The Design and Performance of Musical Instruments

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Abstract

By challenging the students to design and build a musical instrument, we teach the fundamentals of engineering design and acoustics, as well as introduce statics, dynamics, fluid mechanics, and vibrations to liberal arts students and first-year engineers. Using the instrument as a non-threatening medium, students get a chance to do hands-on problem solving from the beginning of their college career. One of the unique aspects of this course is that it is co-taught by the music department and the mechanical engineering department. Students also learn the fundamentals of composition and actually perform an original composition on their instruments in an end-of-semester concert. Students found this course very rewarding and a number of them have continued refining their instruments after the end of the course. In the following paper, we present a general overview of the class as well as the student response with examples of student work and thoughts.

Introduction

Traditionally, first year engineering students have very little exposure to engineering. Instead, they spend the bulk of their year learning many of the fundamental stepping stones for their future engineering courses: physics, calculus, etc. Often, these courses fail to motivate the students and many potential engineers transfer out of the engineering college before they have even done any engineering. At Tufts University, we started a new program for first year students where they get the chance to engineer in their first year and to learn why they need calculus, physics, and chemistry. These mini-courses are taught by the best teachers in the various departments and are based on their personal hobbies. For instance, some of the courses offered are: Design of a Solar House, The Way Things Work, Aeronautics and Space Systems, Image Processing, Introduction to Biotechnology, and Life in Moving Fluids (how animals have engineered solutions to many of their problems). We also offer one such introductory course in the Design and Performance of Musical Instruments. Through the construction and testing of a musical instrument, we teach the fundamental concepts of acoustics, statics, and materials. In this paper we will concentrate on this course as an example of a way to engage first year students in engineering right away.

Course Specifics

The course was divided into three segments: introduction to the fundamental science principles, design and construction of an instrument, and a final concert in which the students present their instruments by playing their own compositions. The bulk of the science principles were introduced through 7 labs (see figure 1). We began each of the classes with a ten minute introduction to the fundamental science and then let the students learn through performing the experiments in the remaining 80 minutes. For most of the experiments, they had a number of choices in how to design, build, and execute the experiment. At the beginning of the following class period, they were required to hand in a 2 page lab report that answered a number of questions we gave them as well as described how they had executed the experiment. This write-up served two purposes: first to give them some practice in writing up what they saw and thought, and second to make sure that every student thought about the questions we asked.

1. *How loud is noise?*
   Students walked around with a sound meter - getting an idea what 60 dB versus 80 dB means.
2. *Wave motion*
   By using a plastic picture frame and an eyedropper, they were able to visualize waves and their interaction with each other as well as with walls and arbitrary shapes.
3. *Tension and sound*
   Students built a simple guitar neck with a board, two strings, some tuning pegs, and two hinges. By varying the tension and the string material, they could see how these affected the resulting tone.
4. *Seeing vibrational modes*
   Students were able to see the modal vibrations of a metal plate by drawing a bow across the thin side of a plate. Salt on the top of the plate would accumulate in the nodes - thereby showing the vibration modes of the plate. They also watched their strings and tuning forks move by using a strobe light to illuminate them.
5. *Doppler shift and playing the straw*
   Students swung a noisemaker around by a rope, hearing the Doppler shift. In the second half of the lab, they taped a number of different length straws together and played them like a set of pan pipes - both in and out of water (node and anti-node at the end).
6. *Visualizing nodes in a tube*
   In order to better understand the behavior of air in a wind instrument, the students operated a Kundt's Tube demonstrator. This demonstration has a speaker energizing the air above a pool of kerosene in a long tube. The antinodes have enough energy to kick up kerosene droplets and allow the students to see where the nodes and anti-nodes are in the tube.
7. *Digital recording and aliasing*
   Students recorded their whistle, sampling it at different frequencies to hear the effect of undersampling when they played it back (undersampling drops the whistle frequency). They also identified the frequency of their whistle using a spectrum analyzer.

