Teaching Industrial Applications of Vibration Measurement and Analysis Techniques

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Abstract

A new junior level technical elective titled Industrial Vibrations has been developed for Mechanical Engineering Technology students at the University of Maine. The course addresses the needs of local industries such as paper production and shipbuilding, but the concepts are applicable to a wide range of industries. Course prerequisites include calculus, but not differential equations, and strengths of materials. Dynamics is a corequisite. Technical Vibrations focuses on three areas: 1. analysis of one degree of freedom spring-mass-damper systems with an emphasis on the design of machinery foundations; 2. use of a portable spectral analyzer to perform resonance testing and machinery vibration testing; 3. room airborne noise predictions due to machinery noise. MathCAD is used to solve graphically the second order ordinary differential equations describing free and forced single degree of freedom systems. Machinery measurements are taken at the University Central Heating Plant using the CSi Model 2110 Machinery Analyzer. Predictive maintenance concepts are addressed.

Objectives of New Course "Industrial Vibrations"

A large percentage of graduates of the Mechanical Engineering Technology program at the University of Maine are employed in industries such as pulp and paper, shipbuilding, and manufacturing of electronic components. These and many other manufacturing industries have a need for engineers familiar with techniques to measure and suppress vibrations of industrial equipment. An elective course, Industrial Vibrations, was developed to respond to these needs.

The course Industrial Vibrations was based on three broad objectives. Students successfully completing the course were able to: 1. design basic industrial structures for resonance avoidance; 2. measure vibrations and analyze the data in the time and frequency domains; 3. work with basic acoustic concepts to reduce noise in industrial environments.

In my most recent industrial position I was a Mechanical Engineer in the Noise, Shock, and Vibration Department at Bath Iron Works, shipbuilders and engineers. Some of the vibration tests that we performed included modal testing ship decks, bump testing electronic cabinets, and monitoring machinery during sea trials. We designed machine foundations for resonance avoidance, applied acoustic treatments to reduce ship vulnerability to detection by underwater weapons systems, and designed acoustic treatments to reduce airborne noise. My goal in Industrial Vibrations was to incorporate as many of these interesting and challenging topics as possible into the course.

All of the students in the elective class were in their third and fourth years of study. Five of the nine students in the class had worked in the field of maintenance engineering at a paper mill in Maine and were familiar with the use of vibration analysis in machinery monitoring. The course prerequisites were Strengths of Materials and Calculus. Dynamics was a corequisite. This approach is unique in that many, if not most, courses in vibrations require a background in dynamics and ordinary linear differential equations. The course format was three weekly one-hour classes. The books and materials used in the course are listed in References 1-10.

This paper highlights the non-lecture activities used to support the topics above. The activities included vibration measurements in the laboratory and at our campus steam plant, solving differential equations graphically using MathCAD in a computer laboratory, and noise measurements simulating machinery noise in a laboratory.

Lecture Topics

Typical topics in vibration courses were introduced. In the applied context, students calculated spring constants for helical coil springs, beams with applied masses, and torsional springs. They calculated natural frequencies for mass-spring systems such as equipment foundations including parallel and series systems. The Fundamentals of Engineering Handbook[3] and steel vendor data[4] were used to support the calculations. Students calculated damped and undamped magnification factors for systems with rotating equipment (sinusoidal inputs). They estimated steady-state vibration amplitudes for those systems. Students designed table-top beam-mass systems that could be built for the next class taught.

During the measurement portion of the class students selected from vendor literature[5] appropriate accelerometers to perform specified vibration measurements. They identified a range of machinery faults from vibration measurements in the time and frequency domains. They described the general concepts of the Fourier transform including the assumptions of the Fast Fourier Transform. They identified solutions to problems such as aliasing and leakage. They explained and described appropriate measurement techniques. Students also outlined the basics of preventative maintenance programs including the advantages of predictive maintenance and steps to carry out such a program.

Students calculated bearing frequencies for ball and roller bearings. Given simulated measurements for four-run rotor balancing they calculated the resulting balancing mass and location. They studied the concept of a tuned vibration absorber and the calculations to design the absorber[8].

During the acoustic portion of the class students calculated sound pressure and sound power levels in decibels from pressure and power units respectively. They performed sound power level estimates from direct field sound pressure level measurements. They calculated A-weights from octave band measurements. They investigated the effect of acoustically isolating a noise source in a box.

