Laboratory Instruction in Acoustics and Vibration

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Abstract

Eight laboratory exercises have been developed for a senior-level course in “Acoustics, Noise and Vibration” to introduce students to sound and vibration engineering. Laboratory topics include wave propagation in fluids and solids, acoustic and mechanical impedance, and signal processing. The laboratory exercises demonstrate governing physical principles, provide experience using state-of-the-art tools and techniques in sound and vibration engineering, and introduce applications in architectural acoustics and noise and vibration control. The laboratory exercises are sequenced to facilitate comprehension, with each successive exercise building on concepts demonstrated previously.

In this paper we describe the laboratory exercises, explain the objectives and learning outcomes expected of each exercise, and discuss how the sequence of exercises enhances comprehension. Full laboratory procedures will be available on the Internet.

Introduction

Strong demand from students and employers prompted the recent development of a new concentration in Acoustics, Noise and Vibration at GMI Engineering & Management Institute. Two courses in acoustics and vibration have been created and three more are planned as a cooperative effort between Mechanical Engineering and Applied Physics. GMI’s instructional Acoustics, Noise and Vibration (ANV) Laboratory was made possible by grants from the National Science Foundation and industry.

Eight laboratory exercises have been developed for the senior-level course “Acoustics, Noise and Vibration” to introduce students to sound and vibration engineering. The laboratory exercises demonstrate governing physical principles, provide experience using state-of-the-art tools and techniques in sound and vibration engineering, and introduce applications in architectural acoustics and noise and vibration control. The laboratory exercises are sequenced to facilitate comprehension, with each successive exercise building on concepts demonstrated previously. The sequence of exercises is:

1. Introduction to Sound Waves,
2. Simple Sound Sources and Directivity,
3. Introduction to Frequency Analyzers and Signal Processing,
4. Sound Power and Vector Sound Intensity,
5. Absorption Coefficients and Impedance,
6. Room Acoustics and Reverberation Time,
7. Acoustic Filters and Transmission Lines,
8. Waves in Solids and Modal Analysis.

All of the experiments are designed to demonstrate physical principles. Several are also designed to demonstrate applications or to give experience with widely-used tools and techniques in sound and vibration engineering. In another paper[1] we present more detailed discussions of laboratories 3 and 8 which demonstrate the value of coupling computer simulations with experiments to avoid mistakes, improve quality, and enhance confidence in both the computer model and test results. In this paper we describe the laboratory exercises, explain the objectives and learning outcomes expected of each exercise, and discuss how the sequence of exercises enhances comprehension. Full laboratory procedures (in TeX or Postscript formats) will be made available on the world wide web.[2]

Laboratory Descriptions

1. Introduction to Sound

This laboratory whets the students' appetite for acoustics by exposing them to a sampling of acoustic phenomena and applications. Students informally test the frequency limits of their own hearing, measure the speed of sound, perform a simple sonar rangefinding exercise, and observe the cancellation of sound. Equipment is limited to function generators and oscilloscopes (which students have used in previous laboratory courses), a loudspeaker, and a microphone. Emphasis is placed on discovering some of the more basic aspects of sound, including the relationships between frequency, speed, and wavelength, the behavior of a single frequency signal, and the concept of sound cancellation by another sound.

2. Simple Sound Sources and Directivity

The second laboratory exercise introduces students to the concepts of monopole and dipole sources, and the directionality of a more complex source. Students use a Sound Level Meter (Radio Shack #33-2050) to measure the sound radiated by a 3 inch cone loudspeaker at various frequencies with and without a baffle. Students are expected to convert a measured decibel level to an acoustic pressure. After measuring the sound levels around a 1 m radius circle centered at the speaker, the students observe some differences between a dipole source (speaker without a baffle) and a monopole source (speaker in a large baffle). They should see the figure-eight (dipole) and omnidirectional (monopole) directivity patterns developed theoretically in lecture. This laboratory exercise also shows students that one reason loudspeakers are placed in boxes is to separate the front and back of the speaker–transforming a dipole source into a monopole source which radiates sound more effectively. Measurement of the directivity pattern of the baffled speaker with increasing frequencies shows narrowing of the main lobe and the appearance of side lobes, indicating the directional behavior of a complex sound source.

