USE OF SOUND RECORDINGS AND ANALYSIS FOR PHYSICS LAB PRACTICES

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Abstract

The study of oscillations, waves, and sound is included in most first-year courses on Physics, however, analyzing audio recordings to understand and test physics experiments in laboratory practices is not a common practice, compared for example with the use of visual techniques. In this paper, we fill in this gap showing the usefulness of the application of sound recording and its analysis in Physics Laboratory practices of first-year Engineering University studies. Sound recording is very simple and implemented in commonly available technology tools, such as smartphones. The analysis can be done with ease in free open-source applications, such as Audacity. This means that this experimental procedure can be easily implemented and extensively used, even in distance learning, which is particularly convenient in a pandemic context. In fact, we illustrate in this work how this approach let us to successfully transform two in-person lab practices into sessions that can be run remotely: the study of free fall and measurement of the coefficient of restitution of a ball bouncing when released from a certain height, and the measurement of the speed of vehicles by analyzing the Doppler effect of the sound that the motor vehicles produce. With this, we conclude that this is a powerful technique that should be considered, alone or in combination with other techniques, for instance video analysis, when planning the lab practices of Physics courses.

Keywords: teaching, distance learning, first-year physics, lab practices, audio recording, waveform analysis, spectral analysis, coefficient of restitution, Doppler effect.

1 INTRODUCTION

The sense of hearing is very important for human life, as it plays a key role in enabling communication with the environment. It is a powerful source of information, that continuously receives and processes streams of sound waves through 3 orders of magnitude, in the range 20 Hz - 20 kHz, and 12 orders of magnitude in terms of sound intensity. It is also an important aspect to understand physics, and thus, included in most of general Physics courses. However, there is little use of sound as source of information to understand/test physics in Lab practices, compared for example with the use of visual techniques.

In this paper, we try to fill in this gap showing the usefulness of the application of sound recording and its analysis in Lab practices of Physics subject of first-year Engineering University studies. Sound recording is very simple and implemented in popular technology tools, for instance smartphones. The analysis can also be done efficiently with available free applications either in the smartphone or laptops, such as Frequency analyser [1] or Audacity [2]. Therefore, the procedure can be easily implemented in the lab or for extensive use in virtual lectures online, or more generally in distance learning. In fact, the use of this technique has allowed us to transform some classical in-person lab practice sessions into practice sessions running remotely during the confinement due to the pandemics.

Two examples and experiences of the application of sound recording and its analysis in Lab practices will be fully described (Figure 1): the study of the free fall of a bouncing fall released from a certain height and its coefficient of restitution, and the calculation of velocity of vehicles by analysing the Doppler effect of the sound produced. We suggest that the approach suggested below can be extended to other examples, such as vibration and stationary waves in strings and/or surfaces, echo-localization, etc. With this, we illustrate that this is a powerful technique, and we encourage it to be considered, alone or in combination with other techniques (e.g., video analysis or smartphone sensor recordings) when planning lab practices in Physics courses.

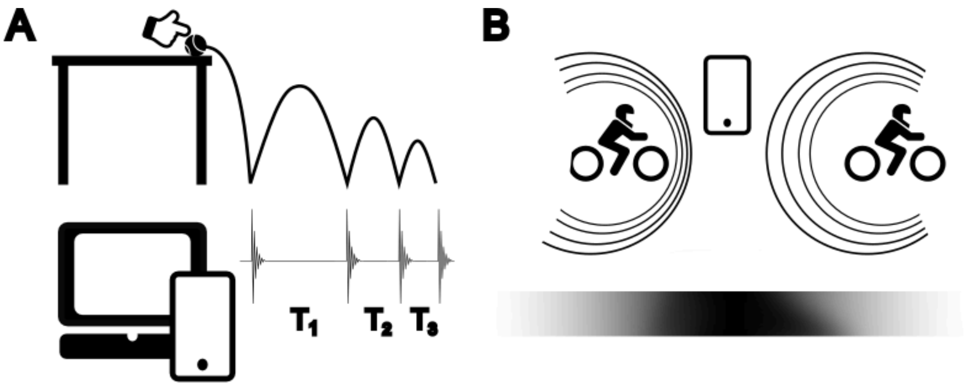


Figure 1. Two examples of the application of sound recording and its analysis in Lab practices: (A) the study of the free fall of a bouncing ball released from a certain height and its coefficient of restitution; and (B) the estimation of the speed of a motorbike by analysing the Doppler effect of its sound.

