Development of a Mechanical Vibrations Course for Engineering Technologists

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Abstract

A senior-level, elective course in mechanical vibrations has recently been developed for the Mechanical Engineering Technology program at Penn State Erie, The Behrend College. The course has many similarities to traditional vibrations courses offered in Mechanical Engineering programs across the country but it also has some distinct differences. The course is similar in that there is a progressive development of vibration theory from the natural response of single-degree-of-freedom systems without damping to the forced response of multiple-degree-of-freedom systems with damping.

The course is different in that there is a lab component and that there are course objectives on vibration measurement, practical vibration suppression techniques, and computer simulation. These similarities and differences exist to support the role of the engineering technologist working in the field of vibrations or simply encountering vibration problems in general mechanical design and analysis.

This paper will discuss further the similarities and differences to traditional vibrations courses, course goals and their relation to Mechanical Engineering Technology program outcomes, student evaluation of the course value and effectiveness, and plans for continuous improvement. It will also discuss current laboratory activities, the selection of textbook and laboratory manual materials, and vibration laboratory equipment needs.

Introduction

The course is currently entitled Vibrations for Technologists and has been offered twice to date; the Fall semester of 2001 and the Fall semester of 2002. Each offering has had 14 students. Based on laboratory capacity, the course limit has been set at 16 students. It will continue to be offered every fall semester. In addition to providing basic vibration theory, the course is set up to address needs specific to the technologist working in the field of vibrations as follows.

Since engineering technologists are often involved in the acquisition of vibration data such as in preventative maintenance programs, topics such as transducer characteristics, advantages, and disadvantages are covered along with signal analysis and digitizing properties. And, since engineering technologists are involved in vibration suppression, practical techniques involving frequency ratio, damping, and tuned absorption are covered. Also, since engineering technologists are often called upon to perform computer simulations of mechanical systems, a portion of the course is focused on computer modeling, the importance of defining proper boundary conditions, and interpretation of results in dynamic analyses.

The course fills an emerging and often neglected need in engineering technology education. According to Accreditation Board for Engineering and Technology, there are 68 other U.S. schools offering baccalaureate degrees in Mechanical Engineering Technology. A review of their respective web sites indicates that only eleven of those schools offer a vibrations course in their Mechanical Engineering Technology program. (For six of the 68 schools, it was unclear from their web sites if a vibrations course was offered in MET.) Of the eleven schools offering a vibrations course in MET, only three were found to have a laboratory component. (For three of the eleven schools having a vibrations course in MET, it was unclear from their web sites if the course had a lab component.)

Justification

The need for a vibrations course was identified largely through the required, senior-level capstone course whereby students work in teams on industry-sponsored projects. A local company that is a world leader in vibration, shock, and motion control products sponsors some of the projects. Another local company that is a world leader in the manufacture of locomotive engines sponsors additional projects. Projects from these companies and others were requiring a basic knowledge of vibrations by the students.

Graduates of the Mechanical Engineering Technology program are often placed with these local companies. A vibrations course prepares students to be more productive on their senior projects and to be more prepared for potential placement with local companies.

Three full-time Mechanical Engineering Technology faculty at Penn State Erie have strong industrial backgrounds in various fields of vibrations. The course was established, in part, to take advantage of this residing faculty expertise. Also, the creation of a vibrations course and procurement of the required equipment is a first step in establishing a basic and applied research program with these and other regional companies. Further, students in various engineering societies were identifying a need to understand and suppress vibration to make their projects successful and competitive, such as the High Mileage Vehicle competition for the Society of Automotive Engineers.

Structure

The vibrations course is a 400-level technical elective offered in the Bachelor of Science in Mechanical Engineering Technology program. The course is structured to have a substantial laboratory component. It is currently offered in a 16-week semester with 2 hours/week of lecture and 2 hours/week of laboratory. The course has three prerequisite courses as follows.

The course is a follow-up to a required 200-level Machine Elements and Dynamics course and expands the fundamental knowledge of dynamics to the principles of basic vibration theory. A required 200-level Intermediate Calculus and Differential Equations with Applications course provides the needed understanding of the solution to differential equations used in vibration analysis and a required 300-level Mechanical Measurements and Instrumentation course aids student understanding of laboratory techniques used in vibration measurement.

