The use of Doppler effect in science education

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The use of Microcomputer Based Laboratory (MBL) methods and tools is very popular in science education now. The researches believe that students can learn the most important concepts and investigative skills more effectively through guided activities that are enhanced by the use of powerful MBL tools for the real time collection, display and analysis of the experimental data [1].
Taking into account the important and interdisciplinary role of Doppler effect in physics education we propose the use of the MBL methods and tools to perform simple experiments enabling the qualitative verification of Doppler law for acoustic waves in the real time.

Introduction

If a car is moving while its horn is blowing, the frequency of the sound you hear is higher as the vehicle approaches you and lower as it moves away from you. This is one example of the Doppler effect, named from the Austrian physicist Christian Doppler, who discovered it in the year 1842.

In general, a Doppler effect occurs whenever there is relative motion between a source and an observer. When the source and the observer are moving toward each other, the observer hears a frequency higher than the frequency of the source in the absence of relative motion [2]. When the source and observer are moving away from each other, the observer hears a frequency lower than the source frequency. This change of frequency is known as the Doppler effect.

This effect is no limited to the kind of sound waves. All waves show a similar effect. In particular, all electromagnetic waves, including visible light, undergo a Doppler shift when there is relative motion of observer and source. However, because of the unique nature of electromagnetic waves, the analysis of their Doppler shift is different from the analysis we used for sound waves.

The Doppler effect is seen as the apparent shift in wavelength of a wave motion due to the relative motion between the source and the observer. This effect for light enables astrophysicists to determine the velocity and direction of distant stars. Light from a star that is seen to be shifted towards the red end of the electromagnetic spectrum means that the star is receding, whereas light that is blue-shifted means that the star is approaching the observer [3].

Experimental setup

To analyse the Doppler effect for sound, we will demonstrate a relation between the frequency shift and the velocity of moving bodies (source or observer) relative to the medium (air) in which the sound waves propagate. To simplify situation, we consider only the special case in which the velocities of both source and observer lie along the line joining them.

To investigate the velocity of moving car we are using inexpensive ultrasound motion detector working with continuous, coherent wave of 40 kHz frequency (see fig. 1 and 2), elaborated at our Laboratory [4,5,6]. Using this detector we can obtain the distance measurements with the resolution below 0.2 mm, time with the resolution of 1 μs and with the use of computer we can calculate the velocity with the relative error about 0.2 %.

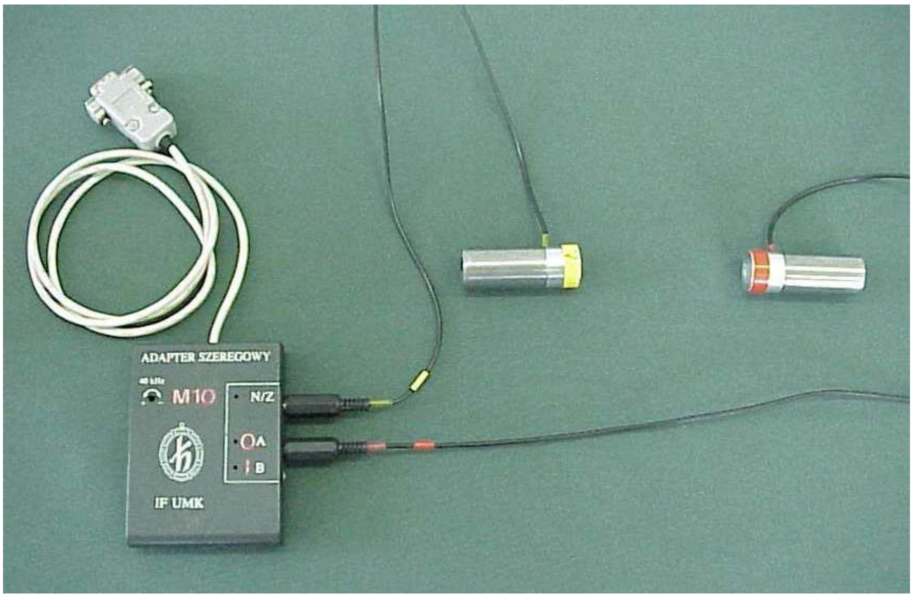

Figure 1. The ultrasound 40 kHz motion detector with transmitter (marked yellow) and receiver (marked red).

