# Acoustic testing and modeling: An advanced undergraduate laboratory

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This paper describes an advanced laboratory course in acoustics, specifically targeted for students with an interest in engineering applications at a school with a strongly integrated industrial co-op program. The laboratory course is developed around a three-pronged approach to problem solving that combines and integrates theoretical models, computational models, and experimental data. The course is structured around modules that begin with fundamental concepts and build laboratory skills and expand the knowledge base toward a final project. Students keep a detailed laboratory notebook, write research papers in teams, and must pass laboratory certification exams. This paper describes the course layout and philosophy and shares personal experience from both faculty and student perspectives. © *2012 Acoustical Society of America*. [DOI: 10.1121/1.3677241]

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## I. INTRODUCTION

The opportunity to study acoustics beyond a superficial introduction to the field is an experience most often reserved for graduate students. Most undergraduate physics students are not exposed to acoustics beyond an introduction to wave phenomena as might be encountered in a freshman mechanics course, and the situation is not that different in undergraduate engineering programs which might offer an elective noise control course. There are quite a few schools offering physics of sound courses as electives for undergraduate students in non-technical degrees, but while these provide a broad exposure to acoustics topics, they can hardly be considered an in-depth experience. However, while the vast majority of acoustics education takes place at the graduate level, undergraduate acoustics education has been a concern of members of the Acoustical Society of America for at least 45 years.[1] Kettering University is one of a handful of schools with several advanced undergraduate courses in acoustics,[2–4] and offers an academic minor in acoustics for physics and engineering students. The laboratory course described in this paper provides an in-depth exposure to acoustics far beyond what most undergraduate students would likely experience, but one which is tailored to student needs in our unique academic environment. In this paper we will provide a brief description of the academic setting that allows for an in-depth undergraduate exposure to acoustics, and then we will describe in some detail the laboratory course that serves as a capstone to this experience. The most important feature of this laboratory course involves a three-fold approach to investigating an acoustic phenomenon synthesizing theoretical models, computational models, and experimental data.

Kettering University is a small private undergraduate school focusing on engineering, applied sciences, and business disciplines. Though the school has undergone many changes[5] since its inception in 1919, the one thing that has always set Kettering apart is the complete integration of classroom teaching and co-op work experience with industrial sponsors. Kettering's student body consists of two separate student populations who alternate between 11 week academic terms in the classroom and 11 week stints working at a co-op job twice each year, respectively. At the end of a 5 year program, each student earns a Bachelor's degree and has 2.5 years of industrial work experience. The industrial hands-on experience is considered part of the education process, beginning in each student's freshman year and culminating in a senior thesis that describes the student's solution to a problem for their co-op employer. Because of this industrial co-op emphasis, all degree programs including physics have a strong application to real-world problems.

The acoustics minor at Kettering consists of four courses starting with a junior level course (differential equations pre-requisite) entitled "Vibration, Sound, and Light"—required for both the acoustics and optics minor—that introduces students to the fundamentals of oscillation, of acoustic waves in mechanical media, and of electromagnetic waves. The second acoustics course, "Acoustics in the Human Environment" exposes students to topics and applications of acoustics encountered in industrial and consulting settings. The third course toward the acoustics minor is either a course in digital signal processing or vibration control, depending on a student's pre-requisite background and degree area. The advanced laboratory course "Acoustic Testing and Modeling" described herein serves as the culmination of the acoustics minor. This course also serves as the advanced laboratory course for all majors in applied physics majors and engineering physics.

When the authors were designing the current acoustics minor course sequence, and especially the advanced lab course described in this paper, several influences came to bear. First was the observation that many of the companies hiring Kettering co-op students use a blend of theory, computer models, and experimental data to solve problems. A second influence was a series of editorials in the acoustics industrial trade magazine *Sound and Vibration*[8] which drew

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attention to perceived deficiencies in engineering undergraduates now entering the workplace.[9–17] Some editorials decried students' lack of ability to correlate models with test data and complained about students who cannot determine whether or not a model result is viable. Others noticed that students who demonstrated an ability to solve clearly defined textbook problems often had considerable difficulty when faced with the more realistic real-world problems that are often less clearly defined and may involve messy or noisy data. Still others expressed a need for improved communication skills related to report writing and technical presentations. A third influence came from the simultaneous development of a new computational physics course by one of the authors. The interplay between theoretical, experimental, and computational scientists,[18] and the necessity of providing a context to assess the validity of a computational result guided the integration of computational and experimental activities.

## II. OVERVIEW OF THE ACOUSTIC TESTING AND MODELING COURSE

The academic minor in acoustics at Kettering University is supported by a well-equipped laboratory capable of providing an advanced experimental experience. This 1160 sq-ft (108 $m^2$) laboratory facility has been equipped through generous donations from several industrial sponsors and is used for teaching as well as for faculty and student research. Equipment includes five stand-alone two-channel FFT analyzers (with FFT, octave band, swept sine, and cross-correlation features), and an assortment of high quality microphones, sound level meters, and two sound intensity probes. Seven computer workstations run MATLAB and LabVIEW for data processing, and COMSOL Multiphysics[6] for finite element modeling of acoustics and structural mechanics problems. Multiple small PCB accelerometers and force-impact hammers along with two computers with STAR Modal experimental modal analysis software[7] support experimental modal analysis testing. Other equipment includes two binaural heads, mechanical shakers, impedance head transducers, DAT recorder, various loudspeakers and microphones, and a collection of musical instruments and other objects for testing. A $3.5\,\mathrm{m} \times 3.5\,\mathrm{m} \times 3.0\,\mathrm{m}$ anechoic room is available for testing of sound sources. In addition to several workbench areas, there is a conference area where 8–10 students can sit around a table and discuss their work; this space is also used for lecture activities when needed.

