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Incorporating Design Projects to Facilitate Students' Understanding of Mechanical Vibrations

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INCORPORATING DESIGN PROJECTS TO FACILITATE STUDENTS' UNDERSTANDING OF MECHANICAL VIBRATIONS

ABSTRACT

Mechanical vibrations course is a required course for our mechanical engineering program. It is a 3-0-3 course for senior students with 3-hour lectures, zero lab hours per week, and a total of three credits. The governing equations of motion for a vibration system are differential equations. Naturally, in the mechanical vibration course, there are lots of derivations of the solutions of solving differential equations. Without these derivations, students will have difficulty understanding the solutions that might affect them to implement vibration theory in practice. Due to this fact, some students lost interest in the course and said that it was difficult and boring. To motivate students to be interested in the course and facilitate them to have a better understanding of mechanical vibration theory, we created two analytical-type design projects. These two design projects are “The design check of a beam under a harmonic exciting force” and “The vibration isolation and absorber”. They are meaningful mechanical design projects in which the mechanical vibration theory is implemented. This paper presents the two projects, and their implementation and shows the class survey results. Most students agreed that the class design projects significantly facilitated them to have a better understanding of mechanical vibration theory and helped them to establish the connection between mechanical vibration theory and its applications and the class design projects should be kept for the mechanical vibration course in the future.

1. INTRODUCTION

One of the primary objectives for mechanical engineering design is that mechanical design must be safe. Two main tasks for safe mechanical designs are that the factor of safety must be larger than the required factor of safety and they do not have resonances. In the course of mechanics of materials, lots of sophomore mechanical engineering students don’t fully understand why the factor of safety for dynamic loads should be at least 2.0. The course mechanical vibrations can fully explain these two issues to mechanical engineering students.

Mechanical vibrations course is a very important course for engineering programs. It is offered in different formats by different engineering programs. Some programs offer it as a junior required course [1,2,3] and some program offers it as a junior elective course [4,5]. Some of these courses are offered with a lab section, but some of these courses are offered without a lab section [1,4,5,6,7]. Mechanical vibration course is a difficult course for lots of students because lots of mathematical derivation processes are needed for solving partial differential equations. Without these derivations, students will have difficulty understanding the solutions, and this might affect them to implement vibration theory in practice. To overcome such issues, lots of different activities have been tried such as physical lab sections, design projects, flipping classes, and using MATLAB [1,7,8,9,10]. All of these activities are to link the vibration theory to some applications or to use some physical and visible approaches to demonstrate the vibration theory. The objective of all these activities is to facilitate students' understanding of concepts and topics delivered during mechanical vibrations.

The mechanical vibrations course in our mechanical engineering program is a required senior-level course. It is a 3-0-3 course with 3-hour lectures, zero lab hours per week, and a total of three credits. Since it does not have a lab section, it is a must that some active activities should be added to this pure-lecturing course to facilitate their learning and understanding of this course. Two approaches have been implemented in this course.

The first approach was to ask students to design, construct, and demonstrate a design prototype which was an SDF (Single-Degree-of-Freedom) system for demonstrating vibrations or measuring some vibration parameters. The main objective of this was to facilitate students to have a better understanding of mechanical vibrations. Each team consisted of 2 to 4 team members and had a $50 budget for constructing their prototypes. The total budget for the whole program in this course was around $2000 ~ $2500 per year. This approach facilitated students to have a better understanding of mechanical vibrations, which was discussed and published at the ASEE 2019 annual conference [1]. However, it was not sustainable because the components purchased for constructing prototypes were typically not reusable. When a budget was available, this approach was worth doing. However, when the budget was tight, we could not implement this approach.

The second approach was to ask students to conduct some class analytical-type design projects in which students would do theoretical analysis without constructing any prototypes. The author has tried this approach for several years by doing different analytical-type design projects. This paper, which is based on the implementation of this approach in the 2023 spring semester, will discuss how to select possible design projects. It will also present the implementation of the second approach and some data analysis from the class survey.

