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Acoustics Education: Experiments for Off-Campus Teaching and Learning

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ABSTRACT

In undergraduate Physics and Engineering courses on acoustics, experiments typically involve the use of a Digital Storage Oscilloscope (DSO) and a Function Generator (FG). These relatively expensive and bulky pieces of bench top equipment make it prohibitive for external, distance, or off-campus students to be involved in experimental work, without attending a residential school. However, there is a growing demand, particularly from the Engineering sector, for courses to be more available remotely. To that end, Edith Cowan University is investigating the possibility of remote laboratory programs, which can be completed by off-campus students to ensure their Applied Physics or Engineering knowledge, is balanced by experimental experience. In this work, we show the implementation of a computer based DSO and FG, using the computers sound card. Here the PCs microphone jack is used as the DSO input, and the speaker jack is used as the FG output. In an effort to reduce the cost of implementing the experiment, we examine software available for free online. A small number of applications were compared in terms of their interface and functionality, for both the DSO and FG. The software system was then used to conduct a number of acoustics experiments relevant to undergraduate Physics and Engineering. These experiments include, the Physics of Music, Standing Waves in Pipes, and the Properties of Sound Waves. There are two primary benefits to the computer based system developed. The first is in terms of the enhancement to learning by students at the undergraduate level, where the knowledge learnt by off-campus students can be significantly improved with the use of practical experimental work. Secondly, remote experiments could provide additional components of laboratory work for students in on-campus subjects where resource issues are making traditional and comprehensive supervised laboratory programs hard to maintain.

INTRODUCTION

Experimental work is an essential component of an undergraduate education in engineering and physical science. This usually takes place on campus in a laboratory with specialist equipment. However, over the last two decades there has been increasing financial pressure to reduce the laboratory component which require small student to staff ratios and significant resources to supply and maintain the laboratory. In a recent survey [1], Australian university physics departments reported the ability to upgrade/upkeep laboratories and laboratory staff was a major challenge. In addition to this, student contact time in laboratories has decreased over the same period of time, and this is most evident for large first year classes.

Normally experimental work is undertaken on campus in a laboratory with specialised equipment. Some experiments can be undertaken using materials at home with a small amount of university supplied supplementary equipment. Previous work has showed that there are some excellent experiments from physics for off-campus students [2]. In the face of decreasing contact time in laboratories, introducing some off-campus experimental work would be a ideal way to maintain the practical portion of the course for on-campus students as well as providing a laboratory component for off-campus students. We are of the view that even some experiments that normally use bulky and expensive specialist equipment could be done by students at home.

In this paper, we use freely downloadable software to turn a PC into a Digital Storage Oscilloscope (DSO) and Function Generator (FG) to investigate sound waves. We demonstrate how students might conduct experiments at home using the microphone and speaker jacks of the PC soundcard for input and output respectively. This is done using some fundamental experiments on standing waves and resonance in pipes as well as the physics of sound and music. Standing waves have been shown to increase the understanding of Physics for science and engineering students [3], hence, the experiments are an ideal choice for students to complete at home. Resonance frequencies are calculated and measured for standing waves in pipes and the Fast Fourier Transform (FFT) function is used to show frequencies present in musical notes.

SOFTWARE

Digital Storage Oscilloscope

There are a small number of freely downloadable sound card based oscilloscopes. These include Zelscope [4], BIP Electronics Lab Oscilloscope [5], Virtins Sound Card Oscilloscope [6], xoscope (for Linux) [7], and Soundcard Oscilloscope [8]. The licence for the use of these varies from program to program. Some are freeware [5,7], other have free trials [4,7] then require a licence, and others have optional licenses [8]. For an extended program either a free use or licensed program will be required, however, the cost associated with licensing these is low, such that an individual student, or the institution would be able to cover (Zelscope for example has a site license of $99.95, one could discuss use of a site license to cover all external students).

Function Generator

In addition to the oscilloscopes, there is also a number of freely downloadable sound card based function generators. Including, Virtins Sound Card Signal Generator [6], Test Tone Generator [9], Tone Generator [10]. In addition to these, Soundcard Oscilloscope [8] has its own built in signal generator. As with the oscilloscope software, various license options exist with the signal generator applications.

