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Integrated Thinking in Mechanical Engineering Education*

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Mechanical engineering (ME) departments in research universities face the challenge of educating mechanical engineers who will graduate with a balanced knowledge in engineering science and mechanical design. The source of this challenge is the inherent difference between teaching analytical thinking, which is required for most engineering-science courses, and design thinking, which is required for project-based design courses. The purpose of this paper is first to propose a new approach that can potentially bridge the educational gap between analytical and design thinking, which we refer to as integrated thinking. Second, we show how it can be applied to various ME undergraduate courses, which we refer to as integrated courses. Our approach reforms science engineering courses by (a) stressing the physical interpretation of mathematical derivations; (b) requiring students to analyze, design, and sketch simple mechanical devices based on the learned theoretical material; and (c) modifying project-based design courses to emphasize the importance of analysis as part of the creative design process. A pilot course focusing on dynamics and vibration which we called Integrated Design and Analysis, was offered in the ME department at the Technion, where it was well-attended by senior ME students. The positive feedback of the students who took the course suggests that integrated thinking might be successfully applied in many areas of ME education, such as fluid mechanics and heat transfer, control, and mechatronics, and that our approach may contribute to changing the current divided pattern in ME education.

Keywords: design education; design thinking; integrated thinking

1. Introduction

Many mechanical engineering (ME) departments in research universities face the challenge of improving design and engineering education [1]. In the past, engineering schools in the United States and the countries that follow US higher-education methods, focused on engineering science and mathematics requirements to help engineering students understand the complex principles of modern technology. However the change toward more theory in the engineering curriculum has produced graduates with far less experience in the practice of engineering and design [2].

Today, the core engineering-science courses are taught using a strong analytical approach. As a result, after two to three years at school most ME students form the notion that analysis or analytical thinking is the only tool or language at their disposal. Senior students who later decide to major in design and manufacturing and become more involved in project-oriented design courses acquire knowledge of design methodology, its language and thinking, and thus gradually learn how to view engineering problems from a new design perspective [3].

Design thinking and analytical thinking differ in numerous ways [4]. Analytical thinking requires that the student learn how to develop a correct solution to a well-defined problem in a specific knowledge domain using the language of mathematics. By contrast, in design thinking the student must weigh several plausible concepts, select the one that best satisfies the customer's requirements, and then describe it in detail using multilingual tools including physics, mathematics, graphics, and verbal and written representation. Analytical thinking may be described as a converging process that leads to a single correct answer. Design thinking may be described as a diverging-converging process in which more than one concept may be found suitable [4].

Beckman and Barry [5] examined a generic innovation process grounded in a model by Owen [6] of how people learn, which views design as a process of knowledge development. Owen suggests that the design process has both analytical and synthetic elements and that it operates in both the theoretical and practical realms. In the analytical design phases, Owen notes, one focuses on discovery, while in the synthetic design phases, one focuses on invention and creating. Owen's model describes the process of mechanical design very well: In the analytical phase, mechanical designers analyze design requirements and try to find new ideas and concepts (a diverging process). Later in the synthetic phase, they try to create a functional solution that meets the design requirements (a converging process). The innovation process presented by Beckman and Barry [5] alternately uses analysis and synthesis to generate new products and business models.

The ability to engage in a creative process to solve a problem or to design a new product is essential in engineering. Daly et al. [7] conducted a critical case study at an American university that offered seven

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engineering courses in which the instructors stated that one of the goals was fostering creativity. The results of the study showed that one aspect of creativity, convergent thinking including analysis, was well represented in the engineering courses. However, teaching how to generate ideas and develop openness to exploring ideas was evident less often. Creative skills, especially those related to divergent thinking and idea exploration, were lacking.

