Hands-on exploration of vibrations and resonance through mobile technology

Elsida Haxhiu[1], *Rilindë* Doli[2], *Polikron* Dhoqin[3]

[1] "Siri Shapllo" High School, Gjirokastra, Albania
[2] Department of Physics, Faculty of Natural Sciences, University of Pristina, Kosovo
[3] Department of Physics, Faculty of Natural Sciences, University of Tirana, Albania

Abstract. This paper presents a teaching experimental project on oscilations designed for physics students. The project aims to help students to study oscilations using the smartphone applications.The smartphones, with their built-in sensors, are well-suited for use as reliable and versatile tools in simple educational experiments.
In this study, a smartphone is used to measure the vibration frequencies of rods with different lengths. The results obtained with the smartphone are compared with theoretical calculations and the agreement is good.
Another experiment is study of phenomenon of resonance with simple laboratory equipments. In this case, another smartphone's application is used to measure the natural oscillations frequency of a system and the frequency of the forcing factor. Again, the results obtained are comparable to theoretical predictions and with a good level of agreement.
In this paper, special attention is paid to the use of the applications "Phyphox" and "Strobe light" and the benefits that students have.
The paper concludes with an evaluation from a pedagogical perspective and provides related recommendations.
Keywords: oscillations, smartphone, sensors, "Phyphox", "Strobe Light", experiment, active learning, autonomous work, resonance, frequency measurement, vibrations, frequency analysis

1 Introduction

Physics education is most effective when theoretical concepts are reinforced through hands-on experimentation. Traditional laboratory work not only strengthens conceptual understanding but also fosters critical thinking, problem-solving, and scientific inquiry skills among students. However, limited access to advanced laboratory equipment in many educational institutions often restricts the scope and quality of experimental activities. In this context, the use of mobile technology, particularly smartphones equipped with various sensors, has emerged as a powerful and accessible tool for enhancing science education. [5]
This study presents a physics project carried out by undergraduate students, focusing on two fundamental topics in mechanics: vibrational modes and mechanical resonance. The project aims to demonstrate how mobile applications such as "Phyphox" and "Strobe light" can be effectively used to perform accurate frequency measurements in simple mechanical systems. [1-3]

The first part of the project investigates the natural frequencies of wood rod with varying lengths, each clamped at one end - a classic model of cantilever vibration. By analyzing the vibrational frequencies as a function of length, students gain practical insights into wave behavior, boundary conditions, and material properties.
The second experiment focuses on the resonance phenomenon in a mass-spring system, where the system is subjected to a periodic driving force. The aim is to identify the driving frequency at which resonance occurs, marked by a significant increase in oscillation amplitude. This experiment helps students understand concepts such as forced oscillations, damping, and energy transfer in oscillatory systems.
In both experiments, students use the sensors embedded in smartphones (e.g. accelerometers, gyroscopes, microphones) through the use of the "Phyphox" and "Strobe light" applications, which provide real-time data acquisition and visualization. These applications can be used for frequency measurements (of good quality), becoming especially useful where access to laboratory equipment is limited. [11]
This work highlights not only the educational value of integrating technology in physics instruction but also the scientific rigor that can be achieved through low-cost, student-led experimentation. The remainder of the paper describes the experimental setup, measurement methodology, results, and pedagogical reflections.

1.1 Purpose of the study

A- To explore fundamental concepts in classical mechanics, specifically:
a) Natural frequencies of wood rods.
b) Mechanical resonance in a mass-spring system.
B- To conduct two separate experimental investigations:
Experiment 1: Measure the natural frequencies of wood rods with different lengths, each fixed at one end.
Experiment 2: Identify the resonance frequency in a mass-spring system by varying the driving frequency.
C- To utilize smartphone applications **(**"Phyphox" and "Strobe light") for:
a) Capturing frequency data in real time.
b) Providing an accessible and cost-effective alternative to traditional lab equipment.
c) Enhancing the precision and convenience of data acquisition.
D- To promote a hands-on, student-centered approach in experimental physics by:
a) Encouraging active learning through direct interaction with physical systems.
b) Making use of everyday technology to bridge theoretical concepts with practical application.
E- To demonstrate the educational value of mobile technology in physics by:
a) Validating the accuracy and reliability of mobile applications for scientific measurements.
b) Showing their potential to modernize and simplify physics experiments in undergraduate settings.

2 Theoretical Background

2.1 A rod fixed at one end

The frequency of oscillations of a rod fixed at one end (cantilever beam) on a horizontal table (Fig. 1), when the free end is bent and then released, depends on several physics factors (parameters). These factors are related to the mechanical properties and dimensions of the rod. These include the length of the rod, the material's properties (such as Young's modulus and density), and the geometry of its cross-section.

