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Hey kid! Wanna build a loudspeaker? The first one's free.

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ABSTRACT

Penn State recently instituted a First Year Seminar (FYS) requirement for every student. This paper describes a "hands-on" FYS on audio engineering that has freshmen construct and test a two-way loudspeaker system during eight 2-hour class meetings. Time and resource constraints dictated that the speaker system must be assembled using only hand tools and characterized using only an oscillator and digital multimeter. The cost of the entire system could not exceed $60/side. The speaker enclosure is made primarily from PVC plumbing parts. The four laboratory exercises that the students perform and write up are designed to introduce basic engineering concepts including graphing, least-squares fitting and error estimation, electrical impedance, resonance, transfer functions, mechanical and gas stiffness, and non-destructive parameter measurement.

1. INTRODUCTION

Dissatisfaction among students, parents, and legislators with large lower-division classes and the widespread use of teaching assistants in those classes prompted Penn State to create a First Year Seminar (FYS) requirement for all undergraduates. Starting in 1999, all first-year students were expected to complete a one-credit FYS as part of their General Education requirement. Although the Graduate Program in Acoustics at Penn State has no undergraduate major, the acoustics faculty felt that an FYS could provide a good opportunity to make Penn State engineering undergraduates aware of our unique acoustics program, as well as provide an experience that would satisfy the four "general goals" (listed in Section 4 of this paper) dictated by the College of Engineering.

Many of our graduate students and faculty came to study acoustics through their appreciation of music and the experience of building their own loudspeakers. We thought that a hands-on seminar where students built their own loudspeaker system might provide an enjoyable and educational introductory experience for freshmen.

The Graduate Program in Acoustics maintains a very active student chapter of the Audio Engineering Society. As their faculty advisor, I challenged the members to come up with a two-way loudspeaker that would satisfy the following constraints:

- Can be assembled safely using only simple hand tools
- Can be constructed during five 110-minute laboratory periods
- Cost less than $60/side, including **all** parts

Five members of the local chapter accepted the challenge: Kevin Bastyr, Mike Daly, John Heake, Nelson Kottke, and Matthew Poese. Interestingly, all entries used PVC plumbing in some part of their enclosure design. For the purposes of the FYS, the Heake design was the most attractive.

2. ENCLOSURE CONSTRUCTION

One complete two-way loudspeaker enclosure is shown in Figure 1. The woofer's enclosure was formed by joining a 10" long section of 6" (nominal) diameter Schedule 40 PVC pipe to a ¾" thick medium-density-fiberboard base. The base had a circular groove routed into it to accommodate the pipe. Two holes are drilled near one end of the pipe to accept two 5-way binding posts. After the cross-over circuit components were assembled, tested, and hot-glued to the base, as shown in Figure 4, the base and pipe were joined with a construction adhesive (*e.g.,* Liquid Nails) dispensed from a caulking gun into the groove.

The woofer was mounted on a 6" Schedule 40 PVC 90° elbow. PVC cement was used to glue a 1" long ring of the 6" diameter Schedule 40 PVC pipe into one end of the elbow to provide an attachment surface for the six pan head screws that held the Axon Model 6S3 Shielded Midbass (woofer) to the elbow. As can be seen in Figure 1, the outer diameter of the 6S3 is exactly the same as the 6"elbow's outer diameter.

An Axon Model T1S semi-rigid, fabric dome tweeter is mounted with four pan head screws to a 3" Schedule 40 PVC cap that is also the same outer diameter as the tweeter. This tweeter enclosure is attached to the 6" elbow using a single, ¼-20 x 3/4" brass bolt and nut. The bolt is drilled out along its axis (#30 drill) to pass the tweeter wires from the tweeter enclosure (3" PVC cap) into the 90° PVC elbow, where the tweeter's leads can be attached to the crossover mounted on the base.

Most students chose to paint or otherwise decorate their enclosures. Krylon makes a spray paint that is formulated for use on plastics. It is marketed as their "Fusion" product and it available in several colors. We have found that the Krylon-brand Fusion spray paint produces a finish that is superior to that of ordinary spray paints when used to coat PVC plastic.

Figure 1. Photograph of the assembled enclosure.

3. CROSSOVER

There were several pedagogical motivations for using a two-way loudspeaker system for this seminar. Freshmen admitted to the Penn State College of Engineering usually have a reasonable understanding of simple dc circuits. They might also recognize an inductor and capacitor, but most have no idea why those components might be useful. The crossover circuit provides a useful introduction to simple ac circuit concepts.

The crossover circuit that is shown in Figure 2 was developed "by ear" rather than by analytical optimization. The students characterize the electrical performance of the circuit by measuring the voltage transfer functions for the woofer and tweeter in Exercise #3.