Figure 1: Seven Laboratory Experiences

After covering lab safety and the general workings of the course, we started them the first day on quantifying sound. Using a sound meter, they walked around outside, trying to find the loudest and quietest sound. This naturally led to how sound propagation, which they learned by making their own wave tanks with picture frames (the cheap plastic box kind) and eye-droppers. They tried using multiple sources and looked at interaction with the walls. A number of students put other objects into the tank and looked at how waves reflected off of arbitrary shapes. This was the first lab where the students were able to exercise their imagination and as a result there was a large variation in the resulting reports.

The first building experience came with the construction of a very simple guitar (see figure 2). These “guitars” are simply a few strings tightened across two hinges on a board of maple. We used this lab as an introduction to how to use a number of the woodworking tools as well as a chance for the students to start thinking about their final project: an instrument of their own choice. For the class, we had a full wood shop to use. As a homework assignment, the students then built a larger amplification box to attach to the end of the neck. By having different students build different shaped boxes, they were able to examine the effect of shape, volume, and material on the instrument performance. This initiated the discussion on the vibration of the box top - which led into the next lab: vibrational modes of a surface. Students first looked at the vibration of their strings and of a tuning fork using a strobe light to “freeze” and then “slow down” the vibrations. Then they looked at the vibrational modes of a thin metal plate by putting salt on the surface of the plate and then rubbing a violin bow along the edge. This caused the plate to oscillate and the salt to collect in the nodes of the plate.

To introduce the wind instruments, we started with building a set of pan pipes from straws and then documenting the difference between a closed and open end to the straw. This gave them insight into nodes and anti-nodes in the air vibration - which we followed up with a Kundt’s Tube demonstration. The Tube is a 10 foot long, 6 inch diameter, transparent Plex tube half filled with kerosene. A loudspeaker at the end sets up standing waves in the tube and the kerosene is light enough that droplets jump around in the anti-node area and are is still in the node regions.

Finally, the last experiment was with digital recording of sound. After a brief overview of sampling theory and how a compact disk player works, students recorded their whistle on a computer and then played it back over the speaker. They could hear the effects of under-sampling (or aliasing) and could see the frequency distribution in their whistle with a spectrum analyzer (built into the program). They also got to filter their signal, amplify various frequency bands, and get a feeling of how much space digital audio requires on a computer hard drive.

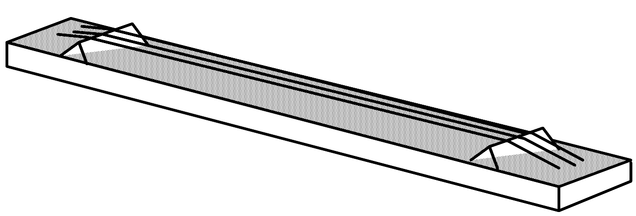

Figure 2: The Simple Guitar

At the end of the experiments, the students then gave a short presentation on one of the major instrument groups - showing how the woodwinds (for example) generate and amplify sound. For the remainder of the semester, the students worked in the college wood shop building their final instruments. In class, one of the professors from the music department (collaborator on the whole project) gave a short course on elementary composition and we answered any questions the students had on the engineering of their instrument. The class culminated in a final concert (given in a small concert hall - with programs and fanfare) where the students played a new composition on their instrument. Instruments ranged from models of existing ones (guitars, bells, a zither, glockenspiel, and a recorder) to new inventions (a sax-pipe, a triangular guitar, and a mandolin with a movable bridge). The compositions ranged from fairly simple to complex theme manipulation and the students enjoyed hearing the various songs and instruments. Figure 3 shows one sample guitar.

Figure 3: A Sample Final Project

Student Results and Evaluation

In general, this course was very popular among the students. They were a self-selected group and therefore were all very interested in the material. This made the class easier to teach and we were able to do more than in a general introduction class where students are required to attend. The greatest complaint among the student evaluations was the amount of time necessary to build the instrument. In future versions of this course we will start them building the instruments sooner - so that the construction parallels more of the class. A surprisingly large number of students have kept their instruments - many returning years after the class to talk about their instruments and changes they have made.