Design is widely regarded as the main activity in engineering [8]. The task of engineers is to create solutions and design systems to meet social, industrial, and commercial needs. Engineering education must, therefore, produce engineers who can design [4]. In order to improve design education, many universities recently started teaching engineering design through senior project courses referred to in the United States as *capstone courses* [3]. Design—educators are responsible for improving the balance between theory and practice in engineering education [9]. Dutson et al. in a thorough review paper of over 100 sources on engineering design courses found that the capstone courses were often developed in order to better prepare graduates to meet the needs of industry [10]. As a result, industry now often offers "authentic involvement" [9] in senior-level project courses by providing needed funding, equipment, and know-how [11]. Industry-sponsored courses also offer instruction and practice in design methodology, conceptual design, and detailed design, ultimately culminating in a product that the student builds and tests [10]. Nonetheless, in some schools, the project-based courses are initiated by internal customers; that is, design professors whose resources are necessarily limited.

Those in favor of industrial projects insist that real engineering is experienced only when students work on a real industrial problem. Those against industrial-sponsored projects argue that many of them require only low-level analyses that do not "push back the frontiers of knowledge" [9]. Both positions are often valid. Students tend to be enthusiastic about working on real industrial projects, but in their preoccupation with creative tasks, design thinking, design methodology, and many additional complex design details, they tend to exert less effort in performing advanced analysis and are content instead with only rudimentary analysis, merely sufficient to guarantee that the product functions.

The disintegration of analysis and design is our main interest in this paper. We will try to answer why it is so common for such little effort to be invested in analysis during the design process and why students and later on also practicing engineers in industry who studied advanced analytical methods for years tend to "forget" to apply advanced analytical methods when it comes to design. We propose a new approach, which we refer to as *integrated thinking* that can be implemented in what we call *integrated courses*. We will try to close the gap between analysis and design by impressing on students that the application of analytical skills during the design process distinguishes the outstanding design engineer from the merely good one. This new approach to teaching does not feature projects or case-studies [12]; our concept of an integrated course combines design and analysis, which are typically taught as two separate disciplines.

Project based learning (PBL) has been widely recognized as an active and integrative learning approach that fosters team creativity and focuses on practical education [4]. Furthermore, traditional lecture-tutorial teaching is often criticized for being a surface-learning approach that is passive [13]. Our proposed integrated analysis and design courses integrate and use both the lecture-tutorial approach for teaching analytical topics and projects to integrate analysis with design.

Integrated courses may also be able to generate new opportunities for research faculty who are interested in teaching courses with design elements by enlisting the help of a teaching assistant with practical design experience. Such courses should focus on understanding the physics behind the mathematical derivations and include examples using industrial applications. They may also encourage design-educators to add analytical components to their courses, thus bridging the type of design and analysis divide described by Todd and Magleby [14].

In the second section we describe in detail the inherent difference between design courses that teach design thinking and analytical courses that mainly apply analytical thinking. In the third section we describe the role of analysis in ME design. In the fourth section we introduce the idea of integrated thinking and integrated-engineering courses, followed in the final section by a brief description of our new course, Integrated Design and Analysis, illustrating how we implemented our integrated teaching approach and presenting feedback and comments from students who completed the course.

2. The difference between analytical thinking and design thinking

The main language in engineering-science courses is mathematics. Problem solving in this field requires that the data be precisely given; only one correct solution is expected, which can only be arrived at by using analytical skills and which is typically bounded by some learned-knowledge domain. The problem-solving process may be described as a converging sequence of equation derivations resulting in the final solution [4]. Typically, the need for creativity is limited throughout undergraduate studies, whereas students studying for advanced degrees *must* be creative to conduct successful research. Modeling is ideal and that sometimes makes use of synthetic symbols. In engineering-science courses, we discourage a trial-and-error approach except if an analytical or elegant solution is impossible. In most cases, work is performed individually, hence it is the student's personal abilities that are evaluated and individual performance that is either rewarded, or—if errors are found, for example, in the derivation process or in the final result—they are penalized. Engineering-science courses supply powerful engineering tools that mechanical engineers apply throughout their careers. Many research faculty believe that the main goal of analytical courses is the training of the next cadre of researchers in academia.

