PHY 201/181 Lab Instructor notes
Lab 10: Accoustics Demonstrations
Fall 2001

1. Sometimes the physics program won't make plots. I haven't determined the cause of this problem. Try logging out and in again. (This worked in the one case I had)
2. The program requires a number in decimal notation "0.333333" not "1/3"
3. The remainder is from Dick South...

I incorporated the double tuning forks to demonstrate beat frequencies; they are stored in the back of the demo cart. I used the oscillator-scope-amplifier equipment on the cart to run many of the demonstrations. The keyboard is convenient for demonstrations of combining frequencies for chords and the concept of octaves. I used the guitar to point out the chromatic factor, 1.0595, in the layout of the frets. It is also useful in demonstrating the doubling of frequency by halving the string length (thus, the fundamental wavelength) by plucking the string, then plucking it with another finger lightly touching the middle of the string, eliminating the fundamental frequency. The keyboard and guitar are stored in my office, available for your use if you so desire.

I replaced the former ADC conversion of generator sine, square, triangular signals with a computer simulation. The program FOURDEMO.EXE is stored on the c: drive of the laptop in Leila's office. I projected the output onto the screen in the lab during the third topic on timbre. It uses simulations of several common waveforms to run the FFT analysis, and it includes the former version of the waveform synthesis algorithm that the students now use in the last part of the experiment. I was able to use a meter stick on the screen to measure the amplitudes on the Fourier frequency display to make charts on the board of the relative amplitudes, showing the 1/n (odd) sequence for the square wave, and the 1/n2 (odd) sequence for the triangular wave. This leads nicely into the recipes in the manual for the waveforms that the students generate at their computers.

To demonstrate phasing, the problem that leads to alternating sign series for the triangular waveform, I included a simulation for a "pulse" waveform. It gives, for the eight 45( segments of the cycle, amplitudes proportional to: 0, 1, 1, 0, 0, -1, -1, 0. This gives the same 1/n (odd) coefficient set as the square wave, when the amplitudes are displayed without phase, but the phasing is different. Another menu option for the program permits the sines to be displayed separately, showing that the 1/n (odd) coefficients have signs: +, -, -, +, +, -, -, +, +, etc., compared to the uniform positive coefficients for the square wave.

I was not happy about the display for the cosine terms, which should have strictly zero coefficients for an odd function. The cosine coefficients are a few percent of the sine coefficients. The display system is confusing, because the PLOTTER procedure that I used scales the plot to fill the whole screen. If you examine the scale factors in the lower left corner of the plot, 4/-2 for example, the first number is the power of 10 that should be used to multiply the Y coordinates to get the true scale. The number is smaller on the cosine plot than on the sine plot, showing that the cosine coefficients are very small. Since the first lab, I have tweaked the recipe for the waveforms to improve their conforming to odd function behavior. I also added a fourth waveform, the ramp, in anticipation of its use in the student exercises. All four of the canned waveforms available in the program are odd functions. This improved version is named FOURDEMT.EXE, and I will put it on Leila's computer for your use, if you want to use it.

Details for using Leila's computer and projector cart are as follows. The laptop takes forever to boot, and it gives a "bad command" warning, which persists for a long time. However, if you wait long enough, it all clears up to give the WIN98 screen. I would suggest that you check this out ahead of time; when I used it, the message did not clear up, and it turned out that the computer thought it had a second CD drive which was not responding. Leila fixed it, and I hope that it stays fixed. To use the program, use the sequence START, RUN, C:\FOURDEMO (or FOURDEMT). When the Proxima projector is connected to the laptop, use FN-F5 to share the screen with the projector.

I congratulate Brett on the beautiful plots printed by his printer module. I do not know how he obtained continuous graphs for the Fourier syntheses, compared to the point plots that I have obtained in the past. Some students complained that the graphs never appeared and would not print. I suggested to students that they might carry the Fourier recipes out to as far as the 19th coefficient, to see improved graphs; those who did not so choose still got nice plots.

Acoustics demonstrations; scripts for Physics Lab

I. The role of intensity

The intensity of the pressure fluctuations that we call sound corresponds to a key attribute of our hearing. High intensity gets our attention, and we call it loudness. However, the relationship between intensity and loudness is not as simple as it might first appear. For all wave motion, intensity varies with the square of the amplitude of the oscillations. The ear is exquisitely sensitive to small intensities, but it is able also to handle large intensities without discomfort. The range of intensities, from the smallest detectable to the normal ear, to that which would cause permanent damage, is about twelve decades. It is hard to imagine a lab instrument that serves over such a wide range of values!