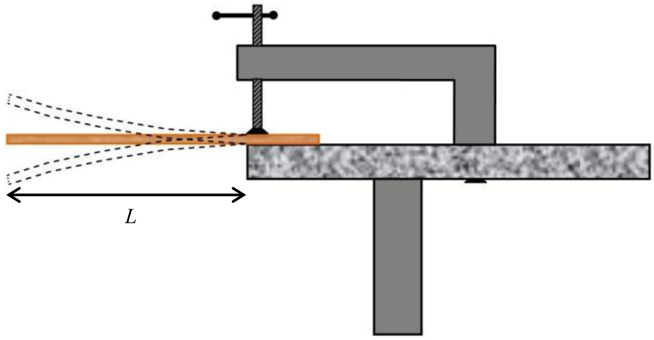

Fig. 1. Rod undergoing transversal vibrations. The rod length (L) is the distance between the free end of the rod and the fixation point.

In general:
- the frequency of oscillation of the rod is inversely proportional to the square of the length of the rod:

$$f \propto \frac{1}{L^2} \quad (1)$$

A longer rod vibrates more slowly (lower frequency). Notice that the length of the rod (L) is considered the distance between the free end of the rod and the point of fixation.
- the frequency of oscillation is greater when the stiffness is greater:

$$f \propto \sqrt{E} \quad (2)$$

Young's modulus (E) or the elastic modulus indicates how stiff the material is.
- the frequency is inversely proportional to the square root of the density of the material:

$$f \propto \frac{1}{\sqrt{\rho}} \quad (3)$$

The greater the mass per unit volume, the lower the frequency.
- the frequency is proportional to the square root of the second moment of area (I), also known as the area moment of inertia.

$$f \propto \sqrt{I} \quad (4)$$

It expresses the geometric property that describes how the area of a shape is distributed with respect to an axis. For example, for a rod with a rectangular cross-section (with width b and height h) its size is:

$$I = \tfrac{1}{12} b h^3 \quad (5)$$

- the frequency is inversely proportional to the square root of the length of the rod:

$$f \propto \frac{1}{\sqrt{L}} \quad (6)$$

The greater the length, the lower the frequency.
The frequency of oscillation (f) of a rod fixed at one end (cantilever beam) on a horizontal table can be found with good approximation by the formula:

$$f = \frac{1.875^2}{2\pi L^2} \sqrt{\frac{EI}{\rho A}} \quad (7)$$

The number $1.875^2/2\pi$ in the above formula comes from solving the differential equation for the free vibrations of an elastic rod fixed at one end and free at the other. [9, 10, 12] (This is beyond the aim of this paper.)

2.2 A mass-spring system

2.2.1 Natural (free) oscillations

A mass-spring system consists of a mass m attached to a spring with spring constant k. When displaced from its equilibrium position, the system undergoes simple harmonic motion (SHM) if there is no damping or external force.
When the system is displaced and released, it oscillates at its natural frequency**,** determined by the properties of the mass and the spring. The equation of motion derives from Newton's second law and for the vertical spring (Fig. 2) has the form:

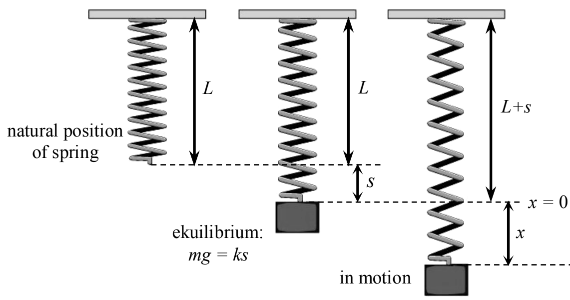

Fig. 2. A spring in its natural position, at equilibrium with mass m attached and in oscillatory motion.

$$x = A\cos(\omega_0 t + \phi) \qquad (8)$$

where:
- A is the amplitude;
- ϕ is the phase constant;
- $\omega_0 = \sqrt{\frac{k}{m}}$ is the angular frequency of natural oscillation;
- $f_0 = \frac{\omega_0}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$ is the natural frequency in Hz (hertz).
- $T_0 = 2\pi\sqrt{\frac{m}{k}}$ is the period of natural oscillation in s (second). [10]

2.2.2 Forced oscillations and the resonance phenomenon

If a real system, where a braking force of the forme acts:

$$F_f = -bv \qquad (9)$$

is also subjected to an external periodic driving force of the form:

$$F_{dr}(t) = F_0 \cos\omega t \qquad (10)$$

then, in the steady-state, the equation of motion of the body has the form:

$$x(t) = A(\omega)\cos(\omega t - \delta) \qquad (11)$$

where:
- where b is the damping coefficient (can be zero in idealized cases);
- ω is the angular frequency of external periodic driving force;
- $A(\omega)$ is the amplitude as a function of the driving frequency;
- δ is the phase shift between driving force and displacement.