In contrast, design courses are multilingual and employ the language of physics, mathematics, graphical drawings, and verbal and written statements. As to problem solving, it is the customer's requirements that define what must be designed and the data is only partially provided or not at all; the designer must therefore estimate [15], measure, or assume all the information needed. Synthesis skills are needed to arrive at a design concept, but they must be supported by a thorough analysis. Thus, a design problem is approached using a diverging-converging process [4], which begins with several concepts that the designer weighs, the best of which is selected and finally translated into a detailed design. Limitless creativity may be exercised in the design process, as long as the solution meets the requirements. In the design process, modeling is used as a concrete tool representing real physical elements; for example, a simply supported beam cannot be placed on two hypothetical triangles, but must rather be physically realized. In design courses we encourage an iteration process in order to refine the options under consideration [16], and we use the trial-and-error approach to arrive at an optimal solution. Error making is integral to the design process and is accepted as a common way of gaining experience. Finally, in most cases, design projects require team work [11, 17, 18], and in many situations individual contributions are less important [16]. The main goal of design courses is educating and training the next generation of design engineers in industry.

We fully agree with the statement that "the purpose of engineering education is to graduate engineers who can design" [4]. The following Table 1 summarizes the features that characterize analytical and design thinking as taught in each type of course, respectively.

3. The role of analysis in ME design

In their extensive review of research in ME design 25 years ago, Finger and Dixon [19] wrote that "without analysis to provide accurate evaluation of expected design performance, design would be based on, at best, guesses and heuristics." In their paper, *analysis* refers to engineering analysis, which they noted, predicts results such as stresses, deflections, heat flow, motions, and the like, adding that it

Table 1. Features of Analytical Courses versus Design Courses

Features	Analytical Thinking in Analytical Courses	Design Thinking in Design Courses
Language	Mainly mathematics	Multilingual: physics, mathematics, graphical representations, verbal and written statements
Data	Precisely stated	Customer's requirements are given and the data may be precisely stated, known, estimated, or measured
Solutions	Only one is expected	Several are possible; all of them should meet the requirements
Skills required	Mainly analytical	Ability to synthesize, but advanced analytical skills make an outstanding designer
Thinking	Converging	Diverging-converging
Creativity	Somewhat limited	Limitless; several design concepts are expected
Modeling	Perfect, using symbolic representation	Imperfect, using realistic representation
Errors	Penalized	Learning from errors is normal
Trial-and-error approach	Discouraged	Encouraged
Work style	Individual	Team work
Main goal	Educate young researchers for academic careers	Educate engineers for design and manufacturing jobs

had become "more widely recognized that analysis supports design, and not the reverse." According to Finger and Dixon [19], analysis is more difficult in the conceptual stage of design, however, once a design has been carried to the detailed design stage, analysis procedures are available to predict or simulate the performance of the design. These statements were probably true at the time their paper was published.

In the last twenty years, the old perception that analysis supports design, each an entity unto itself, has ceased to exist. Ongoing efforts to integrate design and analytical tools are extremely successful. For example, the integration of computer-aided design (CAD) tools and various finite element analysis (FEA) packages [20], allow the designer to utilize analytical tools from the very beginning of the design process. Mechanical designers use modern CAD tools daily, including kinematic and dynamic analysis and computational fluid dynamics (CFD) tools [21], tools capable of reverse engineering accompanied with FEA analysis [22], and dozens of other analytical aids, which used together, allow easy access to analytical knowledge.

With today's ubiquitousness of user-friendly integrated mechanical design tools, the following questions must be addressed: Are we adequately training our undergraduate students to integrate analytical tools in design? Why does the ME education system still separate engineering-science courses and design project-based courses? We will try to provide answers in the next section.

4. Characteristics of integrated thinking and courses

The purpose of the approach we call integrated thinking is to expose all ME students, regardless of their major track, to both analytical and design thinking. First, we introduce the idea of design thinking and later the concept of integrated-engineering courses.

Integrated thinking combines the features listed in Table 1 under both the analytical and design thinking columns. Its multilingual language employs mathematics and physics, graphical representations, and verbal statements. The data may be either precisely given if a specific analytical task is required, or presented as a set of design requirements if the problem is project-based. Both analytical skills and the ability to synthesize are required and likewise the thinking must be both analytically—and design-oriented. Creativity can and should be given full rein and the modeling tools used must be realistic or symbolic, as appropriate. In open-ended problems, trial and error is accepted as a way of learning; in analytical assignments a correct answer is expected. Finally, the work may be carried out both individually or as a team. The main goal of integrated thinking is to ensure that all ME students recognize that analytical and design thinking is inseparable and essential synergetic components that are both needed to becoming a good mechanical engineer.