The vibrations course was initially intended to be a prerequisite for a 400-level technical elective course entitled FEA Dynamics. However, portions of the previously taught FEA Dynamics course have been woven into the current vibrations course and the FEA Dynamics course may no longer be offered. Therefore, a required 300-level Finite Element Analysis Application course has become prerequisite for the vibrations course to insure that the students possess the fundamental FEA working knowledge and modeling skills as they face problems in dynamic simulations.

Course Topics and Goals

This course is similar to traditional vibrations courses taught in Mechanical Engineering curricula in that it starts with a description of harmonic motion, with a natural frequency, as the solution to the differential equation of motion for unforced, 1-DOF systems. See Table 1 in the Appendix for an abbreviated course outline. The course covers undamped, 1-DOF system natural response to initial conditions and then progresses to damped, 1-DOF system natural response to initial conditions. The course moves on to cover the transient and steady-state response of forced, damped 1-DOF systems. The course then focuses on the steady-state response of body force, base shake, and rotating imbalance systems to periodic input. Currently, the course also focuses on spring amplitudes (for transducer function) and suppression techniques involving damping and frequency ratio.

After the above topics are covered, this course differs from traditional vibrations courses taught in Mechanical Engineering in that, instead of using Laplace Transforms to predict the response of 1-DOF systems to non-periodic input, closed-form calculations are presented for shock (or impulse) and random inputs. The conditions for use of the closed-form calculations are also explained.

The lecture topics then continue with multi-DOF systems, similar to a traditional vibrations course. Natural response to initial conditions and forced response to periodic input are investigated. Vibration absorbers and torsional systems with multiple branches are covered at this point.

Throughout the course, students intensely study the instruments of vibration measurement, which is a difference from a traditional vibrations course. Students are to understand the various meters and filtering systems used in vibration measurement. Students are also to understand the signal analyzer, the digitizing process (FFT), the problems it creates (aliasing, leakage, noise, etc.), the solution to those problems (anti-aliasing, widowing, averaging, etc.), and the effects on data collection and reporting.

Textbook and Required Course Materials

Many textbooks and handbooks were considered for the course and Engineering Vibration[1] by Inman was finally selected. There were no textbooks or handbooks optimally suited for all goals of the course. The problem is that many textbooks are strong on basic vibration theory but are weak on the practical aspects of analyzers and transducers important to technologists. Conversely, many handbooks are strong on the practical aspects of analyzers and transducers but are weak on vibration theory.

The text by Inman seemed to be the best compromise. Since most of the students are studying vibrations for the first time, we did not want to leave the topics of basic vibration theory to the weak coverage that exists in most handbooks. A criteria for textbook selection then, was that it had to have significant coverage, preferably at least a chapter, of transducers and significant coverage, preferably at least a chapter, of vibration suppression techniques. The Inman text met both of these criteria. Other textbooks considered were those by Thomson[2], Rao[3], Dimarogonas[4], etc. A further advantage of the Inman text is a classroom PowerPoint presentation already prepared by the author.

Since even the Inman text did not provide detailed coverage of the practical aspects of analyzers and transducers important to technologists, portions of various handbooks were considered as required course materials in addition to the textbook. The three best handbooks found were Machinery Vibration[5] by Wowk, Vibration Fundamentals[6] by Mobley, and Vibration Spectrum Analysis[7] by Goldman. We settled on chapter 4 of the Wowk book which is entitled Instruments. This chapter has good, practical coverage of analyzers and transducers (comparisons, range of costs, etc.) and is currently part of the laboratory manual that students purchase for the course.