2. DESIGN PROJECTS FOR THE MECHANICAL VIBRATION COURSE

The mechanical vibrations course offered in senior year in our mechanical engineering program has 3-hour lectures per week without lab in a 15-week semester. It is typically arranged as two-80-minute lectures per week. The textbook used in this course is "Mechanical Vibrations, 6th edition" by S.S. Rao. The topics covered in this course and their sequence are:

- Chapter 1 Fundamentals of Vibration
- Chapter 2 Free Vibration of Single-degree-of-freedom Systems
- Chapter 3 Harmonically excited vibration
- Vibration isolators (Part of Chapter 9 Vibration controls)
- Chapter 4 Vibration under General Forcing Conditions
- Chapter 5 Two-Degree-of-Freedom systems

- Vibration absorbers (Part of Chapter 9 Vibration controls)
- Chapter 8 Continuous system: FEA simulation for natural frequencies

After discussing with colleagues and students and based on the key topics delivered in this mechanical vibration course, two analytical-type design projects were created and implemented. The primary objectives of these two analytical-type design projects were to link the vibration theory with their applications and to facilitate students to have a better understanding of the vibration theory.

The first analytical-type design project was "The design check of a beam under a harmonic exciting force". The two primary objectives of this were (1) to derive the solution of the Single-degree-of-Freedom vibration system under harmonic force, and (2) to understand why the safety factor under dynamic loading should be bigger than at least two when static load was used for calculation.

An electrical motor is mounted in the middle of a simple-supported beam as shown in Figure 1. The beam made of AISI 1020 steel has a constant cross-section of 0.030 m × 0.125 m (height × width). The span of the beam is 0.5 m. The estimated damping ratio is 0.1. It is assumed that the weight of the beam can be negligible. The whole system can be simplified as a damped single-degree-freedom vibration system. The motor has a mass of 250 kg with a rated speed of 1200 rpm. A rotating force of magnitude $F_0 = 5200 + 50 \times team\#(N)$ is developed due to the unbalance in the rotor of the motor. For this project, each team can have two to a maximum of four team members. It is assumed that the static failure of the beam will be the main concern and be mainly due to the bending stress and the required factor of safety for the beam is 3.0.

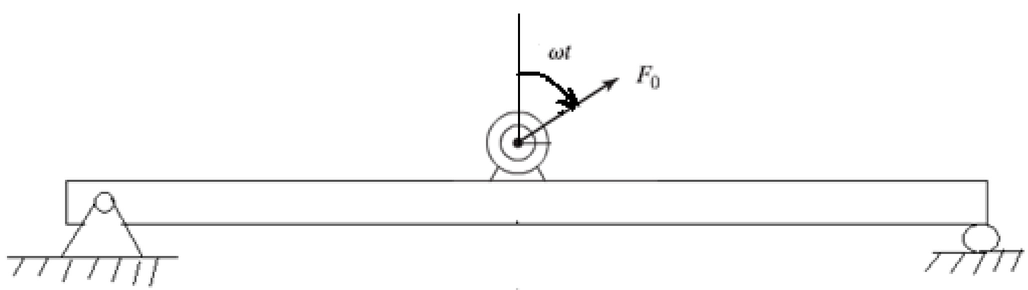

Figure 1 The schematic of the simple-supported beam with a motor mounted in the middle

The main tasks in this design project are:
(1) Simplify the simple-supported beam as a Single-Degree-of-Freedom vibration system and calculate the equipment spring constant.
(2) Build the governing equation of motion.
(3) Derive the solutions of this project and show the detailed derivation process.
(4) Determine the maximum dynamic stress of the beam and then calculate the safety factor.
(5) Write and submit a technical report.

The second design project is "The vibration isolator and absorber". The two primary objectives of the second design project are (1) to implement the concepts of vibration theory to design a mechanical isolator, and (2) to implement the vibration theory to design a mechanical absorber.

In the second design project, it is assumed that a piece of precision equipment is mounted on a support table (the ground). The equipment can be treated as a mass of 127.8 kg with a spring constant of $2.752 \times 10^6 (\frac{N}{m})$. At steady normal operation, the equipment is subjected to a harmonic force: $F(t) = 1000\cos[(272 + \text{team\#} * 10)\text{t}]\ \ (N)$. Each design team can have 2 to 4 team members. The design requirement is that the maximum deformation of the equipment must be less than 0.0005 (m).

The main tasks in the second design project are:

(1) Design a mechanical isolator by changing mass or spring constant or both but the maximum deformation is slightly less than 0.0005 (m). Build the governing equation of motion of a single-degree-of-freedom damped vibration system and derive the solution of a mechanical isolator with a detailed process.
(2) Design a mechanical absorber assuming that the amplitude of the auxiliary mass is less than 0.001 (m). Build the governing equations of motion of a two-degree-of-freedom un-damped vibration system and derive the solution of a mechanical absorber with a detailed process.
(3) Prepare and submit a technical report.

3. IMPLEMENTATION OF THESE TWO DESIGN PROJECTS

In the 2023 spring semester, the two design projects were implemented in my section on mechanical vibrations.