In order to create an integrated approach in ME education we propose using a new model of an integrated-engineering course that modifies existing engineering-science courses by emphasizing the physics behind the mathematical equations and the potential engineering application of scientific phenomena. For example, in an *integrated* fluid mechanics course, the lecturer would not only present a model and derive and explain the equations but would also present a practical example related to the learned material. Similarly, after explaining momentum equations for control volume, the lecturer would demonstrate them with the example of a small rocket accelerating vertically followed by a short video. In tutoring sessions additional practical examples should be introduced and tied in with the learned theory. In addition, throughout the course the lecturer would assign mixed homework exercises including analytical textbook problems as well as two or three design projects that require fluid dynamics analysis as well as conceptual and detailed product design. A course in fluid mechanics taught in such a manner not only explores the fundamentals of the scientific behavior of fluids but also imparts practical tools for designing and building systems and instruments.

The integration principle described above may be applied in many other ME core engineering-science courses, such as heat transfer, dynamics, vibration, control, FEA, and the like. Research and design faculty may both welcome the opportunity to teach integrated-engineering courses; the former, with the aid of a skilled teaching assistant to carry out the design tasks and the latter, specifically those who are experts in one of the engineering science areas. Both teachers and students should expect scientific knowledge in such courses to be translated and applied to engineering design.

The integrated approach is also recommended for project-based design courses such as those that focus on important topics like design methodology, design concept, detailed design, and material selection but which neglect analysis and optimal design. Integrated project-based courses would require thorough modeling of the problem and the use of advanced analytical tools for each design concept before selecting the leading concept and beginning the detailed design and drawings.

By promoting the awareness of integrated thinking, we can educate ME students to understand that the mechanical engineering profession requires analytical and design skills equally, as well as the full integration of both. We can also reduce the existing artificial separation of topics and courses that are regarded as either purely engineering science or purely design. Surprisingly, even the fundamental machine design course [23] in many ME departments does not include a comprehensive project and therefore does not teach design thinking but rather implements analytical thinking for teaching machine elements.

The integrated approach may benefit ME departments throughout the United States and in the many countries that follow the US higher-education system, by enhancing students' experience in the practice of mechanical engineering and design.

5. Application of integrated thinking concept and students' feedback

We applied the concept of integrated thinking in a course centering on dynamics and vibration that we called Integrated Design and Analysis. The lectures included analytical material that was related to specific design problems and was aimed at elucidating the practical applications of the analysis. The focus of the frontal teaching was on understanding the physical meaning underlying the formal mathematical representations by using simple experiments and demonstrations available on the Internet. The tutoring sessions presented examples of how to use analytical methods in dynamics and vibration to design a specific machine. Some of the topics learned in the course repeated material familiar from earlier engineering-science courses and some topics were advanced and closely related to practical design.

Four main assignments were given, all projects that required the integration of analysis with conceptual and detailed design. Each project challenged the students to use the analytical knowledge that they learned in class constrained by the given design requirements, and each presented an open-ended type of problem in which the data were incomplete and had to be partially assumed and estimated. We found that students responded positively to the challenge of an open-ended design problem. Furthermore, they learned that analysis is needed in order to evaluate design parameters, check the plausibility of a concept, and determine if the solution meets the requirements and is stable and robust. Each project corresponded with a different aspect of the material learned in the course: quasi-static analysis of a rigid body and free-body diagrams, vibration, and kinematics of a rigid body and rotational motion of a rigid body, which is considered one of the most complicated concepts to teach in dynamics [24]. The four projects and the course material they corresponded with were:

1. Analysis and design of a garage door that (a) opens up to a 90-degree angle and remains stationary in that position; (b) can be lifted and shut by one person; and (c) self-locks in the closed position (Fig. 1). This project corresponded with the classes on static and dynamic analysis of a door-lifting system and design of a self-locking mechanism.
2. Analysis and design of a vibrating table with a rotating unbalanced mass that stands on a 4-spring support (Fig. 2). Vibrating tables are used in many different industrial applications such as vibratory feeders in food industry, concrete vibrators, and vibrating tables used to test products in order to determine their ability to withstand vibration. This project corresponded with the classes on vibration caused by rotating unbalance, bearings assembly, and design of a vibrating table.
3. Analysis and design of a spring-loaded Whitworth quick-return mechanism (Fig. 3). A