Furthermore, dedicated software Doppler 2.0 for Windows, which was designed by us, allows to control the sound blaster and the loudspeaker (see fig. 2), which are applied to generate the acoustic wave in the open space with different frequency, for example 1000 Hz, etc. The microphone (acoustic sensor) can sample the signal of the propagating wave and the software can calculate the frequency of it using FFT (Fast Fourier Transform) with the resolution of 0.01 Hz.

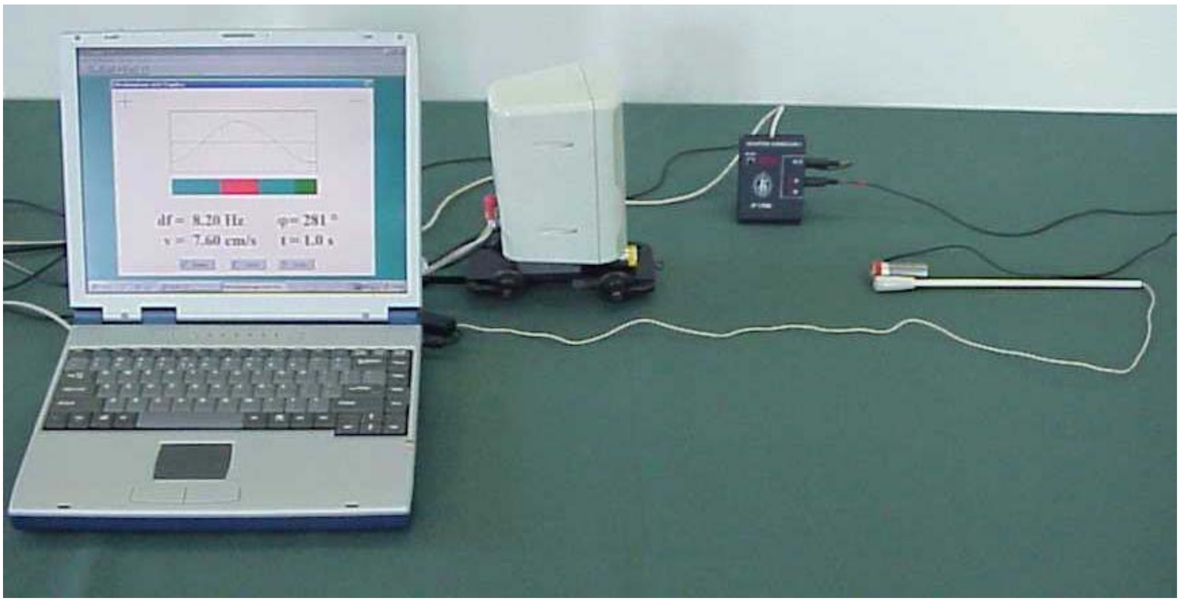

Figure 2. The hardware used in the experiments.

In that way we have possibility to perform of two independent measurements of the propagating acoustic wave frequency and velocity of the moving objects.

Examples of the experiments

1. Observer is moving with a speed of v_o toward the source, which is at rest (v_s = 0)

First let us consider the case in which the observer (car with attached microphone and ultrasound receiver) is moving and the sound source (loudspeaker and ultrasound transmitter) is stationary (see fig. 3).

