

# Low cost alternatives to commercial lab kits for physics experiments

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## Abstract

Conducting experiments in physics using modern measuring techniques, and particularly those utilizing computers, is often much more attractive to students than conducting experiments conventionally. However, the cost of professional kits in the Czech Republic is still very expensive for many schools. The basic equipment for one student workplace in the case of professional kits such as Vernier, Pasco or Coach costs around 800 euro. In this paper some physics experiments in which a computer, or a tablet with Microsoft Windows, is used as the measuring device, along with available physical devices such as a laser pointer, a solar cell or an electret microphone, are presented as suitable and alternative ways to carry out lab work. We show that it is possible to perform very simple school experiments (both as a central demonstration and as individual experimentation), in which high accuracy and clear final conclusions can be achieved at a very low cost. Further information is published on the specialized webpage [www.sclpx.eu/index.php?lang=en](http://www.sclpx.eu/index.php?lang=en). The worksheets are in Czech, but the English version is in preparation.

## AQ1 1. Introduction

Our work is based on our experience with school kits such as Vernier [1, 2], IP Coach [3, 4] and Pasco [5]. It presents an alternative way of conducting physics experiments that can be used as demonstrations or for individual experimentation.



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The most important advantage of the proposed experiments is the very low cost of the basic equipment, as well as the fact that they can be conducted individually at home.

There is a wide range of computer controlled experiments, however, there are only a few publications about simple and smart measurements that can be carried out using a sound card. For example, a photogate timer can be set by an optocoupler connected to an audio input in order to determine the acceleration due to gravity

by timing the oscillations of a pendulum [6] or to assess the force constant  $k$  of a coil spring by timing the oscillations of a mass spring [7]. The computer sound card input and output can be used to measure the speed of sound or resistance and temperature [8–12].

Since 2008 we have been developing our own high school laboratory experiments using a PC sound card [13].

So far we have prepared and tested 30 experiments in the field of mechanics, sound waves and liquids. About 20 other experiments dealing with the properties of solids and liquids, electricity and magnetism or quantum physics are in the screening process. All the experiments published at [www.sclpx.eu/index.php?lang=en](http://www.sclpx.eu/index.php?lang=en) have been tested and evaluated at partner high schools.

## 2. Methods: how do the experiments work?

Some of the experiments use a simple optical gate, composed of a laser pointer and a solar cell, from which the signal is transmitted through a cable to the microphone input of the sound card by a 3.5 mm jack connector. The principle of the optical gate is obvious: the interruption of the laser beam changes the output voltage of the solar cell, producing a pulse which is fed to the microphone input. A basic review of sound card photogates is presented in [14].

In this way, we can measure very short time periods of the order of  $10^{-4}$  s. To record and evaluate the signal, we used the free audio editor (FAE) freeware software [15]. This program can also edit the recorded signal so that we can make a selection of one part of the signal, on which the program calculates the duration (called ‘Length’ in the FAE window). Using the FAE software we can also enhance a weak signal to make it more visible (and more easily measurable) by the students.

An example is shown in figure 1, which is produced by a pendulum that oscillates, cyclically crossing the laser beam. Each double spike (negative then positive) is due to a pendulum passage and the wave shape reflects the presence of the internal input capacitor which is differentiating the laser light signal and accounts for light to dark (the leading edge of the pendulum turns the light off) and dark to light (the trailing edge of

the pendulum passes and the light goes on again) transitions.

Of course, the recording can also be saved in a WAV format audio file so that we can reload the experiment data at any time or load it into other processing and calculus software.

For some experiments, especially those concerning sound, we also use other freeware or shareware programs, i.e. visual analyser (VA) [16] and Sigview 3.5 software [17].

Recall the important fact that a sound card can be used for ac voltage measurements only, because sound cards have a capacitor in series with the input. Both the microphone and the line-in inputs can be used, but they have different input voltage limits (typically in the order of  $\pm 100$  mV or less for the mic input, about  $\pm 1$  V for the line-in input). The output of the solar cell is in the range of 100 mV, so there is no risk of damaging the sound card.