2 PROPOSAL AND METHODS

This study is based in the use of sound recordings and its analysis in learning Physics, specifically to implement this technique for training experimental techniques in first year subjects in Science and Engineering Bachelor degrees. It can be easily implemented in Physics Labs or use it directly for distance learning or for Massive Online Open Courses (MOOCs). Nowadays, sound recordings can be obtained easily using smartphones or laptops/desktops. Most students have access to these devices directly or, e.g., through public libraries, and know how to make recordings, so the process is usually straightforward. There are applications that can be used to analyze audio files in the smartphone. However, editing and analyzing audio recordings is more versatile in a computer with applications, such as Audacity. Audacity is an easy-to-use multi-track audio editor and recorder. It is free, open source, and cross-platform, available in Windows, MacOS, GNU Linux, as well as in other operating systems.

There are specific physics practices that study waves and sound propagation in the Physics Lab syllabus, and thus, it is quite straightforward to introduce the practice with the methodology proposed here. For example, we can consider simple practices, such as the study of stationary waves on a guitar string, to more complex situations, such as stationary waves in surfaces, resonating cavities, echo-localization, Doppler effect in moving sound emitters/receivers, etc. There is quite a lot of literature in using smartphones for teaching and in describing this kind of wave propagation practices, see for example [3-5]. In this paper, the novelty is to focus on designing practices where sound is used as a *messenger*, useful to better understand the physics involved. The first example focuses on the free fall and coefficient of restitution of a bouncing ball by analyzing the sound produced by the bounces of the ball, shifting from the traditional practice that uses direct measurements of the height bounced. The second example focuses on estimating the speed of a vehicle using the Doppler effect by measuring how the frequency of the sound emitted by the vehicle changes when approaching and moving away. These examples are described in detail in next section.

3 EXAMPLES

In this section some examples and experiences of the application of sound recording and its analysis as Physics Lab practices are described. Particularly, the free fall study of a bouncing ball and determination of its coefficient of restitution, and the measurement of the speed of vehicles by analyzing the Doppler effect of the sound that the motor vehicles produce.

3.1 Free fall study of a bouncing ball and measurement of its coefficient of restitution

3.1.1 Theoretical framework

Inelastic collisions between objects are those involving a loss of energy, i.e., the kinetic energy of the system formed by the colliding objects (denoted by 1 and 2 here) is not conserved. The coefficient of restitution is an index that informs how much inelastic a collision is; the coefficient is defined as minus the quotient of relative speeds between the colliding objects:

$$c = -\frac{v'_1 - v'_2}{v_1 - v_2} \quad 0 \le c \le 1$$

The two extreme values of c, 0 and 1, respectively refer to perfectly inelastic collisions (i.e., those in which the two objects stick together) and elastic collisions (when the two objects separate from each other after the collision with no energy loss). In the particular case of a ball bouncing on the ground, we can consider the second object being at rest before and after the collision, in which case the above expression is reduced to:

$$c = -\frac{v'_1}{v_1}$$

The negative sign refers to the fact that the speed after bouncing off the floor is in the opposite direction to the speed before the collision.

The times and heights for a bouncing ball (see Figure 2) can be calculated as a function of the initial height h_0, the coefficient of restitution *c* and the number of bounces *n*, using the equations for the motion of a particle under constant acceleration.

