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A Complete Arduino-Based Mathematical Pendulum Experiment Tool with Real-Time Data Acquisition Using an Excel Spreadsheet

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ABSTRACT
It is very important for students to understand the concept of simple harmonic motion, such as a mathematical pendulum. Students need an experiment tool on mathematical pendulums that is capable of providing measurement results of various physical quantities of mathematical pendulums accurately and precisely. This research aims to (1) describe the specifications of an Arduino-based mathematical pendulum experiment tool, (2) describe the results of measurements of acceleration due to gravity, and (3) describe the effect of changes in deviation on the period at small angles. This research used the experiment method. The research results showed that (1) the Arduino-based mathematical pendulum experiment device is equipped with an HC-SR04 ultrasonic sensor to measure the length of the string and an FC-51 infrared sensor to measure the period with a precision of 94.9% and accuracy of 99%, (2) the average result of acceleration due to gravity measurements at various string length was (9.72 ± 0.19) m/s^2, and (3) the mathematical pendulum period between angles of 1-13 degrees did not show a significant difference, showing that at small angles, the oscillation period is not affected by deviation.

INTRODUCTION

Physics is one of the science subjects that studies the universe, including matter, energy, and their interactions. The purpose of physics learning is to develop student's scientific knowledge, skills, and attitudes. Several principles that can be applied to develop the characteristics of physics learning include active learning, contextual, cooperative, and the use of technology [1]. Physics learning must be carried out actively, both physically and mentally. Therefore, students must be actively involved in the learning, either through experimental activities, discussions, or presentations [2]. Physics learning should be linked to the daily life context to help them understand abstract and complex physics concepts. Physics learning is also able to be carried out cooperatively by involving students in small groups to help them develop critical thinking and problem-solving skills. In order to increase the effectiveness of physics learning, technology can be used, as it is able to present interesting and interactive learning material, as well as facilitate experimental and simulation activities.

Laboratory work is a learning method in the form of structured activities that give students the opportunity to gain concrete experiences that can increase their understanding of the theory or master certain skills related to the knowledge [3]. Laboratory work is not merely an experimental activity carried out by students to prove concepts/laws that have been studied in class but also should be able to facilitate students to discover concepts themselves [4]. Laboratory work must be carried out in an environment that is adapted to the learning objectives so that students are involved in planned learning experiences and able to interact with the experimental equipment to observe and understand phenomena [5]. Therefore, laboratory work can help students to achieve the goals of physics learning such as understanding physics concepts more deeply, because they can directly observe the physical phenomena that occur in the laboratory. Laboratory work also helps students in developing critical thinking skills, problem-solving, psychomotor skills, and scientific attitude [6].

Laboratory work has many advantages compared to other learning methods. Laboratory work allows students to learn the problem-solving process through the observation and manipulation of variables [7]. It also gives them the opportunity to test the theories obtained in real situations [8]. Additionally, laboratory work is very important to support the learning and emphasize the process aspects because of the opportunity given to the students to carry out experiments and develop skills such as classifying, observing, measuring data, interpreting, and communicating [9].

Simple harmonic motion is a physics concept that has a close relationship with everyday life, for instance, the application of the mathematical pendulum in a clock. Nonetheless, several studies show that students experienced difficulties in understanding simple harmonic motion, such as in understanding the concept of harmonious vibrations in the form of mathematical equation representation, describing and reading position versus time graphs, determining factors that cause the total energy of harmonious vibrations remain constant, and determining parameters that influence the magnitude of the spring and pendulum period values [10]. Students' low understanding of simple harmonic motion is shown by their confusion in determining the time of the moving pendulum when the length of the string is changed from the initial length [11]. Besides, the difficulty was also often found in measuring the period of one full vibration correctly so that the laboratory work data deviated from the theory [12].

One of the factors that influences the succession of practical activities is the use of experiment tools that effectively and efficiently help students study a physical phenomenon [13]. Alongside technological developments, the use of electronic technology-based experiment tools has been proven to be able to provide accurate and precise experimental results [14]. The use of technology in physics experiments can be in the form of the creation of experiment tools within the use of electronic sensors, for instance, Arduino-based experiment tools. The use of Arduino-based experiment tools has been widely used in physics experiments such as inclined plane experiments [14] and mathematical pendulum experiments [15] [16] [17].