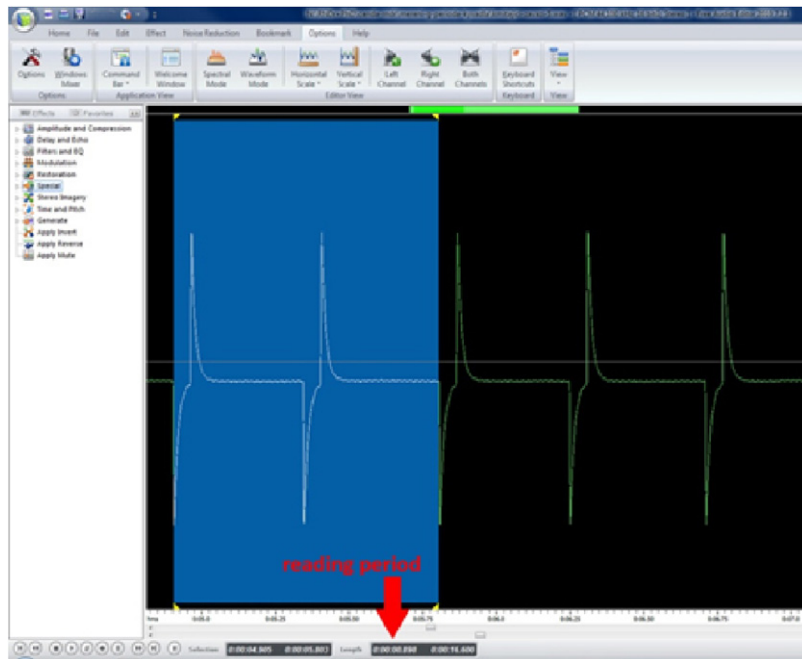
The good thing about using a sound card for electric signal measurements is its high sampling frequency (44.1 kHz standard, but nowadays you can go up to 384 kHz).

In the next section we will briefly describe several interesting experiments in the fields of mechanics and acoustics.

## 3. Materials and methods: interesting, attractive and motivating school physics experiments

Some of our experiments, such as the determination of gravitational acceleration from the pendulum oscillation period, the dynamic determination of a spring constant, or measuring the speed of sound, are quite known and well-documented nowadays [6–8, 12]. We therefore focused our attention on lesser-known experiments or those experiments which were carried out in unusual ways, such as the case of producing sound beats by using wine glasses.

To carry out the experiments described in this section we used the following tools: a notebook or PC, a solar cell, a laser pointer, a pendulum and a cardboard comb with wide teeth cut out. In some experiments we also tested the use of a photodiode in place of the solar cell, but the latter usually has a larger surface than photodiodes and was therefore easier to work with. All the experiments can also be performed by using a



AQ2 **Figure 1.** Output signal from solar cell with reading of the period in FAE.

tablet with a microphone input and the Windows operating system.

AQ3

### 3.1. Free fall—verification of time dependence of the velocity of a falling cardboard comb

Apart from the usual tools, for this experiment we need to prepare a comb cut out from cardboard. All the teeth should be of the same width; in our case the width of the teeth  $d$  was  $(1.0 \pm 0.1)$  cm and the total length of the ridge was about 20 cm. The experimental arrangement can be seen in figure 2.

We let the comb perform a free fall from a fixed height through the photogate. The total time,  $t_i$ , of the passing of the  $i$ th tooth through the laser beam can be determined with the help of FAE, by measuring the time between the moments when the trailing and leading tooth edges cross the beam, marked on the FAE screen by two consecutive spikes of different sign. It is reasonable to associate to the measurement of  $t_i$  an uncertainty equal to  $10^{-3}$  s. By the relation  $v_i = \frac{d}{t_i}$  we can subsequently calculate the approximate value of the average speed of the  $i$ th tooth, whose relative uncertainty, calculated by



**Figure 2.** Free fall of a cardboard comb.

uncertainty propagation, is the sum of the relative uncertainties of  $t_i$  and  $d$ . Since the movement is accelerated, the first tooth has the minimum

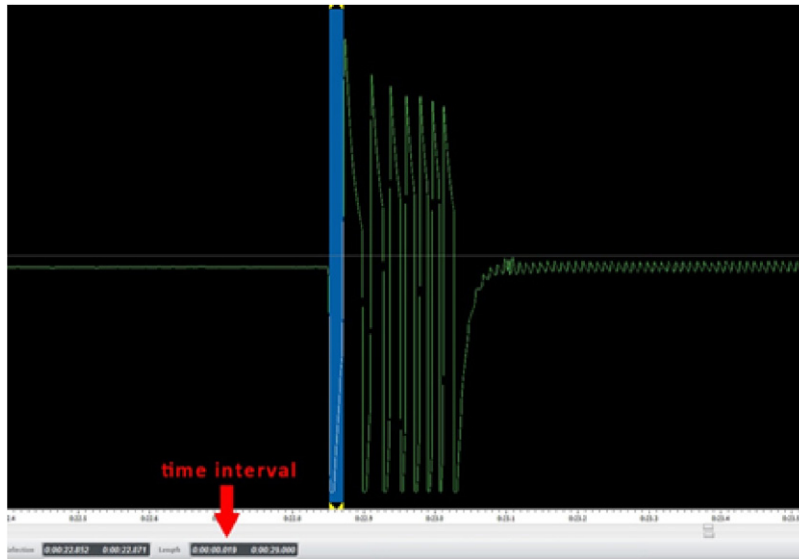


Figure 3. Free fall of a cardboard comb—the signal view.

