Integrating Hands-On Technology and Theory in Vibration Course

Daniel P. Hess
University of South Florida

Abstract

This paper describes an undergraduate vibration course taught in the Department of Mechanical Engineering at the University of South Florida. The course differs from the traditional vibration theory course taught at most universities because it integrates the practice of vibration engineering and design together with vibration theory. This integration is facilitated through lecture, hands-on projects, and laboratory exercises. In addition, students get experience with state-of-the art equipment and software. Compared to the traditional approach, this course better prepares students for the growing opportunities involving the application of vibration technology in machinery and structure analysis.

Introduction

Many universities in the United States offer courses in vibrations to undergraduate engineering students. These courses are generally focused on engineering fundamentals with limited material on technical applications.

Examination of available textbooks for an undergraduate vibration course reveals that only a few textbooks provide material on vibration measurement and this material is generally very limited in scope [1-5]. For example, several texts describe an accelerometer but do not discuss other vibration sensors such as proximity probes and velocity sensors. Furthermore, available texts provide very limited information if any on vibration analyzers, instrumentation and signal processing.

For the practicing engineer, there exist numerous short courses that focus on practical aspects of vibrations such as balancing of rotating machinery, isolation system design, and modal testing. These are generally provided by individual consulting firms, organizations such as the Vibration Institute, or companies that manufacture sensors and analyzers. These short courses generally include a set of notes or an applications text [6-9].

This paper describes an undergraduate vibration course taught in the Department of Mechanical Engineering at the University of South Florida. This course is unique in that it integrates the fundamentals of vibrations together with hands-on experience and exposure to technical applications. This approach is in line with the current interest and trend in numerous areas of engineering and science of integrating technical components and design into engineering courses and curriculum [10-11]. In addition, this course better prepares students for the expanding opportunities in machinery and structure analysis.

Course Lecture Content

The vibration course is designated as EML 4220 Vibrations. It is a 3 credit hour course in a fifteen-week semester. The class meets for three hours of lecture per week. The outline for the lectures is as follows:

Week	Topic
1	Introduction and overview
2	Balancing of rotating machinery
	Single degree-of-freedom systems
3	- free vibration (natural frequency, damping)
4	- forced vibration (resonance)
5	Design of vibration isolators
6	Vibration sensors, monitors and analyzers
	Signal processing
	Two degree-of-freedom systems
7	- natural frequencies & mode shapes
8	- free & forced vibration
9	Design of vibration absorbers
	Multi degree-of-freedom systems
10	- modal analysis
11	- general response
12	Continuous systems
	- strings
	- rods & shafts
	Finite elements
13	- theory
14-15	- applications

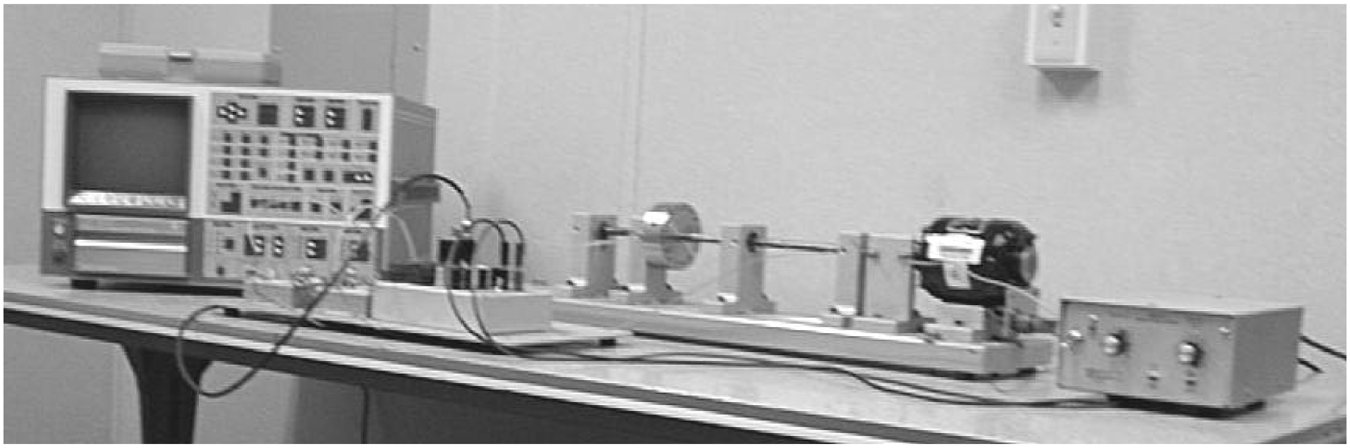

Figure 1 Balancing apparatus and vibration equipment.