In simple harmonic motion experiments, the use of Arduino-based practical tools has been proven to improve students' experimental skills and understanding [18], while real-time visualization with Arduino can be a practical medium for teaching the concept of types of damping [17]. For simple harmonic motion on the topic of a mathematical pendulum, the use of an Arduino with an infrared sensor can provide more accurate and precise period measurement results compared to using traditional tools that still use a manual stopwatch [19]. The use of Arduino with a proximity sensor can be applied to measure the period and length of a string in a mathematical pendulum experiment which has great potential to improve students' understanding [20].

The mathematical pendulum experimental tool developed by Egy and Fauzi used only an infrared sensor to measure the oscillation period [19]. Meanwhile, the experimental tool developed by Sa`adah & Prabowo used a proximity sensor to measure the period and length of the string, with some limitations [20], namely, it has only three string length manipulations and when the string length is less than 0,35 m, the deviation must be greater than 5^0 so that the sensor can detect the oscillation. In addition, both experimental devices did not show the typical characteristics of simple harmonic motion, namely, at small angles, the oscillation period is not affected by changes in deviation.

According to these two studies, an Arduino-based mathematical pendulum practical tool was developed using infrared for the period measurement and an ultrasonic sensor for the string length measurement. Therefore, the objectives of this research are (1) to describe the specifications of an Arduino-based mathematical pendulum experimental device, (2) to describe the results of measuring acceleration due to gravity, and (3) to describe the effect of changes in deviation on the period at small angles.

METHOD

This research was experiment research. This experiment is based on the case of a simple pendulum consisting of a mass attached to a string, which is then given a small displacement. Mathematically, this pendulum can be described by a differential equation

$$\frac{d^2\theta}{dt^2} + \frac{g}{l}\theta = 0 \tag{1}$$

Assuming that the swing occurs at a small angle so that $\sin\theta \approx \theta$, the period of the pendulum can be expressed by the equation

$$T = 2\pi\sqrt{{}^{l}/_{g}} \tag{2}$$

The acceleration due to gravity was calculated based on Equation (2)

$$g = 4\,\pi^2 \frac{l}{T^2} \tag{3}$$

The dependent variable of this research was the acceleration due to gravity, while the independent variables were period, length of string, and angle of deviation. Then, g was reported in Equation (4)

$$g = \bar{g} \pm \Delta g \tag{4}$$

Where Δg represents the standard deviation. Δg calculated based on the Equation (5)

$$\Delta g = \sqrt{\frac{\sum(g_i - \bar{g})^2}{n(n-1)}} \tag{5}$$

with n representing the number of measurement data.

The data of acceleration due to gravity was collected after calibrating the tool by measuring the length of the string and the period. Calibration of the string length was carried out by comparing the results of measuring the length of the string with a ruler and measuring the length of the string with the developed tool. The calibration of the oscillation period was carried out by comparing the measurement results of the period by a stopwatch with the measurement results of the period by the developed tool. The existence of the difference in the results of the length measurement of the string and the period was determined by using statistical analysis of the two-tailed t-test at an error rate of 5%. The two-tailed t-test equation used is shown in Equation (6).

$$t = \frac{\bar{x}_1 - \bar{x}_2}{s\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \tag{6}$$

s represents the standard deviation

RESULTS AND DISCUSSIONS

The experimental equipment circuit is shown in Figure 1.

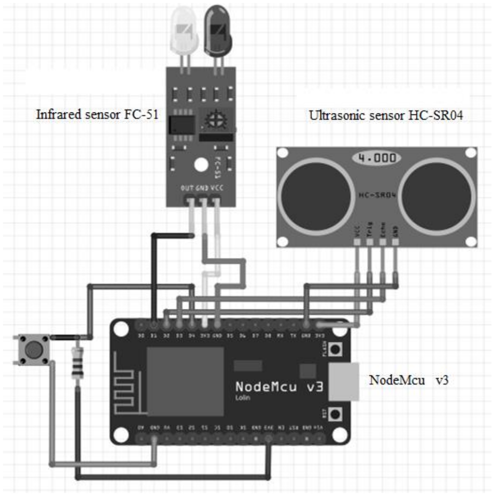

Fig 1. *Electronic circuit of the experimental equipment*

This practical tool for measuring the length of the string and the period of the mathematical pendulum is equipped with an HC-SR04 ultrasonic sensor to measure the length of the string and an FC-51 infrared sensor to measure the pendulum period, connected to the NodeMCU v3 microcontroller. A 330 Ω resistor is used to limit the current flowing to the 3V3 pin on the NodeMCU v3. The developed experimental equipment is shown in Figure 2.