3. Introduction to Frequency Analyzers and Signal Processing

Many of the laboratory exercises which follow require the use of one of the two frequency analyzers in the ANV laboratory: a Brüel & Kjær (B&K) Dual Channel Real-time Frequency Analyzer Type 2133 (octave band) and a Hewlett-Packard (HP) 35670A Dynamic Signal Analyzer (FFT). This third lab introduces students to the use of these analyzers as well as teaching them some important concepts in signal analysis. To introduce some of the features of the B&K octave band analyzer, the students investigate and compare the spectra of white and pink noise as measured in frequency bands. They observe that white noise has the same energy at all frequencies, but has an increasing power spectrum on an octave band scale. Pink noise maintains a constant octave band power spectrum, but its energy decreases with increasing frequency. Students also use the octave band analyzer to calibrate a B&K condenser microphone using a B&K pistonphone. Comparison is then made between a decibel measurement with the calibrated microphone and a sound level measurement made with the sound level meter from lab 2.

Students also perform a computer-based Fourier analysis (FFT) using Mathcad[3] on a signal generated numerically.[1] This introduces students to the complications of aliasing, leakage, and relating the digital representation of a signal to its analog counterpart. Students are also introduced to “windows” for controlling leakage. These concepts are revisited in lab 8.

4. Sound Power and Vector Sound Intensity

Between the third and fourth weeks of the term, course lectures introduce concepts and applications involved with measurements of sound intensity and power. In the laboratory students are given an opportunity to measure the vector sound intensity of a common noise source, namely, a vacuum cleaner. The students must first identify the major frequency components of the noise, using a microphone and the HP FFT analyzer, and obtain an average frequency spectrum. Students then connect a B&K Sound Intensity Probe to the B&K 2133 analyzer and setup the analyzer to display the vector sound intensity produced by the noise source. A wire mesh is built around the source and vector intensity measurements are made with the intensity probe in each grid of the mesh. Using software built into the B&K 2133 analyzer the students are able to produce vector field plots and surface plots of the intensity for any surface at any frequency.

5. Absorption Coefficients and Impedance

Industrial and architectural applications of acoustics cannot be discussed without considering the sound absorbing properties of acoustic materials. In laboratory 5 students measure the sound power absorption coefficients of several materials using an impedance tube. In order to help students understand the theoretical concepts involved as an incident plane sound wave reflects from a partially absorbing surface, they are asked to calculate the absorption coefficients by hand. One end of the impedance tube is driven by a loudspeaker at a single frequency, and the sample is placed at the other end of the tube, held in place by a rigid cap. Students locate a pressure maximum (antinode) and minimum (node) by moving a microphone along the length of the tube and observing the pressure level using the B&K 2133 octave band analyzer. After calculating the standing wave ratio, sound power absorption coefficient, and the mechanical impedance of the sample by hand the students are allowed to use an older B&K analog analyzer which measures the absorption coefficient directly. Testing several samples shows how sound absorption varies with frequency for different types of materials.

6. Room Acoustics and Reverberation Time

Some of the absorbing materials analyzed in lab 5 are found in GMI's McKinnon Theater. Armed with absorption coefficients and room dimensions, students are able to calculate the average absorption of the theater and then estimate its reverberation time.

Measurements of the reverberation time of the theater are performed using impulse and interrupted noise techniques. Using a special cursor function on the B&K 2133 octave band analyzer, the reverberation times may be measured directly over a desired range of frequency bands simultaneously. Students then compare their predictions to measured reverberation times. In addition, GMI's McKinnon Theater has some undesirable acoustical characteristics. These are demonstrated for the students who then are asked to suggest methods for improving the quality of the theater's sound.

A small, rectangular classroom is used to demonstrate room modes. Students use the room dimensions to calculate the frequencies of the first several standing wave modes in the room. A loudspeaker is placed in a corner of the room and driven at one of the room's natural frequencies. Students then walk around the room with hand held Radio Shack sound level meters, locate the pressure nodes, and map out the “mode shapes” of the room.

