It is all about pitch: An introductory design project in acoustics for 1st year undergraduate engineering students

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JASA ARTICLE

It is all about pitch: An introductory design project in acoustics for 1st year undergraduate engineering students[a)]

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ABSTRACT:
This acoustics project evolved responding to a challenge to increase the role of analysis in design for 1st year students early in their engineering careers. Student teams must design three musical instruments each producing a single note meeting frequency and sound level specifications using different physical sound generation processes. They are given background material, example analyses, references, and resources. A key requirement is that they create a spreadsheet with equations guiding the design of each instrument before proceeding with construction. Students experience the entire design process: brainstorm, analyze, create, build, test, iterate, present, demonstrate, and report. This introduces the range of resources available to them. An emphasis is on comparing theory and experiment and explaining reasons for any disagreements. As implemented, this project concentrated over about a two week period, provided an introduction to a major design project continuing for a full semester.
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I. INTRODUCTION

In the process of developing a design course for 1st year undergraduate students at the University of Colorado, Boulder, several parallel sections of the course tested a variety of approaches (Carlson *et al.*, 1995; Abarca *et al.*, 2000). These converged on a core of content that was being considered for broader adoption in the Engineering School at the University of Colorado, Boulder. As a component of the evaluation, Dean Richard Seebass sat in on a section of the course for a semester. He was "invisible" and the students ignored him "totally." There was only one class including (1 hour lecture and two 2 hour labs per week) that he could not attend.

At the end of the semester, he made it clear that he valued the course content that had been created. He also made it clear that he wanted more analysis integrated in a seamless manner into the course. This was the stimulus for the design challenge described here. The goal was to show 1st year engineering students that "analysis is your friend." It is all about pitch: A 1st year undergraduate introductory design challenge addressed this using acoustics. Other sections used differing approaches. Some, in future semesters, adopted this project. This project, designed for a short (~2 week) introduction, exercised students in the design process. Radish and Steinberg (1999) emphasized the need for increasing the emphasis of analysis in design.

Some previous efforts to incorporate analysis in these design projects are described by Bedard (1999). However, these analyses were not embedded in the design loop as an essential driver of the project. Although the design of a surface tension propelled craft was analytically driven (Bedard 1999), the conclusion was a race and not controlled by specifications. Other projects (e.g., a Rube Goldberg design and a reverse engineering project) had an analysis component, but analysis did not drive the projects. After the development of the pitch project, the main projects also involved a clear analysis component from the onset. For this exercise, the definition of a musical instrument is quite broad—something that produces a sound meeting the frequency and sound level specifications. This wide definition encourages creativity and invention. Since being created this project has been used for about 40 classes.

II. COURSE INTRODUCTION

A. Course syllabus/introduction

There are typically ~30 students in each section with five students on a team. Students are introduced to the machine shop, spatial visualization, laser cutters, three-dimensional (3D) printers, electronics shop, and specific workshops directed to project choices. They have access to the classroom, tools, and the laboratory after hours with staff available. They work both in and outside of class.

Course Description: GEEN1400 An introductory design course for First year Engineering students.

The purpose of this course is to provide an introduction to engineering through a series of projects done in interdisciplinary teams. The goal is to learn in a hands-on way valuable engineering skills including communication skills, how to function in teams, and a variety of computer tools as

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appropriate to projects, such as programming microcontrollers, dynamic modeling software, or computer-aided design (CAD). Specific learning objectives for the course include:

(1) Open-ended hands-on design experience: Apply iterative design process to improve design; define functional requirements and specifications; generate alternative design concepts; and work within constraints.
(2) Teamwork skills: Learn and practice effective teamwork skills; learn how to rely on other team members to give and receive help; demonstrate increased understanding of diversity; and practice conflict resolution.
(3) Communication skills: Develop a professional relationship with an engineering faculty member; develop technical writing and oral presentation skills; make an effective poster to summarize project; and learn and practice active listening skills.
(4) Engineering methodology: Understand the role of analysis in the design process; solve engineering problems with appropriate tools; and effectively apply technical skills to produce prototypes and design artifacts.
(5) Engineering ethics: Understand the importance of an ethical code for the practice of engineering; appreciate that difficult, "gray" situations arise in engineering practice; and develop an ethical process that will yield appropriate decisions when needed. While not specifically addressed as part of the pitch project, engineering ethics is an integral component of the course. A lecture in engineering ethics often precedes the pitch project.