The amplitude of oscillation reaches a maximum when the driving frequency ω is close to the natural frequency ω_0. This is known as ***the resonance phenomena***.
The amplitude of the forced oscillation is given by:

$$A(\omega) = \frac{F_0}{\sqrt{(k - m\omega^2)^2 + (b\omega)^2}} \tag{12}$$

In the undamped case ($b = 0$), this simplifies to:

$$A(\omega) = \frac{F_0}{\left|k - m\omega^2\right|} \tag{13}$$

The amplitude becomes very large when:

$$\omega \to \omega_0 = \sqrt{\tfrac{k}{m}} \tag{14}$$

This is ***the resonance condition***.

When the damping is present, the resonance peak is broader and its maximum occurs when the frequency of driving force is slightly less than the frequency of natural oscillation (ω_0).

$$\omega_{res} = \sqrt{\omega_0^2 - \frac{b^2}{2m}} \tag{15}$$

3 Methodology

The project consists of two distinct experimental setups, each designed to investigate a different physical phenomenon. Both experiments were carried out using smartphones equipped with the "Phyphox" and "Strobe light" applications (Fig. 3), which utilize the phone's built-in sensors for data acquisition.

Fig. 3. The two applications used in the experiments, downloaded to a smartphone

3.1 Vibrating rod experiment

In the first experiment, a wooden rod of variable length were fixed at one end to the edge of a stable table, forming a cantilever configuration (Fig. 4). The free end of each rod was manually displaced and released to induce transverse vibrations. The smartphone was placed near the vibrating rod, and the sound sensor (microphone) within the "Phyphox" application was used to record the frequency spectrum of the vibrations. The dominant frequency of the rod's vibrations (for each of its lengths) was identified using the Fast Fourier Transform (FFT) analysis provided by the application (Fig. 7). [8]

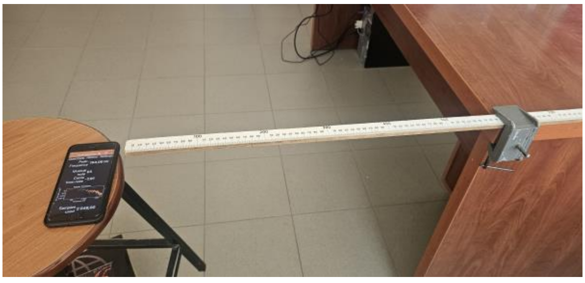

Fig. 4. A wooden rod of variable length, fixed at one end to the edge of a table, oscillates when displaced and released its free end.

3.2 Resonance in a mass-spring system

The second experiment involved a vertical mass-spring system (Fig. 5). A small body was suspended from the vertical spring. The natural frequency of the system was measured using the “Strobe light” application. Forced oscillations were induced in the system using a rotating mechanism. The device has been adapted that converts the rotational movement achieved by the handle into a translational movement of an axis. The mechanism was rotated at different frequencies which were measured using the “Strobe light” application. The frequency of the mechanism was gradually changed until resonance was observed. The resonance frequency was identified as the frequency at which the oscillation amplitude reached its maximum.

Fig. 5. The experimental setup that made it possible to realize forced oscillations.

3.3 How to measure the vibration frequency of a cantilever rod using the “Phyphox” application

To measure the frequency of vibrations of a rod that is fixed at one end (a cantilever beam), the “Phyphox” application on a smartphone can be used, which allows you to analyze sound or motion using the phone’s built-in sensors. [3, 4]

i. Materials needed:

- A wooden rod or ruler fixed at one end (Fig. 4);
- A smartphone with the “Phyphox” application installed (Fig. 3);
- A clamp or support to hold the bar firmly;
- A stand or surface to keep the smartphone stable.

ii. Steps to follow:

- Install and open “Phyphox” on your smartphone (available for free on iOS and Android);
- From the main menu, in the “Acoustics” section, select “Audio Spectrum” or “Audio FFT” (Fig. 6); (These tools analyze the sound frequencies picked up by the microphone.)
- Firmly fix the rod on one end-this simulates a cantilever.
- Place or hold the smartphone near the free vibrating end of the bar (close enough for the microphone to capture the sound).
- Pull the free end of the rod slightly, then release it and let it vibrate freely.
- On the “Phyphox” screen, you will see a graph, in which a frequency spectrum is shown (Fig. 7).