The Acoustic Testing and Modeling course is offered twice a year during 11-week Winter and Spring academic terms, typically to 5–8 students at a time. The course counts for 4 academic credit hours, and meets three times a week for two hours each session during an academic term lasting 11 weeks. Only a handful of class meetings involve what might be called a traditional lecture, and then mainly on a just-in-time basis when specific a theoretical background is necessary for students to develop a physical model of a problem. The rest of the class time is split between experimental data collection and analysis and computer modeling and interpretation of results.

The overall structure of the course consists of two modules each lasting approximately 5-1/2 weeks, to fit within 11-week academic terms. The modular approach allows for variety in the course from term to term, and allows for the potential to tailor the experimental topics to accommodate student interests. To date we have implemented two modules, one each for air-borne sound and structural vibration and are in the process of developing two more. Each module culminates in a specific project and a group research paper. Currently the air-borne sound module ends with students measuring the vector sound intensity radiated by a tuning fork and comparing measured data with theoretical and computer models. The structural vibration module ends with students comparing computational models of a structure of interest with experimentally determined mode shapes and frequencies of the actual structure. A future air-borne sound module involves an investigation of acoustic impedance and its applications to extracting sound absorption coefficients and the design of acoustic filters and mufflers. A planned structural acoustics module includes an exploration of the circuit analogies between electrical, mechanical and acoustic systems, the design and performance of vented boxed loudspeakers, and the radiation of sound from vibrating surfaces.

Throughout each module, as they progress toward the final project, students gradually build up their skills and knowledge base. They learn how to use the laboratory equipment they will need, and gain practice analyzing data. They gain experience building simple computer models of the systems they are testing. All through the course students maintain a detailed laboratory notebook, journaling their research experience. At the end of each module, they work in teams to write a research paper synthesizing the results form the three approaches, drawn from the contents of their laboratory notebooks.

## III. MODULE #1: VECTOR INTENSITY RADIATED BY A TUNING FORK

At the beginning of the air-borne sound module students are introduced to different types of microphones. They learn how to calibrate a microphone using the comparison calibration technique and a pistonphone, how to determine the sensitivity (in V/Pa) of a microphone, and how to set up a microphone-FFT analyzer system to measure sound pressure levels accurately. They also learn some basic operations using a FFT analyzer to observe microphone output in both time and frequency domains. The usefulness of the decibel scale is discovered experimentally during the introduction to the FFT analyzer. The first major experiment students conduct is to measure the sound pressure (in Pa) and sound pressure level (in dB) as a function of distance from a simple source consisting of a small boxed loudspeaker producing white noise. Students are given general guidelines, but are expected to figure out the parameters of the experiment by themselves. One group of students takes measurements in our anechoic chamber, while another group takes measurements in the laboratory classroom. The expectation is that the sound pressure level will drop $-6\,\mathrm{dB}$ (corresponding to a halving of the pressure amplitude) each time the distance from the source doubles, and this is what the group in the anechoic room finds. Upon comparing data sets, the group taking measurements in the open lab space discovers that beyond a certain distance their sound pressure levels no longer drop by the expected $-6$ dB per doubling of distance, and may even remain relatively constant. This leads to a discussion of the critical distance, and allows for a definition of the free-field and reverberant field. Further discussion of the theory for spherical waves introduces the parameter $kr$ (product of wavenumber and distance from the source) and distinguishes between the near-field and far-field of a source.

This first hands-on experience is followed by a brief theoretical discussion of sound source models and the important quantity $ka$, where $k$ is the wavenumber associated with the sound wave and $a$ is an appropriate dimension of the source.[19] The class is split into two groups, with one group experimentally measuring the sound radiation from a 10-cm diameter boxed loudspeaker at multiple frequencies while the other group begins learning how to model the radiation of sound from simple sources using finite element software. The two groups switch tasks, but are expected to share information to aid in refining the model and/or experimental parameters. Figure 1 compares student experimentally measured directivity patterns for the sound radiated by the 10-cm boxed loudspeaker at frequencies of 100 Hz ($ka < 1$) and at 5000 Hz ($ka \approx 10$) with the predicted directivity patterns for the same frequencies obtained from a 2-D computer model of the sound radiation sound source consisting of a box with three rigid walls and one surface with a specified pressure amplitude. The conclusion students reach is that a sound source may be treated a "simple source" as long as $ka < 1$. When building this computer model, students encounter issues regarding mesh size and wavelength, and must learn to compromise the size of their model to match the available computational power.