B. Laboratory resources provided

Launch Point
First stop for engineering questions
3D printer/ laser cutter issues
Manufacturing Center
General machine tools
Metal, plastic and wood. Saws, drills, mills, lathes. Pneumatic Hand tools
Project Depot and Checkout
Miscellaneous parts and tools, materials testing, equipment, instruments, sensors, and related issues
Electronics Centers
Simulate, build, and test electronic circuits and printed circuit boards
Arduino, microcontrollers, and data acquisition
Programming and collecting measurement data (primarily used later in the semester)

C. How teams are formed

Teams are developed using a combination of student backgrounds and techniques in a 2 hour interactive session (e.g., autobiographical sketches, a capability check list—students have rated their abilities in about 20 areas, social styles profiles, an "ice breaker" exercise, and special needs). The goal is to have interdisciplinary, diverse design teams. Students who are related (in one case triplets) or from the same high school are placed on different teams, often with some grouching involved. Different sections use variations of this process.

III. THE PITCH PROJECT

A. Project goals

The primary goal for the semester is a major design project. Teams will present to the public at an exposition at the end of the semester. There are judges assigned to each section to review their final projects.

Purposes of the introductory Pitch Project:

- Demonstrate the importance of analysis in design
- Encapsulate the entire design process into a relatively short period (∼two weeks)
- Engage students with resources that are available to them
- Provide an initial experience for students to work with their design team (producing three designs, a formal presentation, final report, and concert demonstration)
- Provide multiple tasks requiring teamwork to accomplish
- Develop skills in analyzing differences between theory and experiment

B. Introduction to the pitch project

An electronic and hard copy of a hand out is given to students when the pitch challenge is introduced in class. This is reviewed in detail with equations, and examples, covering a wide variety of possible instruments (e.g., a total of 18 instrument possibilities with four appendices, one providing a table of useful properties covering a range of materials). Typically, students will have the hand outs physically with them with their own annotations for the duration of the project.

C. Musical instrument design sequence

- Receive specifications and constraints
- Brainstorm instrument choices
- Guiding equations, suggestions, and resources are provided in an electronic and hard copy handout, which are reviewed in class
- Create spreadsheets using equations to guide instrument design
- Spreadsheets reviewed by professor or teaching assistants before starting construction
- Measure prototype frequencies using spectrum analysis software
- Iterate design as necessary to meet specifications
- Compare theory and measurements and develop explanations for any disagreements
- Prepare report, power point presentation, and participate in orchestra

D. Specifications

Each of the design teams is assigned three musical notes based upon three different sound generation processes and that need to match the frequency to within 3% and produce a sound level of 70 dB at a range of 1 meter. With five design teams the class will produce 15 instruments. There are usually five to six notes assigned in total, so there could be three separate instruments assigned the same note on different teams. If the music chosen for a concert has a predominance of one or more notes these are favored in making note assignments. The music chosen is intended to be familiar and not complex. This choice drives the distribution of notes assigned.

IV. EXAMPLES OF EQUATIONS PROVIDED TO HELP GUIDE THE DESIGN OF INSTRUMENTS

Guiding equations are provided for the most frequently designed instruments and some examples are given below. These are examples of the information provided for some possible instruments. As teams chose other instruments, additional references provided give detailed background. General valuable references are given in the resources section below.

A. Helmholtz resonators

A common Helmholtz resonator is a liter bottle of soft drink that sounds a note as you blow across the top. You may have noticed that the tone changes as you finish off more and more of the drink. The resonator was named after the well-known acoustics scientist. A drink bottle is usually available to demonstrate a spectral analysis display. When the same bottle is squeezed it will not produce a tone. Why is this? This is left unexplained for students to think about. The demonstration is intended as a hint for students that asymmetric volumes do not work.