Software Choice

Several of these oscilloscope applications were tested for the purpose of comparison [11]. This involved looking at the ability of the application to measure the frequency of standing waves in pipes. The applications were not tested for accuracy, but for usability. This work assessed, comparatively, how easy it was to perform a pre-existing laboratory session, using the computer based oscilloscope in place of the bench top DSO. The conclusion of this work was that the Soundcard Oscilloscope [8] with its real looking interface, the spectrum analyser functionality and the built in signal generator, was the best choice. The wonderful by product of this, is that Soundcard Oscilloscope is free from public education purposes. Figure 1 shows screen shots of the Soundcard Oscilloscope, for both the oscilloscope (top) and the signal generator (bottom).

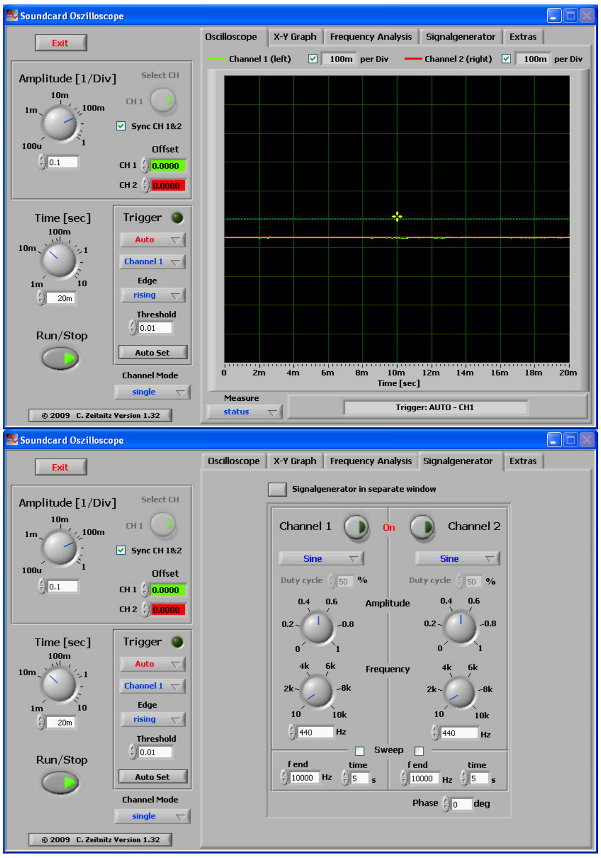

Figure 1. Screen shot of the Soundcard Oscilloscope (top), and in the signal generator mode (bottom)

EXPERIMENTAL METHODOLOGY

Physics of Music

Utilising just the DSO, experiments were performed to look at the sound from music instruments. This is an ideal experiment to utilise the oscilloscope, in particular the FFT spectrum analyser functionality. Musical instruments can commonly be found in the home, so equipment is available. If not, a simple and cost effective instrument to utilise is a recorder. These are typically available from variety stores for a couple of dollars.

The experiment conducted utilised various tuning forks, and a recorder. The tuning forks represent ideal reference freqencies to characterise the performance of the DSO in terms of uncertainty. This gives students an opportunity to investigate the concepts of precision and accuracy. Clearly the method here is not very involved, the tuning fork is simply struck against the knee causing it to vibrate, then it is brought close to the microphone. The software can be set to the FFT mode (shown in Figure 2), and the box marked "peak hold" can be checked. After the spectrum has been captured, the oscilloscope can be stopped, and the data and figure can be saved. The onscreen display also shows the peak frequency.

After looking at the single frequency spectrum of the tuning fork, musical instruments will offer a more interesting analysis. The same method used for the tuning fork can be used for a musically instrument. Different notes can be played and the difference between them can be analysed quantitatively. Although the actual experimental method for this part of the work is minimalistic, it is important to remember that Fourier's theorem and the FFT will usually be seen for the first time when conducting experiments at this level. Hence, there is a substantial theory to walk the students through, and how the time based signal corresponds to the frequency spectrum. Having said that, a similar simple experimental method could be used to capture time based signals, and then a software package could be used to do the FFT.