7. Acoustic Filters and Transmission Lines

In laboratory 5 students are introduced to the concept of reflection of sound from an impedance discontinuity. In lecture this concept is expanded to include discussion of acoustic transmission lines and acoustic filters. The effects of changes in pipe cross-section, side branches, and Helmholtz resonators are discussed in terms of low-pass, high-pass, and band-stop filters. In lab 7 students are given an assortment of PVC pipe pieces of varying length and diameter with appropriate connectors. They are asked to drive a 1 m length of pipe at one end with a speaker and white noise, and measure the frequency spectrum of the sound pressure at the other end using a microphone and the HP FFT analyzer. They are then challenged to assemble pipe pieces into low-pass, high-pass, and band-stop filters and to compare the resulting frequency spectra with the original unfiltered pipe to see if the expected filter response was achieved.

8. Waves in Solids and Modal Analysis

In this laboratory students study the vibration of a cantilever beam using analytical, computational, and experimental techniques. Analytically, the natural frequencies for a simple structure like a clamped-free beam, may be obtained from an analysis of the differential equations of motion and application of the boundary conditions. Students are asked to calculate the natural frequencies of the first few flexural and torsional modes of the beam. Then, using a finite element program (*weCan for Windows*[4] was chosen for its ease of use) the students compute the natural frequencies and are able to observe animated mode shapes. Computed results reveal to the students that simple analytical approaches fail at higher frequencies where rotary and shear inertia effects cannot be ignored.

Students measure the vibration of the beam using an experimental technique called fixed-response impact modal analysis. Computer animations of the beam motion are used to decide where to attach an accelerometer to measure the beam response. The beam is excited by striking it with an impact hammer with a force transducer. The HP FFT analyzer is used to measure frequency response spectra. Here, students must use some knowledge of windowing, presented in lab 3, in order to capture the hammer impact and accelerometer response with minimum leakage. The software package STAR Modal[5] is used to curve fit the frequency response functions and to produce natural frequencies and animations of the measured structural modes. Comparison between experimental and computational results shows close agreement in mode shapes, though several computed modes are not usually observed experimentally due to the orientation of the accelerometer.[1] Also, the experimental frequencies are usually lower and students are guided to suspect mass loading by the accelerometer. Students are shown how to remove the mass loading effect using the STAR Modal software.

While this lab exercise does not explain all the concepts involved in finite element or experimental modal analysis, it does introduce students to both techniques, and demonstrates some of their advantages and disadvantages as well as how they can be used in conjunction to support each other.

Summary

Eight laboratory exercises have been developed at GMI for use in a senior level Acoustics, Noise, and Vibration course. The exercises have been designed to introduce students to acoustic phenomena and applications as well as to familiarize them with the instruments and techniques used to study, detect, or alter noise and vibration.

The labs are organized partly to correspond to the layout of the lecture portion of the course. In addition, many of the labs build upon concepts, skills, or equipment familiarity experienced in a previous laboratory exercise, thus enhancing the learning experience.

For readers interested in obtaining more details about the equipment used in these exercises or the exact procedures followed, full descriptions of all labs mentioned will be made available over the Internet.[2]

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References

1. Cameron, T. and Russell, D., "Coupling Simulation and Experiment in Noise and Vibration Engineering," accepted by the Division of Experimentation and Laboratory-Oriented Studies for presentation at the ASEE Annual Meeting, 23-26 June 1996, Washington D.C., Session 3226.
2. Full descriptions of laboratory exercises may be downloaded from the WWW URL address: http://www.gmi.edu/~drussell/anvlabs1.html
3. Mathcad 5.0, MathSoft Inc., 201 Broadway, Cambridge, MA 02139. Tel. 800-628-4223.
4. weCan for Windows, Student Edition ($50), Aegis Software Corporation, UPARC Research Center, 3190 William Pitt Way, Pittsburgh, PA 15238-1360, Tel. 412-826-3470.
5. StarModal, part of the StarStruct suite, from GenRad Structural Test Products, 2855 Bowers Ave., Santa Clara, CA 95051-0917. Tel. 408-970-1600.

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