It is hard to imagine how our language would even describe such a range. A demonstration will show how this problem is met.

Use the oscillator and scope to set the following amplitudes at about 1000 Hz, turning on the speaker amplifier after each amplitude setting to let the audience sample the loudness of the tone. Ask them to rate their perceptions of the set of five samples. 2 cm, 2.8 cm, 4 cm, 5.6 cm, 8 cm Does the loudness seem to increase in a regular pattern? Would we be satisfied to have the five sounds graded as increasing in regular, linear, increments? Note that the intensity of the sound has been doubled with each new tone.

If we sense an ordinary arithmetic increment, when the intensity has actually been progressing geometrically, then our ears perform a logarithmic transformation. The quantity often used to define loudness is SPL = 10 log10(I/Io), where Io is the intensity at which sound is no longer heard, 10-12W. We need to do a couple of practice problems to illustrate calculating SPL from intensity, and vice versa.

How well we hear tones depends also on the frequency. The ear is most sensitive to middle frequencies, in the range of 1000-2000 Hz, and gradually less sensitive at higher and lower frequencies. The Fletcher-Munsen curves display this for a range of intensities. Note that, for very loud sounds, the loudness is perceived as fairly uniform over a broad range of frequencies. As the loudness decreases, the ear retains high sensitivity at the center frequencies, but less at the low and high frequencies. What seems to be a good balance at the live rock concert becomes distorted on a recording of the concert when it is played at lower volume: the bass and treble tones are too weak. Boosting the bass usually satisfies the listener. The missing treble tones do not seem as noticeable, but they become troublesome in a less obvious way, as we will demonstrate later.

What are the long-range effects of exposure to loud sounds? It would appear to be a universal truism that the acuity of hearing diminishes with age. Some studies correlate the damage with exposure to excessively loud sounds. One study suggested that primitive aged people living in environments where loud sounds are rare maintain their hearing much longer than those privileged to be exposed to chain saws and rock concerts. The mechanism for the damage is probably a thickening of the ear drum, not unlike the callusing of a farmer's hands. It is typical to find that the highest frequencies are lost first. Suppose we demonstrate the range of frequencies at which the class can hear.

Dial a sequence of frequencies from 40 Hz, doubling and asking for a show of hands if the sound is heard, then shifting to 2000 Hz increments at 8000 Hz, and 1000 Hz at 15000 Hz. I usually remark at about 9000 Hz that I hope the group is enjoying itself: my perception has disappeared at that point.

So, who cares if we lose the higher frequencies? It is rare that any musical instrument plays a note above 2000 Hz, and the pitch of human speakers is well below this range. What are we losing? The answer will come in the third of today's topics.

The effect of flattening the intensity sensation in hearing is that humans do not discern small changes in intensity very well. However the positive aspect is that we process information well at a wide range of intensities. If I stand beside a student while talking to the whole class, his ear may be two feet from my mouth, while someone in the rear of the room is 20 feet from me. Given the inverse square rule for diluting a spherical wave, the person in the back receives only 1% as much energy as the person in the front! If I am giving $100 to the near person, I am giving $1 to the far person, and that doesn't seem fair. One would expect that either the person in front is experiencing great pain, or the person in the back is struggling to hear what is going on. Instead, we all process the same information comfortably. In architectural terms, it would be an interesting problem to try to place each of 2000 people in the audience of a concert hall exactly 80 feet from the orchestra. Instead, the people in the cheap seats in the peanut gallery seem to be able to enjoy the symphony just as much as those seated in front.

The sensitivity of the ear is truly phenomenal. It has been suggested that, if our ears were any more sensitive, we would be inundated with the roar of the red blood cells colliding with the wells of the blood vessels. The ear is even more amazing when we examine the design aspects for building such an instrument. It is a well known aspect of wave transmission that vibrations encountering an interface with a very different density are mostly reflected, with very little energy passing the interface. For human hearing, the transmission medium is the air, and the receiving medium is protoplasm, with a density 1000 times as large. Sound should simply bounce off, with very little of its energy available to trigger any detecting devices. This is a classical example of impedance mismatch. For example, when you get a flat tire, you certainly have enough muscular energy to lift the corner of the car, but your muscles do not seem to up to the task. However, with a lever (or a jack), you can trade distance of exertion for intensity of exertion, and the car is lifted. The ear presents itself as a low density interface by using a thin membrane with high compliance, coupled through a series of levers that convert low force - large displacements in the air to large force - small displacements, suitable for triggering biochemical changes in the inner ear. How was evolution clever enough to think up all this?