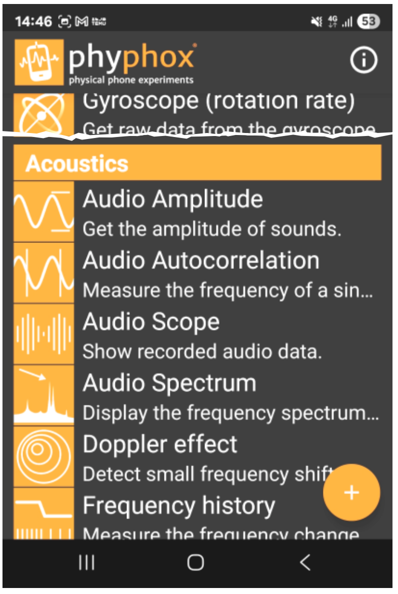

Fig. 6. The “Audio Spectrum” program used in the “Phyphox” application.

When a body vibrates, it produces not just one frequency, but a signal of harmonics. The spectrum found in “Phyphox” is a real reflection of this mixture, and each peak on the graph is a term in the Fourier series of the oscillation. In this way, an experimental tool is used to visualize Fourier series.

The horizontal axis (*X*) shows frequency (in Hz); the vertical axis (*Y*) shows amplitude in arbitrary units (arb. units). Arbitrary units are used when amplitude is not calibrated in standard units like decibels. They're useful for comparing relative strengths of different frequencies, not their absolute loudness. [11]
- Look for the dominant peak in the graph - this corresponds to the natural frequency of vibration.
Depending on the application, the fundamental frequency (peak) may also be displayed written on the screen, as shown in the figure. (The fundamental frequency in this case is 164.06 Hz.)

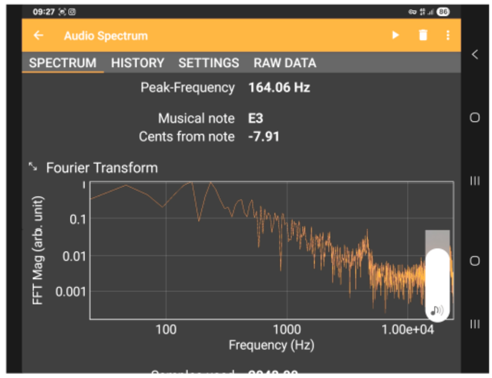

Fig. 7. Furie analysis of a sound, obtained from the "Phyphox" application.

Note: To get the best results, you need to:
- Perform the experiment in a quiet environment to reduce background noise.
- Use a stable surface or phone holder to minimize movement.
- Make sure the rod is not touched during the measurement.
- Try several times to see if the frequency value is stable.

3.4 How to measure the oscillation frequency of a mass-spring system using the "Strobe light" application

To measure the oscillation frequency of the mass-spring system, the "Strobe light" application on a smartphone can be used (Fig. 3), or any application that gives us stroboscopic effects.
This application visually measures the oscillation frequency of systems that perform periodic oscillations, such as the spring-body system. It works based on the stroboscopic effect, where a flashing light is used to create the illusion of a stationary or slowly moving object. This occurs when the frequency of the flash matches the frequency of the object's movement.

i. Materials needed:
- A mass hanging from a vertical spring, forming a classic mass-spring oscillator (Fig. 5);
- A smartphone with the "Strobe light" application installed (Fig. 3);
- A mechanism that causes forced oscillations (e.g. a rotating system).
- A stand or surface to keep the smartphone stable.

ii. Steps to follow:
- Open the "Strobe Light" application on your phone.
- The application emits flashes of light at a user-defined frequency (you can adjust the flash rate in Hz).
- Direct the flashing light toward the oscillating system in a dim or dark environment.
- Slowly adjust the strobe frequency. When the frequency of the strobe matches the frequency of the mass's oscillation, the mass will appear to stand still or move very slowly (Fig. 8). [11]

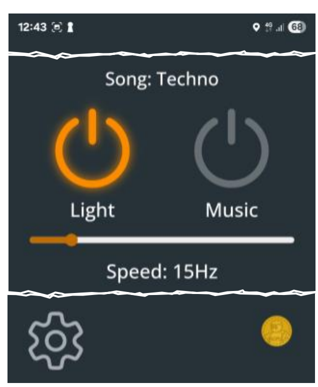

Fig. 8. Adjusting the stroboscopic frequency.