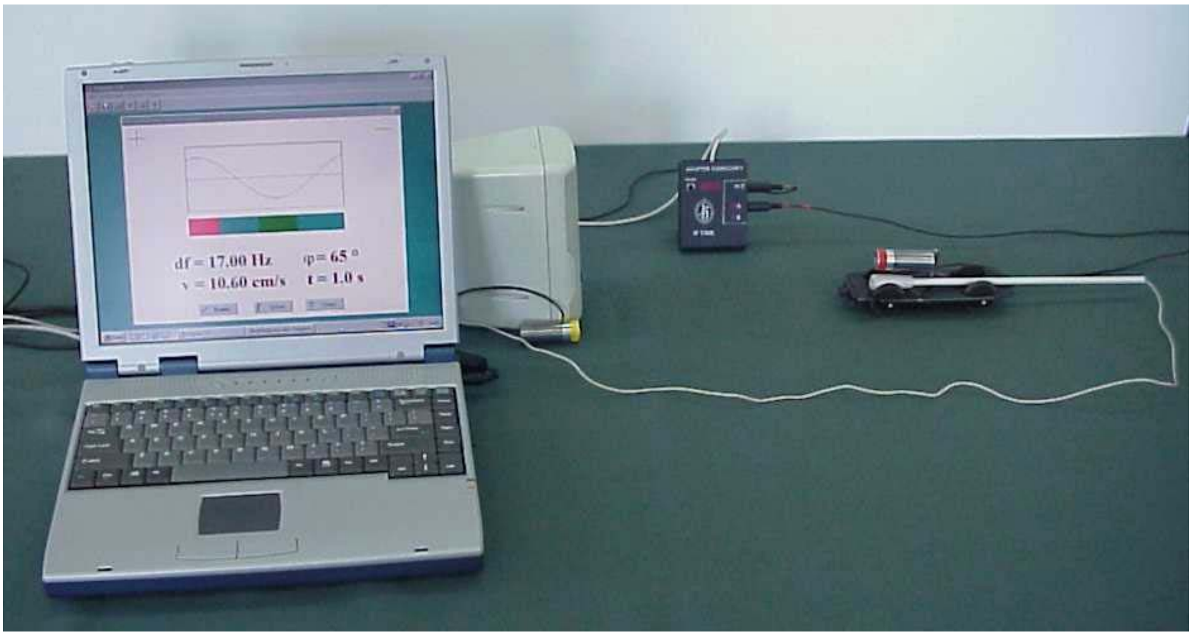

Figure 3. A car with microphone and ultrasound receiver is moving with a speed v_o toward the loudspeaker and ultrasound transmitter, which are at rest on the table.

For simplicity, we assume that the air is also stationary and all velocity measurements are performed relative to this stationary medium, as you can see in the picture below (fig. 4).

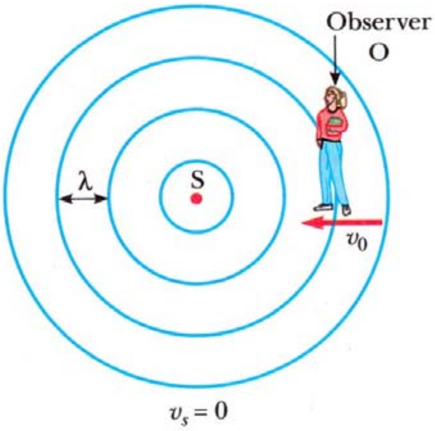

Figure 4. An observer moving with a speed of v_o toward a stationary point source S hears a frequency f', which is greater than the source frequency f.

The frequency f' heard by the observer can be expressed as:

$$f' = f\left(\frac{v + v_o}{v}\right), \tag{1}$$

where: v - the speed of sound in the air.

We would like to present the dependence between the frequency shift and the velocities of source and observer relative to the air in which the sound waves propagate.

We can change the formula (1) to:

$$f' = f\left(1 + \frac{v_o}{v}\right), \tag{2}$$

$$f' - f = \frac{f}{v} v_o \ . \tag{3}$$

As we can see the change of frequency f'-f is proportional to the speed of the observer v_o.

To exemplify this case we have performed many experiments, in which the loudspeaker has generated the acoustic wave of frequency equal 1000 Hz. The results are plotted in the fig. 5.