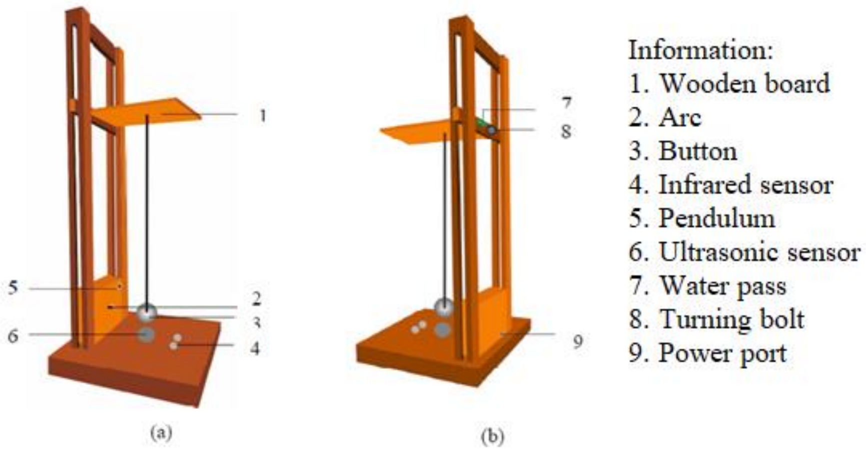

Fig 2. *Mathematical pendulum experiment equipment (a) front view (b) back view*

The working principle of the HC-SR04 ultrasonic sensor is that the sensor emits ultrasonic waves, which are reflected by a board and return to the sensor. The NodeMCU v3 microcontroller calculates the distance between the sensor and the board by multiplying the speed of the ultrasonic waves, which is 340 m/s, by half the time taken for the waves to travel from the sensor and back. The FC-51 infrared sensor emits infrared light, which is reflected back to the sensor when an object obstructs the light.

The NodeMCU v3 microcontroller calculates the time taken for the pendulum to pass the sensor for the first time until it passes the sensor for the third time (the period of one complete oscillation). The results of this data are displayed in a spreadsheet in real-time.

The calibration results of the tool by measuring as much as 20 observation data of the pendulum period showed that the average period measurement result by stopwatch was 1.64 s with a standard deviation of 0.09 while the period measurement result by the developed tool was 1.62 s with a standard deviation of 0.08. According to the statistical calculation results of the two-tailed t-test, the 20 observation data were in the critical area -2.08596 < t < 2.08596. By using the two-tailed t-test, the t value was obtained to be 0.532486, which was still in the critical area. Therefore, it was concluded that there was no significant difference between the period measurement result by the stopwatch and the developed tool. The results of the calibration by measuring the length of the string were carried out on a string length of 0,30 m. According to the measurement results and analysis of the two-tailed t-test, the observation data was in the critical area of 2.08596 < t <2.08596 with a t value of 1.73. Based on these results, it can be concluded that there was no significant difference in the length measurement result of the string by the ruler and the developed tool. The calculation result of the accuracy and precision of the developed experimental tools showed an accuracy of 99% and a precision of 94.9%. Thus, it can be concluded that the developed experimental tool is capable of gaining highly precise and accurate experimental data values.

The measurement of the acceleration due to gravity was carried out on five variations of string length, namely 0.40 m, 0.50 m, 0.60 m, 0.70 m, and 0.80 m. The example of the calculation results for the acceleration on a string length of 0.40 m is shown in Table 1.

Table 1. Calculation of Period and Acceleration due to Gravity on a String Length of 0.40 m

No	T (s)	g (m/s^2)
1	1.27	9.78
2	1.27	9.78
3	1.28	9.63
4	1.27	9.78
5	1.28	9.63
6	1.28	9.63
7	1.27	9.78
8	1.26	9.94
9	1.28	9.63
10	1.28	9.63

According to Table 1, the average acceleration due to gravity for ten observation data on a string length of 0.40 m was 9.72 m/s^2 with a standard deviation of 0.12. At a string length of 0.40 m, the acceleration due to gravity was in the range of (9.60 -9.84) m/s^2. The recapitulation of the calculation of acceleration due to gravity for various string lengths is shown in Table 2.