The volume does not have to be spherical but should be much larger than the neck volume. This system is an analog of a spring/mass system. The air in the neck is the mass in this case and the compressibility of the air in the volume of the spring.

The equation predicting the resonant frequencies of the system is

$$F = \frac{c}{2\pi}\left(\frac{S}{L_c V}\right)^{1/2}, \tag{1}$$

where F is the frequency, c is the speed of sound, V is the volume, S is the area of the neck (typically πa^2), and L_c is the corrected length of the neck,

$$L_c = L + 16a/3\pi, \tag{2}$$

where L the neck length and a is the neck radius.

Examples of Helmholtz resonators are certain bottles and containers of various kinds. Also, the sound some people can make when blowing through cupped hands is probably a result of this type of resonance.

B. Organ pipes

The expression for the resonant frequency for an organ pipe open at both ends is

$$F = Nc/2L, \tag{3}$$

where N defines the fundamental and harmonics with integers 1,2, c is the speed of sound, and L is the pipe length.

If the pipe is closed at one end the expression is

$$F = (2N - 1)c/4L. \tag{4}$$

For an instrument consisting of a hollow tube blown at one end (such as a didgeridoo), these relationships could be used as working models to estimate the frequencies produced.

C. Corrugated tubes

Blowing continuously through a smooth tube produces no noticeable tones. However, when a tube is corrugated, as are some straws for water bottles, a strong tone can result. This effect has been used in operas with dancers twirling the tubes to produce internal flows and sound (e.g., The Magic Flute). A toy has been constructed based upon this phenomenon.

Scientific studies have been done in an effort to understand the physics (e.g., Crawford, 1974; Cadwell, 1994; Kristiansen and Wiik, 2007; Nakiboglu *et al.*, 2012). You can model this in part by considering the tube to be an organ pipe open at both ends. However, you also need to model the process causing the pipe to sound. This can be done by determining the frequencies generated by the flow in the pipe passing over the corrugations and then estimating the conditions under which these frequencies become matched.

Thus for the organ pipe,

$$F = Nc/2L, \tag{5}$$

where N defines the fundamental and harmonics with integers 1,2 c is the speed of sound, and L is the pipe length.

The corrugation frequency can be estimated by taking the ratio of the estimated flow speed in the tube to the corrugation spacing,

$$\mathrm{Fcorrugation} = U/d, \tag{6}$$

where U is the estimated flow speed, and d is the distance between corrugations. As the flow speed increases or the corrugation spacing decreases the frequency generated may be expected to increase. The loudest sound should occur when the corrugation frequency matches one of the organ pipe resonances.

D. Vibrating strings

For a clamped/clamped string the frequencies may be computed from

$$F = NCs/2L, \tag{7}$$

where N is an integer defining the fundamental and harmonics, L is the string length, Cs is $(T/\rho)^{1/2}$ and T is the tension (e.g., in Newtons} ρ is the linear density of the string (e.g., kilograms per meter).

E. Aeolian harp

When wind blows through wires or around the eves of a house, mournful sounding tones are produced. This happens because alternating eddies are shed from the obstacle in the flow. These eddies are called Karman vortices after the scientist who studied them.

The frequency may be estimated from the following relation:

$$\mathrm{F} = \mathrm{St}\,\mathrm{U}/\mathrm{D}, \tag{8}$$

where St is a dimensionless number called the Strouhal Number (for a cylinder the value is 0.2) U is the flow speed, and D is the diameter.The aeolian harp sound has been celebrated in poetry for its beauty and has also been called strange and eerie (providing background for the movie *Exorcist*).

F. References to provide more general background

Valuable general references are Olsen (1947), Kinsler and Frey (1962), Rossing (1990), and Fletcher and Rossing (1998). The book by Hopkins (1996) has practical advice for the construction of a range of instruments. Usually, passing the book around for student teams to look at and offering to copy a "limited" number of pages (after one student asked for pp. 100–165). Additional references were provided to teams exploring other possible instruments.

V. NOTE ASSIGNMENTS

The range of frequencies used in this specification is between 200 and 500 Hz. Frequencies below this will result in instruments larger and possibly overwhelming a shared classroom. Higher frequencies could require more precise construction. This specified frequency range usually results in instruments constructed with typically available hand tools. An example of note assignments is shown below.