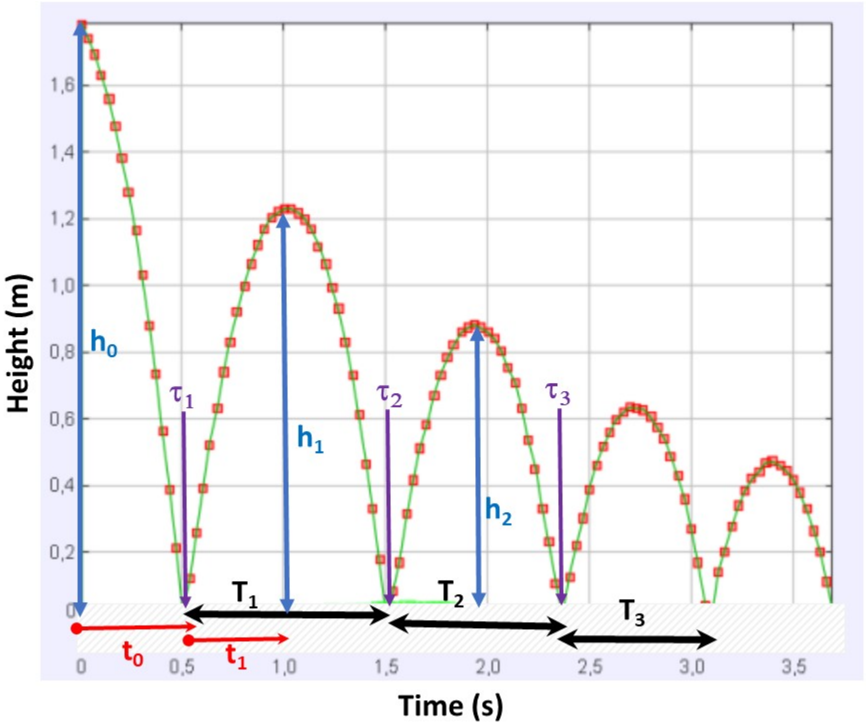


Figure 2. Height-time graph of a bouncing ball.

If the ball is released from a height of h_0 (i.e., with no initial speed), the time it needs to reach the ground is:

$$0 = h_0 - \frac{1}{2} g t_0^2 \Rightarrow t_0 = \sqrt{\frac{2h_0}{g}}$$

And the speed at the time it reaches the ground, v_0, is given by:

$$v_0 = g t_0 = \sqrt{2 g h_0}$$

After bouncing on the ground, the speed of the ball can be expressed in terms of the coefficient of restitution:

$$v'_0 = c v_0 = c\sqrt{2 g h_0}$$

The height reached by the ball after the first bound, h_1, can be determined by imposing that the speed of the ball at this point is zero. First, we find the time, t_1, it takes for the ball to reach this height:

$$0 = v'_0 - gt_1 = c\sqrt{2gh_0} - gt_1 \Rightarrow t_1 = c\sqrt{\frac{2h_0}{g}}$$

Then, we use t_1 to find the height reached, h_1:

$$h_1 = v'_0 t_1 - \frac{1}{2}gt_1^2 = c\sqrt{2gh_0}c\sqrt{\frac{2h_0}{g}} - \frac{1}{2}gc^2\frac{2h_0}{g} = c^2h_0$$

Similarly, after the second bounce, the ball will reach a height h_2 in a time t_2 given by:

$$h_2 = c^2h_1 = c^4h_0\ ;\ t_2 = c^2\sqrt{\frac{2h_0}{g}}$$

We can use this approach repeatedly, and, in general, after the n-th bounce the ball will reach a height h_n in a time t_n:

$$h_n = c^{2\mathrm{n}}h_0\ ;\ t_n = c^n\sqrt{\frac{2h_0}{g}}$$

Traditionally, this practice is done by measuring the height after each bounce. It can also be studied through simulations [6]. Here, we propose a different approach: to record the sound of the bouncing ball, and use this recording to determine the time at which the bounces occur: τ_1, τ_2, …, τ_n. Since the motion of the ball is symmetric in terms of the time spent in going up and down, it is straightforward to derive that the time differences follow the relationships: $T_1 = \tau_2 - \tau_1 = 2\ t_1$, $T_2 = \tau_3 - \tau_2 = 2\ t_2$, etc. Hence, the relationship for T_n is