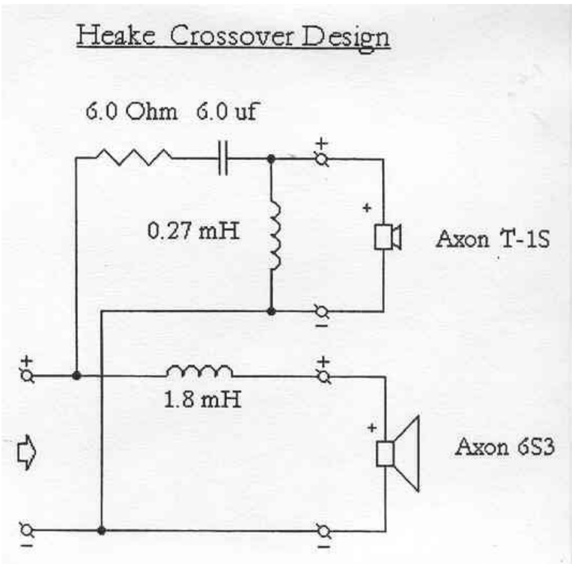

Figure 2. Crossover circuit.

4. LABORATORY EXERCISES

There are four general goals for an FYS offered within the College of Engineering:

a) Introduce students to a specific field, or a number of fields, of study in engineering.
b) Acquaint students with tools, resources and opportunities available to them.
c) Provide exposure to some of the professional skills and competencies associated with academic study and the practice of engineering.
d) Encourage networking and interaction with faculty, students and engineers.

To address goal (c), the students were required to turn in four laboratory exercises. Each exercise required that they obtain data during the laboratory period, analyze and present the data in a short report prepared outside of class, and turn in the reports at the following class meeting.

Many of the students arrive at the university without exposure to the normal requirements for graphical presentation and analysis of data. For that reason, the first three exercises include a sample spreadsheet with proper column headings that include appropriate units, and a sample graph that has the proper axis labels (with units), legend, title, etc. If a student's report does not conform to those standards, it is returned to the student and then resubmitted after the student made the indicated changes.

Satisfaction of the other three goals did not require any specific effort by the students. During the first two class meetings they are introduced to loudspeaker fundamentals, the simple harmonic oscillator equation, and simple passive ac circuit concepts, without use of complex numbers.

4.1. Woofer Input Electrical Impedance

In the first exercise, the students measure and plot the magnitude of the input electrical impedance of their woofer. The woofer is connected to a function generator through a 330 Ω "current limiting" resistor. The students measure and record both the current through the woofer and the voltage across the woofer's terminals from 10 Hz to 2.5 kHz. The lab write-up provides the recommended measurement frequencies and suggests that they acquire enough additional points around the mechanical resonance frequency that they are able to determine the resonance frequency to within ±0.1 Hz.

The students are required to enter their data into a spreadsheet, use the spreadsheet to calculate the magnitude of the woofer's electrical input impedance by dividing the voltage by the current at each frequency. They then use the spreadsheet program to plot the impedance *vs*. frequency as a semi-log graph. Most students have not previously used logarithmic axes for data presentation.

4.2. Woofer Stiffness and Moving Mass

Having learned to identify the mechanical resonance frequency of the woofer by the peak in the electrical input impedance in the first exercise, they are asked to measure the woofer's resonance frequency when between one and five US nickels (which each have a mass of 5.00 gm) are placed on the cone. These six resonance frequency measurements can be made fairly quickly since the students have convinced themselves, during the first exercise, that the current limiting resistor lets them find the resonance frequency by simply locating the frequency at which the peak in the voltage across the woofer's terminals is observed.

The students are introduced to the use of a least-squares fit to a straight line for determination of a two-parameter function. The equation for the natural frequency f_o of a simple harmonic oscillator is

$$f_o = \frac{\omega_o}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{k}{m_o}}\,, \qquad (1)$$

where k is the suspension stiffness and m_o is the moving mass. Squaring and inverting (1) produces equation (2) for each measured periods T_i, in terms of each added mass (nickels) m_i placed on the loudspeaker's cone,

$$\frac{1}{f_i^2} = T_i^2 = \frac{4\pi^2}{k} m_i + \frac{4\pi^2}{k} m_o\,. \qquad (2)$$

By plotting the resonant period squared *vs.* the added mass, the student extracts the mechanical stiffness of the woofer from the inverse of the graph's slope. The moving mass is determined from the ratio of the intercept to the slope. These results will be used in Exercise #4 to determine the contribution of the stiffness of the gas in the enclosure to the stiffness of the woofer's suspension. As evident in Figure 3, the precision of that determination of stiffness and moving mass can be quite high using only six frequency measurements. Based on the square of the correlation coefficient, R^2, and the number of data points [1], the relative statistical uncertainty in the slope, and therefore the woofer's stiffness, may be as small as ±0.5%.