Design Loop Note Assignments
It's All About Pitch Fall 2018

Notes	Frequency (Hz)
C	261.6
D	293.7
E	329.6
F	349.2
G	392.1

Team Wombat	C, D, E
WAVVY	D, E, F
SPARA	E, F, G
Flatiron Force	F, G, C
Marc B	G, C, D
Team Maximum Effort	C, D, E

VI. SPREADSHEET REQUIREMENTS

A spreadsheet is a requirement before teams can proceed with the construction of a design. This involves having a plot of frequency as a function of a parameter that they have chosen to control their design (e.g., frequency as a function of tension on a string).

The teaching assistants provide a review of Microsoft Excel with example instruments at the start of this phase. Many students will have rated themselves as having a knowledge of 5 out of 10 at Excel. Other spreadsheets that individual students are familiar with have been used.

VII. INSTRUMENT DESIGN AND TESTING

A. Instruments designed

Example of a student design (The Manhattan Project):

The team chose a Helmholtz resonator in the form of a flask to meet a 329.6 Hz frequency design requirement. They filled the flask with water in increments and measured the frequency as a function of free volume. Their plot showed excellent agreement between theory and experiment until the free volume was less than 0.15 liters. At small free volumes, the experimental frequency was less than theoretical (Fig. 1). They hypothesized that as the volume became smaller compared with the neck volume, the neck acted as an organ pipe (a sensible working theory).

As measurements are pushed to the limits of a basic theory, which in general works quite well (in this case the free volume of the resonator becomes comparable to the volume of the neck) it could be that a major project would need to be initiated to completely understand disagreements between theory and experiment. Possible reasons for disparities can usually be suggested with confidence.

B. Frequency testing with examples

Leaving the spectral display showing in class on a screen at the front of the room during the testing process was evocative. Thus, any student can see testing in progress, including background noise (e.g., sawing, drilling, water/sink sounds). Some students have been inspired by the background noise. In the testing process students are interacting with sound on a personnel level (banging, plucking, thumping, blowing, —) and processing what other students are doing. This testing capability was also usually available after normal class hours.

The testing process used Raven Lite Spectral Analysis Software, available from Cornell University. Typically, a spectrogram displaying intensity and frequency as a function of time was projected on a screen at the front of the classroom. A cursor placed on the center of a displayed frequency, usually defines the frequency to about 1 Hz.

Two examples of these displays are included below. Figure 2 is a spectrogram of a wine bottle Helmholtz resonator showing frequencies for a 1/2 and 1/3 filled bottle. In this case, there are no harmonics visible. Measurements using a graduated cylinder defined the volumes involved.

Figure 3 is a spectrogram of a string instrument showing fundamental and harmonic frequencies. Typically, students would then tune their instrument to meet design specifications.

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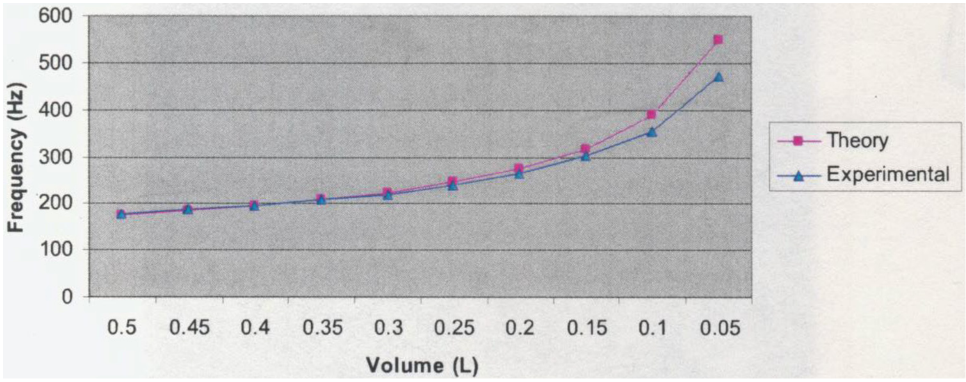

FIG. 1. (Color online) Shows plots of frequency in Hz as a function of free volume in cc comparing theory and experiment for a Helmholtz resonator. Data were obtained at various volumes by adding water to the resonator.