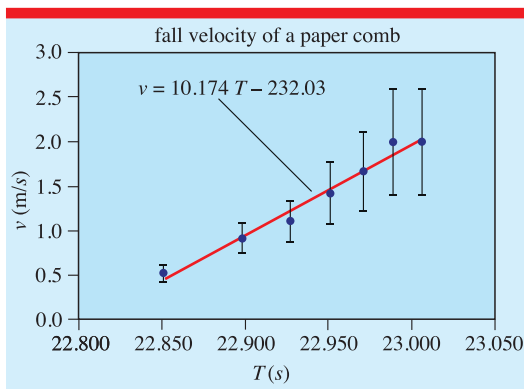


Figure 4. Free fall of a cardboard comb—MS Excel graph with linear regression. The uncertainty bars were obtained by uncertainty propagation in the  $v = dl/dt$  formula.

speed, while the last tooth reaches the maximum speed. The graph of speed versus time  $T$  (where time ‘zero’ is arbitrary and depends on when the user starts recording the signal) can then be approximated by a linear function, where the constant of proportionality is the value of gravitational acceleration.

Figure 3 shows the recorded signal in FAE, whereas figure 4 offers a corresponding graph produced by MS Excel.

The uncertainty of the slope (i.e. on  $g$ ) can be calculated by various approaches, e.g. by simply using the results from the LINEST MS Excel

function (which, however, neglects the uncertainties of the experimental points).

In our experiments, a value for  $g \pm \Delta g$  obtained by LINEST was  $(10.2 \pm 0.7) \text{ms}^{-2}$ .

### 3.2. Determination of the coefficient of kinetic friction from acceleration on an inclined plane

Using plasticine (modelling clay) we affix a cardboard comb onto a wooden block. After that we let the comb slide freely along an inclined plane making an angle  $\alpha$  with the horizontal one. We must make sure that the laser beam intersects with the teeth of the comb. We carry out measurements for three different inclinations of the plane (e.g.  $30^\circ$ ,  $35^\circ$  and  $40^\circ$ ).

Next we measure in FAE the transit time of the first and the last tooth. After that we calculate the instantaneous velocity by using  $v = \frac{\Delta s}{\Delta t}$ , where  $\Delta s = 1 \text{ cm}$  (comb tooth width).

The acceleration is determined by the relation  $a = \frac{\Delta v}{\Delta t}$ , where  $\Delta v$  is the speed variation between the first and the last tooth and  $\Delta t$  is the time between the passages of the two teeth.

Finally, we use the equation for the acceleration of a body sliding on the inclined plane with friction coefficient  $f$ :  $a = g \cdot \sin \alpha - f \cdot g \cdot \cos \alpha$  and get the following formula for the friction coefficient:

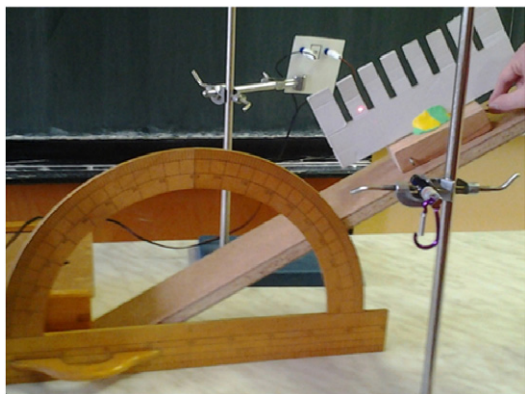


Figure 5. Measuring the friction coefficient.

$$f = tg\alpha - \frac{a}{g \cos \alpha} \quad (1)$$

The experimental arrangement can be seen in figure 5. The recorded signal in FAE is similar to that in figure 3. Also the uncertainty treatment is similar to the one in section 3.1, as far as the uncertainty on  $a$  is concerned, after which uncertainty propagation also involves the uncertainty on  $\alpha$ .

In our experiments, the average value of the calculated friction coefficient was  $\bar{f} = (0.32 \pm 0.04)$  which is in good agreement with the tabular value for the kinetic friction coefficient in the range  $f = 0.2 - 0.5$  for wood on a wood surface.

### 3.3. The demonstration of sound beats by using visual analyser

For this experiment we need a pair of external speakers and an external microphone. First we connect the speakers and the microphone to the sound card. The PC microphone is placed between the speakers, approximately 30 cm from them. This distance has proved to be optimal for the level of the recorded signal.

Having started VA, we select the *Main* table on the right hand side of the screen and click on *Wave Gen*. This opens the *Waveform Generator* window, in which we click on the *Main* table and select *Enable* for each channel. After that we enter close frequencies for both channels.