## II. The role of frequency

Human hearing is very sensitive to changes in frequency. Below about 20 Hz, we perceive a buzzing sound; from 20 to 20000 Hz, each frequency gives us a distinct impression of tone, and above 20000 Hz, we longer detect the sound.

Listening to two sounds with only slightly different frequencies is an interesting, if familiar, experience. We have two tuning forks that can be tuned to the same or slightly different frequencies. What is your impression of the effect?

We have seen that there is a logarithmic interpretation in our perception of the intensity of sound as loudness. There is a similar interpretation for the human perception of frequency.

Different frequencies of vibration are sensed as different pitches or musical notes. We get an interesting result when we examine several notes, each of which has double the frequency of its predecessor: [keyboard] A(110), A(220) , A(440), A(880). There is a sense in which these notes seem the same. If we play them all simultaneously, they blend so completely that we conclude that nothing interesting has been added beyond what we would have by hearing only one of the tones. Making a chord in this manner is like making warm water by adding hot to cold.

If doubling the frequency leads, in a cycle fashion, to repeating what we have heard before, a geometric doubling of frequency corresponds to an arithmetic increase in what we call pitch. Such is a logarithmic progression. Many modern musical instruments are designed to generate equally spaced pitches in such a way as to divide one doubling of frequency ( an octave) into 12 equal intervals, called chromatic half-tones. Each new higher pitch differs in frequency from its predecessor by a fixed factor. If this factor multiplies a starting note twelve times, we arrive at the octave note, which sounds pretty much like the note on which we started. The factor required is one which accumulates the effect of doubling after 12 applications, and it is the twelfth root of 2 = 1.0595; multiplying a frequency by this factor generates the next tone available on the keyboard.

It is of interest to consider what we perceive when we hear several pitches simultaneously, each arising from its own independent oscillator. Some combinations are pleasing, while others are grating. Some combinations occurring as a progression in time seem to convey a story or a development of emotions. It is interesting to try combining some tones that have a simple relationship in their frequencies. In particular, let us examine combining notes which are integer multiples of some starting frequency, such as 110 Hz.

Frequency Half-tones Half-tones to first octave equivalent (subtract 12, 24, 36,...)

| | | |
|---|---|---|
| 110 | 0 | 0 A |
| 220 | 12 | 0 A |
| 330 | 19.01955 | 7.01955 E |
| 440 | 24 | 0 A |
| 550 | 27.86314 | 3.863136(=4) C# |

Rejecting two of the A tones, which all sound about the same, keeping the central A(220), and using the octave equivalents of the other two notes which place them closer to the chosen A, the chord that approximates combining the five integer frequency multiples is A, C#, E, called the A major triad. The major chord is the work horse of western harmonies. It is interesting without being overwhelming. Psychologically, it conveys a sense of well being. "God is on His throne; all is well with the world." There's plenty of food in the pantry; the kids are all doing well.

Contrast this with the following slight modification, which totally upsets the simplicity of tones combined in integer multiples of frequency. Our major chord combined the fundamental note, A, with another that is four half-steps up, C#, and another which is three half-steps up from there, E. If we leave the A and the E as is, but lower the middle C# one half-tone to C, the progression becomes three half-tones followed by four, instead of four followed by three.

The resulting minor chord, A, C, E has a very different psychological impact. I can't meet the mortgage; my wife has left me; the kids are all on drugs.

If we try uniform half-tone progressions, rather than uniform frequency progressions, the result is even more bizarre. Choosing four notes, each three half-tones higher than its predecessor, the resulting diminished chord, A, C, D#, F#, really gets your attention! It feels like something the dentist would use to remove plaque. We would not sit still for a symphony that used only such combinations.

Other combinations lead to families of progressing chords: C,E,G, then F,A,C feels as if it is going somewhere; adding G,B,D,(and F) leaves us dangling, waiting to get back to C,E,G.