C. Sound level testing

A sound level meter is passed around the class and introduced. Each team sits at their own table and has a chance to work with and test the meter. The sound level meter is available both in class and outside of class for their use. They know that their "official" measurement will be made at a range of 1 meter by one of the teaching assistants. Most instruments readily meet the specification of 70 dB at 1 meter. Exceptions have been string instruments not having a resonator or aeolian harps. Achieving the signal level is usually solved by a resonator or an electronic amplifier.

VIII. EXAMPLES OF INSTRUMENTS DESIGNED

A. Frequent choices

Why were these instruments often chosen? Students seemed attracted to instruments that they had direct experience with. Less chosen instruments seemed to be driven by curiosity or having a correlated skill of an individual team member (e.g., electronics background):

- Helmholtz resonators
- String Instruments
- Organ pipes
- Gongs
- Chimes
- Drums

B. Less frequent choices

- Electronic Circuits- Often students would first produce square waves and than realize filtering was required to create a tone.
- Corrugated Tubes—Crawford (1974)
- Aeolian Harps
- Tuning Forks—Richardson (1947), Wood (1966)
- Whistles
- Kalimbas
- Wine Glasses-Akay (2002), Chen (2005)
- Liquid Gongs
- Rattles
- Water sources (e.g., bubble plumes)
- Colliding objects (e.g., spheres, boards)
- Friction/rubbing Instruments

When students come up with a strange and unusual instrument (strange and unusual means those that the professor is not familiar with), it can be challenging to provide a

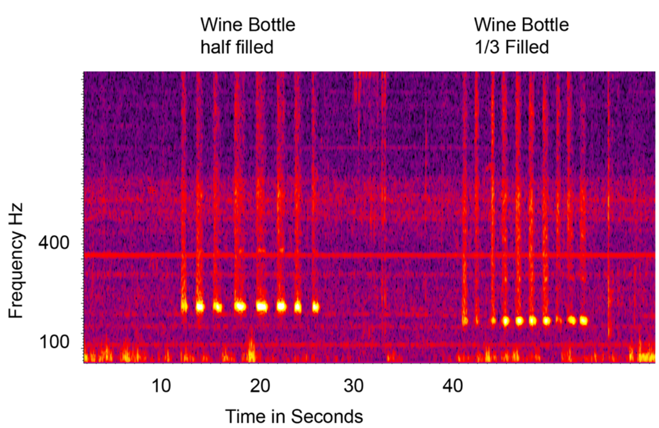

FIG. 2. (Color online) An example of a spectrum analysis display for a Helmholtz resonator using the Cornell Raven Lite software. This shows the observed frequency as a function of the time of observation for a 1/2 and 1/3 full wine bottle. A cursor placed at the center of the tone displayed indicates the frequency to about 1 Hz.

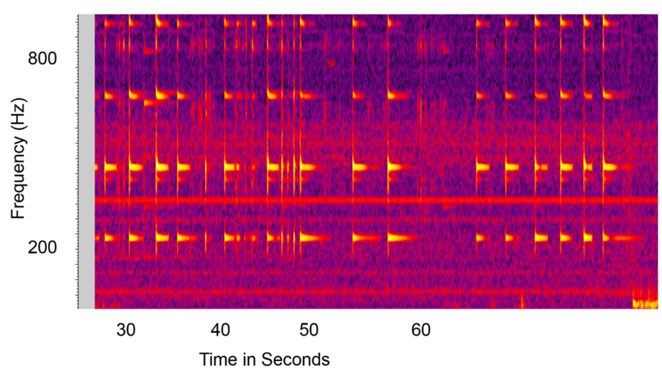

FIG. 3. (Color online) A frequency analysis display showing frequency as a function of time during testing of a string instrument. Students could obtain data for frequency as a function of string tension or string length from such testing.

reasonable guiding equation. But that was part of the spirit of the message-if theory does not work ask why.