$$T_n = c^n 2\sqrt{\frac{2h_0}{g}}$$

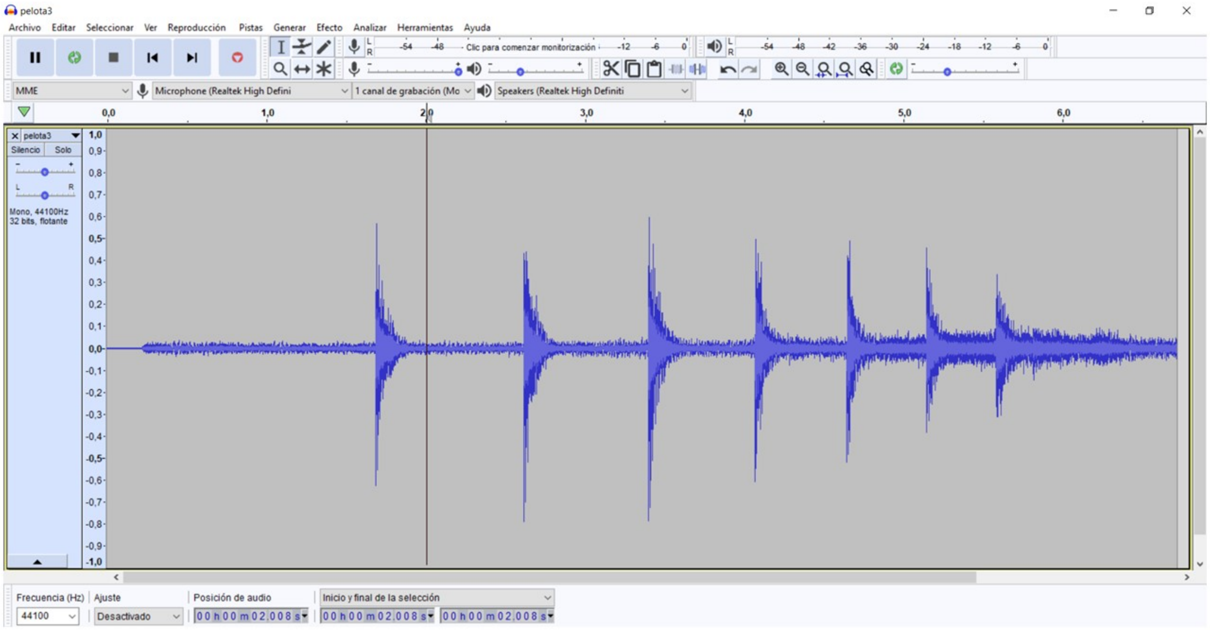
It is convenient to derive a linear relationship out of the previous expression by taking logarithms

$$\ln(T_n) = \mathrm{n}\ln(c) + \ln(T_0)$$

Then, by plotting $\ln(T_n)$ as a function of n, we find a straight line of slope $a = \ln(c)$ and the y-intercept equal to $\ln(T_0)$. The coefficient of restitution can be calculated from the slope of this line, $c=e^a$.

3.1.2 Analysis of the sound of a bouncy ball using Audacity

For the practice, students need to record the sound of the bouncing ball after it is released from a certain height. Figure 3 shows a screenshot of Audicity displaying the sound wave from the bouncing ball released from a height h_0=147 (1) cm. Since the hits on the ground produces an impulse sound of high intensity, it is easy to identify the times, τ, at which the different bounces occur, with ms precision, from which the time intervals between bounces can be easily computed. Note that it is easier to work with the time intervals between bounces than with the absolute times, as it avoids having to release the ball and to start the recording at unison. This procedure can be repeated several times to add statistics to the analysis. Figure 4 shows the results of the experiment following the procedure described here, including the equation of the best linear fit. We can observe a very good correlation. The coefficient of restitution of the bouncing ball can be estimated from the slope of the linear fit with high accuracy, c= 0,8619 (57), and we can derive the height from which the ball was released easily from the Y-intercept: h_0=1,373 (58) m.



MME
Microphone (Realtek High Defini
1 canal de grabación (Mo
Speakers (Realtek High Definiti

Mono, 44100Hz
32 bits, flotante

Frecuencia (Hz): 44100
Ajuste: Desactivado
Posición de audio: 00 h 00 m 02.008 s
Inicio y final de la selección: 00 h 00 m 02.008 s – 00 h 00 m 02.008 s

Figure 3. Screenshot of Audacity displaying the waveform of the sound produced by the bouncing ball.

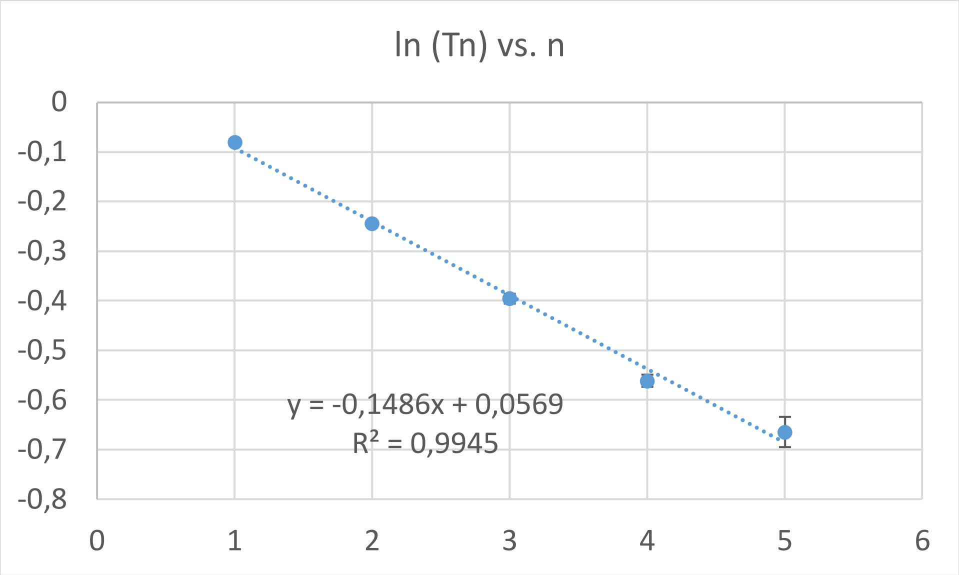


Figure 4. Ln(T_n) vs. n graph.