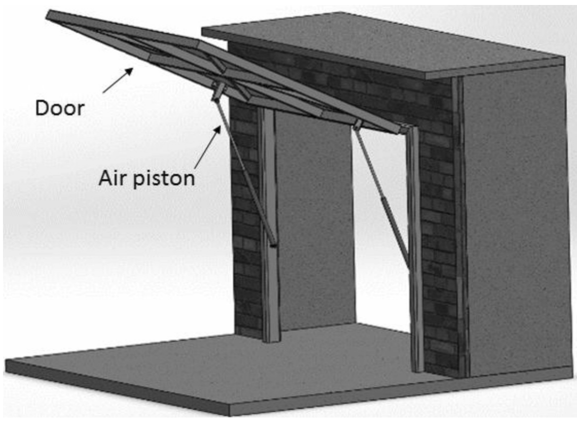

Fig. 1. Project 1—Self-locking garage door.

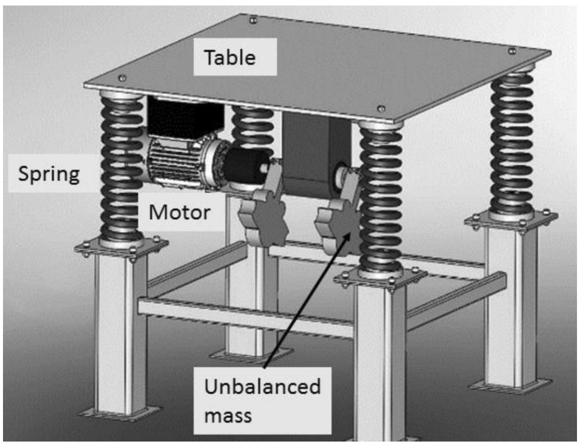

Fig. 2. Project 2—Vibrating table with a rotating unbalanced mass.

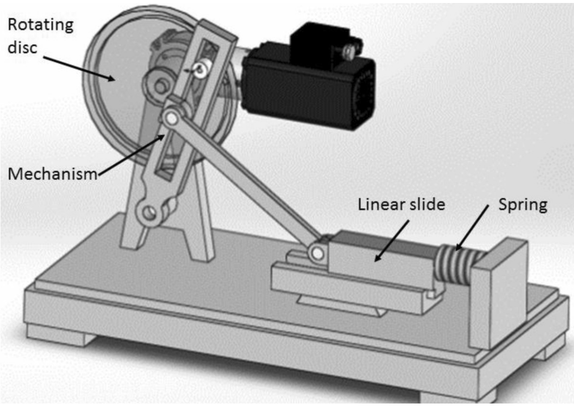

Fig. 3. Project 3—Whitworth quick-return mechanism.

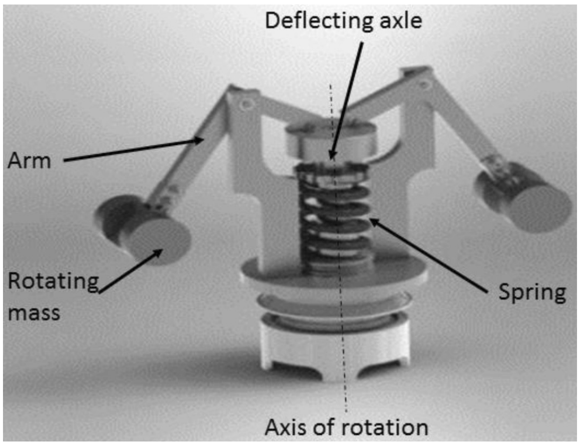

Fig. 4. Project 4—Harnell's centrifugal governor.

quick return mechanism is used when there is a need to convert rotary motion into reciprocating motion with variable speed: As the disc rotates, the slide moves forward and backward. Many machines use this type of mechanism, one of which is the shaping machine tool. In this project, students were required to apply what they learned about planar kinematics of a rigid body, analysis of a quick-return mechanism, and design of a spring-loaded mechanism.