Finally, at the bottom right of the window we set the *Main* table on Channel (s) and select A + B, after which we start measuring by pressing

the *On* button in the upper left hand corner of the screen.

To listen to the audio beats we can set the frequencies at approximately 500 Hz and 505 Hz. This way, the beat frequency is low enough and the effect is audible.

If we want to depict it on a graph, we have to select more dissimilar frequencies in order to make sure that the amplitude variation of the sound beats is sufficiently evident. In our case we selected 500 Hz and 530 Hz (see figure 6). The experiment can also be performed without external speakers and an external microphone, but it will of course lack the desired sound effect and will have the graphical output only.

### 3.4. Demonstration of the sound beats using wine glasses

We carry out this experiment in a similar way. As a source of sound, we can use two wine glasses filled with water. The water in both glasses should be at approximately the same level. The microphone was positioned between the two goblets, in the middle. Two students must slide their fingers on the glass while a third one records the sound.

The experimental arrangement can be seen in figure 7, whereas the recording of sound in FAE is shown in figure 8.

It is also possible to make the experiment more quantitative by asking the students to measure the beat frequency from FAE records.

### 3.5. Determination of sound speed by Doppler effect and sound beats

When a source of constant and pure sound frequency is rotating around a point external to the source, its movement toward and away from the observer (e.g. a PC microphone) causes the Doppler effect to occur, with increasing and decreasing sound frequency when the source is moving toward or away from the observer, respectively. By performing the experiment in the presence of walls or panels that reflect the sound waves, direct and reflected waves of different Doppler shift reach the microphone contemporarily. If these frequencies are close, audible sound beats are formed. The experiment described hereafter allows us to show the effect.



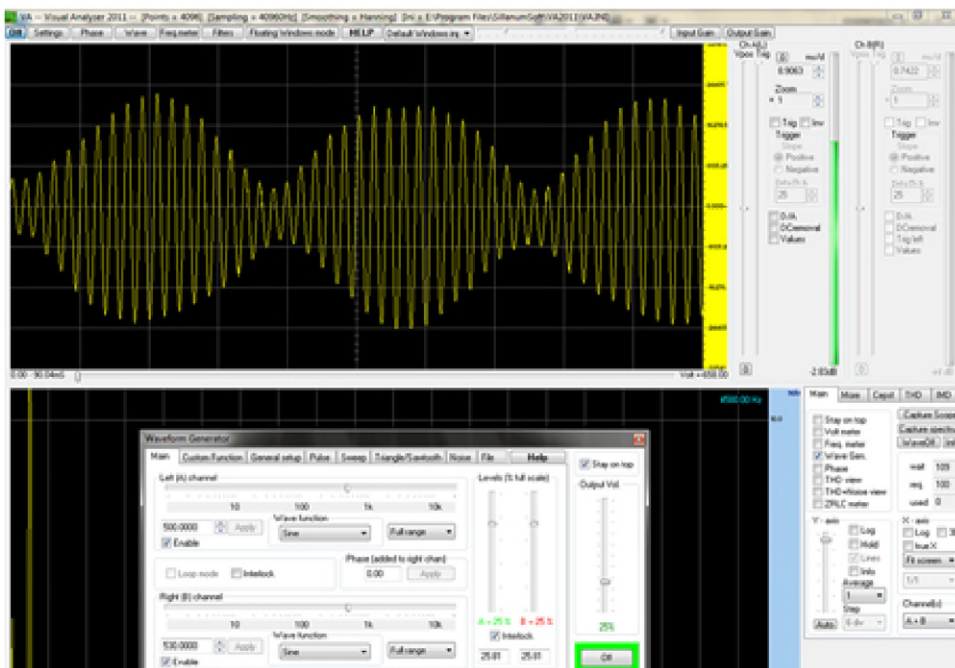


Figure 6. Sound beats using visual analyser.



Figure 7. Sound beats produced by wineglasses.

We recovered the power supply cooling fan from an old computer. CPU cooling fans are not suitable because of their small power. Using glue we attached to the fan blades two screws, to which we fixed a wooden shaft which will be made to rotate by the fan rotation. The shaft must be positioned symmetrically in order to prevent undesirable vibrations of the whole apparatus. On one end of the shaft we placed a plastic yardstick by which we set the sound source distance from the centre of rotation. By setting the distance between the sound source and the rotation centre we can choose the maximum linear velocity of the sound source.

At the same end of the shaft we fixed the source of a sinusoidal signal of known frequency. We used a piezoelectric sound transducer with a frequency of 4.4 kHz, connected directly to a 9V battery by a switch, see figure 9. Another option may be a smartphone with a signal generator app running.