Homework problems are assigned after each section of the outline is covered. These are not collected or graded, however, the solutions are posted one week after the problems are assigned.

The first week of the course provides a general introduction to the field of vibrations and an overview of the course. During the second week, the lecture jumps into balancing of rotating machinery. Covering this material early in the course provides the students with an excellent application of vibration theory. In addition, this provides an opportunity to introduce basic vibration measurement and to describe frequency response and other concepts from a very physical perspective.

Once the concepts and procedures of balancing have been covered, the students sign up in pairs for a one-hour laboratory exercise on balancing. This provides the students with some hands-on activity and experience with vibration equipment quite early in the course. Within about two weeks, all of the students complete this exercise. Details for this exercise are provided in the next section.

During the third and fourth weeks of lecture, free and forced vibration of single-degree-of-freedom systems is discussed. Here the concepts of natural frequency, damping ratio, resonance, frequency response, Fourier series, superposition principle, and convolution integral are presented.

In the fifth week, principals of vibration isolators are presented. Concepts of transmissibility and isolation efficiency are defined. Once this material is covered, the students are given two weeks to design and build an isolation system for a small machine that exhibits excessive vibration. Then, each student signs up for a fifteen-minute time slot to demonstrate the performance of his or her design. Details for this project are provided in the next section.

Meanwhile, one week of lectures are dedicated to vibration sensors, monitors, and analyzers. Relevant principals of signal processing such as Fourier transforms, anti-aliasing filters, leakage, windowing, and averaging are discussed.

Next, two weeks are spent introducing concepts such as mode shapes associated with two degree-of-freedom systems, and solving the free and forced response including frequency response for such systems. This provides the essential background necessary in the design of vibration absorbers. After one week of covering the fundamentals of vibration absorbers and their design, the students are given two weeks to design and build a vibration absorber for a small machine that exhibits excessive vibration. Then, each student signs up for a fifteen-minute time slot to demonstrate the performance of his or her design. Details for this project are provided in the next section.

During the tenth and eleventh weeks of the course, the lecture covers modal analysis and the general response of multi-degree of freedom systems. Since this is an extension of what was covered for two degree-of-freedom systems, new concepts such as matrix representation and the use of the eigenvalue problem in modal analysis are introduced.

Only one week is allocated for continuous systems. The vibrations of strings, rods and shafts with various boundary conditions are covered. The students are taught how to derive partial differential equations, to calculate natural frequencies and mode shapes, and to solve the equations using separation of variables.

The limitations for exact solutions of continuous system models for anything beyond the classic problems such as beams, membranes and plates with certain boundary conditions is discussed. This leads into a discussion of discretization of continuous systems.

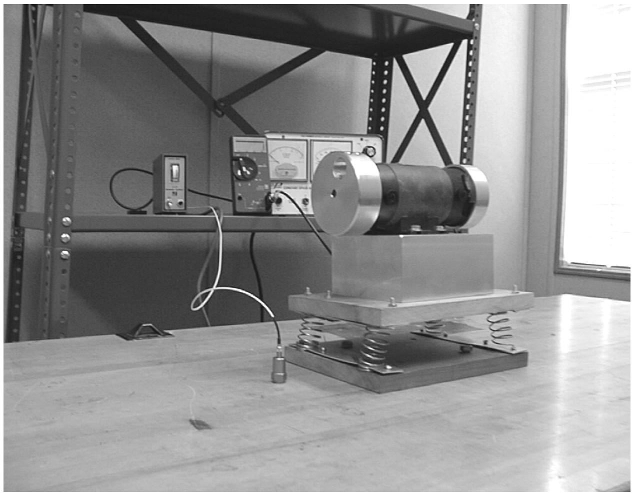

Figure 2 Machine with representative isolation system.

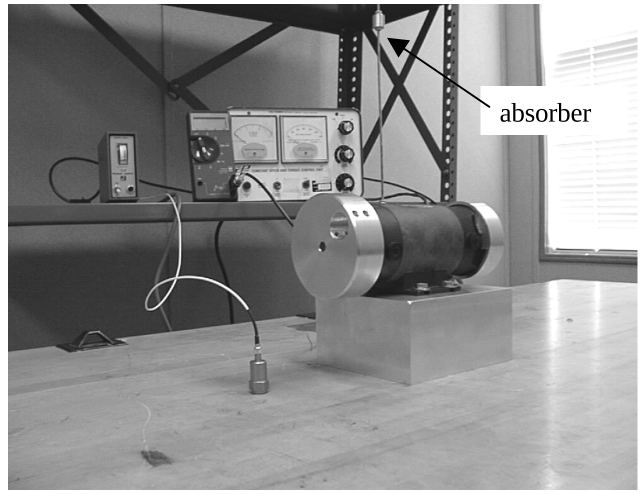

Figure 3 Machine with representative vibration absorber.