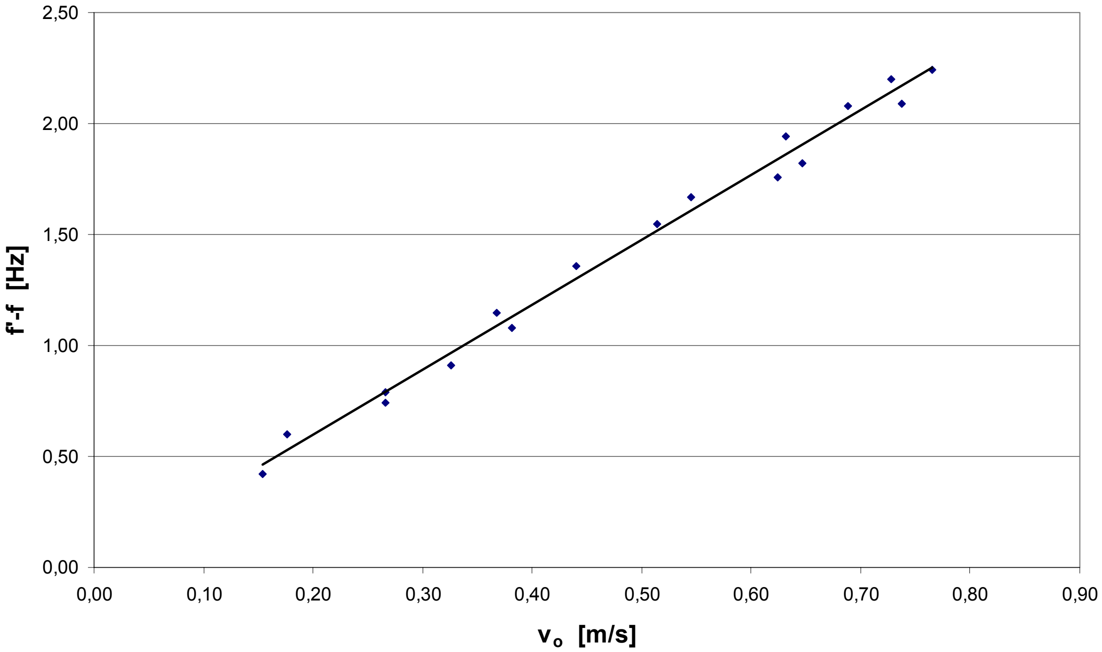

Figure 5. The results present the relation between the frequency shift and the velocities of moving observer toward the stationary source.

We obtained a linear relation between the change of frequency f'-f and velocity of observer v_o. Using the method of a linear regression we got the following coefficients of regression: a = 2.9258 ± 0.0776 and b = 0.0137 ± 0.0407. Theoretical value of the first coefficient from formula (3) is a = 2.8736. Hence, the relative error of is equal about 1.8 %.

2. Observer is moving with a speed of v_o away from a stationary source

In this case the observer (car with attached microphone and ultrasound receiver) is moving and the sound source (loudspeaker and ultrasound transmitter) is stationary (see fig. 3).

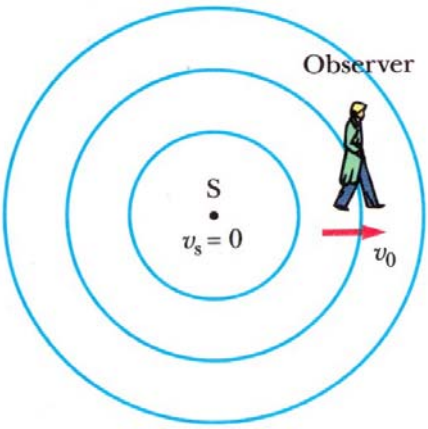

Figure 6. An observer moving with a speed of v_o away from a stationary source hears a frequency f’, that is lower than the source frequency f.

The frequency heard by the observer is lowered now to:

$$f' = f\left(\frac{v - v_o}{v}\right). \quad (4)$$

We can change the formula (4) to:

$$f' - f = -\frac{f}{v} v_o . \quad (5)$$

To exemplify this case we have performed many experiments, in which the loudspeaker has generated the acoustic wave of frequency equal 1000 Hz. The results are plotted in the fig. 7.