Integration with Liberal Arts Education

One of the benefits of the introductory courses, especially this musical instruments course, is that they integrate engineering with the general liberal arts education. Because of the limited math and science included in these classes (they have no prerequisites), they are an ideal platform from which to teach non-engineers some fundamental engineering concepts and to make engineering a more known and less feared subject. In particular, these courses have been very popular among pre-service teachers. In typical teacher education programs across the nation, the science content is pitifully small, often less than one-third of one class. There is no engineering content. Yet these are the people who are going out to teach the next generation of students; the danger is that these teachers may have a hand in perpetrating these math, science, and engineering phobias. So by having pre-service teachers take these engineering classes, they get an introduction to both science and engineering principles (such as elementary acoustics and engineering design). More importantly, they learn that they are capable of engineering - largely alleviating the fear of the subject. In this particular class, we had one pre-service teacher and about 10% of the class were non-engineers. The pre-service teacher has since used much of the class material in her elementary school classroom and has repeatedly remarked how surprised she was that the material was not as mysterious as she had been led to believe.

By working closely with the Music Department at Tufts, we hope to increase the non-engineering population of the class. Gaining leverage from the student's love of music and interest in the subject, we have been able to keep them involved long enough for them to get over their initial preconceived notions about engineering. We also use this to our advantage in the other direction: opening the liberal arts education to the engineering student. In fact, we are now looking at extending this single class into a full minor within Mechanical Engineering. Integrating this course with the Music Department and with Liberal Arts education in general strengthens the foundations of engineering by encouraging a creative response to learning the basics of the discipline. By the same token, students in this course are likely to learn that Music Theory and Composition are considerably more concrete and structural than they might have thought. Thus, the course cannot go wrong with its interdisciplinary goals: it brings the creative aspect emphatically into technical pursuits, and the technical into the creative. By encouraging each student to build an instrument, learn to play it, and write a piece of music for it, this innovative course bridges two disciplines that are too often treated entirely separately. Engineers and non-engineers alike are the beneficiaries of this integration.

Conclusion

The main idea of this course is to give first-year engineering students a chance to perform some engineering before they start the typical grind of math, physics, and chemistry classes. By doing this, one can show them the reason for learning the math and science as well as give them a taste of engineering in the beginning. In particular, the course The Design and Performance of Musical Instruments gives first year engineering students and liberal arts majors (particularly pre-service teachers) the chance to learn engineering through building an instrument. Since there is a wide variety in the offered courses, the students in any one of these courses are self-selected and therefore are more motivated to work than in a typical general introductory engineering course. These introductory courses in general, and this one in particular, have been very successful - with high marks from both student and faculty evaluations. Probably the best evaluation marker for the program as a whole, though is that since the inception of these introductory courses, Tufts has gone from have a net decrease of engineers at the end of the sophomore year, to a net increase. For the first time in the history of the college, more non-engineers are becoming engineers than the other way around.

Future Direction

The popularity of this particular course has led us to building a minor in the engineering of a musical instrument. We are teaming up with Selmer and Steinway and Sons to develop a program where mechanical engineering students have the opportunity to take a musical instrument track through the mechanical engineering curriculum and graduate with a BSME with a minor in Musical Instrument Engineering. Their minor will include learning statics, dynamics, fluid mechanics, and vibrations through building and testing their instrument. It will culminate in the student working as a summer intern at an instrument manufacturing plant and then returning senior year to do a research project for the company. For instance, these might be investigations into the responsiveness of various woods, the effect of cryogenic treatments to metals on the microstructure and in turn the playability of the instrument, the effect of different glues and varnishes on the performance of an instrument, and so on. From informal surveys, we have found that almost half of our mechanical engineers consider themselves musicians in one way or another and about 10% would definitely want to get such a minor. In reality, the construction of an instrument is just like any other manufacturing process, this one simply has a lot more mystique about it than does the construction of a computer chip.