We balanced the other end of the wooden shaft by another 9V battery so as to prevent unwanted oscillations of the entire system at high speeds. We placed the microphone at the minimum comfortable distance from the oscillator in the plane of rotation. Walls or panels were at about 50 cm from the volume taken up by the rotating shaft and the microphone, so as to insure multiple reflections and interference phenomena. The experimental arrangement can be seen in figure 10 and the recorded signal is shown in figure 11, where sound beats are evident.

Measurements can be repeated for different values of the sound source distance from the centre of rotation, but using the larger distances is better in order to achieve larger Doppler shifts. After a few preliminary tests we selected the distance at which we put the sound source to be 24 cm. Similarly, optimal conditions were

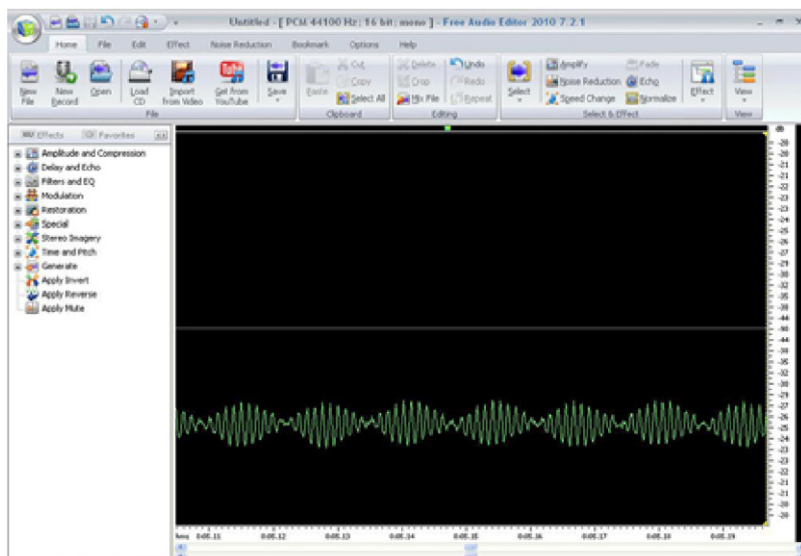


Figure 8. Recorded beats in Free Audio Editor.

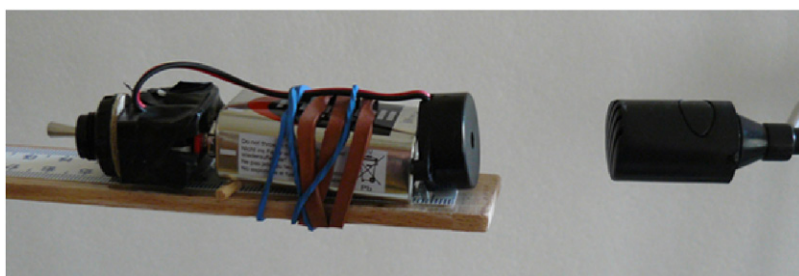


Figure 9. Piezoelectric oscillator with 4.2 kHz frequency and PC microphone as a receiver.

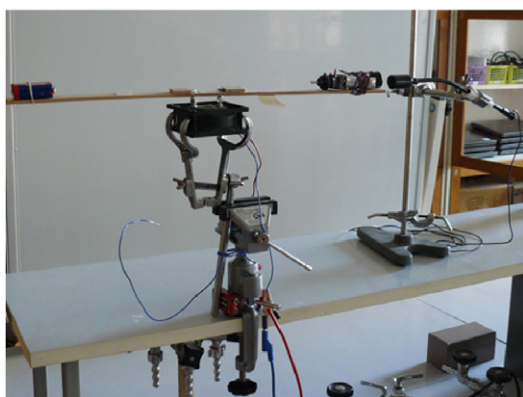


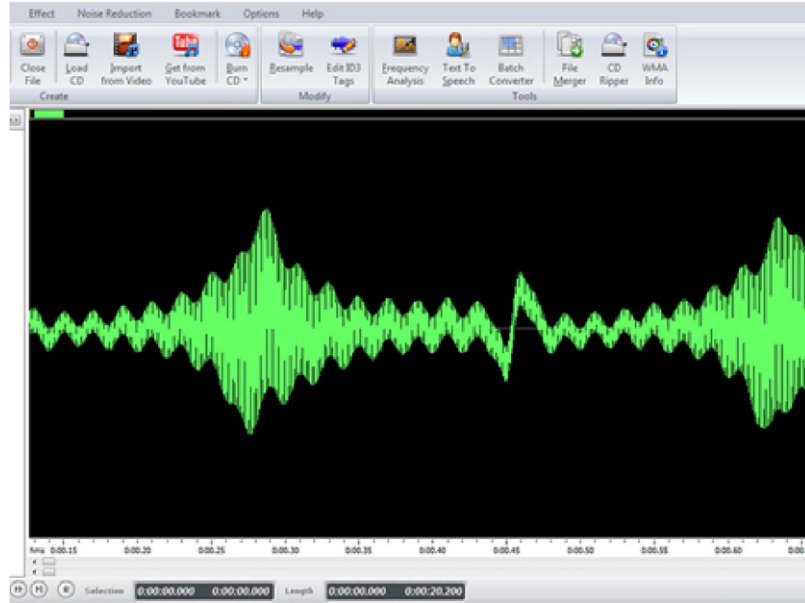
Figure 10. Measuring the velocity of sound using Doppler effect.

