the computer tool, such as stress analysis; and miss out many other functionalities in the computer tool, such as fluid flow, heat transfer, mechanical vibrations, etc. It is understandable that even we teach a stand-alone finite element class, we could not teach all functionalities in the computer tool. However, by carefully selecting a set of functionalities that are most relevant to the job scope of a mechanical design engineer, we can prepare our graduates to be good entry-level engineers.

For those students who plan to continue their advanced studies in the fields, taking a finite element analysis course can still be very beneficial. The author has advised many MS students' theses and guided them to obtain positions in research/development organizations[11,12,13]. The research organizations hire mechanical engineers who can design innovative/complex devices generally used in unconventional areas, such as space exploration, intelligent robots, advanced vehicles, etc. Many engineers who have advanced degrees tend to use the commercial computer tools along with self-developed modules to improve certain functionality which the commercial tools could not solve under a particular environment. Ironically, when the technology of "self-developed" modules become matured, they often be included by the software company in their new updated versions. In other words, the research industries often help the development of the computer tools used in the future design and manufacturing industries.

Summary and Conclusions

Performing computer simulation to virtually test and refine designs has become a norm for a mechanical design engineer's job duty in many industries. The author would suggest that every undergraduate mechanical engineering graduate should possess the computer simulation abilities, especially, using finite element analysis to solve a variety of mechanical engineering design problems. Some schools have made finite element analysis and design a required course in their undergraduate mechanical degree; some have not. The trend shows that the design and manufacturing industry will employ more entry-level mechanical design engineers who have finite element analysis computer skills fresh out of the college. As we teach finite element analysis and train the students the skills of

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using commercial packages in academia, we save the time and efforts from our industry partners.

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