4. Analysis and design of a Hartnell-type centrifugal governor (Fig. 4). Centrifugal governors are used to control the speed of an engine utilizing proportional control principles. In this project the students applied the complicated principles of rigid body dynamics and rotational motion of a system.

In the centrifugal governor project, for example, students were asked to analyze the governor's axle deflection versus the speed of rotation using Lagrange equations and alternatively, use a quasi-static solution. Using the Lagrange equations resulted in complete non-linear equations defining the governor's dynamic behavior. After the linearization process, the students were able to evaluate stability in transient motion and response in a steady state. Using a quasi-static approach, they modeled the governor for steady-state rotation, applying the centrifugal force as an external load on the governor and later analyzing the governor using a free-body diagram. Both methods resulted in a similar equation for calculating deflection of the axle at each rotational speed.

The students were asked to submit a conceptual design of the governor. Fig. 5 shows three different design models of the Hartnell-type centrifugal governor that were proposed by three different 1—or 2—student teams.

In each of the four projects students received a set of requirements and were asked to submit a thorough analysis, conceptual design, and detailed design. The analysis and the design concepts were described in a technical report and the detailed design was submitted as a production file, which contains technical drawings of all the production-ready designed parts, and a bill of material (BOM) listing all the elements (produced and purchased) that are required for the assembly of a product. By working on these projects, the students learned that mechanical design must be approached holistically, beginning with an understanding of the technical

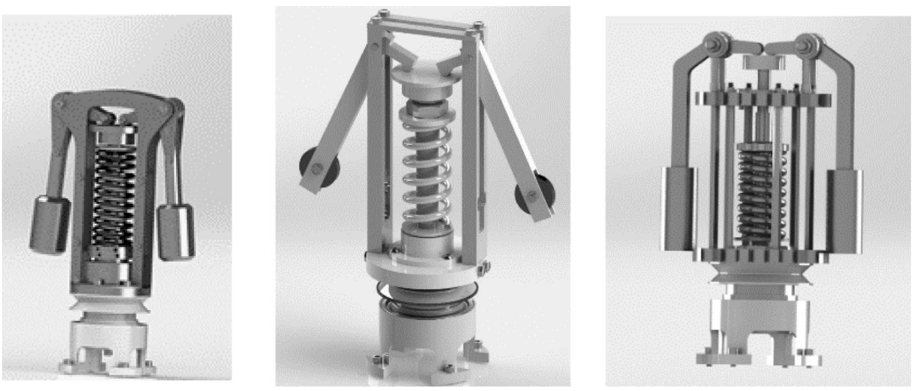

Fig. 5. Three different designs of a centrifugal governor.

requirements, continuing with a thorough analysis of the concepts (diverging phase), and culminating in a detailed design of the product and production file (converging phase).

After the course was completed and the students were graded, we asked them to participate in a short survey to assess the course and its contribution to their ME education: Twenty-one agreed to participate. Their responses clearly reflected their understanding that this course was different from the typical engineering-science courses that they had taken before and that it enabled them to apply their acquired analytical knowledge to design problems.

Following are a number of random student responses to the two questions that appeared in our survey: first, in response to the question, "What is the difference between the course Integrated Design and Analysis and the analytical courses in dynamics or vibration?"

> I think this is one of the most practical courses I've taken so far. It really does integrate various disciplines of mechanical design applications (the only major disciplines missing are fluid dynamics and heat transfer). I really feel more confident using analytical tools, and I have a better understanding which type of problem I'm dealing with. In analytical courses we solve only well-defined problems.

> Whereas the standard courses in dynamics or vibration focus on teaching the basic theories, this course focuses more on the physical and practical applications of the theory that influence design parameters and requirements. While the standard courses give analytical problems, of varying degree of difficulty, this course proposed practical design problems, without a single solution, expecting the student to choose a solution based on a compromise between different design requirements.