In week 5, after the completion of Chapter 2: Free Vibration of Single-Degree-of-Freedom System and before lecturing about Chapter 3: Harmonically Excited Vibration, the first design project was released and explained to students. During a lecture, we spent around 10 minutes explaining the objectives and main tasks of the first design project. We asked them to form a team with 2 to 4 team members to complete this project. Since it is an analytical-type design project, it was allowed to be completed by an individual. They had three weeks to complete the design project. In the second lecture session during these three weeks, we spent around 10 minutes on a Question-and-Answer section about the design project.

Through the interaction with students, most of the students better understood the solutions of the single-degree-of-freedom damped vibration system because they were required to derive and explain the process in their technical report. As for the calculation of the factor of safety, some of the teams determined the maximum defections and then calculated the factor of safety. Some of the teams determined the maximum dynamic forces and then calculated the safety factor. This project significantly increased their interest in vibration theory because they implemented it to solve a design project.

In week 10, after the completion of Chapter 3 Harmonically Excited Vibration, the second design project was released. They had three and a half weeks to complete this project. The technical report was required to be submitted before the final exam period. They could use the same team, or they could form new teams to conduct the second design project. It was also allowed to be completed by individuals. In the second lecturing session during these three and a half weeks, around 10 minutes was reserved for the Questions and Answers section about the second design project.

Through the interaction with design teams, the second design project presented them with the meaningful application of mechanical vibration theory. Some students said that they now had a better understanding of cushions between engines and the housing frames and could design and select proper cushions.

4. CLASS SURVEY AND DATA ANALYSIS RESULTS

At the end of the 2023 spring semester, a class survey was assigned. The class survey had three questions and one open comment.

Question #1: The class design projects significantly facilitate me to have a better understanding of mechanical vibration theory.

☐Strongly Agree ☐Agree ☐No opinion ☐Disagree ☐Strongly Disagree

Question #2: The class design projects helped me to establish the connection between mechanical vibration theory and its applications.

☐Strongly Agree ☐Agree ☐No opinion ☐Disagree ☐Strongly Disagree

Question #3: The class design projects should be kept for the mechanical vibration course in the future.

☐Strongly Agree ☐Agree ☐No opinion ☐Disagree ☐Strongly Disagree

Question #4: Any comments about the class design projects?

17 out of a total of 21 students completed the class survey. The class survey data is shown in Table 1 The survey results are depicted in Figure 2. The percentage of "Agree and above" on three survey questions is shown in Table 2 and depicted in Figure 3.

Table 1 Class survey data

Survey Question #	Strongly agree	Agree	No opinion	Disagree	Strongly Disagree
#1	41.18%	47.06%	5.88%	5.88%	0%
#2	52.94%	41.18%	0%	5.88%	0%
#3	52.94%	29.41%	17.65%	0%	0%

Table 2 The percentage of "Agree and above" of three survey questions

	Survey Question #1	Survey Question #2	Survey Question #3
Percentage of "Agree and above"	88.24%	94.22%	82.45%

Per class survey results, 88.24% of students agreed that the class design projects significantly facilitated them to have a better understanding of mechanical vibration theory. 94.22% of students agreed that the class design projects helped them to establish the connection between mechanical vibration theory and its applications. 82.35% of students agreed that the class design projects should be kept for the mechanical vibration course in the future.