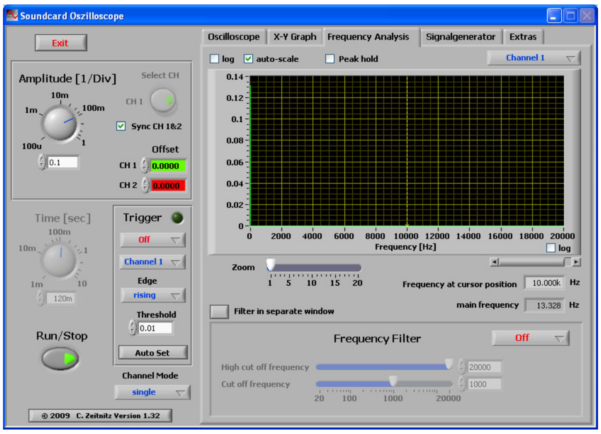

Figure 2. Screen shot of the frequency analysis function

Standing Waves

A standard experiment to be conducted in first year laboratories is investigating standing waves in pipes. This type of experiment is ideal to familiarise students with the oscilloscope (either analogue or a DSO). Here open-closed pipers were used, since it is easier to generate a resonant frequency in them. The primary means of generating a resonant vibration in a the pipe was by blowing across the open end. However, from the preliminary work [11], it was noted that using a DSO (either bench top or computer based) means that the standard length model, that is [12],

$$f = \frac{c}{4L} \ , \tag{1}$$

Where f is the fundamental frequency, c is the speed of sound, and L is the length of the pipe, does not account for the difference between the measured and predicted frequency, taking into account the experimental uncertainty. Hence, the main purpose of the experimental work was to develop a method to accurately characterise the discrepancy between the simple 1D model and the experimental result. This discrepancy, which became necessary to explain to students in the laboratory with the upgrade from analogue to digital oscilloscopes, is due to the end correction effect. The sound exiting from the end of the pipe is not planar, it is in fact hemispherical, since the sound radiates away from the end of the pipe isotropically. The average height of the hemisphere then needs to be added to the length of the pipe to give the effective length, this then gives the fundamental frequency as [13],

$$f = \frac{c}{4(L + 0.3d)} \ , \tag{1}$$

where d is the diameter of the pipe. The end correction effect is depicted in Figure 3.

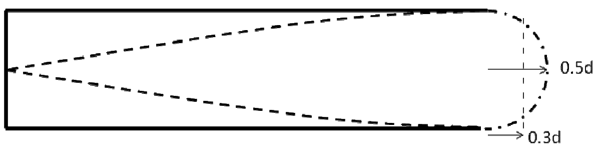

Figure 3. Open-closed pipe showing the hemispherical wave front and the 0.3d relative to the radius

To quantify the end correction effect, the FG was used to transmit a tone from the PCs speaker. The FG has a building sweep function, where the start frequency and the stop frequency can be set, along with the time required to complete the sweep. The open end of the pipe was positioned between the speaker and the microphone, with the pipe perpendicular to the sound propagation. This will then generate a sympathetic vibration in the pipe, which will be maximal at the resonant frequency of the pipe. The experimental setup is depicted in Figure 4.

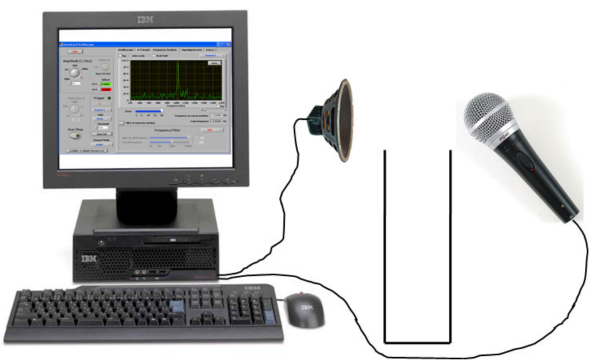

Figure 4. Experimental setup for the frequency sweep of the pipe

The problem with including the end correction effect is that the resonant frequency is a function of two variables, that is, *f*(*L*,*d*). To overcome this problem, the solution in theory, and as we show the implementation, is simple, however, the theory may be considered to be complicated. The solution is to use multiple linear regression. Based on the idea that Microsoft Office^{TM} is likely to be located on the desktop PC that is being used as the DSO and FG, Excel^{TM} can be utilised to perform the multiple linear regression. This, as mentioned above, is simple in practice. First the data needs to be linearised, which is done by regressing *R* and *d* versus *c*/4*f*. The result of this is regression coefficients of 1 for *L*, and 0.3 for *d*.