Industrial Vibrations responded to several of the new TAC/ABET criteria defining the non-technical skills effective engineers require. Students reviewed on-line journal articles to promote the concept of life-long learning[10]. One of the articles dealt with engineering ethics[9]. They also used product data from various vendors[4-6]. Students worked together on short-term teams in cooperative learning exercises in class and on projects out of class. They interacted with staff at the steam plant, learning to describe their project requirements to university staff without formal engineering training. They developed hands-on and analytical skills directly applied to industrial problems.

Resources

One class a week was based on a laboratory test or a computer-based calculative method. A range of resources was available to support these experiences.

The School of Engineering Technology is developing an Industrial Vibrations Laboratory. Included in the available laboratory equipment is a single-channel CSi Fourier Analyzer and accessories including accelerometers. These particular analyzers are strongly marketed in Maine and are used in many paper mills. The equipment is hand-held, stores spectra, and is reasonably easy to operate. Students used the analyzer to perform several tests in the laboratory setting. They measured the natural frequencies of spring-mass systems using the Fourier Analyzer. They also measured the vibrations associated with a table-top fatigue tester. Two sets of tests took place at the campus steam plant measuring steam driven pump vibrations.

The School of Engineering Technology has available a computer laboratory referred to as the "CADD Lab" composed of twenty computers and a teacher station. The laboratory is supported by funding from the School, the Dean of the College of Engineering, and student fees. The CADD Lab is set up in paired desks for students to work independently but to discuss their activities. A wide range of industrial standard software packages is available in the laboratory. Students used MathCAD 2000[11] to perform calculations in the CADD Lab. MathCAD was used to solve differential equations graphically without requiring students to have completed a course in differential equations.

A Maine firm supplied the Industrial Vibrations Laboratory with an octave-band sound level meter to measure airborne noise in a laboratory setting during the semester. Noise from an industrial setting was recorded on a cassette tape and played through a stereo system in the laboratory.

One-hour Laboratory Tests

Students performed several short tests during the one-hour lecture period. These experiences were closely guided and required students to take a minimal amount of data and then perform calculations using the data out of class. During several tests students used the CSi Fourier Analyzer. The use of Fourier analyzers in the Senior Mechanical Engineering Laboratory in the Department of Mechanical Engineering in the Thomas J. Watson School of Engineering and Applied Science at the State University of New York at Binghamton is described in an article in a recent issue of Sound and Vibration: "The FFT spectrum analyzer is an invaluable tool for mechanical engineers in today's world of measurement and analysis of mechanical systems. FFT analyzers are an essential tool in such fields as vibration and shock data analysis, machinery monitoring and analysis of complex waveforms. Use of the FFT analyzer is required in many industries, including military, transportation, aerospace, manufacturing and consumer products. Many mechanical engineers today make careers in the fields of vibration and machinery analysis; the knowledge of principles and applications of the FFT analyzer is essential for these disciplines[12]."

In the first test period, students measured spring constants of several springs using a dial indicator and hanging weights, and measured the natural frequency of a spring-mass system using the CSi Fourier Analyzer with an accelerometer. They viewed the system response in the time and frequency domains.

In the second test period students performed a bump test with the CSi analyzer on a small steel beam clamped in a vise. They analyzed the time signal to determine the log decrement of the beam and they noted the damped natural frequency from the frequency domain. They also measured the natural frequency of series and parallel spring systems with attached masses. They compared measured to predicted frequencies.

In the third test period students used the CSi analyzer and measured spectra associated with a motor driving an eccentric (in the form of a table-top fatigue tester). This was a belt-driven arrangement and as a result both motor and driven frequencies were evident in the spectra.

In the fourth test period we met at the campus steam plant and students used the CSi analyzer to measure the vibrations of a steam driven lube oil pump. This class emphasized plant safety issues. Pairs of students then brought the analyzer to the plant during the week to measure the vibrations of the same piece of equipment and store the data in the analyzer. This allowed students an opportunity to obtain experience operating the measurement equipment independently.

During the acoustic portion of the class students measured prerecorded industrial noise from a speaker using an octave band sound level meter. The speaker was then covered with a plywood box to simulate a noise barrier for the equipment. Students used direct field measurements from the speaker as a basis to predict the noise reduction due to the box, then compared their predictions to measurements.

Each of these experiences was limited to a single hour of class time. It was important to assure that each student had an opportunity during the class time to handle the measurement equipment and to review the data taken. Questions about the procedures could be posed to students and their questions about procedures could be answered immediately.