Laboratory Equipment

Although many machinery diagnostics can be accomplished on a single-channel analyzer, a 2-channel analyzer was initially purchased for the possibility of basic and applied research with local industry. We initially purchased the 2-channel analyzer in the form a PCMCIA module which provided a 32 bit floating-point DSP operating at 50 MHz with integral anti-aliasing filters. With a laptop computer acting merely as the human interface and data display, the module did all signal processing and provided 100 dB dynamic range. This system was ultra-portable but we quickly realized that we would outgrow the capabilities of this analyzer with the potential applied research and traded it in on a larger, but still portable, 4-channel analyzer. The laptop computer acts as the data display but it also now shares in the signal processing tasks.

The analyzer is configured with 3 input channels and 1 output channel. The system is expandable in increments of 4 channels. Some software options purchased with the analyzer were Waterfall and Spectrogram plotting capabilities and Order Tracking. Both features will help us work with local industry since many local companies work with variable speed engines.

Accelerometers are the only type of transducer purchased to date. Three 10 mV/g and three 100 mV/g accelerometers have been purchased along with appropriate conditioners and cables.

Additional peripherals include an accelerometer calibrator and an instrumented 1-lb impact hammer. A calibrator was deemed necessary for inexperienced students and a 1-lb hammer is considered the most versatile size.

The total cost of purchased laboratory equipment was approximately $20,000. See Figure 5 in the Appendix for a picture of the purchased equipment. See Table 3 in the Appendix for itemized costs of the equipment.

Laboratory Exercises

Some laboratory exercises are still under development, but the laboratory portion of the course consists of three major sections: 1) simple physical experiments, 2) computer simulations, and 3) signal analyzer usage. Students initially do series of simple physical experiments involving 1-DOF systems to quantify spring constant, natural frequency, mass moment of inertia, logarithmic decrement, damping coefficient, etc. Then students do a series of computer exercises involving ANSYS and Matlab. In Matlab, they will build models of lumped-parameter systems and investigate natural and forced responses. In ANSYS, they build models of simple continuous systems and investigate predicted natural and forced responses. Finally, students use the signal analyzer in a series of exercises to investigate actual natural and forced responses to structures closely represented by the models previously built in ANSYS and Matlab. Figure 6 of the Appendix shows the setup for modal analysis of a simply supported beam.

An example of a simple physical experiment from the first section of the laboratory is shown in Figure 1 of the Appendix. Students use free vibration to measure the mass moment of inertia of a connecting rod by two independent methods, first as a compound pendulum and then by using a trifilar suspension. Careful measurements have resulted in a 0.4% difference in the mass moment of inertia determined from the two methods. The experiment is done in English units to help students understand the difference in lb_m and lb_f and to help them understand the use of g_c.

During the first section of the lab, the students must also complete a Fourier Transformation of a simple periodic function by hand calculations so they can start ‘thinking’ in the frequency domain and can have an appreciation for what a signal analyzer will be doing for them. During the first two sections of the lab, the students are also doing extensive reading on analyzer and transducer topics from the laboratory manual so they are prepared to conduct laboratory exercises during the third section of the laboratory.

The finite element analysis (FEA) section of the lab utilizes the commercial FEA software, ANSYS, as a simulation tool for dynamic structural problems. The students are led beyond the static analysis FEA experience of their prerequisite course in FEA Applications into modal, harmonic, and general transient dynamic simulations. In a few weeks time, the students experience numerical eigenvalue extraction of natural frequencies and harmonic sweeps of simple, linear, damped and undamped systems.

The FEA section of the lab culminates with a nonlinear, general transient problem involving impact and dynamic response. See Figure 2 of the Appendix. The system shown requires nonlinear modeling because of the contact between bodies and because the falling object experiences large deflections and rotations. The small block falls and impacts the beam. This excites vibrations in the beam and also, the block rebounds and falls back onto the beam. Figure 3 of the Appendix shows the graphical response of the transient problem and Figure 4 of the Appendix shows the animated response of the transient problem.

Evaluation

The students are evaluated with two mid-term examinations plus a final examination. Also, laboratory assignments constitute a relatively large portion (about 30%) of the course grade. A smaller portion of the course grade (about 20%) is determined by out-of-class assignments. The examinations constitute the remainder of the course grade. From faculty outcomes assessment, the performance level of students and the dispersion of work quality in this course are consistent with that of other upper division engineering technology courses.