The first experiment we performed was a comparison between the two methods of measuring the resonant frequency. We selected a small number of the 19 readily available open-closed pipes. Then we generated the resonant frequency in the pipe by blowing across the open, and used both the time based signal, and the frequency spectrum to determine the frequency. Next we used the sympathetic vibration method, again using the time based signal and the frequency spectrum to determine the resonant frequency. To calculate the theoretical values, the length and diameter were measured using a pair of vernier callipers. To assess the effect of the measuring device, a rule was also used to measure these dimension for comparison.

Next, we measured the resonant frequency of all 19 pipes, comparing the values to the theoretical values from the 1D model and the end correction effect. This data was then used for the multiple linear regression. Again, the pair of vernier callipers was used to measure all the lengths and diameters used to determine the theoretical frequencies.

RESULTS

Physics of Music

Three tuning forks were used to investigate the frequency spectrum analyser. These were an A flat at 426Hz, an A at 435Hz, and a C at 512Hz. The frequency spectra for the A note tuning fork and the C note tuning forks are shown in Figure 5. In the spectrum we can see the strong signal at the frequency of the tuning fork, 435Hz, and a small signal at the first harmonic, 870Hz.

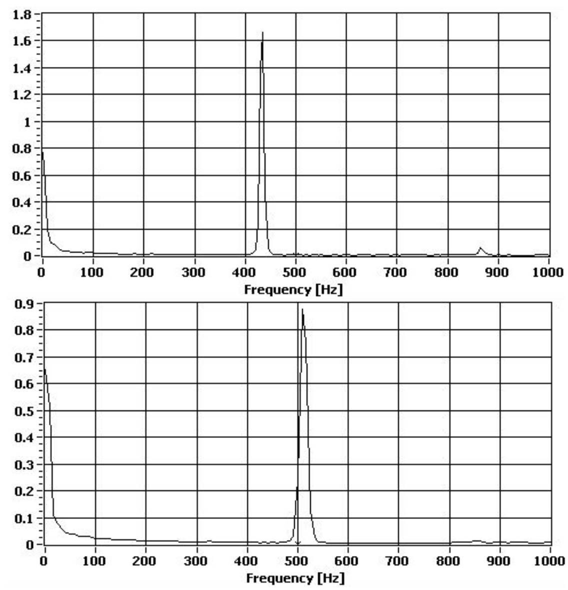

Figure 5. Frequency spectrum of the signal from the 435Hz, A note tuning fork (top), and the 512Hz, C note tuning fork (bottom)

Next, the spectrum analyser was used to look at the output from a recorder at various notes. Figure 6 shows the frequency spectrum of both an A note and a C note played on the recorder. We can see the interesting features of the recorders spectrum, which is lost in the time domain information. Specifically students can easily see the harmonics, evenly space, and the fundamental frequency, which both occur at twice the frequency of the tuning forks, 870Hz for the A, and 1024Hz for the C.

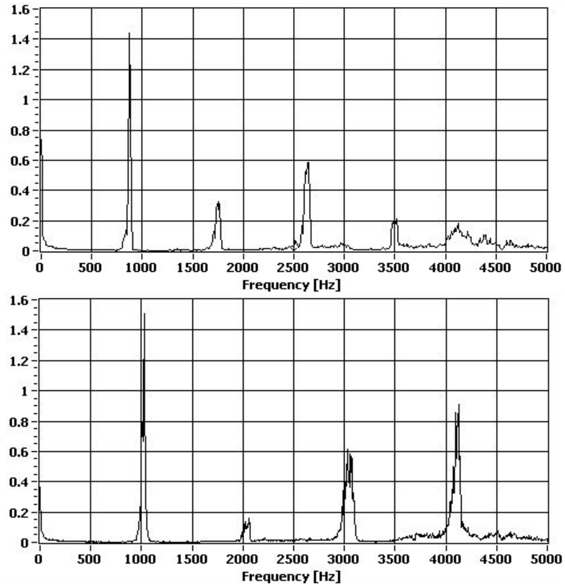

Figure 6. Frequency spectrum of an A note (top) and the a C note (bottom) played on the recorder