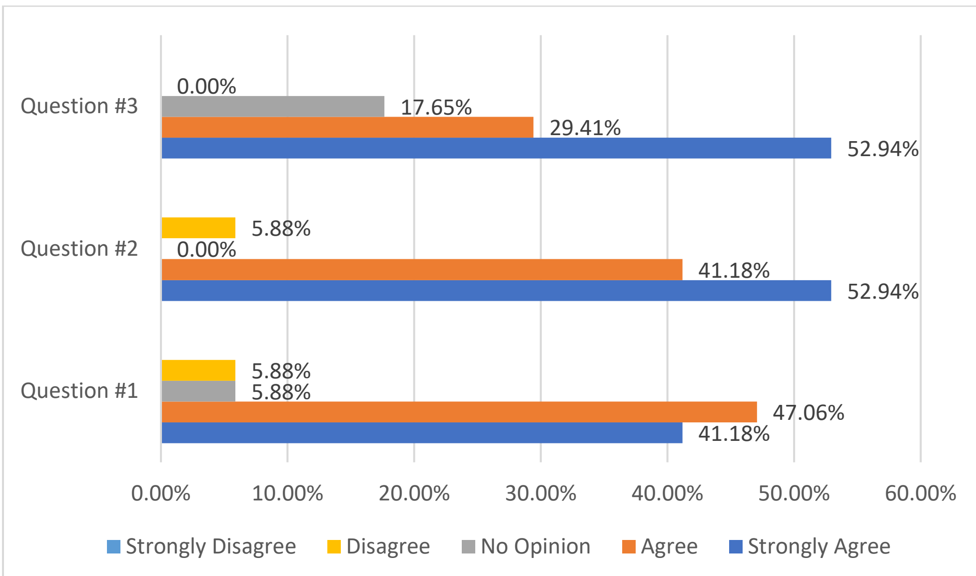

Figure 2 The survey results on three survey questions

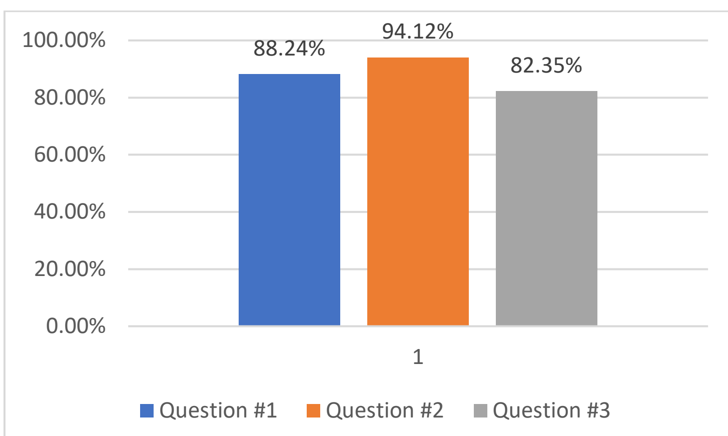

Figure 3 the percentage of "Agree and above" of three survey questions

For the open comment survey question, the following are some comments.

- "The project definitely helped me get a better understanding of mechanical vibrations through a project rather than a lecture."

- "I think the design projects were a huge help. While in the lectures we talk about real-world applications, the projects give us a true understanding of how it is applied. The homework helped prepare for our exams, but the projects helped with exams and an overall understanding of why we are learning what we are learning."
- "This project provided students with a very good understanding of mechanical vibration in the real world."
- "This project was extremely helpful in my understanding of vibration isolation and absorbers. Researching the introduction was very useful in developing an understanding that helped me answer conceptual equations on exams. Solving both sections of this project was also super helpful in understanding everything. This is a very good project to give students!"
- "This helped to highlight the differences in how isolators and absorbers work, and why you would choose one over the other. The project was well laid out, and the class lectures made the analytical design work fairly straightforward."
- "Overall great projects that showed the effectiveness of mechanical design to reduce or eliminate potential damage due to vibration."
- "I believe I learned a lot from doing the 2 class projects. They both had examples from vibration theory in the real world that I think I would be able to utilize once I get into the workforce. I would highly recommend keeping these projects for the course in the future."
- "The class design projects are a great chance to better understand the application of vibrations and work as a team, but it would be nice to have time in class to work with our groups on the projects."
- "Good project, just wish more time was given to get it done, and more time with the second method ideas and equations."

Based on the interaction with students and these comments through the class survey, the meaningful design projects in which the mechanical vibration theory is implemented can significantly facilitate students to have a better understanding of mechanical vibration theory.

5. DISCUSSIONS AND CONCLUSIONS

Mechanical vibration course is an important course for mechanical engineering programs. It has been offered in different formats such as a required course, an elective course, a course with lecturing only, or a course with both lecturing and labs. There are lots of mathematical derivations for solving the governing equations of motion, which are differential equations. However, it should not be delivered as a math course. It should include some applications of mechanical vibration theory in mechanical design.

For a mechanical vibration course without a lab section, the analytical-type design projects can be a very effective approach to facilitate students to have a better understanding of mechanical vibration theory. We created two design projects and implemented them in our mechanical vibration class, which were "The Design Check of a Beam under a Harmonic Exciting Force" and "The vibration isolator and Absorber". These two projects established good links between the mechanical vibration theory and its real-world implementation. Per the class survey, 88.24%

of students agreed that the class design projects significantly facilitated them to have a better understanding of mechanical vibration theory. 94.22% of students agreed that the class design projects helped them to establish the connection between mechanical vibration theory and its applications. 82.35% of students agreed that the class design projects should be kept for the mechanical vibration course in the future.

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