At this point it should be pointed out that emphasis of the computer modelling approach in this course is not an attempt to teach students all of the details and features of the modeling software or the theory behind the computational method, but rather the emphasis is on having students gain familiarity with the steps required to create a valid finite element model (drawing geometry, setting the physics, meshing, and post-processing) and the practice of using experimental data and theoretical expectations to refine and improve a computer model. An oft-repeated complaint expressed in several *S*ound and Vibration editorials[9–17] was a frustration with students' inability to determine whether or not a computer model results are correct, or even reasonable. Undergraduate students often display a tendency to trust the results of a model simply because it was produced with computer software, with no validation that the model parameters were appropriate for the problem in question. The emphasis on using computer models in this course is to focus on the choices made while constructing a model and to encourage students to continually refine their model based on experimental results and theoretical expectations.

It is also important for students to realize that there is often more than one way to obtain a valid result. For example, when constructing a 2-D finite element model of an acoustic dipole source using COMSOL Multiphysics, there are several approaches one could use. One could enclose a dipole type source element within a geometric subdomain. Or, one could create two identical monopole sources, each consisting of a monopole type source element within a geometric subdomain,

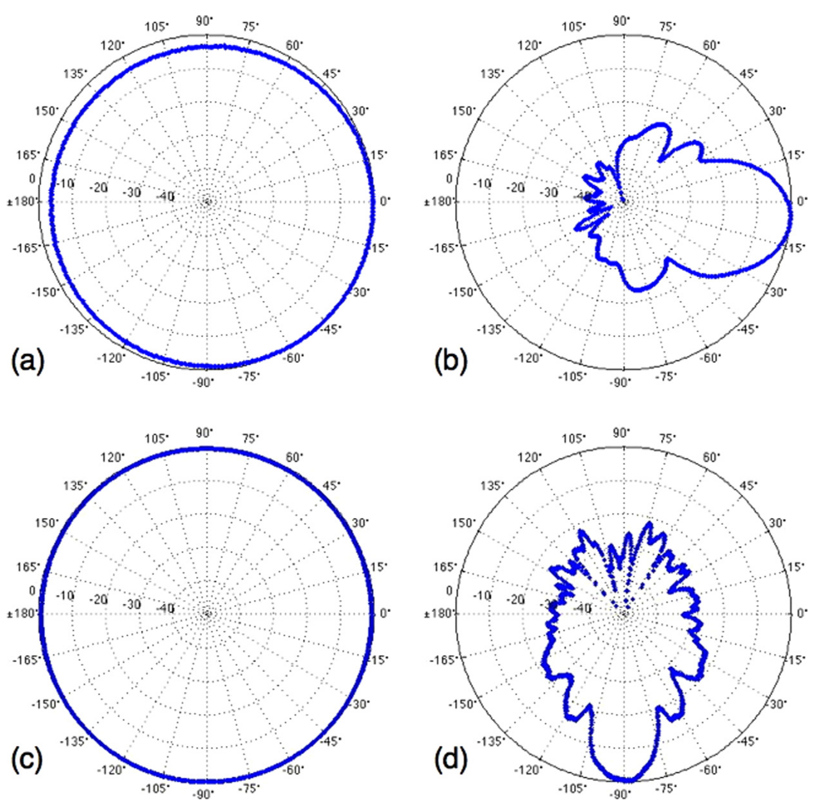


FIG. 1. (Color online) Student data showing the directivity of a 10-cm diameter boxed loudspeaker: experimental data for (a) 100 Hz and (b) 5000 Hz, compared to a student computer model prediction of the directivity for (c) 100 Hz and (d) 5000 Hz. The orientations of the speaker for the experimental data and model are not the same.

but with opposite phases. As yet another alternative, one could create a surface element and assign opposite polarity pressure boundary conditions to create a dipole source. Students are encouraged to be creative, and often end up competing with each other. Some students produced very detailed models of sources that closely approximate the physical dimensions and shape of the loudspeakers used in the experiment. The bottom line is that students are required to compare the model results to experimental data and theoretical expectations and make modifications where necessary to bring the two into as close agreement as is possible in the time allowed.

Dipole sources are followed by quadrupole sources, and this necessitates a bit of just-in-time lecturing because the theoretical models become somewhat complex. Expanding the experimental investigations and computer models to include acoustic dipole and quadrupole sources follows.[19] Four identical loudspeakers, connected to a 4-way switch box allowing for individual level control and switches for reversing polarity, rotate on a turntable while the resulting directivity is measured with a stationary microphone. After students have conducted an experimental measurement and computer model of the directional characteristics of dipole and quadrupole sound sources, they investigate the behavior of a large tuning fork. Using a strobe light to examine its motion while vibrating in its fundamental mode[20] students discover that a tuning fork vibrates as a linear quadrupole source,[21] a conclusion which is validated by experimental measurements of the tuning fork directivity pattern. Experimental data is used to fine tune computer models of the sound field radiated by a longitudinal quadrupole source.

At this point the students are almost ready to begin working on their first major project. A class meeting is devoted to discussions of theoretical and experimental approaches to sound intensity, and then students are set free to explore the vector sound intensity around a tuning fork using the theoretical, experimental and computational skills they have developed. Depending on the number of students in the course, the class might be separated into two teams, one to work on developing a computer model of the vector sound intensity radiated by the tuning fork while the other group experimentally measures the vector intensity using an intensity probe and a turntable apparatus. Splitting the class has the advantage of requiring the two teams to talk to each other to share data and results to create a single report. Student teams collaborate to write a research paper summarizing and comparing their theoretical, computational and experimental results for the tuning fork intensity.