looked for by varying the frequency of the oscillator. Using higher frequencies gives better results in the determination of Doppler shifts.

The maximum speed that could be achieved with a 12 V fan was approximately  $7.5 \text{ m s}^{-1}$ . This value can be calculated from the time period of the circular motion. Unfortunately at this speed, due to imperfect balance, the whole system began to vibrate and measurement was almost impossible. Finally, we set the voltage value at between 6 V and 8 V, at which the speed of the source reached approximately  $4 \text{ m s}^{-1}$ . Naturally, the optimal voltage value may vary from fan to fan.

Hereafter we consider only the rotation phases in which linear velocity is maximum, toward or away from the observer (quadrature relative to the microphone), which gives maximum Doppler shift and more evident beats, also allowing a simple mathematical treatment.

When we take into account the well-known relationship for the Doppler effect,



**Figure 11.** The signal view with a noticeable modulation by sound beats.

$$f_{1,2} = f_0 \frac{v_s}{v_s \mp v} \quad (2)$$

where  $f_{1,2}$  are the observed frequencies,  $f_0$  is the emitted frequency of a sound source,  $v_s$  is the velocity of sound waves in the medium and  $v$  is the velocity of the source relative to the medium, we can calculate the frequency of the sound beats as the difference between  $f_1$  and  $f_2$ .

The frequency of sound beats  $f_{sb}$  is given by:

$$f_{sb} = f_0 v_s \frac{2v}{v_s^2 - v^2} \quad (3)$$

From the above expression we have to solve a quadratic equation where the roots are:

$$v_{s1,2} = v \frac{f_0 \pm \sqrt{f_0^2 + f_{sb}^2}}{f_{sb}} \quad (4)$$

The root with the minus sign has no physical meaning. We can simplify the second root by the condition  $f_{sb} \ll f_0$  as follows:

$$v_s = 2v \frac{f_0}{f_{sb}} = 2vf_0 T_{sb} \quad (5)$$

where  $T_{sb}$  is the time period of the sound beats.

The most difficult aspect of the measurement is the determination of the frequency of sound beats or their period. FAE is not suitable for such

measurement because the spectral analysis does not find maximum and minimum frequencies. We tried to use the Audacity software, which offers frequency analysis of the recorded signal and can search the largest recorded frequency. However, this program has proven poor precision in the determination of the frequency peaks. It should be noted that a measurement uncertainty in the period of sound beats of the order of  $10^{-3}$  s to  $10^{-4}$  s causes a change in the calculated velocity of sound waves of the order of several tens of  $\text{m s}^{-1}$ . Therefore we looked for a more accurate audio signal analyzer and found the Sigview software [17]. Sigview uses fast Fourier transforms (FFT) for frequency spectrum analysis. The software is shareware and can be used free of charge for 21 d.

By using FAE we can determine with sufficient accuracy the period of rotation of the sound source, save the recording to WAV format and subsequently open in Sigview. Next, we use the mouse to select the area that corresponds to one period of the source motion, and using the magnifying tool we can enlarge it if necessary, see figure 12.

In the Sigview toolbar we click on the FFT button, which performs spectral analysis of the signal and draws the graph, see figure 13.

Finally, we use the *Peak Detector* tool to find the peaks of the signal. The tool can be activated with the right mouse button over the graph of the