- This visual "freezing" effect occurs because the light illuminates the object at the same point in each cycle.
- The frequency shown on the application at the moment the motion appears frozen is the oscillation frequency of the system (in Hz).
- The same procedure is followed to observe the phenomenon of resonance. As the frequency of the mechanism that causes forced oscillations is changed, the amplitude of the oscillations also changes. The moment when "a frozen" image is seen, when the amplitude is maximum, is the moment of observing the phenomenon of resonance. The corresponding stroboscop frequency at this point is "the resonance frequency" of the system. [6, 7]

4 Results

4.1 A rod fixed at one end

In the first experiment, we investigated the vibration frequencies of a wooden rod (mulberry wood), with one end fixed and the other end free. It is known (Eq. 7) that the theoretical fundamental frequency of oscillation for this case is given by:

$$f = \frac{1.875^2}{2\pi L^2}\sqrt{\frac{EI}{\rho A}} \qquad (7)$$

Since we want to study the reliability of measurements made with smartphones, we bring this function to a more convenient form.

$$f = \frac{1.875^2}{2\pi}\sqrt{\frac{EI}{\rho A}}\cdot\frac{1}{L^2} = \frac{K}{L^2} \qquad (7.1)$$

$$K = \frac{1.875^2}{2\pi}\sqrt{\frac{EI}{\rho A}} \qquad (7.2)$$

Here, K represents a constant, which depends on the characteristics of the rod. For our experiment the parameters for the rod used (mulberry wood) are as follows:

$E = 9\ 320\ \text{MPa} = 9.32\times10^9\ \ \text{N/m}^2$

$\rho = 650\ \ \text{kg/m}^3$

$b = 27.3\ \text{mm} = 0.0273\ \text{m}$

$h = 8.14\ \text{mm} = 0.00814\ \text{m}$

$A = b\cdot h = (0.0273\ \text{m})(0.00814\ \text{m}) = (222\times10^{-6})\ \text{m}^2$

$I = \frac{1}{12}bh^3 = \frac{1}{12}(0.0273\ \text{m})(0.00814\ \text{m})^3 = 1.230\times10^{-10}\ \ \text{m}^4$

Making the substitutions in (7.2) we find that the theoretical value for K_{th} is:

$$K_{th} = \frac{1.875^2}{2\cdot3.14}\sqrt{\frac{(9.32\times10^9\ \frac{\text{N}}{\text{m}^2})(1.23\times10^{-9}\ \text{m}^4)}{(650\ \frac{\text{kg}}{\text{m}^3})(222\times10^{-6}\ \text{m}^2)}} = 10.6400\ \frac{\text{m}^2}{\text{s}}$$

This value will be compared with the value found using data from experimental measurements (Table 1).

L (m)	0.75	0.7	0.65	0.6	0.55	0.5	0.45	0.4
L^2 (m^2)	0.5625	0.49	0.4225	0.36	0.3025	0.25	0.2025	0.16
$1/L^2$ (m^{-2})	1.78	2.04	2.37	2.78	3.31	4.00	4.94	6.25
f (Hz)	20.24	25.13	27.47	34.28	36.14	44.53	59.63	67.17

Table 1. Measured frequency values, for different ruler lengths.

To increase the accuracy and reliability of the experiment, with the data in the table and based on (Eq. 7.1) we construct the linear dependence graph (Fig. 9, ①):

$$f = K_{exp} \cdot x \qquad (7.1^*)$$

where $x = 1/L^2$.