The instructor's teaching effectiveness and the quality of the course are evaluated by having students rate certain aspects of teaching and course content on a numerical scale from 1 to 7 near the end of the course. Students also have the opportunity to provide anonymous written comments at that time. From these ratings and comments, the course is perceived by the students as value-added for their core set of knowledge and skills.

On the first day of class, students are also provided the list of 8 Course Goals and Objectives. See Table 2 in the Appendix. On the last day of class, they are asked to assess their mastery of the goals on a numerical scale from 1 to 5. The student outcomes assessment on this scale are again consistent with other upper division engineering technology courses.

The prerequisite courses and placement of the vibrations course in the curriculum seem appropriate. Many students initially seem overwhelmed with the development of and solution to the basic differential equation of motion for a vibrating mass but quickly utilize their mathematics background and embrace the fact that the equation form, and solution, applies to many different physical systems. Although Laplace Transforms aren't used in the course for handling non-periodic inputs, the basic procedure is briefly described for the students. For most students, it is enlightening to see application of an apparently abstract topic learned in their mathematics courses.

During the development of forced response relationships for various types of single-degree-of-freedom systems, some students get confused with all the quantities that can be determined by the steady-state response formulas. Immediately after coverage of these systems, students are provided with a summary calculation sheet and explained to, first, determine what type of vibration system (body force, base shake, rotating imbalance, transducer) exists in a problem and then to determine what vibration quantity (mass displacement, spring and/or damper force, relative displacement, etc.) is important to solve the problem. This summary sheet, and discussion of it, clears up a lot of confusion and has resulted in very positive student feedback.

The main strength of the course is that the engineering technology faculty have many practical, industry examples to explain and demonstrate vibration theory which results in very positive student feedback. The main weakness of the course is that none of the engineering technology faculty are yet proficient with vibration signal analysis equipment.

Students have stated that the course was interesting and beneficial. Some recent graduates have stated that they wish they had taken the course so they could be more productive in their respective industry positions. It is a technical elective that tends to fill quickly during registration although it competes with other, more established and popular technical electives.

Continuous Improvement

The third section of the laboratory obtains the most negative student comments, largely because it is still under development. Since the equipment is now fully operational, specific exercises with assignable outcomes are being developed for this third section of the laboratory. They include forced frequency response, natural frequency determination, etc.

Other negative student comments pertained to the textbook author's PowerPoint presentation used by the instructor. During the first offering, the students believed the PowerPoint topics were beyond what was in the text but, during the second offering, that was clearly explained to the students not to be the case and there were no negative comments about the PowerPoint presentations.

The work with Matlab during the second section of the lab is also still under development. The Simulink suite of software tools for Matlab is believed to be an excellent way to bridge the gap between analytical mathematical treatment of mechanical vibrations and experimental analysis. The graphics-based block diagram language of Simulink allows students to 'build' the differential equation(s) for single-degree-of-freedom, as well as multiple-degree-of-freedom, systems. The Simulink software package includes a wide array of system input functions including step, impulse, random, user defined, and sinusoidally varying. Frequency domain response characteristics are easily obtained using Simulink. The use of Matlab, then, provides a means for the student to develop a dynamic model of, for example, an automobile's suspension system, and perform sensitivity analyses on several, or all, of the system's key parameters with virtually instantaneous results.
Matlab, and its companion language Simulink, when applied in a course on mechanical vibrations oriented toward mechanical engineering technologists, appears to be an effective tool for increasing student comprehension of vibration properties. The student can perform dynamic modeling and analysis of a wide variety of mechanical systems while maintaining focus on gaining a physical understanding of the system rather than wasting time and effort with the inevitable coding, debugging, and reprogramming associated with dynamically simulating systems in more traditional, text-based programming languages.

Ideally, a fourth section to lab would be desirable. This section would address and demonstrate typical vibrations encountered with industrial equipment such as misalignment, bearings, gears, vane passing, fans, cavitation, oil whirl, piping, looseness, belts and pulleys, reciprocating machines, turbomachinery, etc. Due to time constraints, it is not clear if we will ever be able to add this section to the laboratory.