This tuning fork project is interesting for a number of reasons. First, the sound field and the vector intensity radiated by a tuning fork is surprisingly complex, with a very clear distinction between near-field and far-field regions in the vicinity of the fork tines. Students are able to learn a considerable amount of acoustics from a seemingly simple object. Figure 2 shows the result from a student's finite element model of the normalized vector intensity map in one quadrant of the sound field around a tuning fork. The vector intensity plot shows significant circulation of the sound energy in the near-field, including a point on the x-axis where the direction of the intensity vector reverses. The

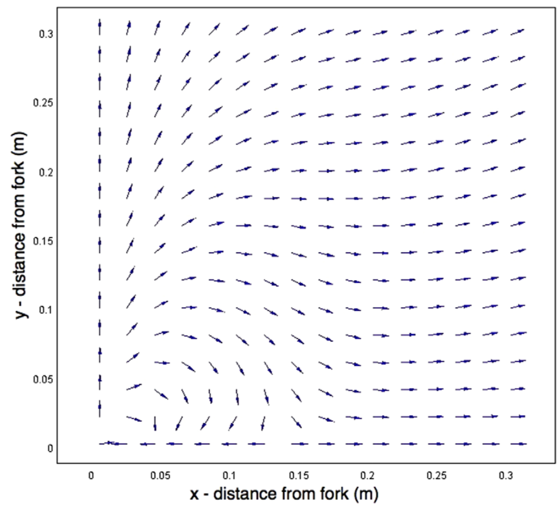


FIG. 2. (Color online) Results from a student's finite element model showing a 2-D map of the vector intensity in one quadrant in the horizontal plane of the region surrounding a tuning fork. The tuning fork tines are aligned to vibrate in the x-direction.

features of this computer model are in good general agreement with theory[22] as well as with the experimental data the students collect. However, the location point on the x-axis where the intensity vector reverses direction is found to be 13.5 cm from the fork axis according to the computer model, while both measured data and theory show the turning to be 18.0 cm from the fork axis.[23] This disparity between model and measurement provides an opportunity to teach students some important lessons about realistic research problems. Many students are content to state that their experimental results and computer models are "close" without further elaboration. Some students just chalk the differences up to "human error" and ignore them. Other students are bothered by the differences, but do not know how to discuss or explain them. Students need to know that not all problems, even seemingly simple ones, do not always have nice tidy answers, and that when models and experiments do not agree we need to start questioning why.

## IV. MODULE #2: MODAL ANALYSIS OF A VIBRATING STRUCTURE

The structural vibration module begins with a brief theoretical review of single-degree-of-freedom vibration, and a hands-on experiment with a nonlinear oscillator with a stiffening spring and hysteresis effects. A short theoretical introduction to multiple-degree-of-freedom oscillators is followed by an experimental investigation of mode shapes and frequencies for multi-DOF systems, ending in an experimental investigation of standing waves on a string. The professor then leads students through the theory for standing waves on a string, especially paying attention to various types of boundary conditions. This is followed by construction of computational models of a steel string with fixed and mass-loaded boundary conditions.

Students then spend several class periods measuring the vibrational mode shapes and frequencies of a rectangular beam using several different methods. First, they attach a small NeFeB magnet to one corner of the beam and use an electromagnetic coil to drive the beam into vibration.[24] A small microphone is used to scan the pressure right next to the vibrating surface, and changes in the phase of the Lissajous pattern between the driving signal and the microphone response indicates the crossing of a nodal line.[25] This scanning technique allows students to map out several bending and torsional modes, and plotting frequencies versus the number of nodal lines identifies differences in the frequency ratios of the two types of vibration. The exploration of beam vibrations continue as students learn how to use a force-impact hammer, accelerometer and a two-channel FFT analyzer to produce a frequency response function consisting of the ratio of acceleration to force. They explore the effect of hammer tip stiffness, hammer mass, impact location and the principle of acoustic reciprocity.[26] The amplitude of a peak at a specific frequency for the imaginary part of the frequency response function (consisting of the ratio of acceleration to force) represents the mode shape amplitude for that specific location at that frequency.[27] Recording the amplitudes of the peak in the imaginary part of the frequency response function at a specific frequency as the hammer impact location moves along the length of the beam constitutes a "poor man's modal analysis" and allows one to sketch the mode shape corresponding to that frequency.[28]

After this initial experimental introduction to the vibrational behavior of flexing beams, time is spent developing the theory of the fourth-order differential equation of motion and the solutions for flexural bending waves in a beam, paying special attention to the effects of boundary conditions. Students are given a homework assignment to determine the frequencies and plot mode shapes for a free-free beam with the dimensions and approximate material properties of the beam they have been studying experimentally. Subsequent class periods are devoted to having students work through a complete experimental modal analysis of the free-free beam using the STAR Modal software package for extracting mode shapes and frequencies from the frequency response functions. Finally, they create a finite element model of the free-free beam and compare the mode shapes and frequencies with experimental data and theory. Examples of student experimental data are shown in Fig. 3, and computer model results in Fig. 4. The data shown in includes the first three bending modes and the first torsional mode for the free beam.