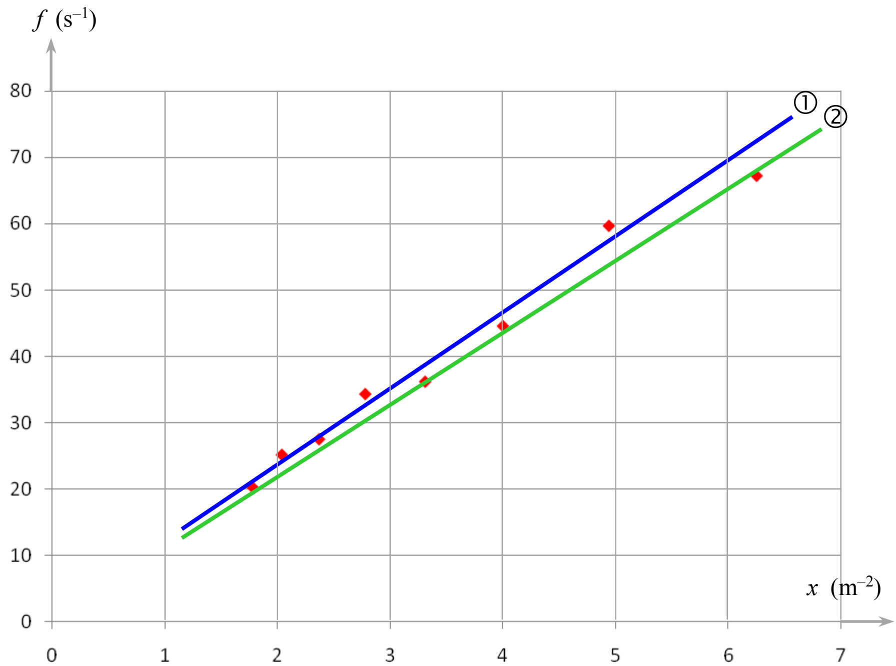

Fig. 9. Graph of the dependence of the oscillation frequency from the inverse of the square of L ($f \sim 1/L^2 = x$).

4.2 A mass-spring system

The study of the phenomenon of resonance with the mass-spring system consists of comparing the frequency of the forcing factor with the frequency of the free oscillations of the system. The frequency of the free oscillations of the system is found if the coefficient of elasticity of the spring and the hanged mass in it are known.

The spring may have a known coefficient of elasticity, but even if this coefficient is not known, it can be found with a simple experiment, based on Hooke's law. Various masses are attached to the spring and the elongation of the spring is measured in each case.

$$mg = k \cdot \Delta l = k(l - l_0)$$

From these measurements (Table 2) the average value of the elasticity coefficient is found:

m (kg)	0	0.02	0.04	0.06	0.08	0.1	0.12	0.14	160
l (m)	0.29	0.305	0.325	0.34	0.355	0.372	0.395	0.407	42.5
Δl (m)	0	0.015	0.035	0.05	0.065	0.082	0.105	0.117	13.5
k (N/m)		13.1	11.2	11.7	12.1	12.0	11.2	11.7	11.6

Table 2. Measurements for finding the coefficient of elasticity of a spring.

$$\bar{k} = \frac{\sum_{i=1}^{8} k_i}{8} = 11.830 \ \frac{\text{N}}{\text{m}}$$

To study the phenomenon of resonance in a mass-spring system, we hang a body with a mass of m = 150 g = 0.150 kg. From the calculations, based on (Eq. 14) we find the cyclic frequency of free oscillations of the system:

$$\bar{\omega}_{01exp} = \sqrt{\frac{\bar{k}}{m}} = \sqrt{\frac{11.830}{0.150}} = 8.880 \ \text{rad} \cdot \text{s}^{-1}$$

The cyclic frequency of the free oscillations of the system has also been found from measurements with the "Strobe light" application. For this, different oscillation frequencies are measured and the mean frequency is calculated:

$$\bar{f} = \frac{f_1 + f_2 + f_3 + f_4}{4} = \frac{1.29 + 1.36 + 1.32 + 1.28}{4} = 1.310 \ \text{s}^{-1}$$

Then the cyclic frequency of free oscillations of the system is calculated:

$$\bar{\omega}_{2exp} = 2\pi \cdot \bar{f} = 2 \cdot 3.14 \times 1.310 \ \text{s}^{-1} = 8.230 \ \text{rad} \cdot \text{s}^{-1}$$

With two ways of finding the natural cyclic frequency (the first based on the theoretical formula and measurements and the second on measurements with the application) we have values, the difference between which is 0.62 rad/s^{-1}. To discuss the resonance phenomenon, we take the average value of these frequencies, which is:

$$\bar{\omega}_0 = \frac{8.880 \ \text{rad} \cdot \text{s}^{-1} + 8.230 \ \text{rad} \cdot \text{s}^{-1}}{2} = 8.560 \ \text{rad} \cdot \text{s}^{-1}$$

Using the device, we perform forced oscillations. Meanwhile, using the application, we measure the rotation frequency of the mechanism, that is, the forcing factor, and using a ruler, we measure the amplitude of the oscillations. With the results found from the measurements (Table 3), a graph of the dependence of the amplitude of the oscillations on the frequency of the forcing factor is constructed (Fig. 10).

f (s^{-1})	0.32	0.64	0.95	1.27	1.59	1.91	2.23
ω (rad·s^{-1})	2	4	6	8	10	12	14
A (cm)	6	7	10	17	14	6	4

Table 3. Measurements of amplitude and frequency during resonance phenomena.