Standing Waves

The results of the comparison between the various methods to experimentally measure the resonant frequency are shown in Table 1. The results for only two pipes are show, which were randomly selected, one from the cluster of shorter pipes, and one from the cluster of longer pipes. These results again show that the 1D model does not agree with the measured frequency, within the experimental uncertainty. We do see, however, that the end correction effect values agrees with the measure results with the experimental uncertainty. The most significant result from this, is that blowing across the open end of the pipe generates a resonant frequency that is close to the frequency measured from the frequency sweep. This is true, provided the signal in the pipe is generated in a manner that minimises any interference with the sound exiting the pipe.

Table 1. Comparison of Experimental Methods to determine the resonant frequencies of

Pipe Number	*16*	*4*
L (rule)	*0.08352*	*0.14806*
L(vernier)	*0.084*	*0.148*
d (rule)	*0.01968*	*0.01976*
d(vernier)	*0.02*	*0.020*
f (1D)	*1018*	*580*
f (end)	*950*	*553*
f (scope)	*915*	*534*
f (FFT)	*928*	*540*
f(sweep)	*940*	*545*

Figure 7 shows the frequency sweep of one of the pipes (number 4). To remove the frequency response of the microphone and the speaker, the received signal with the pipe between the speaker and the microphone, was divided by the received signal without the pipe. The individual signal is shown in Figure 8.

The results of the comparison between the resonant frequency measure experimentally and those predicted theoretically by (1) and (2) is shown in Figure 8. The results clearly show that the 1D model does not suitably explain the observed resonant frequency, with the predicated value consistently above the measure value. However, by including the end correction effect, the data agrees to a very high degree, well within the experiment uncertainty previously discussed. From Figure 9, we can see that the resonant frequency predicted by the 1D model becomes even more significant when the fundamental frequency is higher. This is explained by the fact that the end correction effect becomes more significant as the length of the pipe becomes shorter.

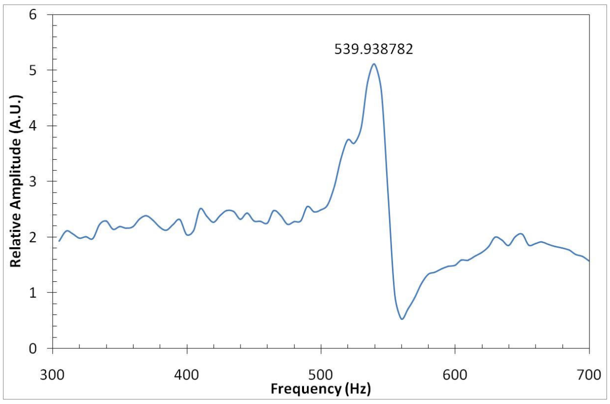

Figure 7. Frequency sweep from 300Hz to 700Hz on pipe number 4, normalised

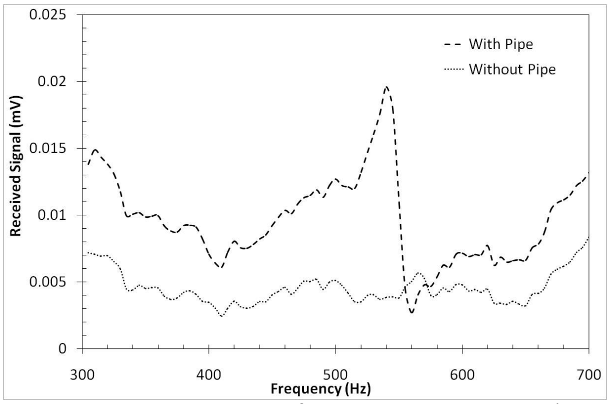

Figure 8. Frequency sweep from 300Hz to 700Hz on pipe number 4, and the frequency response of the speaker-microphone system without the pipe