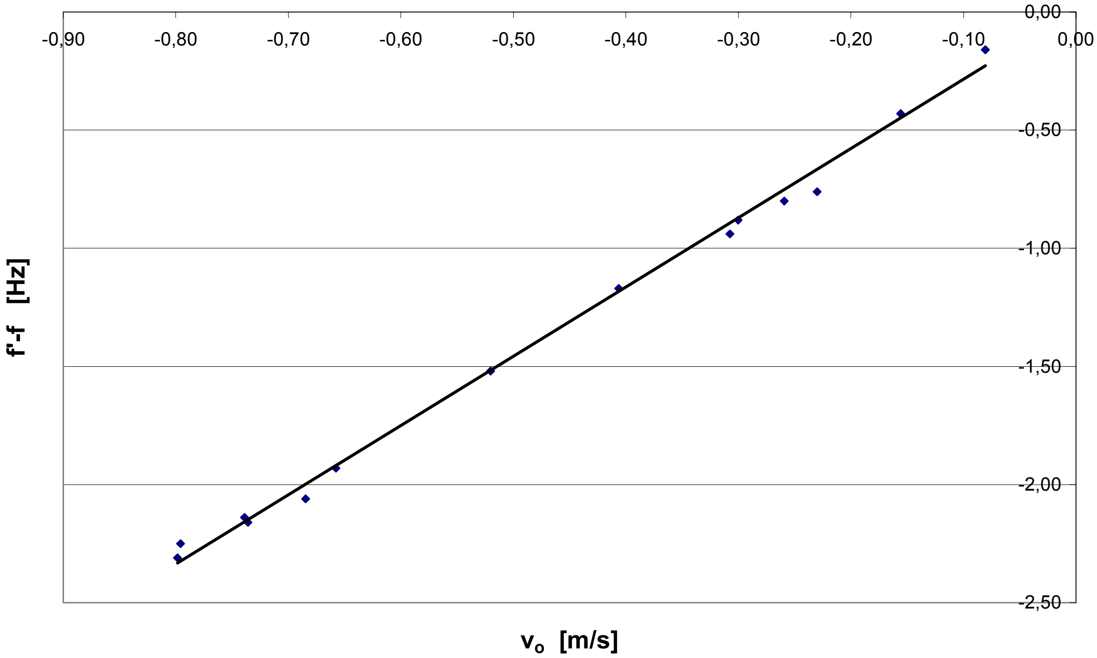

Figure 7. The relation between the frequency shift and the velocities of moving observer away from the stationary source.

The change of frequency f'-f is proportional to the velocity of observer v_o too. The coefficients of linear regression are, as follows: a = 2.9307 ± 0.0507 and b = 0.0079 ± 0.0263. Theoretical value of a is equal 2.8736 and relative error is about 2 %.

3. Source is moving with a speed of v_s toward a stationary observer

Now we consider the situation in which the source is in motion and the observer is at rest (see fig. 8).