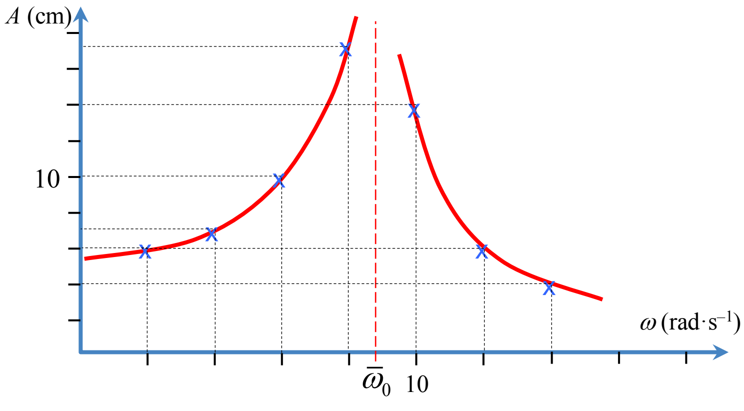

Fig. 10. Graph of the dependence of the amplitude of oscillations from the frequency of the forcing factor, during the phenomenon of resonance.

5. Analysis and discussion

5.1 A rod fixed at one end

One of the goals of the experiments is the use of smartphone applications for measurements in physics and the verification of theoretical laws through the experiment.
In the first experiment, the quantity measured with the "Phyphox" application is the vibration frequency of a rod (in our case a ruler) fixed on one side.
The reliability and accuracy of the measurements made with the mentioned application is evaluated by comparing the angular coefficients of the two graphs, the theoretical one and the experimental one. Measurements of the oscillation frequency were made for eight different lengths of the ruler. For each case, ten measurements were made and the average frequency was found.
A table was constructed with the values found (Table 1). Using statistical methods, an experimental graph (Fig. 9, ① line) was constructed, the slope of which is calculated to be 11.5600 m^2/s. (The points are found from experimental measurements.) The theoretical value of the slope of the line of this dependence (Fig. 9, ② line), mentioned above, is 10.6400 m^2/s. The absolute change of these coefficients is:

$$\Delta K = K_{exp} - K_{th} = 0.9200 \text{ m}^2/\text{s}.$$

Meanwhile, the relative difference between these two values is:

$$(K_{exp} - K_{th})/K_{th} = 8.7\%.$$

We believe that this is a satisfactory result for the method and application used to perform the measurements. This shows that the "Phyphox"-"Audio spectrum" application can be used for quantitative measurements, in addition to qualitative ones.
Data taken from technical physics manuals were used to find the theoretical value of the coefficient of elasticity.
Of course, during the measurements, care was taken to limit other sounds that could influence the measurement of the fundamental frequency values. This was achieved by repeating the measurements for a certain length of the ruler.

5.2 A mass-spring system

The purpose of the second experiment was to identify the resonance frequency. Its measurement is done with the "Strobe light" application.
With the two methods used, we have found approximate values of the cyclic frequency of natural oscillations of the body-spring system. The difference between them is 0.65 $rad \cdot s^{-1}$. This assesses the reliability of the method of using the smartphone application.
We will continue the discussion by considering the average value of the values found, which we will call the frequency of free oscillations of the system mass-spring, which in this case is $\omega_0 = 8.56$ $rad \cdot s^{-1}$.
The reliability and accuracy of the measurements made with the mentioned application are assessed by ascertaining in which cases the resonance phenomenon is most noticeable (Fig. 11).
Amplitude measurements were performed for seven different frequencies of the binding force, frequencies which were measured using the application. In four cases the cyclic frequency was smaller and in three cases larger than the frequency ω_0 of the free oscillations of the system. Both from the table and from the graph of the dependence of the amplitude from the frequency, it is easily ascertained that the amplitude reaches the largest value when the frequency of the forcing factor approaches (to the left or right) the frequency of the free oscillations, i.e. ω_0. This is the theoretical condition for observing the resonance phenomenon, the experimental completion of which confirms the reliability of the application used.

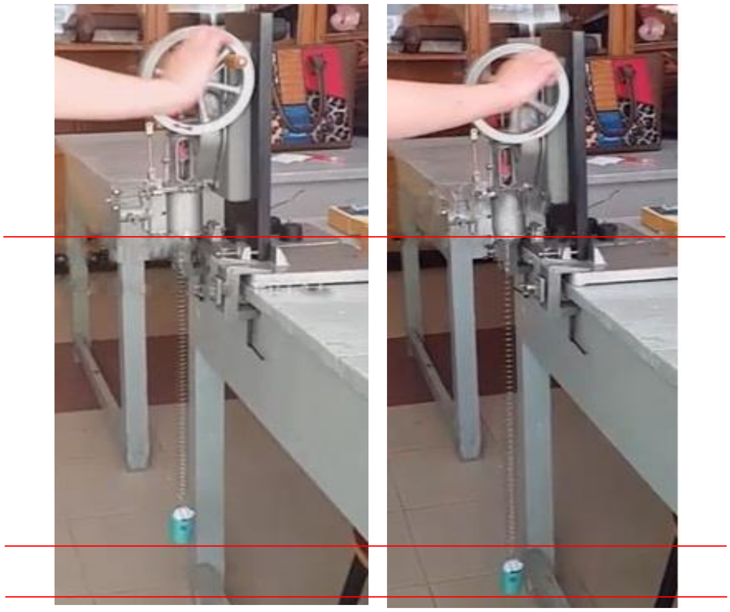

Fig. 11. Moments of carrying out the experiment and observing the resonance phenomenon.