C. Vegetable instruments

The introduction to the project used several humorous examples of instruments made using vegetables being played. One example used a carrot, showing how it evolved into an instrument. Another example is the 1st Viennese vegetable orchestra. They serve vegetable soup to their audience after a concert. Several teams have been inspired to create a vegetable instrument. The most notable of these efforts involved a Helmholtz resonator constructed using a coconut and a carrot. The problem was after a few days the carrot drooped and the coconut smelled funny. A lesson was that vegetable instruments should not be encouraged.

IX. PRESENTATION/FINAL REPORT

Students present a PowerPoint presentation on their pitch projects. They review their designs, theory versus experiment plots, and possible explanations for any differences between theory and experiment. They also discuss team dynamics and areas for improvement. Resource people from the laboratory attend these presentations. Questions and comments are invited.

As a component of their final report, teams are asked to provide feedback on the impact of the project on their team dynamics and make suggestions for changes, improvements to the exercise. On a team of five over a short (∼two week period) with three designs required it is not easy to "hide" and not contribute. The variety of physical processes involved usually attracts most team members. Typically students are highly engaged.

The students are given the report requirements. An emphasis is on providing plots of theory versus observations. A typical plot could show frequency as a function of length for an organ pipe or frequency as a function of volume for a Helmholtz resonator (as in Fig. 1). For string instruments, the tension measured using a force gauge is used to create a graph.

Quotes from Team Reports:

"People got to know each other on an individual basis as well as their working habits and skills."

"Theory doesn't always represent reality."

Team Osprey

"Most of all we learned the design process is anything but a straight line."

The Manhattan Project

"We discovered how theoretical equations and actual results can vary."

"Most of us have overcome our fear of Mike and the workshop." (Mike was a key resource person. He could appear grouchy on the outside.)

Team Shake and Bake

"This intro project taught our team valuable information regarding the overall design process. We learned about the importance of theory vs experimentation (i.e., designing before jumping into experimentation), and that creating modular devices whose frequency could be adjusted easily makes it much easier to account for the difference between theoretical and experimental results. We also realized the importance of meeting requirements and comparing theory to experiment. Lastly, we learned that we can accomplish more by leveraging the diverse skills of each team member."

Team Wombat

X. THE CONCERT

Often engineering students will have a dual engineering/music major and are encouraged to lead our orchestra. The instruments with the same assigned note sit at a table. Before starting, each table plays their assigned notes. There is always amazement at the result since they are all on pitch (the professor admits to this amazement as well, looking at a strange group of disparate instruments). They then play a piece of music with one or two practice rounds. Music used included "When the saints," and "Row, row, row your boat." Students who do not play an instrument (two per team), plus teaching assistants and professor perform in a chorus. Ending advice to the students "please keep your instruments intact in your lockers in case we are asked to give a performance," which has happened twice.

XI. COURSE EVALUATION

- Students usually are open and quite vocal in giving feedback throughout the semester and are also encouraged to do so in presentations and reports.
- There is an interactive feedback interview at the end of each semester. This involves a professor from another section and someone acting as a recorder organizing an open discussion on the positive aspects of the section course as well as suggestions for areas needing improvement (often valuable suggestions have been incorporated into the course). The professor and teaching assistants are not present for the interview.
- In addition, faculty/course questionnaires are administered as well as an intro/exit summary

XII. CONCLUDING REMARKS

After completing this introductory project, the design teams typically transitioned smoothly into their major project, which extended through the semester with the mechanics of knowing available resources and developing effective team dynamics accomplished. They applied analysis in defining their next design project and were sensitive to the iterative nature of the design process. They have often produced impressive, multidisciplinary main projects, as have other sections of this class.

Some student teams have taken on an acoustics-based effort for their following main project. The students have a wide range of choices, bounded, but largely directed by team interests. One example was an acoustic radiometer as a demonstration device; another was to demonstrate using ultrasound to produce audible, directed sound. A thermoacoustic refrigeration device and projects incorporating acoustic detection or ranging were also taken on. Although the primary goal of the pitch project was to create engineers skilled in the design process, they became comfortable working with acoustics.

The pitch project is usually enjoyable for all.

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