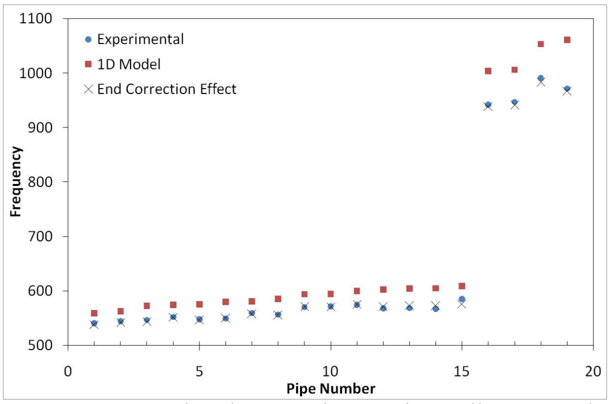

Figure 9. Comparison between the experimentally measured resonant frequency, and those predicted theoretically, from both the 1D model and the end correct effect

The regression analysis from the 19 sample pipes, where the resonant frequency was generated by blowing across the open, is shown in Table 2. We see the coefficient for the intercept is -0.001±0.002, which effectively means it is zero. The coefficient of the length variable is 1.004±0.008, which includes 1 within the statistical uncertainty. Finally, the diameter coefficient is 0.32±0.06, which includes 0.3 with the statistical uncertainty. Even when just blowing across the open end of the pipe to generate the resonant frequency, the experimental results agree with the end correction effect theory within the statistical uncertainty. For comparison, a simple linear regression analysis was performed for L versus $c/4f$. The result of this was a coefficient for L of 1.02±0.01. This value does not agree with the simple 1D model's predicted value of 1 within the statistical uncertainty.

Table 2. Regression Analysis Output

	Coefficients	*Standard Error*
Intercept	*-0.0011*	*0.0015*
X Variable 1 (d)	*0.3170*	*0.0594*
X Variable 2 (L)	*1.0041*	*0.0078*

DISCUSSION

Findings

Overall, the software was simple and effective to use. Looking at the signals from the tuning forks gives student an ideal way to visualise the signal in the time domain on the oscilloscope, and to see the frequency domain equivalent, of a device that emits only a single frequency. Although a tuning fork is not necessarily something that is common in the home, the intention would be to include a tuning fork in the small experimental kit that would be sent to the student. The same could also be done with the recorder, giving students instructions on generating the required notes. Students would also be able to investigate the spectrum of any other instruments that they have available to them.

The frequency sweep method was so effective, that it effectively shows the variation of acoustic impedance, not just the resonant frequency. This means that the experiment could be adapted to more specific acoustic experiments at high levels in a university.

Future Work

The use of the FG has not been overly stressed in the work considered here. The use of the FFT function and blowing across the pipe allow is enough to generate data to give the end correction. However, using the FG as an audio generator would allow the psychophysics of sound to be investigated; specifically, the lower frequency response of hearing. It would also be possible to look at perceived tones [14].

Although Soundcard Oscilloscope has proven to be very effective, with all the required functionalities necessary to undertake this work, other software is required. Ideally, we would like to look at the ability to use Labview [15] (which was used to develop the Soundcard Oscilloscope software) to develop in house software. This would mean that the software is always available and maintained, keeping it up to date, and more importantly free to use, if the license for Soundcard Oscilloscope was to change. This would make an ideal project for a Physics/Computer Science student.

The final aspect of this work that will be explored in greater detail in future work is the use of the DSO for analogue electronics. The output of the sound card, approximately 3V peak to peak, is suitable for use in analogue electronics, in particular looking and RC, RL, and RLC circuits.

CONCLUSION

In conclusion, we have successfully demonstrated the use of a soundcard based oscilloscope for acoustic experiments. These experiments were equivalent to those conducted within a teaching laboratory setting, and in the case of analogue oscilloscopes, they were significantly better. We showed how the soundcard based oscilloscope and function generator could be used to accurately determine the resonant frequencies of standing waves in pipes. We also showed how the FFT based spectrum analyser enables students to accurately visualise the frequency spectrum from musical instruments. This work will make it possible for both on-campus and off-campus (distance learning) students to actively participate in quantitative experimental work on acoustics without the need to be present on-campus.

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