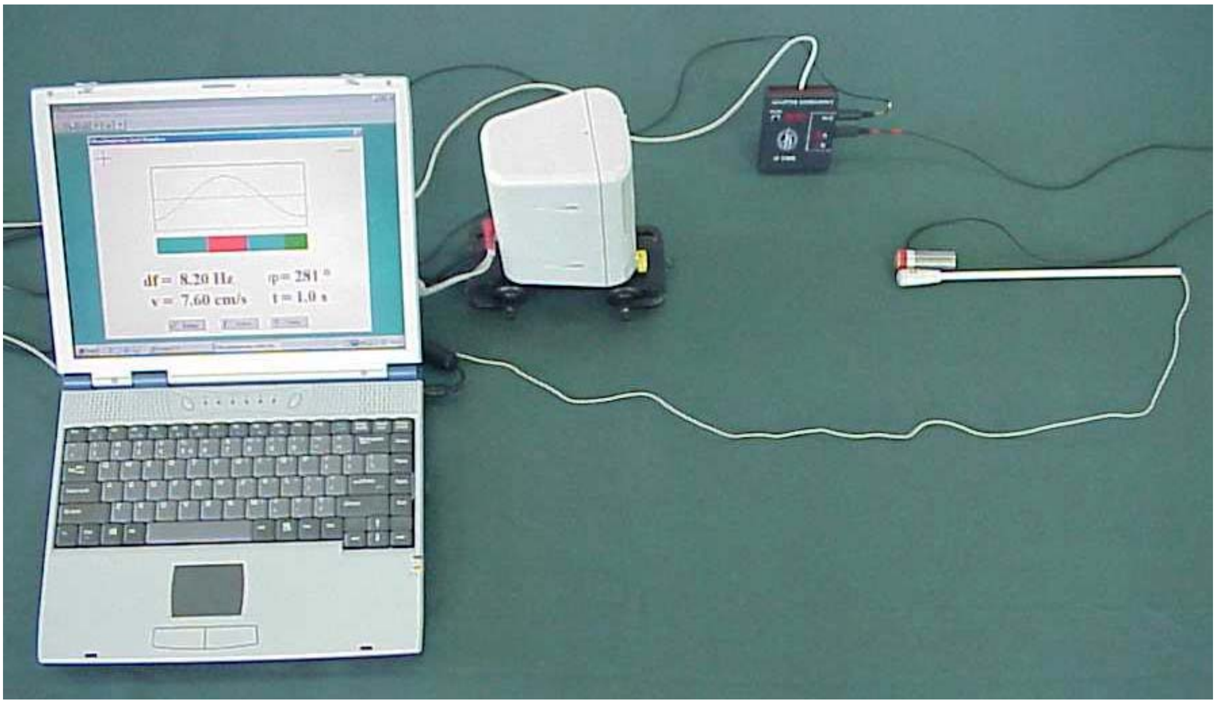

Figure 8. A car with attached loudspeaker and ultrasound transmitter (marked yellow) is moving with a speed v_s toward the microphone and ultrasound receiver, which are at rest on the table.

The model of this situation is shown in the figure 9.

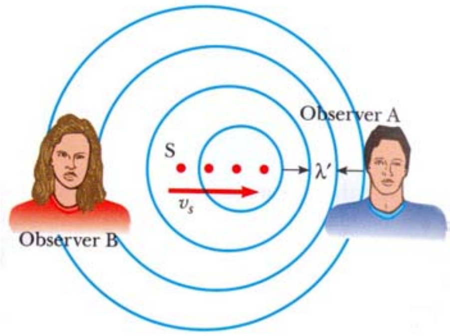

Figure 9. A source S is moving with speed v_s toward stationary observer A and away from stationary observer B.

Observer A hears an increased frequency:

$$f' = f\left(\frac{v}{v - v_s}\right) \quad . \tag{6}$$

We can change the formula (6) to:

$$\frac{f' - f}{f'} = \frac{1}{v} v_s \quad . \tag{7}$$

The results adequate experiments are plotted in the fig. 10.

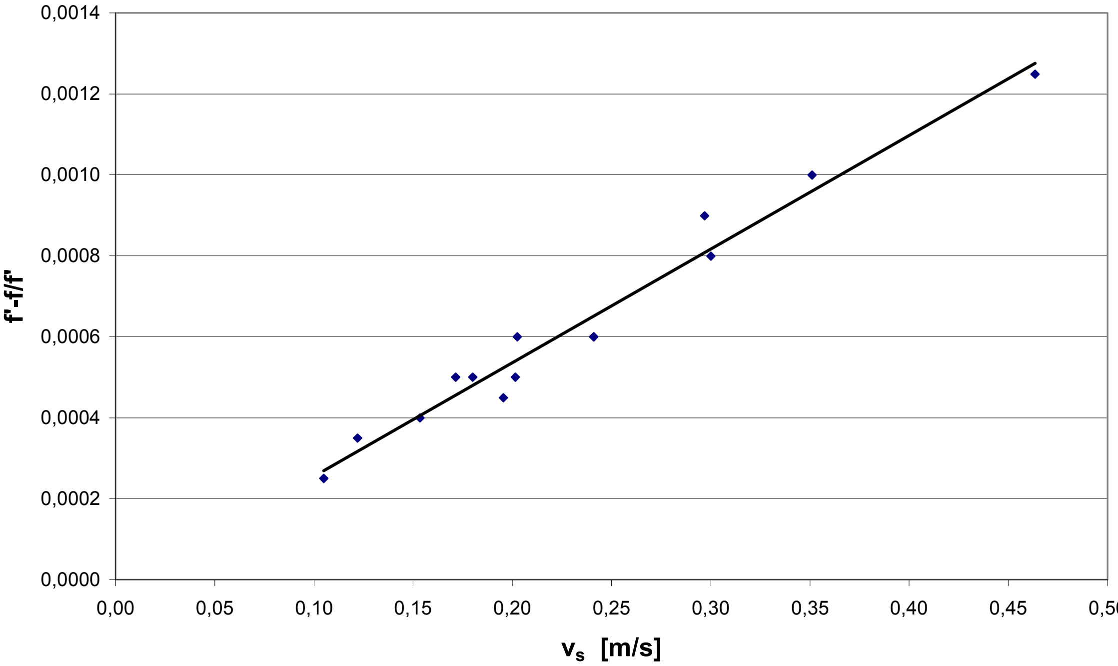

Figure 10. The results shows the relation between the change of frequency f'-f divided by the measured frequency f' and the velocity of the source v_s.