The last topic of the course is finite element analysis which is the most widely used discretization method. Basic finite element theory is covered in one week. Only simple examples such as rods and shafts with a few elements and nodes are worked out by hand in detail. In addition, comparisons are made between finite element model and continuous model solutions. The last two weeks of lecture introduce features of ANSYS finite element software that are essential for the students perform a vibration analysis of a structure using the student edition of ANSYS finite element software.

During the thirteenth week of the semester, the students are scheduled for a laboratory exercise for a demonstration of modal testing of a structure. The students then have the rest of the semester to develop a finite element model of this structure and to perform a modal analysis. Details for this project are provided in the next section.

Hands-On Projects

As indicated in the previous section, the course includes four hands-on projects. Each one of the four projects counts for one-quarter of the grade for the course. The resources required to facilitate these projects are vibration equipment, a graduate teaching assistant for 10 hours per week, and some laboratory space.

All of the vibration equipment that is used for the course was borrowed from the author's research laboratory or donated from industry. The support for the teaching assistant comes from the Department. The space is a 300 square foot room that was earmarked for undergraduate use.

The first project is a laboratory exercise on balancing. The students sign up in pairs for a one-hour time slot. During the first half-hour of this time, the graduate teaching assistant demonstrates the use of vibration sensors and monitoring equipment, and demonstrates two different balancing procedures. The first method requires a phase measurement whereas the second method does not. The second method can be performed using a voltmeter to measure the sensor output. Then each student has fifteen minutes to independently demonstrate either balancing procedure. If the student is successful in reducing the vibration level by a factor of at least 10, then the student receives an A. If the student is not successful, the student reschedules for a second trial. If the student is successful during the second time, then the student receives a B and so forth. The balancing apparatus and vibration equipment used for this project is shown in Figure 1.

For the second project, each student designs and builds an isolation system for a small machine that exhibits excessive vibration. First, the students are scheduled to examine the machine in the laboratory. This gives the students an opportunity to see the machine first hand and to take appropriate measurements needed for the design. Then, each student has about two weeks to design and build an isolation system. Finally, each student is scheduled for a fifteen-minute time-slot to demonstrate the performance of his or her design. The transmissibility must be reduced by a factor of at least 20, otherwise the student has to redesign and reschedule until this criterion is met. Each student submits a report documenting the design, calculations, and performance of his or her isolation system. The student grade for this project is a function of the quality of the report and the number of design iterations needed to meet the design requirement. An example of a typical isolation system attached to the small machine is shown in Figure 2.

For the third project, each student is given about two weeks to design and build a vibration absorber for a small machine that exhibits excessive vibration. Since the

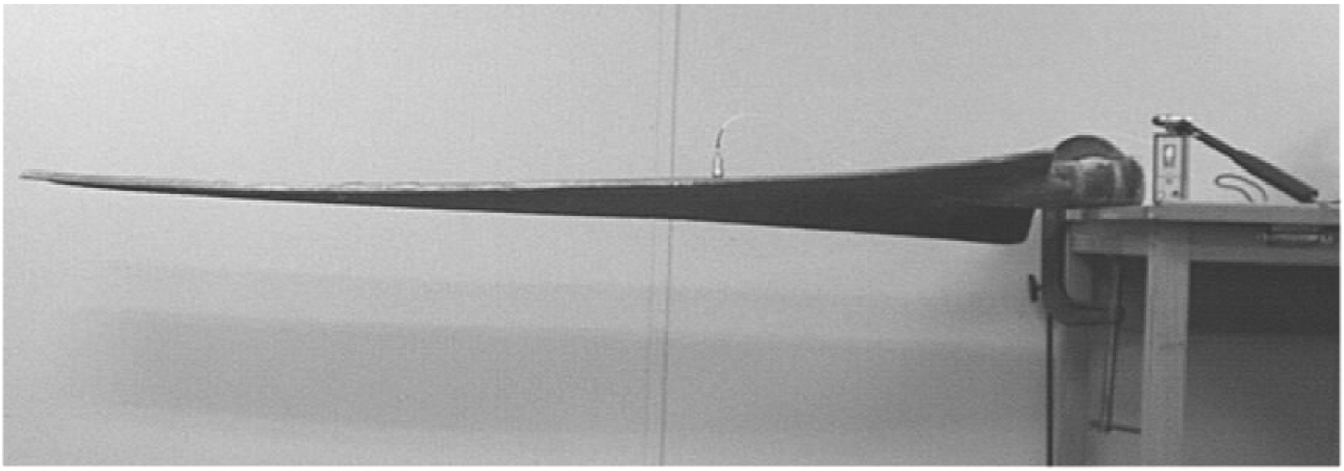

Figure 4   Cantilevered fan blade from a cooling tower used for modal testing and finite element analysis.

machine is the same one used for the second project, the students are already familiar with the machine specifications. Each student is scheduled for a fifteen-minute time slot to demonstrate the performance of his or her design. The vibration level of the machine base must be reduced by a factor of at least 10, otherwise the student has to redesign and reschedule until this criterion is met. This project requires a written report documenting the design, calculations and performance of the vibration absorber. The quality of the report and the number of design iterations needed to meet the design requirement determine the grade. A typical vibration absorber design attached to the small machine is shown in Figure 3.