Students quickly discover that the computer model predicts a number of mode shapes that are not observed experimentally nor predicted theoretically. The experimental and theoretical results only account for transverse flexural bending waves in one direction while the computer model predicts flexural waves in other directions as well as longitudinal and torsional modes as well. The material properties (Young's modulus and density) of the beams used for experimental data are not exactly known, so students must use their experimental data to fine-tune the parameters of their computer model and theoretical calculations. This is another point where it is possible to stress the importance of comparing and synthesizing data from several viewpoints, discussing the similarities and differences between mode shapes and frequencies obtained through different methods and to weigh the validity of different results. Students are not specifically told what to do, though well-timed hints are provided. Few students, on their own, think to construct a table in their lab notebook comparing the frequencies or node locations from the five different approaches they have used to study the same beam. Most students are satisfied to state that the results from different methods are "close" without any further elaboration. This laboratory approach encourages students to synthesize results from multiple approaches into a single coherent description of structural vibration.

For the project phase of this module, students are given the opportunity to study the vibrational characteristics of a relatively simple object. Some opt to study the vibration of the same tuning fork for which they studied the intensity in first module while others often chose to explore a sports implement, such as a baseball bat, hockey stick or golf club. A preliminary computer model of the structure is made, and experimentally obtained mode shapes and frequencies from a complete experimental modal analysis of the actual structure are used to refine the parameters of the computer model. Depending on the size of the class, students are sometimes split into teams, with one team focusing on developing the computer model while the other team was conducting the experimental modal analysis. Finally, the various student teams collaborate to write a research paper comparing the results of the experimental and computational investigation of their particular structural object.

## V. STUDENT DELIVERABLES

### A. Laboratory notebooks

The core component of this laboratory course, both in terms of student effort as well as grades, is the laboratory

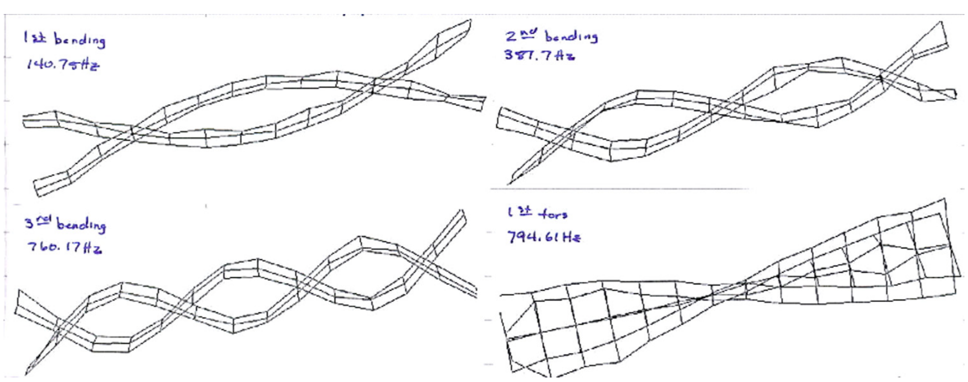


FIG. 3. (Color online) Student data (scanned from a laboratory notebook) showing mode shapes for a free-free bar as obtained through experimental modal analysis. Frequencies for the first three bending modes are 140.75 Hz, 381.7 Hz, and 760.17 Hz.

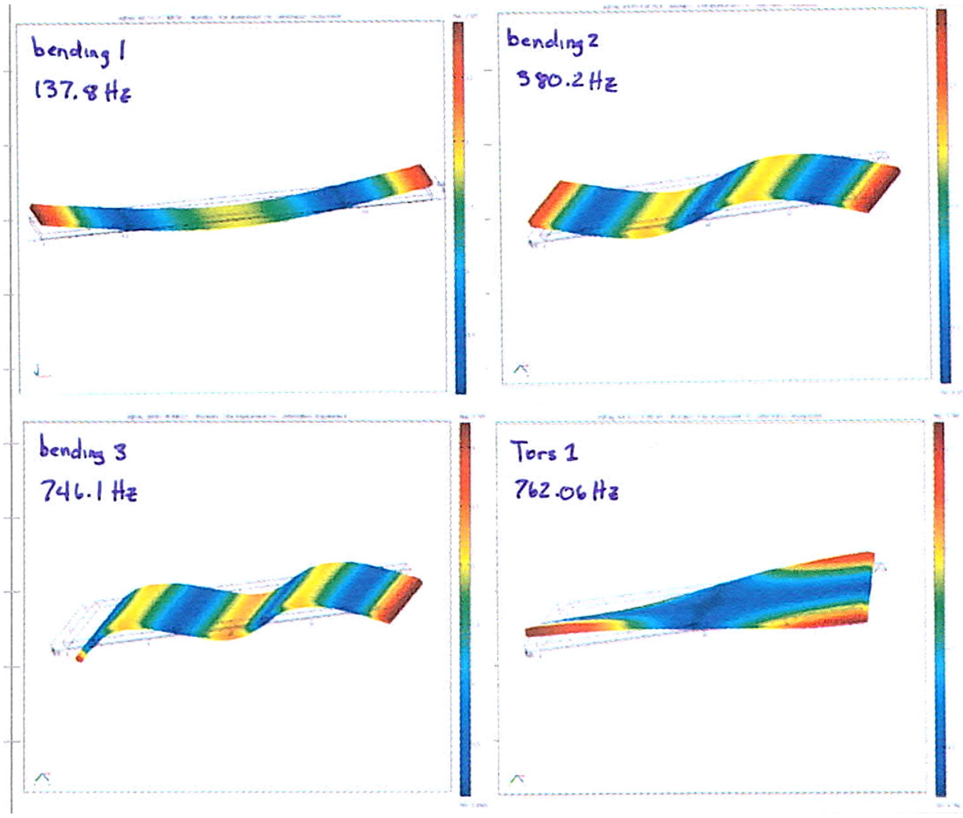


FIG. 4. (Color online) Student data (scanned from a laboratory notebook) showing mode shapes for a free-free bar as predicted from a finite element computer model. Frequencies for the first three bending modes are 137.8 Hz, 380.2 Hz, and 746.1 Hz.