Conclusion

The overall reaction to the course, from the students and faculty points of view, has been extremely positive. Since multiple faculty, all with extensive backgrounds in vibrations, are involved, students gain a very broad perspective on the topic which seems to be appreciated by the students. The course affords faculty the opportunity to develop or enhance expertise in many fields of vibration. As a result, the course is seen as a valuable tool in outreach to local and regional industry.

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Biography

SHANNON SWEENEY, P.E. is an Assistant Professor of Engineering at Penn State Erie where he has been teaching since 1996. His research interests are materials testing, industrial statistics, and vibration analysis. He has M.S. and B.S. degrees in Mechanical Engineering, 12 years of full-time industrial experience, and 3 US patents.

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JAMES TURSO, Ph. D. is an Assistant Professor of Mechanical Engineering at Penn State Erie. He holds M.S. and Ph. D. degrees in Nuclear Engineering from the Pennsylvania State University. He has 10 years of industrial experience with a career focus on robust process/vibration control and model-based diagnostic system development.

Appendix

Table 1. Abbreviated Course Outline

<u>Lecture</u>	
Free Vibration – Equation(s) of Motion, Solution, Initial Conditions	(2 hr)
Harmonic Motion – Definition, Representations	(2 hr)
Viscous Damping – Definition; Critically, Overdamped, and Underdamped Motion	(3 hr)
Stiffness – Series and Parallel Connections, Equivalent Systems	(2 hr)
Harmonic Excitation – Undamped 1-DOF Systems; Beating; Resonance	(2 hr)
Harmonic Excitation – 1-DOF Body Force, Damped, Frequency Response	(3 hr)
Harmonic Excitation – 1-DOF Base Motion, Damped, Frequency Response	(2 hr)
Harmonic Excitation – Rotating Unbalance	(1 hr)
Harmonic Excitation – Relative Displacement, Transducer Response	(1 hr)
Other Forms of Damping – Friction, Structural, Equivalent Viscous	(1 hr)
Simplified Response to Impulse	(1 hr)
Simplified Response to Random Input	(1 hr)
2-DOF Systems – Natural Frequencies, Mode Shapes, Frequency Response	(2 hr)
Tuned Absorbers – Effects of Damping, Design	(2 hr)
Torsional Vibration, Other Multi-DOF Systems	(2 hr)
Exams (3)	(4 hr)
<u>Laboratory</u>	
Time and Frequency Domains, Fourier Transformation	(2 hr)
Measurements – Stiffness, Damping Coefficient, Mass Moment of Inertia	(4 hr)
Mathcad Exercises	(4 hr)
Matlab/Simulink Exercises	(4 hr)
Finite Element Analysis Dynamics	(4 hr)
Experimental Vibration Analysis, General	(2 hr)
Experimental Vibration Analysis, Steady-State	(5 hr)
Experimental Vibration Analysis, Transient	(5 hr)

Table 2. Course Goals and Objectives

1. Understand the terminology of dynamic systems with respect to vibrations and periodic motion
2. Solve the differential equations which describe the response of a 1-DOF system
3. Use classical formulae to calculate the lowest natural frequencies of complex structural systems
4. Use classical formulae to calculate the effects of damping on dynamic systems
5. Understand the advantages and limitations of measurement devices
6. Understand vibration signal processing and analysis
7. Modify components of dynamic systems to avoid conditions of resonance
8. Design systems for vibration suppression