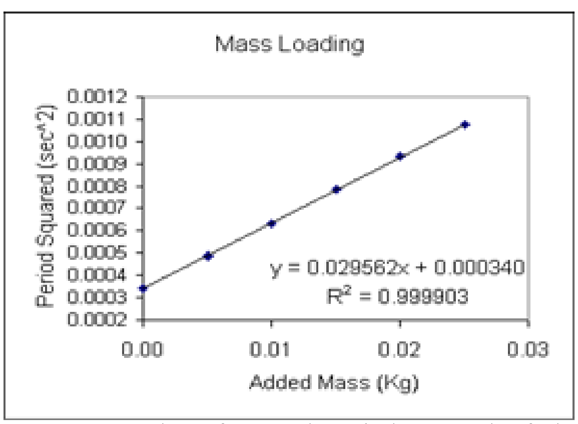

Figure 3. Plot of natural period squared of the woofer as a function of the masses (nickels) added to the loudspeaker's cone. The straight line is a least-squares fit to the data.

4.3. Crossover Transfer Function

The third exercise requires that the students assembly the crossover circuit and attach the woofer and tweeter. They then measure and graph the voltage transfer function of the crossover circuit and identify the frequency where the functions intersect. Again, they use a logarithmic frequency axis and calculate the voltage transfer function, expressed in decibels, using measured data that is put into a spreadsheet.

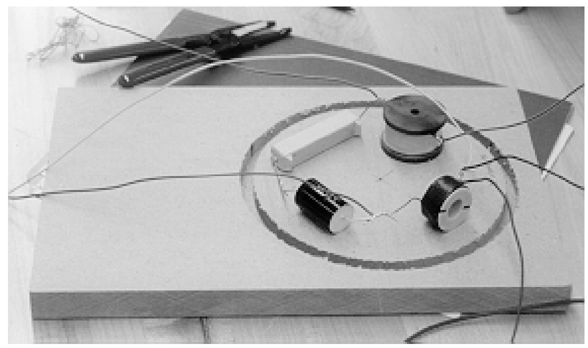

Figure 4. Crossover components are attached to the enclosure base using a hot glue gun. Also visible is the groove in the base used to join the base to the 6" PVC pipe with an adhesive dispensed from a caulking gun.

4.4. Enclosure Gas Stiffness

The final exercise requires that the student measure the increase in the resonant frequency of the woofer when mounted in the enclosure. Since the moving mass of the woofer has not changed, they can use equation (1) to determine the total stiffness and subtract the suspension stiffness measured in Exercise #2 to determine the contribution to the stiffness provided by the air confined within the enclosure.

The students then stuff the enclosure with polyester floss and re-measure the woofer's resonance frequency. The decrease in the resonance frequency is then attributed to the difference between adiabatic compressibility of the air in the "empty" enclosure and (nearly) isothermal compressibility of the air that is in intimate thermal contact with the floss, which has a far greater heat capacity than the air.

5. CONCLUSIONS

As technology advances, more engineering knowledge and techniques are added to an undergraduate curriculum of necessarily limited duration. Over the last decade, the importance of computers in engineering has reduced the opportunity for "hands-on" engineering experiences. In addition to exposing freshmen to some audio engineering concepts, this FYS also provides students an opportunity, early in their engineering education, to measure an impedance curve and a transfer function, before taking classes where these concepts are introduced mathematically. It also provides experience in the acquisition and analysis of data, which produces a high-precision numerical result, that should give them some "faith" that the theoretical concepts that they will learn in classes have both validity and utility. Just the act of soldering a circuit and troubleshooting its performance is an experience that is otherwise generally absent from the curriculum.

Students who have taken this seminar seem to be pleased by the experience. All of them are very proud of themselves on the last day when their "product" is auditioned. They also enjoy spending the class time doing hands-on measurement and fabrication tasks (while listening to music, of course). Thus far, 46 students have taken this FYS. 38 of the students chose to spend $60 to purchase an additional set of components and assemble a stereo pair in class.

Although it is still to early to determine whether any of the students who have taken this FYS will apply for admission to Penn State's Graduate Program in Acoustics, it is clear that the seminar has met the goals set by the College of Engineering.

6. REFERENCE

[1] J. Higbie, "Uncertainty in the linear regression slope", Am. J. Phys. **59**(2), 184-185 (1991).

7. ACKNOWLEDGEMENTS

The development of this seminar, and the ability to offer each student the components for one two-way loudspeaker at no charge, was supported by the Penn State College of Engineering. The authors are grateful to our Student Chapter of the Audio Engineering Society for supporting the project that produced so many interesting designs.