notebook. Students are required to continually maintain and update a bound laboratory notebook that contains all class notes; any homework; summaries of assigned reading materials; descriptions, photos and/or sketches of all experimental apparatus; details descriptions of computer models; detailed descriptions of experimental procedures; data and results from computer models and experiments, presented through tables and plots; discussion of results comparing experiment with theory and computer models; and evidence of cross referencing through citations linking back and forth between related material throughout the notebook. The lab notebook is essentially a journaled scrapbook of a student's entire experience during the course. The lab notebook also serves as the primary source of information for the two research papers the students write at the culmination of each project.

Significant time during the first class period is spent discussing the role that the notebook will play, as well as for sharing some guidelines for maintaining a good lab notebook.[29] The practice of maintaining detailed laboratory notebooks is the personal practice of both authors of this paper. However additional justification for requiring laboratory notebooks is supported by a recent survey of experimental practices in industry which revealed that the practice of maintaining a detailed laboratory notebook seems to be in sharp decline in industry and government labs, with some detrimental consequences.[30,31] From an educational perspective, a laboratory notebook serves two very important purposes. First it provides students with a complete history of a research project from start to finish, including all of the dead ends and wrong turns along the way, as well as the breakthroughs and bursts of insight. Secondly, maintaining a detailed notebook greatly aids in the comparison of theoretical and computational models with experimental results, which is a primary goal of this laboratory course.

Lab notebooks are collected four times throughout the term, and are graded according to a rubric. Points are awarded in four categories: **Navigation** (table of contents, citations linking back and forth between related material), **Clarity** (legible writing and layout, professional looking tables and plots, identification of different types of material), **Completeness** (are all components present: theory notes, homework, reading summaries, descriptions of experimental setups and apparatus, experimental data, results with discussion, computer model parameters and results), and **Thoroughness** (minor elements: apparatus sketches are labeled, units for data, comments provided to explain mathematical derivations, correct bibliographies, margin notes indicating revision, review, and updating content). Each category has five levels of performance, and the grade is a sum of scores in each category. Plenty of allowance is given for individual style and personal preference. For example, students are not required use the same method for distinguishing different types of material, or for indicating citations linking to related material, but those two features must be present and easily identified. When deficiencies are found, students are encouraged to go back and add material before the next time notebooks are graded.

Figure 5 shows a page scanned from a student notebook summarizing results, from the air-borne sound module, of the sound radiated by monopole, dipole and quadrupole sound sources. The notebook contains photographs showing the experimental setup (a detailed written description of the setup was on the previous page of the notebook), along with