Figure 1. Measurement of Mass Moment of Inertia by Free Vibration

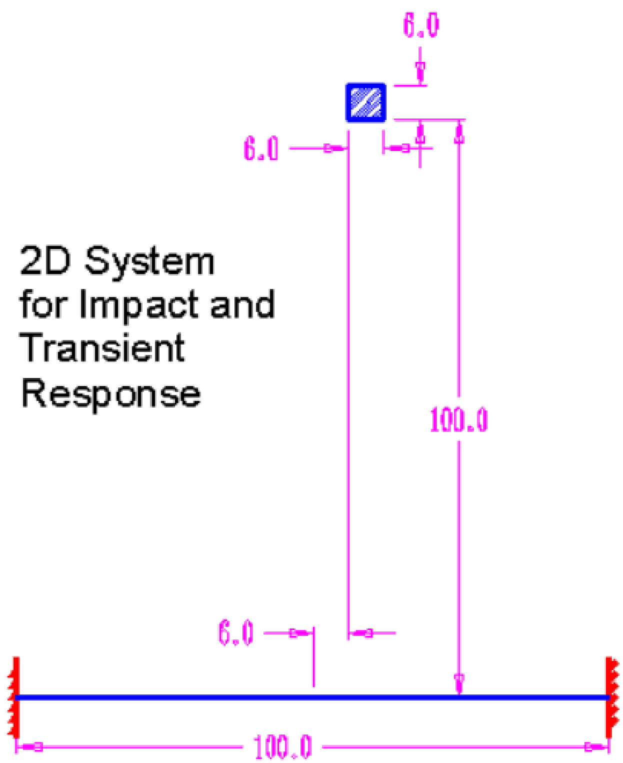

Figure 2. General Transient Response Problem by Finite Element Analysis

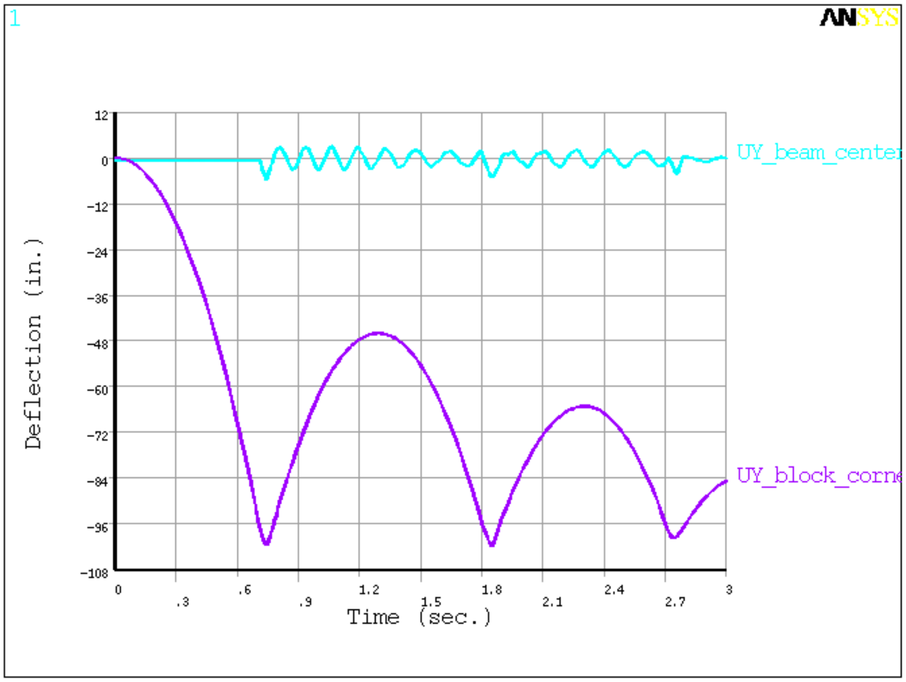

Figure 3. Graphical Response of General Transient Problem

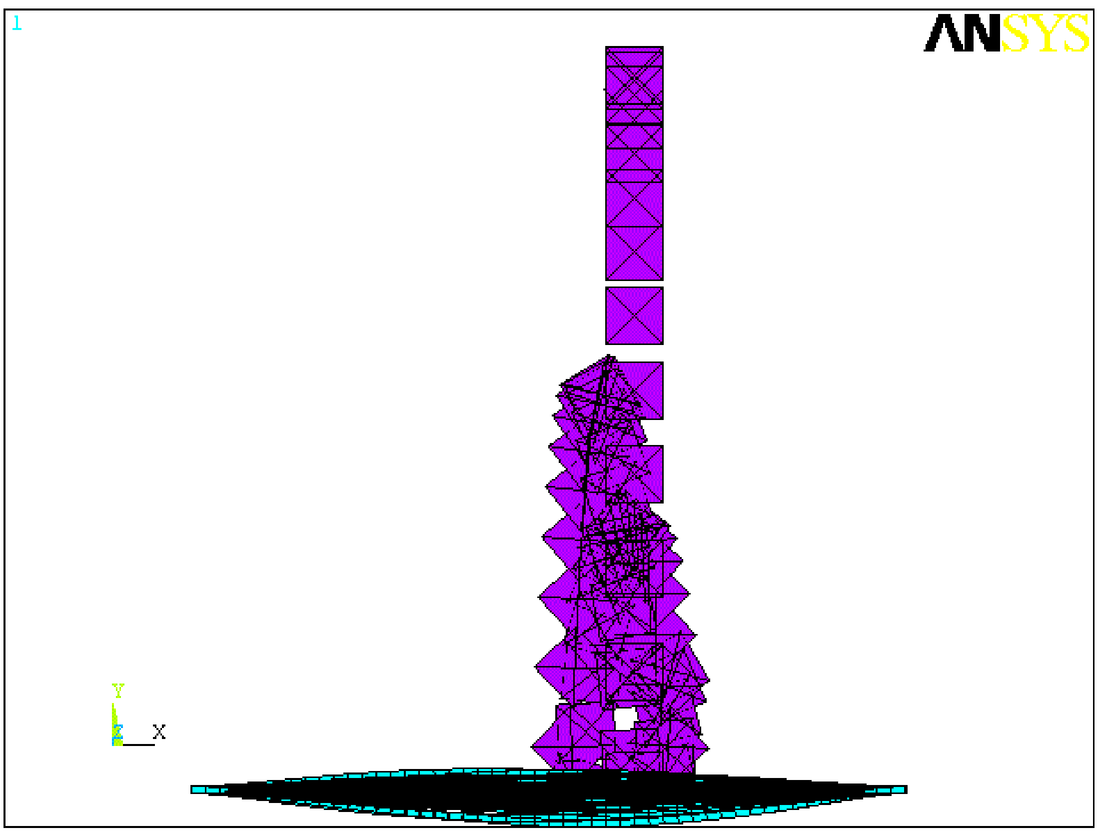

Figure 4. Animated Response of General Transient Problem

Figure 5. Vibration Analyzer and Peripherals

Table 3. Laboratory Expenses