Such regular combinations seem to be inherent is the way we interpret tones used in music. The idea of combining notes with integer multiples of frequencies will come up again in our next topic, the quality of sounds. (Ten minute break)

III. The role of quality (timbre)

So far we have found a physical basis for two obvious aspects of the sense of hearing: loudness and pitch. Our third topic is more subtle, but no less important. We will examine a simulation of three different sound sources, all with the same loudness and pitch. What is your impression as to how they are different?

Use the oscillator at about 110 Hz. Amplify the sine wave, then the triangular wave. Switch between them several times. Then compare the sine and the square wave. The use of a low frequency makes the effects of the overtones striking, especially in the square wave, because they fall in the ear's most sensitive range. As a variation, try it with 500 or 1000 Hz first, to hear much milder overtone effects.

Could you be convinced that there is something extra being added to the sine sound to make the other sounds? How could we isolate what has been added to give these new qualities?

There is a mathematical technique, ascribed to Joseph Fourier, that suggests that any periodic function, no matter how bizarre its form, can be represented as an infinite sum of sine waves. This might seem general enough to be true if we were allowed to pick from all sine waves, but this theorem lays out a special, restricted set: sine waves that have frequencies that are integral multiples of the fundamental tone. Each of these new sine waves is to be added into the mixture with a particular amplitude. (It also is assigned a particular phase, but we will assume that this is not important for our present examples.)

To describe a 110 Hz triangular wave (or square wave) we start with a 110 Hz sine wave, then add to it measured amounts of the multiple frequencies: 220, 330, 440, 550, ... This sounds a little like the way we made a major chord, with integer multiples of a starting frequency. Then why do we not near a chord, rather than a single sound with a new quality? The difference is that these oscillations are locked precisely in phase and amplitude. Independent oscillators drift out of and into phase, allowing the ear to detect different sources when we play a chord. The Fourier series mixture controls the phase precisely.

We will now use a demonstration program to analyze some common waveforms for the coefficients of their frequency spectrum.

Use FOURDEMT to display and transform the square and triangular waveforms, tabulating on the board the centimeter heights of the 1, 3, 5, 7, 9 peaks, measured with a meter stick on the screen. Have the students normalize the heights, by dividing all of them by the first, to get values such as 1.00, 0.33, 0.20, etc. If you examine the pulse waveform, the amplitudes are the same as for the square wave, but the sine display demonstrates that half of the coefficients are negative. This should prepare them for the directions in the manual for trying alternating-sign term syntheses, as required to form the triangular wave. The ramp waveform can be displayed and named to help them identify the result they will see when they do the final 1/n synthesis. You may or may not want to display its frequency graph.

To return to some unfinished business: who cares if, after the abuse of enough chain saws and rock concerts, we do not hear frequencies above 2000 Hz? Is it important to you to be able to distinguish an oboe from a violin? Is it satisfactory for you that all people's voices sound the same, and you cannot distinguish who is phoning from just the voice? Will you be comfortable when, in talking to someone who is 3 feet away, you notice that the person has perfect diction, but across the room, the person has a lisp, and the sounds of s, sh, and th all become indistinguishable? After a while, without the feedback of your ears, you will be the one with the lisp. Will your spouse be delighted to have you turn up the TV volume to maximum while she is trying to sleep in the next room? Will it bother you that, while you can carry out a reasonably intelligent conversation with men, women's voices become impossible to follow? Will you be happy telling the five-year-old grandchild to go away because, try as hard as she will, she cannot make you understand anything? I can testify to these things: it's a bummer! I highly recommend protecting your hearing.

You will now try to synthesize these waveforms by adding together sine waves by your own recipe on the lab computers. There will be a surprise in the last part: we have largely neglected phasing in our discussion, and one of these waveforms requires that successive non-zero terms receive alternating + and - signs (equivalent to 0 and 180 degrees of phase) when we try to synthesize it from sine waves. (The recipes given in the manual now guide them through exactly what coefficients and signs to use. I suggested that they try more coefficients - out to 19 - to get better graphs, but his is not a necessary variation.)

If the demonstration program (FOURDEMT) appears to be a plausible temporary substitute for real signals from an ADC, a C variation of it could be generated in the future for student use on the Linux computers, instead of having it as a demonstration.