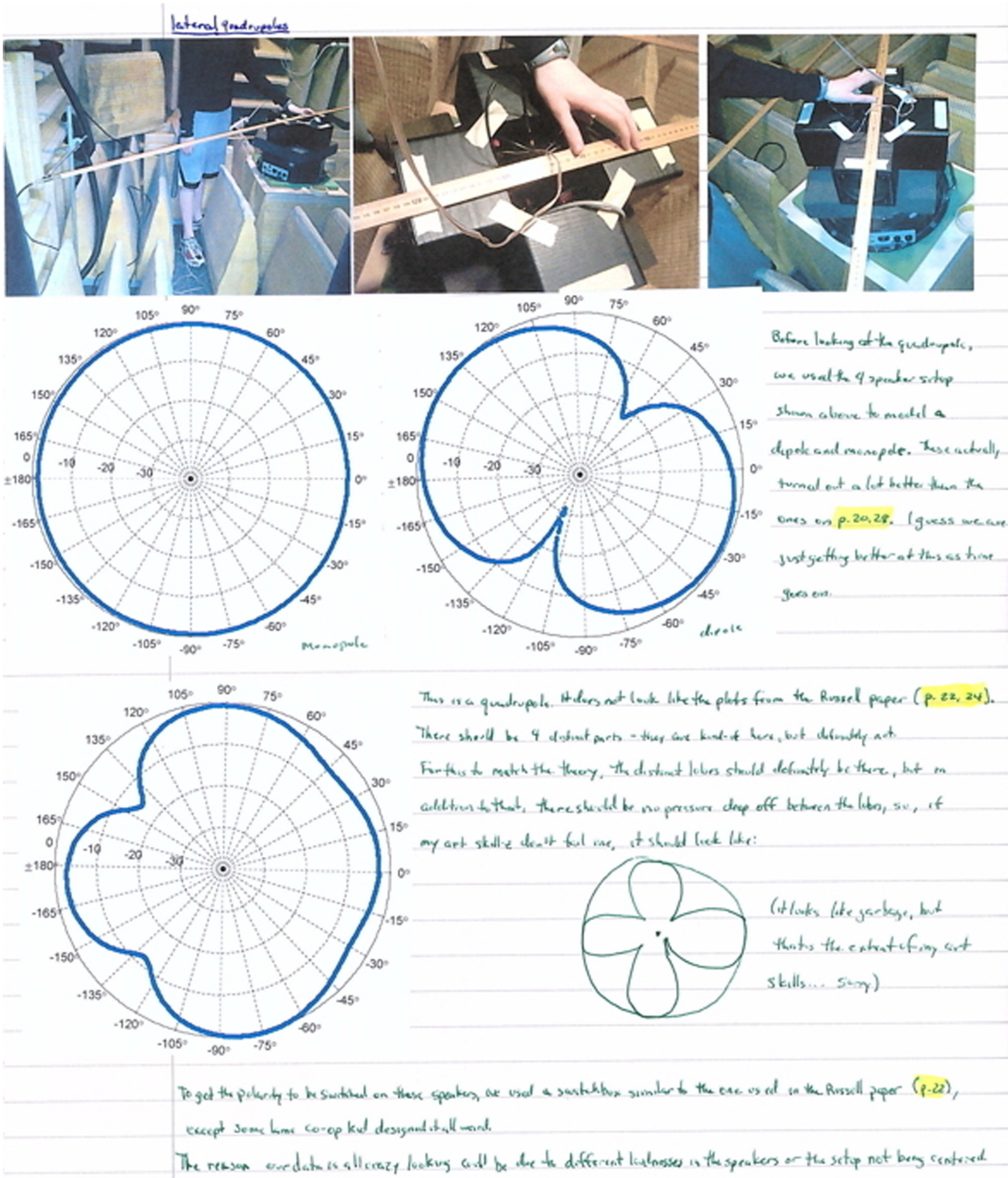


FIG. 5. (Color online) Scanned page from a student lab notebook showing experimental directivity patterns for monopole, dipole, and quadrupole sources.

results from the experiment, and discussion of those results. In this case, the quadrupole directivity data did not turn out as cleanly as expected, and the student drew a sketch of what the expected results should have looked like. The student has highlighted page numbers linking to related material (data, theory and computer models) elsewhere in the notebook. Another page from the same student's notebook is shown in Fig. 6 and summarizes the experiment to measure the bending and torsional mode shapes for a free-free beam using the microphone scanning technique. This student used different color pens to identify different types of content (discussions of theory, explanations of experimental setups, measurements and data, and discussion of results). Margin notes on the left side of the page were added later when the student was going back through the material. Again, links to other pages in the notebook refer to related material, including theoretical predictions, the computer model results shown in Fig. 4 and experimental results in Fig. 3.