Table 2. The Calculation of Acceleration Due to Gravity for Various Lengths of String

No	l (m)	g (m/s^2)
1	0.40	9.72 ± 0.12
2	0.50	9.67 ± 0.46
3	0.60	9.75 ± 0.14
4	0.70	9.71 ± 0.13
5	0.80	9.70 ± 0.14

Based on Table 2, the acceleration due to gravity varied from (9.70 ± 0.14) m/s^2 at a string length of 0.80 m and (9.75 ± 0.14) m/s^2 at a string length of 0.60 m. The average acceleration due to gravity for the five variations of string length was (9.72 ± 0.19) m/s^2. Thus, the measurement range for acceleration due to gravity at five variations of string length from 0.40 m to 0.80 m was (9.60 - 9.84) m/s^2.

According to the theory, one of the main characteristics of simple harmonic motion in a mathematical pendulum is that the period of small oscillation is independent of its deviation. Therefore, period measurements were carried out by varying the deviation angle values. The calculation results of the mathematical period of the pendulum at various angles are shown in Table 3.

Table 3. Comparison of Mathematical Pendulum Periods at Various Angles

Deviation (degree)	**1**	**3**	**5**	**7**	**9**	**11**	**13**	**15**
Period (s)	1.57	1.60	1.60	1.60	1.60	1.60	1.60	1.61
	1.60	1.60	1.60	1.60	1.60	1.60	1.60	1.61
	1.61	1.59	1.60	1.60	1.60	1.60	1.61	1.61
	1.60	1.60	1.60	1.60	1.60	1.60	1.60	1.61
	1.59	1.60	1.60	1.60	1.60	1.60	1.60	1.61
	1.60	1.60	1.60	1.60	1.60	1.60	1.61	1.61
	1,.59	1.60	1.60	1.60	1.60	1.60	1.60	1.61
	1.60	1.60	1.60	1.60	1.60	1.60	1.61	1.61
	1.59	1.60	1.60	1.60	1.60	1.60	1.60	1.61
	1.60	1.59	1.60	1.60	1.60	1.60	1.60	1.61
Average	1.60	1.60	1.60	1.60	1.60	1.60	1.60	1.61

Based on Table 3, the oscillation period of the mathematical pendulum was independent of deviation from an angle of 1^0 to 13^0. The slight difference in period at angles of 1^0, $2^{0,}$ and 13^0 does not indicate any changes in period because the rounding of the average period by taking three significant figures still resulted in the relatively same value.

The calculation result of the acceleration due to gravity using this experimental tool can serve as a complement or refinement to the previous mathematical pendulum, as can the use of an ultrasonic sensor to measure the length of the string [16] [19] [20]. The use of infra-red sensors is a solution to the use of proximity sensors which caused limitations in the form of the inability of the mathematical pendulum to measure periods at angles below 5^0. Therefore, this mathematical pendulum experiment tool becomes one of the solutions to improve the concept understanding and skills of the students [21]. This tool will allow students to be able to learn how to determine the acceleration due to gravity accurately and precisely. Besides, students will easily understand the special characteristics of simple harmonic motion, namely the independence of the oscillation period to deviation at small angles.

The response rate of the Arduino affects the accuracy or deviation of the data obtained. Therefore, in addition to ensuring that the sensors used have a high response rate, another important factor to consider when using this device is to check the stability of the data displayed on the spreadsheet before deciding whether to use the data. This is crucial to ensure that the microcontroller can read and record data from the sensors quickly and accurately. The experiment should be conducted in a room with constant weak lighting, as strong or fluctuating light intensity will interfere with the performance of the infrared sensor. Additionally, it is very important to ensure that there are no other objects too close to the measurement path of the HC-SR04 sensor. Objects near the measurement path can reflect ultrasonic waves, causing inaccurate measurements.

CONCLUSION AND SUGGESTION

Based on the description, it can be concluded that (1) the Arduino-based mathematical pendulum experiment tool is equipped with an HC-SR04 ultrasonic sensor to measure the length of the string and an FC-51 infrared sensor to measure the period with a precision of 94.9%. and accuracy of 99%, (2) The average measurement result of acceleration due to gravity at various string length variations was (9.72 ± 0.19) m/s^2 and (3) the mathematical pendulum period between 1^0-13^0 degrees did not show any significant differences, which shows that at small angles, the oscillation period is independent to its deviation. In this research, the deviation angle was still measured using a manual arc. In future research, it would be better to continue with the addition of an accelerometer sensor so that the deviation angle can be measured accurately and in real-time.

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