3.2 Calculation of vehicle speed by analyzing their sound

3.2.1 Theoretical framework

The Doppler Effect consists in the change of the apparent frequency of a wave that is emitted by a source and received by an observer when there is a relative motion between them. This is a physical phenomenon appearing on very different situations with lots of applications. For example, some radars use this effect to determine the speed of objects in motion. In astronomy, it is possible to measure the speed of stars and galaxies from the change in frequency of their electromagnetic spectrum. In medicine, the Doppler Effect is at the basis of the measurement of blood flow and of Doppler ultrasonography imaging.

The frequency reaching the receiver, when the source moves with respect to it, varies according to the following expression:

$$f' = f\,(v-u_r)/(v-u_s)$$

where f is the “natural” frequency emitted by the source, v is the speed of the wave, u_r is the projection of the velocity of the receiver towards the source, and u_s is the projection of the velocity of the source towards the receiver. In this expression, u_r and u_s are positive if the motion is in the direction of the wave propagation reaching the receiver, and negative when they have opposite directions. As a result, the frequency increases when the emitter approaches the receiver, and it diminishes when the emitter moves away. In our example, the receiver is at rest (the mobile phone recording the sound wave), and the source will be moving (vehicle). Therefore, the previous expression reduces to:

$$f' = f\,v/(v-u_s)$$

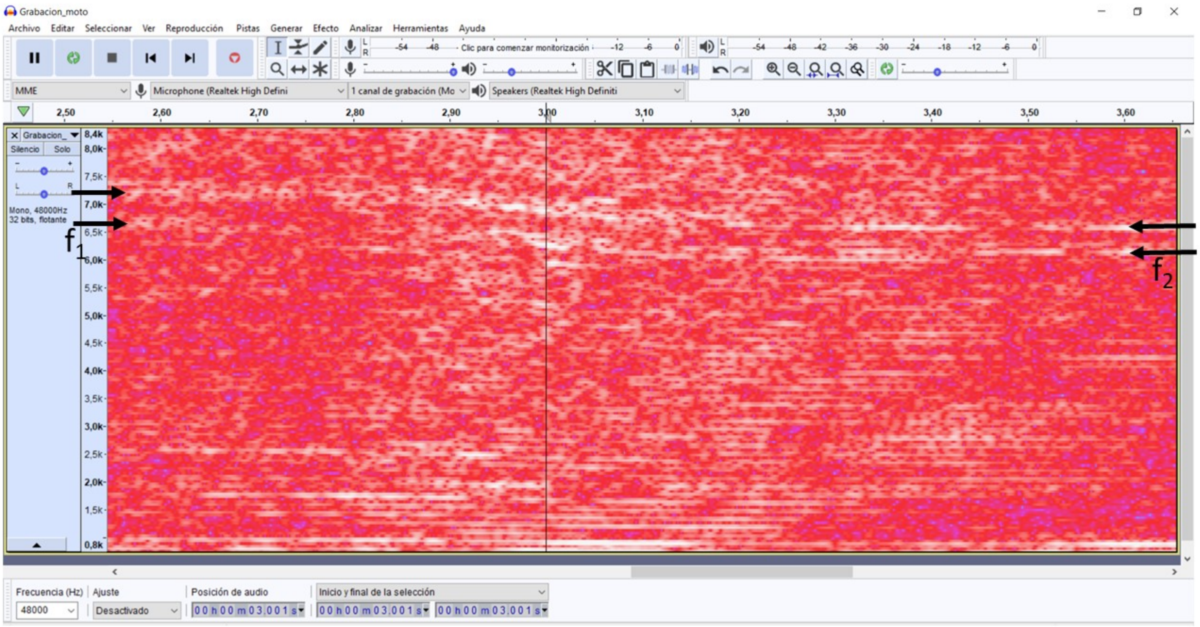
In this expression when the source approaches the receiver, u_s is positive, resulting in an increase of the received frequency. In contrast, when the source moves away, u_s is negative and the received frequency decreases. This is the reason for the characteristic sound when a vehicle is driving by. Specifically, if the vehicle is travelling at a constant speed v_s and produces a sound of frequency f, the frequency reaching the receiver will be of larger magnitude $f_1 = f\,v/(v-v_s)$ when it is approaching, and of smaller magnitude $f_2 = f\,v/(v-v_s)$ when it is moving away. We can isolate v_s from these two equations as follows:

$$v_s = v\,(f_1 - f_2)/(f_1 + f_2)$$

Hence, it is possible to determine the speed of a vehicle by measuring the sound frequencies when the vehicle is approaching and when it is moving away.