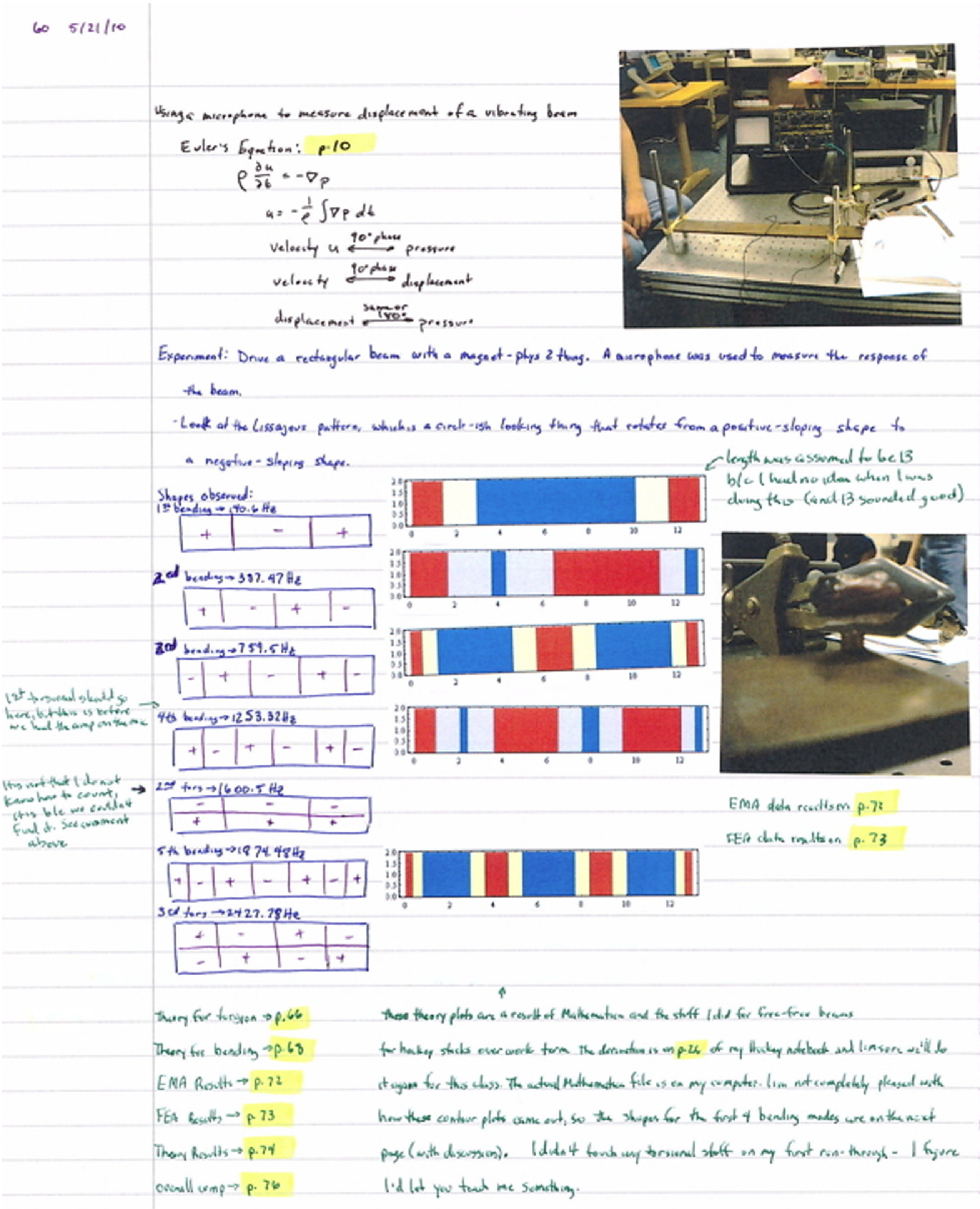


FIG. 6. (Color online) Scanned page from a student lab notebook showing experimental mode shapes and frequencies for a free-free beam with the microphone scanning method.

## B. Homework and reading assignments

Most of the content in the laboratory notebook comes from activities conducted during the laboratory class period, in the form of theoretical derivations, data collection and analysis of model and experimental results. However, several times during the term students are assigned materials to be read and summarized in their laboratory notebooks. For example they might be asked to read a short journal paper or excerpt from a textbook that pertains to a specific topic under investigation. A few additional brief homework assignments help students practice presentation skills (i.e., making graphs), or guide students in the development of the theoretical models. Summaries of reading assignments are expected to have complete bibliographic entries, detailed enough that it would be possible to quickly find the original source from the citation alone. Homework involving any kind of mathematical derivation is expected to have accompanying written comments explaining the mathematical steps and the meaning of results.

### C. Research papers

Each of the modules culminates in a research paper, written in a style and format similar to those published in *American Journal of Physiscs* or *Journal of the Acoustical Society of America*. The papers are a group effort, with two to four students collaborating to write a summary of the project. Each paper places specific emphasis on explaining and comparing the theoretical model, computer model, and experimental results. The first drafts of each paper are submitted anonymously and are reviewed, using a process similar to that used for this journal, by the professor teaching the course and one other faculty member not associated with the course. Reviewer comments are returned to the students, who then have the option of making changes to their paper before submitting the final version.

### D. Certification exams

Twice during the term, before approaching the major project portion of each module, students are given a certification exam to check whether they have each individually learned to properly use laboratory equipment and to carry out experimental techniques. Students rotate through a number of specific experimental tasks in a round-robin setting. Students are allowed to use their lab notebooks (hence the importance on keeping a good record of experimental procedures) and are expected to perform tasks such as calibrating a microphone, setting up an FFT analyzer to record a specific type of measurement, recording a frequency response function, building a simple computer model, plotting a set of data, and recording a specific set of data for an experiment.

## VI. SUMMARY

In this paper we have described an advanced undergraduate laboratory course in acoustics, a field which is not often encountered in any depth at the undergraduate level. The approach taken with this laboratory course is very appropriate for Kettering University students given the nature of the co-op program and the industrial emphasis of the school's undergraduate education. The combination of fundamental theoretical models, computational models, and experimental results as a means of studying a problem is intended to prepare students for real world problem solving. The emphasis on team collaboration and dialogue between computational and experimental teams is similar to what many of our students encounter when they go to industry or to graduate school. The requirement of keeping a detailed laboratory notebook work is good preparation for any future research experience. And, the use of a certification exam to verify that students know how to use specific lab equipment or to perform certain important experimental tasks mimics practices in the real world and would be applicable to any field.

We should make it clear that this approach to a laboratory course involves a significant sacrifice of topical material that students can be exposed to during an academic term. This active learning approach focuses on fewer topics in greater depth, and places more of the responsibility to design the experiment, develop models, analyze the results and synthesize information on the students themselves. The focus is not so much on teaching students everything there is to know about the field of acoustics, but rather to use acoustics as an avenue to provide students with the laboratory and critical thinking skills necessary for careers in both industry and academia.

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[4]The Physics Department at Rollins College does not offer upper level courses in acoustics, but does provide undergraduate students with significant research opportunities in acoustics. http://www.rollins.edu/physics/moore-research.html (Last viewed May 20, 2011).
[5]Prior to 1982 the school was known as the General Motors Institute, and from 1982 to 1997 it was known as GMI Engineering & Management Institute.
[6]COMSOL Multiphysics 3.5a, http://www.comsol.com (Last viewed May 20, 2011). One of the authors has a single-seat research license for COMSOL, but we were fortunate to discover that our school's Mechanical Engineering department has a 35-seat student license while only using 19 of them. We were able to install six of the remaining student licenses on the computers in the acoustics lab.
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