> It's the first course that teaches how to integrate between analysis and design; it is very important for us the students who are about to enter the marketplace. The difference between the courses is the practical applications that connect us to reality. In dynamics and vibration courses we learn many derivations of equations, but in the end we don't know what to do with them. In this course we learned only some core elements of this material, but we learned how to use them in engineering practice.

> In the analytical courses we were asked every week to deal with some specific and limited aspects of the learned material. In this course, for each project we had to address a broad range of analytical challenges that had to meet design requirements, using hardware such as springs and bearings. This makes a huge difference in the way one understands the material.

The second question had two parts: "What is the difference between solving analytical problems in dynamics or vibration and designing a machine that rotates or vibrates, and what are the tools that you use for each of them?" Many students indicated that there is a difference between a typical textbook homework problem in dynamics and the design of a rotating machine, and they were able to intuitively explain the difference between analytical thinking and design thinking and the meaning of an integration of the two.

> When solving a problem in dynamics, it remains on a theoretical level, so we don't really understand the physics behind it. When one has to design a machine that meets certain requirements, one has to understand how it operates and how to model it correctly in order to design it.

> In order to solve an analytical problem we use mathematical tools such as differential equations or algebra. But in order to design a vibrating machine, one has to think beyond differential equations or algebra. One must think, how do things happen? Why do they happen? What do they cause? And design accordingly.

> Analytical problems, by definition, are problems that have a single solution. On the other hand, most engineering and real-world problems are not so. To solve practical design problems, one has to rely on theory to get a direction or an estimate of the behavior of the system and then use tools to converge to a set of possible solutions. From this set of solutions, we can choose the most appropriate one, depending on the requirements.

> When we solve a problem in dynamics or vibration, it remains on a theoretical level. In analytical courses we use analysis and software tools to get a numerical solution. When you design a machine that vibrates or rotates, you have to understand how to interpret the numbers that you calculated and understand how the machine is supposed to operate. In this course we used analytical tools, but we also had to use CAD tools and catalogs for hardware selection and make it all work together.

6. Discussion

During the first two or three years of undergraduate studies, ME students mainly study engineering-science courses and analytical thinking; as a result, they assume that in order to become a mechanical engineer one mainly needs analytical skills. Students who decide to major in mechanical design enroll in project-based design courses and are then surprised to discover that design skills are quite different from analytical skills. In project-based design courses they are exposed to a new way of thinking, a new language, and a different way of approaching problems. Students who select other majors such as control, energy, or biomechanics are barely exposed to design thinking in their undergraduate ME studies, and in most cases they encounter it for the first time on the job in industry. By introducing the idea of integrated thinking and implementing it in a new integrated type of science course, we can guarantee that all ME students, regardless of their major, will learn both analytical and design thinking.

The current ME education system draws a line between analytical engineering-science courses and project-based design courses; research faculty teach the analytical courses and design faculty teach the design courses. While all ME students learn analytical thinking, only students who major in design and manufacturing are thoroughly trained in design thinking. Hence the need to offer a new type of analytical course with embedded design elements, exposing students of all majors to the potential implementation of the learned theory and ensuring that students will learn that analysis and design both are equally needed to becoming an engineer.

Faculty also benefit: Research professors gain an opportunity to teach integrated-engineering courses that require both analytical and design thinking. Likewise, design professors can teach integrated-engineering courses with strong analytical content.

Integrated Design and Analysis was introduced as a pilot course that focused only on dynamics and vibration and has so far only been taught twice, both times successfully. The course requires that the instructor or at least the teaching assistant have a good understanding of the design process. Furthermore, it would be useful to apply our teaching method to mechanical engineering to determine if it can be used effectively more broadly in engineering education.

7. Conclusions

The idea of integrated thinking was applied successfully in the Integrated Design and Analysis course. The feedback from the students clearly shows that they understood and appreciated the uniqueness and benefits of the new approach to their education.

The main benefit for students in an integrated-engineering course is gaining the understanding of the holistic nature of ME, in which theoretical and scientific concepts are embedded in practical mechanical design.

As a secondary recommendation, we suggest reforming project-based courses that focus mainly on design methodology and detailed design, neglecting analysis. Our integrated project-based course aims to strengthen the analytical component, including design optimization, and to make use equally of analytical and design thinking.

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