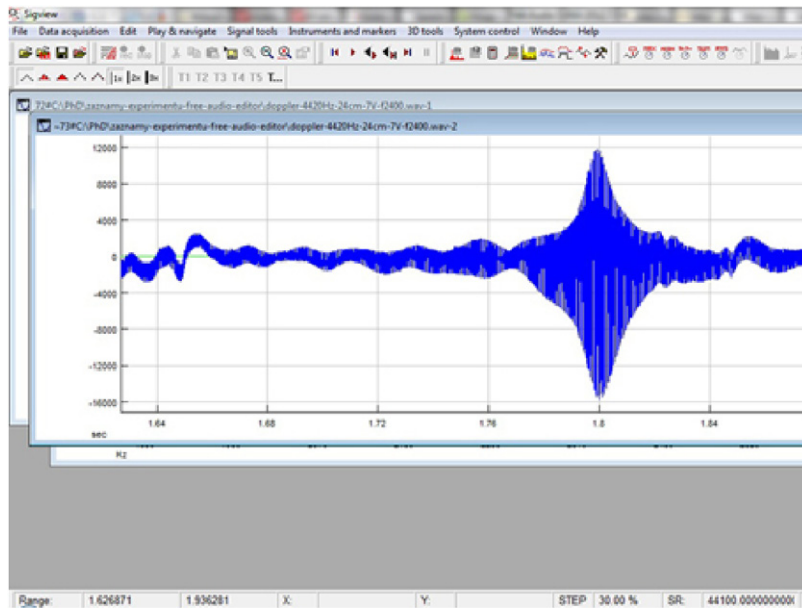


Figure 12. Selected area in Sigview.

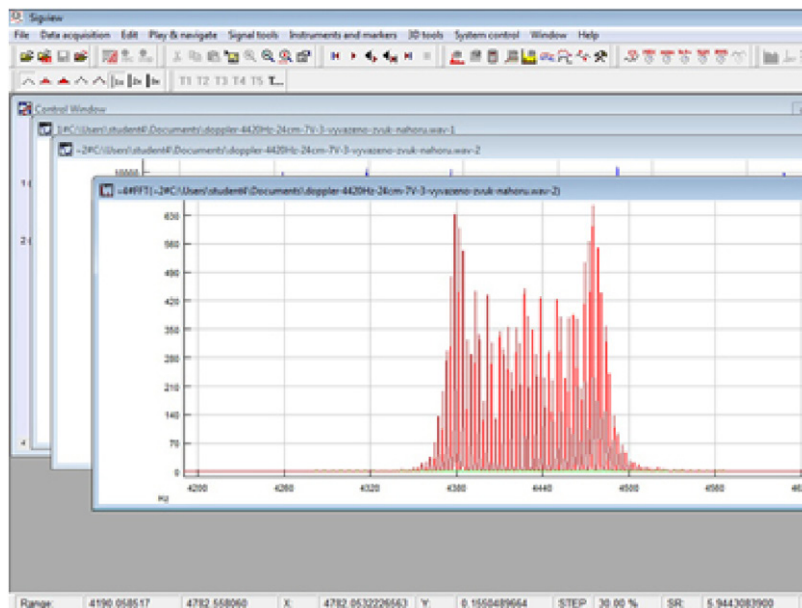


Figure 13. Fast Fourier transform of selected area of a signal.

spectral analysis. The good way to limit the search results to only one or two largest peaks in the recording signal is to set up the *Positive threshold* lower limit for the lookup value on the y-axis.

The graph with the highest peaks is illustrated in figure 14.

As an example, table 1 reports a selection of experimental values. We measured the oscillator

frequency at rest by using VA. Its value is reported as  $f_0$  in table 1.

In table 1  $U$  represents the value of the supply voltage of the fan,  $T$  is the period of motion of the rotating oscillator as measured by FAE,  $v$  is the linear velocity calculated for a constant value of distance  $r = 0.24$  m from the centre of rotation, and  $f_{\max}$  and  $f_{\min}$  are the highest and the

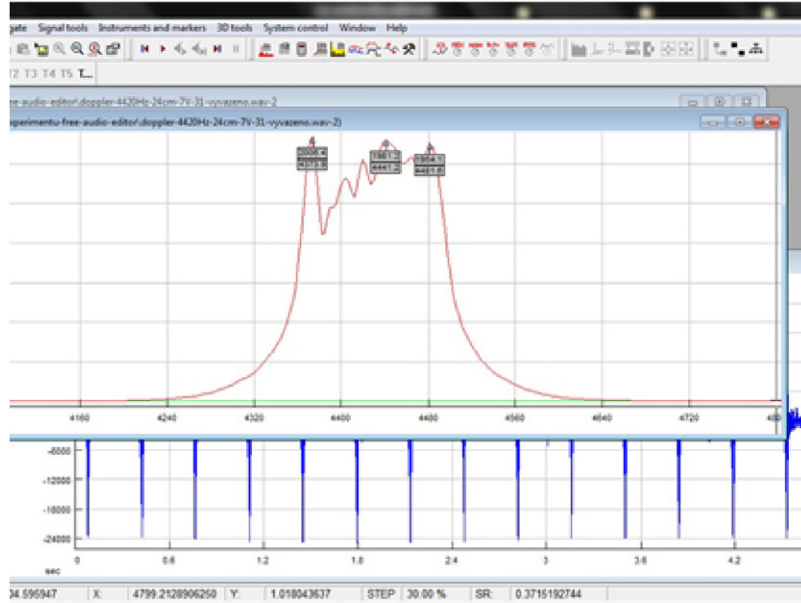


Figure 14. Marking the highest peaks in the signal.