(including university discounts where applicable)

4-Channel Dynamic Signal Analyzer (Data Physics)	6560
Windows-Based Software	2000
Order-Track Analysis (&RPM-Based Spectral Analysis)	3200
Laptop PC (Gateway)	1660
1# Impact Hammer (Endevco)	1170
Calibrator (B + K)	1750
Accelerometers (6 @ 240 ea.; Endevco)	1440
Conditioners (3 @ 315 ea.; Endevco)	930
Cables, Magnets	550
Cabinet	650
Total	$19,910

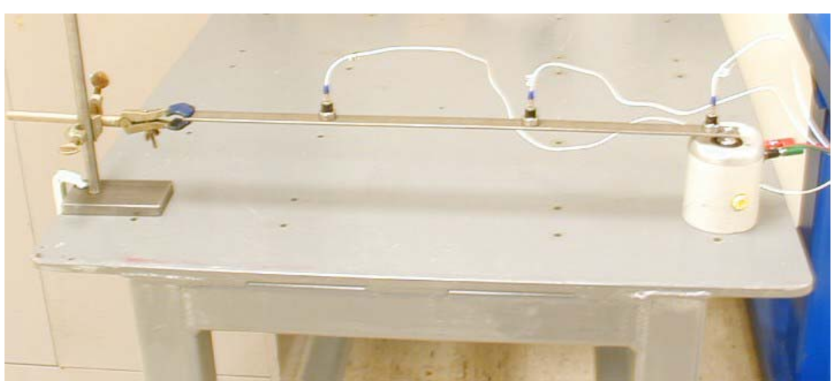

Figure 6. Modal Analysis of Beam with Vibration Analyzer