These experiences added interest to the class as a break from traditional lecture. They provided visual and hands-on experiences to support the lecture. Students had opportunities to use industrial equipment and software.

Analytical Methods and MathCAD

Classes were held in the CADD Lab at several points during the term. One of the available programs in the CADD Lab is MathCAD 2000[11].

During the first computer lab period students programmed second order linear ordinary differential equations describing a linear spring-mass-damper system. Students were given specific written instructions in the form of a short tutorial to set up the solve block. They were shown the Help section of MathCAD so they could practice independently and self-teach some of the basic concepts. The following example illustrates a MathCAD program for a homogeneous case for the given variables:

x:= displacement
t:= time
m:= mass
c:= viscous damping constant
k:= linear spring constant

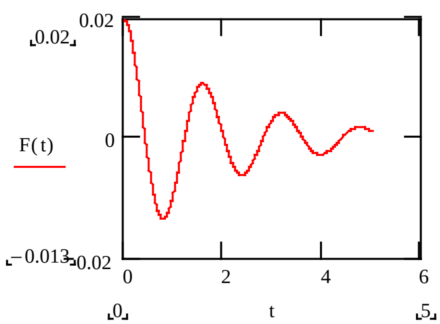
$m := 2 \qquad k := 32 \qquad c := 2$

Given

$x(0) = .02 \qquad x'(0) = 0$

$$m \cdot \frac{d^2}{dt^2} x(t) + c \cdot \frac{d}{dt} x(t) + k \cdot x(t) = 0$$

$F := \mathrm{Odesolve}(t, 5)$



The Odesolve block was easy to program and well supported in the Help section of MathCAD. Students could manipulate the constants and initial conditions and examine the effect of the changes both qualitatively and quantitatively. They could also obtain numeric results at a point in time. However, the data resulting from this solver does not reside in a vector that can be ordered to determine, for example, the time and amplitude of the maximum response. They could obtain graphically the numeric results to questions about the system response at different times by “zooming in” on areas of the graph by changing the maximum and minimum axis values.

Students were required to display an understanding of the concept of convergence by manipulating the step sizes until the solutions at a given time for different step sizes were within given tolerances. This was the first introduction students had to the concepts of applied numeric analysis. Students need skills to identify when solvers have provided “correct” solutions and when the “solutions” need refinement. Students learned how to identify “solutions” requiring a smaller step size to be accurate. Equation solvers can be found on standard graphing calculators today. Our graduates are likely to have at their disposal tools to perform numerical analysis without needing to write programs. Engineers using equation solvers need to be able to examine the solutions critically and to apply techniques to assure that an “accurate solution” has been found.

In later sessions students solved the same differential equation given in the example in the damping ratio – natural frequency format, and they solved equations with harmonic forcing functions. They investigated the steady-state responses of the harmonically forced systems. The steady-state responses were then related to magnification factor.

Conclusions

The elective course Industrial Vibrations was developed to respond to the needs of students entering careers in pulp and paper, shipbuilding, and other manufacturing industries. Students successful in the course will be able to perform basic vibration measurements analyses on systems likely to be found in these settings. They will also be able to use acoustic concepts to address issues of airborne noise in their work environments.

The laboratory and computer activities supporting the classroom lecture were well received by students. They participated enthusiastically in tests using industrial equipment. They commented regularly that they found the vibration measurement activities to be helpful in visualizing concepts in vibration analysis. They also gained confidence in their abilities to measure vibrations successfully. Similarly they found using a sound level meter to be a useful way to understand airborne noise concepts.

Students were also receptive to learning the basics of MathCAD. Those who had not studied differential equations were able to understand solutions to second order linear differential equations representing vibrating systems. Those who had studied differential equations were able to visualize solutions they had studied analytically. All students developed an awareness of the need to critically examine solutions from equation solvers. The concepts of natural frequency, damping and magnification were clarified by graphing solutions to the equations.

I stressed to students that after completing the course they would be prepared to read technical literature about the types of vibration problems they would encounter in industrial settings. They reported that they felt prepared to enter positions such as Maintenance Engineering that rely on vibration measurement and analysis techniques.

Future Directions

This course would be improved by moving from a lecture format to a lecture-lab format; perhaps two hour lecture, two hour lab. Improvements in the Industrial Vibrations Laboratory, including the recent acquisition of a machinery fault simulator, will support student success in learning about industrial vibrations. Having available software to perform machinery trending on campus steam plant equipment would be an enhancement. Acquiring equipment to introduce modern balancing and alignment techniques would also be beneficial.

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