Table 1. Determination of sound velocity from Doppler effect.

$f_0$	$U$ (V)	$T$ (s)	$v$ ( $\text{m s}^{-1}$ )	$f_{\text{max}}$ (Hz)	$f_{\text{min}}$ (Hz)	$T_{\text{sb}}$ (s)	$v_s$ ( $\text{m s}^{-1}$ )
4420	6	0.421	3.58	4474	4385	0.011 24	356
4420	7	0.376	4.01	4479	4379	0.010 00	355
4420	8	0.322	4.68	4487	4369	0.008 48	351
4430	6	0.388	3.89	4444	4350	0.010 64	366
4430	7	0.376	4.01	4445	4338	0.009 35	332
4430	8	0.347	4.35	4447	4325	0.008 20	315
4470	6	0.448	3.37	4475	4382	0.010 75	323
4470	7	0.360	4.19	4427	4315	0.008 93	334
4470	8	0.331	4.56	4473	4352	0.008 26	336

lowest frequencies measured using FFT analysis in Sigview, respectively.  $T_{\text{sb}}$  is the period of sound beats calculated from  $1 / (f_{\text{max}} - f_{\text{min}})$  and  $v_s$  is the speed of sound determined by equation (5).

From the measurement results we found that at a low value of fan voltage of about 4V the velocity of the sound source is so low that the sound beats are hardly noticeable. Conversely, if the speed of the sound source is too high, undesirable vibrations in the whole system are produced. In school laboratory conditions we mostly have no opportunity to strengthen the whole structure by fixing it to the table so as to avoid improper vibrations at high speed. We have to fix the structure using a small clamp with swivel joint at the top that allows you to position the jaw in different directions. However, the construction cannot eliminate the resonance vibrations at higher speeds.

Therefore, we performed the measurements for only those values of the supply voltage at which there were no visible resonant vibrations of the kit.

The average value of the sound velocity and its uncertainty can be simply calculated from table 1 by respectively considering the arithmetic mean of  $v_s$  data and the standard uncertainty of the mean, obtaining  $\bar{v}_s = (341 \pm 6) \text{ m s}^{-1}$ . For a more accurate treatment, one should evaluate the uncertainties on each  $v_s$  value, verifying their relative importance and using them as weights. In particular, uncertainty propagation in equation (5) gives:

$$\begin{aligned} \Delta v_s &= v_s \cdot \left( \frac{\Delta v}{v} + \frac{\Delta f_0}{f_0} + \frac{\Delta T_{\text{sb}}}{T_{\text{sb}}} \right) \\ &= v_s \cdot \left( \frac{\Delta T}{T} + \frac{\Delta r}{r} + \frac{\Delta f_0}{f_0} + \frac{\Delta T_{\text{sb}}}{T_{\text{sb}}} \right). \end{aligned} \quad (6)$$

By considering the rule of combination of measurements of the same quantity with differing uncertainties,

$$\bar{v}_s = \frac{\sum_i w_i v_{s,i}}{\sum_i w_i}, \quad \Delta \bar{v}_s = \sqrt{\frac{1}{\sum_i w_i}} \quad (7)$$

where  $w_i = (1/\Delta v_{s,i})^2$ , we obtain  $\bar{v}_s = (337 \pm 4) \text{ m s}^{-1}$ . The values obtained correspond quite well with the tabulated value  $343.7 \text{ m s}^{-1}$  at  $20^\circ\text{C}$ .

#### 4. Conclusion

All computers or notebooks have a built-in sound card, the input/output interface that can directly receive or generate analogue signals. Although such sound cards have a limited potential because of the ability to process alternating signals only, and have limited bandwidth, they can make physics education more efficient and more interesting at a very low price. Simple sensors such as a solar cell or a PC microphone can be directly connected to the sound card input.

In this paper we have shown several experiments from the fields of mechanics and acoustics. We have verified that the optical gate consisting of a solar cell and a laser pointer allows us to take measurements comparable with experiments performed using professional kits such as Vernier [1, 2] IP Coach [3, 5] or Pasco [5].

The advantage of our approach is the ability to conduct experiments not only as a demonstration, but also as students' laboratory exercises. Another advantage is the affordability of the equipment used, which may offer an interesting alternative to the most expensive professional kits for a variety of primary and secondary schools.

A very low price, ease of use and comprehensibility of the experiments make it possible for students to turn their computers into measurement devices, focusing their attention on improving their physical skills and, last but not least, making physics more attractive to them.

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