The fourth project involves finite element analysis of a structure, for example, a cantilevered fan blade from a cooling tower as shown in Figure 4. First, the students are scheduled for a laboratory exercise in which the teaching assistant demonstrates modal testing of a structure using an impact hammer and an accelerometer. These test results provide the students with the first few natural frequencies of the structure and some qualitative information about the associated mode shapes, such as whether the mode of vibration is bending or torsion, etc. The students are given 15 minutes each to take dimensional measurements of the structure. The students then have the rest of the semester to develop a finite element model of the structure and to perform a modal analysis. Each student is required to submit a report by the end of the semester that documents the finite element model, the modal analysis of the model, and a discussion comparing the results of the computed results with the results obtained from modal testing. The grade for this project is based on each report.

Assessment

In an effort to assess the value of integrating the hands-on projects with theory in the vibration course, the following survey was developed for the students to complete near the end of the course:

1. Are the projects / hands-on exercises useful?
2. What do you like most about the projects?
3. What do you like least about the projects?

Responses to the first question have been virtually a unanimous yes. This was expected since engineering students generally enjoy designing and building.

What most students liked about the projects is that they actually get to use vibration sensors and analyzers and solve some real problems. Instead of just working out problems and designs on paper, they are able to follow through the whole process of analysis, design, build and test.

Responses to question three have been quite varied. One of the things some students liked least about the projects is that they had to schedule laboratory meetings outside of class time. Another problem for some students is the cost associated with building the vibration isolation system and vibration absorber. Some students also feel rushed for time during their scheduled laboratory time. The responses from question three have been used and will continue to be used to improve the projects.

From the instructor's perspective, the integration of the hands-on projects with the theory has been very positive. It keeps the students interest level up, making the course more pleasant to teach. In addition, it provides the students, including future graduate students that may want to work in the area of dynamics, with some experience with vibration equipment and real problems.

Summary

It has been shown that it is feasible to integrate hands-on technology and theory in a single-semester vibration course. The approach incorporates a series of projects and laboratory exercises. The resources required for this approach are minimal since the vibration equipment was borrowed from the author's research laboratory or donated from industry, and since some laboratory space earmarked for undergraduates was available.

Student responses to the integrated approach used in the vibration course have been generally positive. Results from a student survey have been used and will continue to be used to improve the course.

Acknowledgment

The author gratefully acknowledges the support of the National Science Foundation under Grant Nos. CMS-9501824 and CMS-9629217.

References

1. Meirovitch, L. *Elements of Vibration Analysis*, Second Edition, McGraw-Hill Inc., 1986.

2. Thomson, W. T. and Dahleh, M. D., *Theory of Vibration with Applications*, Fifth Edition, Prentice Hall Inc., 1998.

3. Inman, D. J., *Engineering Vibration*, Prentice Hall Inc., 1996.

4. Rao, S. S., *Mechanical Vibrations*, Third Edition, Addison Wesley, 1995.

5. Dimarogonas, A., *Vibration for Engineers*, Second Edition, Prentice Hall, 1996.

6. Mitchell, J. S., *Machinery Analysis and Monitoring*, Second Edition, PennWell Publishing Company, 1993.

7. Taylor, J. I., *The Vibration Analysis Handbook*, Vibration Consultants Inc., 1994.

8. Wowk, V., *Machinery Vibration: Measurement and Analysis*, McGraw-Hill, 1991.

9. Eshleman, R. L., *Machinery Vibration Analysis*, Short Course Notes, Vibration Institute, 1996.

10. Villarreal, E. E. and Butler, D., "Giving Computer Science Students a Real-World Experience," *Proceedings of the Conference on Integrating Technology into Computer Science Education*, 1998, pp. 40-44.

11. Howell, S. K., Collier, K. W., Larson, D. S., Hatfield, J. M., Hoyle, G. W., and Thomas, G. A., "Integrated Engineering Design Experience: Freshman to Senior Level," *Investing in the Future ASEE Annual Conference Proceedings*, 1995, pp. 2598-2608.