3.2.2 Analysis of the sound of a motorbike using Audacity

For the practice example, the sound of a motorbike driving by is recorded using a smartphone. Then the sound file is analyzed in Audacity. Figure 5 shows a screenshot of Audacity displaying the spectrogram of the sound wave. We can observe directly in the image a larger intensity in the central region, which corresponds to the time when the motorbike is the closest (around *t* = 3 s). It can also be appreciated the change in frequency, higher when the motorbike is approaching (2.6 s) than when the motorbike is moving away (3.6 s). We can use Audacity’s Plot Spectrum Analysis Tool to identify the main frequency peaks of the sound wave in both periods. Table 1 summarizes the time regions used, the values of the main frequency peaks measured and the calculated speed of the motorbike assuming a sound speed value of 340 m/s. Notice that despite the little control of the experience, just a random motorbike with its characteristic sound, the results seem to be quite precise and consistent. We have not controlled the speed by other methods, but the value is reasonable considering that the speed limit is 50 km/h and the traffic was fluent.



Frecuencia (Hz): 48000
Ajuste: Desactivado
Posición de audio: 00 h 00 m 03.001 s
Inicio y final de la selección: 00 h 00 m 03.001 s 00 h 00 m 03.001 s

Figure 5. Screenshot of Audacity displaying the spectrogram of the sound produced by a driving by motorbike.

Table 1. Frequencies for the two main peaks in the time regions and the speed of the motorbike obtained.

f_1 (Hz) 2,55 s - 2,65 s	f_2 (Hz) 3,55 s - 3,65 s	v_s (m/s)	v_s (km/h)
7196	6560	15,7	56,6
6684	6114	15,1	54,5

4 DISCUSSION AND CONCLUSIONS

In this paper, we have proposed the convenience of using sound recordings and perform waveform and spectral analysis for Physics Lab practices. The are several advantages aimed to motivate students: availability of the tools, simplicity of methods, large coverage of topics, easy to implement both in a Physics Lab or in distance learning, and close to real life experiences. To show this, we have presented two clear examples of application: the study of a bouncing ball in free fall and the empirical estimation of the speed of a motorbike. These examples illustrate that the simplicity and easy implementation of the experimental procedure is compatible with achieving experimental high standards in measurement quality, data processing and final analysis. Finally, the techniques and tools presented here may be combined with other methods. For instance, with tools and techniques of video analysis, such as Tracker, so supplementary measurements can be done in parallel, allowing the cross-check of the results.

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REFERENCES

[1] J.A. Gómez-Tejedor, J.C. Castro-Palacio, and J.A: Monsoriu, “Frequency analyser: A new Android application for high precision frequency measurement”. *Computer Applications in Engineering Education*, vol. 23, no 3, pp.471-476, 2015.

[2] Audacity team, Audacity, Accessed 14 January, 2021. Retrieved from https://www.audacityteam.org/,

[3] J.A. Sans, M.H. Gimenez, I. Salinas, F.J. Manjón, V. Cuenca-Gotor, J.A. Monsoriu and J.A: Gomez-Tejedor, “Smartphone for teaching experimental Physics”. In I10th International Technology, Education and Development Conference, INTED2016, Valencia, Spain. ISBN: 978-84-608-5617 (Vol. 7, pp. 1580-88), 2016.

[4] S. Staacks, S. Hütz, H. Heinke, and C. Stampfer, “Simple time-of-flight measurement of the speed of sound using smartphones”, *The Physics Teacher*, vol. 57, no 2, pp.112-113, 2019.

[5] PhysicsOpenLab, Sound Experiments, Accessed 14 January, 2021. Retrieved from http://physicsopenlab.org/2019/05/13/sound-experiments/

[6] J. Riera Guasp, (2009). Estudio del coeficiente de restitución a partir del bote de una pelota. Accessed 14 January, 2021. Retrieved from http://hdl.handle.net/10251/5153.