In this case the change of frequency f'-f divided by the measured frequency f' is proportional to the velocity of the source v_s. The coefficients of linear regression are following: a = 0.002807 ± 0.000144 and b = -0.000026 ± 0.000036. Based on formula (7) we could calculate the value of coefficient a. It is equal 0.002863 and relative error is about 2 %.

4. Source is moving with a speed of v_s away from a stationary observer

Observer B hears a lower frequency than f:

$$f' = f\left(\frac{v}{v + v_s}\right) \quad . \tag{8}$$

The formula (8) can be transformed to:

$$\frac{f' - f}{f'} = -\frac{1}{v} v_s \quad . \tag{9}$$

Again, we have done many experiments for this case and the results are presented in the fig. 11.

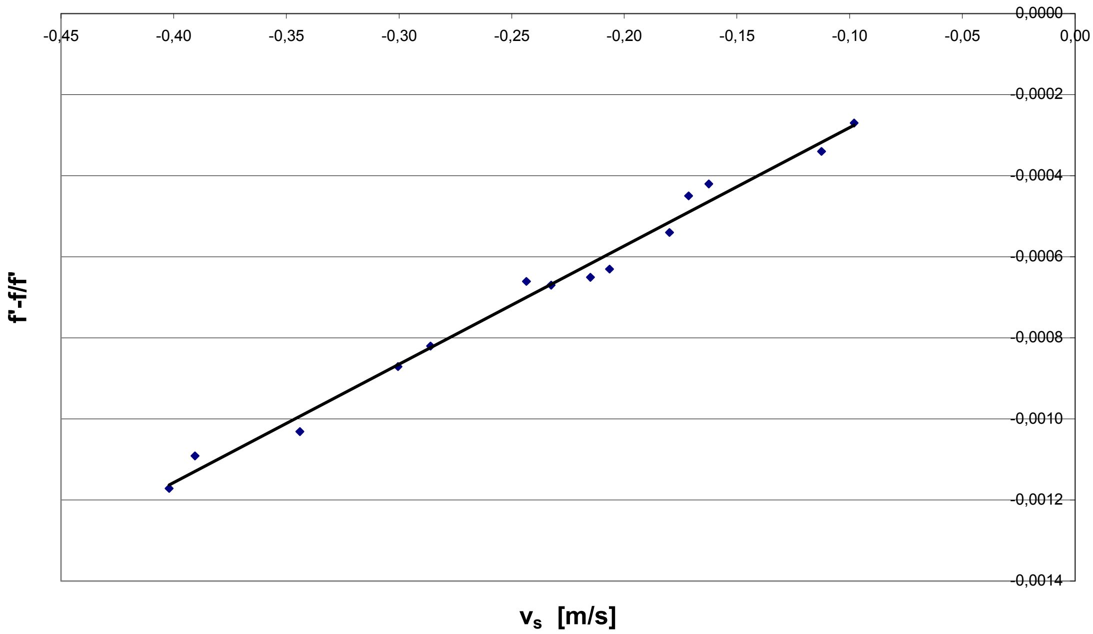

Figure 11. The results show the relation between the change of frequency f'-f divided by the measured frequency f' and the velocity of the source v_S.

In this case the change of frequency f'-f divided by the measured frequency f' is proportional to the speed of the source v_S too. We obtained the value of coefficients, as follows: a = 0.002918 ± 0.000091 and b = 0.000010 ± 0.000023. The theoretical value of a calculated from the formula (9) is 0.002858 and relative error is about 2.1 %.

Conclusions

The use of MBL methods and tools allowed us to present the quantitative verification of the Doppler law for acoustic waves. The achieved results and dependencies are very satisfactory for us and we hope that students will better understand and apply this effect.

References

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