Of course, the realization of the second part of the experiment is somewhat difficult, because two measurements must be made simultaneously, the frequency of the forcing factor and the amplitude of the oscillations. However, with a little effort, the expected theoretical conclusion can be ascertained qualitatively. This was achieved by repeating the measurements several times, for the same frequency of the forcing factor.

6. Conclusions and suggestions

This study successfully achieved its primary goal of demonstrating how smartphone applications can be effectively integrated into physics teaching, particularly in exploring classical mechanics concepts such as natural frequencies and resonance. Through two separate experiments, measuring the vibration frequencies of wood rod and studying the resonance phenomenon in a mass-spring system, the research highlighted the potential of smartphone technology to serve as an accessible, accurate, and cost effective alternative to traditional laboratory equipment.

In the first experiment, the "Phyphox" application was used to measure the vibration of the rod with various length. The experimental results, averaged over ten measurements for each length, were compared with theoretical predictions. The analysis showed a close agreement: the experimental slope of the frequency-length dependence was 11.5600 m^2/s, compared to the theoretical value (10.6400 m^2/s). The relative error of 8.7% is considered acceptable, confirming that the application provides reliable quantitative data.

In the second experiment, "Strobe light" was used to determine the resonance frequency of a mass-spring system. The natural frequency found was $\omega_0 = 8.65$ rad/s, and the resonance confirmed by observing maximum oscillation amplitudes when the driving factor frequency approached ω_0. Despite the challenge of simultaneous amplitude and frequency measurements, the repetition of trials helped achieve consistency and align results with theoretical expectations.

Overall, the use of smartphones enables hands-on learning, encourages student interaction with real systems, and provided results that validate theoretical models. These findings demonstrate that the applications of smartphone can enhance both the teaching experience and the precision of experimental physics at the undergraduate level.

Below we can give some recommendations for improving physics teaching through the use of smartphone applications.

- To strengthen the connection between theoretical concepts and real-world phenomena, physics teachers should formally include applications of smartphones.Their use can modernize the learning experience and make experiments more engaging and relatable.
- Students should be encouraged to design parts of the experiment themselves, formulate hypotheses, and use smartphone to test them. This fosters active learning, critical thinking, and deeper conceptual understanding.
- Since smartphones are widely available, their use helps reduce reliance on expensive equipment. This enables all students, regardless of resources, to perform meaningful scientific investigations, both in the lab and at home.
- Students should not only collect data but also reflect on its accuracy, limitations, and alignment with theoretical expectation.

References

1. R. Vieyra, C. Vieyra, P. Jeanjacquot, A. Martí, M. Monteiro, Turn your smartphone into a science laboratory (2015)
2. M. Á. González, M. E. Martín, C. Llamas, Ó. Martínez, J.Vegas, C. Hernández, Teaching and Learning Physics with smartphones (2015).
3. C. Llamas, M. Á. Gonzalez, C Hernández, J. Vegas, Open source hardware based sensor plat form suitable for human gait identi cation (2017)
4. M. Á. González, A. Gómez, M. Á. González, Smartphones in the air track, examples and diffculties (2019)
5. P. Klein, J. Kuhn, A. Müller, S. Gröber, Multidisciplinary Research on Teaching and Learning (2014)
6. J. Kuhn, P. Vogt, A. Müller, Analyzing elevator oscillation with the smartphone acceleration sensors (2014)
7. J. Chevrier, L. Madani, S. Ledenmat, A. Bsiesy, Teaching classical mechanics using smartphones (2013)
8. S. Whitney, Vibrations of Cantilever Beams: Deflection, Frequency (1999)
9. D. Gritsenko, J. Xu, R. Paoli, Transverse vibrations of cantilever beams: Analytical solutions with general steady-state forcing (2020)
10. https://courses.lumenlearning.com/calculus3/chapter/simple-harmonic-motion/
11. https://phyphox.org
12. https://vlab.amrita.edu/?sub=3&brch=175&sim=1080&cnt=1