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Time-period Measurements of Reversible Pendulum Using Arduino

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ABSTRACT

Purpose of the study: The purpose of this study is to improve the Kater's reversible pendulum experiment by integrating an Arduino microcontroller and infrared sensor to obtain more accurate, reliable, and automated measurements of oscillation periods for determining the acceleration due to gravity.

Methodology: The methodology used in this study includes Kater's reversible pendulum, Arduino Uno microcontroller (Arduino, Italy), infrared (IR) sensor, digital stopwatch (Casio HS-3V-1R), personal computer with Arduino IDE software, data recording using Microsoft Excel, and review of related literature and student feedback survey.

Main Findings: The main findings of this study show that the modified Kater's reversible pendulum integrated with Arduino Uno and an infrared sensor successfully automated oscillation measurements, minimized human error, and improved timing accuracy. The system produced a reliable value of gravitational acceleration, g = 9.85 m/s², confirming high precision and effectiveness of the experimental setup.

Novelty/Originality of this study: The novelty of this study lies in modifying the traditional Kater's reversible pendulum by integrating an Arduino Uno and infrared sensor for automated oscillation measurement. This innovation advances existing methods by reducing human error, improving precision, and providing students with exposure to modern microcontroller applications, thereby enhancing both experimental accuracy and educational value.

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1. INTRODUCTION

Most of the experiments in the undergraduate Physics lab involve the determination of time intervals that are often measured using a stopwatch. Stopwatches are useful for experiments based on oscillations with time-interval measurements in seconds. Using the Kater's pendulum, Kater measured 86,293.44 vibrations every sidereal day last year in London (lat. 51° 31′ 8.4″ N) [1]. Experiments that require time intervals in milliseconds or microseconds require automation as they cannot be performed manually. For example, one can determine the frequency of rotation of a fast-rotating object; an electronic clock that measures time intervals in at least milliseconds is required [2]. Similarly, in the pendulum-based experiments, automatic on/off switching is required to be controlled during the experiment. For such measurements, microcontrollers [3] having a clock speed of ~MHz can be utilized.

A reversible free-swinging pendulum (Kater's pendulum) was invented by British physicist and army captain Henry Kater in 1817 to measure the local acceleration due to gravity [4]. In this context, we present the

Kater's pendulum experiment [5] in which time interval measurements are crucial in the determination of a physical quantity. In this experiment, uncertainties in observations arise due to a very short time lag between the start time and the stopping time of the stopwatch, depending on the observer's reaction times. Attempts to replace the stop-watch with the photocell [6] and using an electronic counter do not provide the flexibility of setting optimum conditions. For example, it is desirable to have the maximum number of oscillations for minimum angles of swing so that damping effects can be avoided. In experiments involving the Arduino, it is possible to set these conditions through the computer program to get better results with more confidence. We achieve more flexibility and ease in experimenting with the Arduino. Our set-up can be used with any oscillation-based experiment, but we chose Kater's pendulum because students have always found it lengthy and uncertain to perform confidently. The experiment is important because it gives the most accurate value of the 'g' and involves taking a large number of measurements about different pivot positions to get better results, but it is a tedious process to record data manually.

To address this issue, we need to take the following steps:

- simplify the process of experimenting,
- improve the technique of taking the measurements more accurately, and
- visualize the oscillations in real time.

By using Arduino interfacing, we are automating the experiment, so the measurements will be more accurate and will be completed in an optimum time. In pendulum-based experiments, damping of oscillations is common. In our setup, we can visualize oscillations in real time by seeing the damping effects for large amplitudes of vibrations. Thus, we can optimize the minimum amplitude and maximum number of oscillations to get better results.

Recently, the application of Arduino microcontroller in conducting physics experiments has generated a lot of interest [7]-[10]. The various experiments were conducted to enhance the accuracy and simplicity of the value of g with a pendulum using the Arduino set-up, and a magnetic sensor has been reported [11]-[20]. In contrast, the objective of this study is to design and implement an automated device using an infrared (IR) sensor for contactless detection of each oscillation.

Theoretical Background:

A pendulum oscillates about a horizontal axis with an angular displacement θ . Assuming a pendulum of length 'h' and having moment of inertia 'I', its motion is governed by the rotational form of Newton's second law

$$I\frac{d^2\theta}{dt^2} = -mgh\, sin\theta \qquad ...(1)$$

Using the approximation $sin\theta \approx \theta$ for small angles, the general solution of the above differential equation can be written as

$$\theta(t) = \theta_o \cos\left(\sqrt{\frac{mgh}{I}}t + \varphi\right) \qquad ...(2)$$

The time period of oscillation T is given by

$$T = \frac{2\pi}{\omega} = 2\pi\sqrt{\frac{I}{mgh}} \qquad ...(3)$$

The parallel axis theorem gives us

$$I = I_{cm} + mh^2 = mk_{cm}^2 + mh^2 \qquad ...(4)$$

We can eliminate k_{cm}^2 if we use two positions,

$$hT_A^2 - hT_B^2 = \frac{4\pi^2}{g}(h_1^2 - h_2^2) \qquad ...(5)$$

After solving for the value of 'g'

$$g = \frac{8\pi^2}{\frac{T_A^2+T_B^2}{l_A+l_B}+\frac{T_A^2-T_B^2}{l_A-l_B}} \qquad ...(6)$$

In Figure 1, we show the pendulum apparatus and the Arduino interface set-up for the experiment [21], [22].

For Kater's pendulum, high precision is achieved when the time periods T_1 and T_2 (measured from both knife edges) are equal or nearly equal. [23]-[25].

2. RESEARCH METHOD

2.1 Experimental Setup

The experimental setup, shown in figure 1, was assembled using a Kater's pendulum (manufactured by LABCARE Instruments & International Services) and the Arduino microcontroller (Uno R3 CH340G ATmega328p Development Board). An IR sensor (MH Sensor Series Flying-Fish) was positioned at the base of the pendulum to detect oscillations accurately. When the pendulum passes over the IR sensors, it detects and sends a signal to the Arduino. A Passive Buzzer (KY-006) is integrated in the setup to provide an audible alert for each pass. All components were connected and organized on a 170-point Mini Breadboard (SYB-170 White), facilitating a compact and efficient wiring layout.

(a) (b) (c)

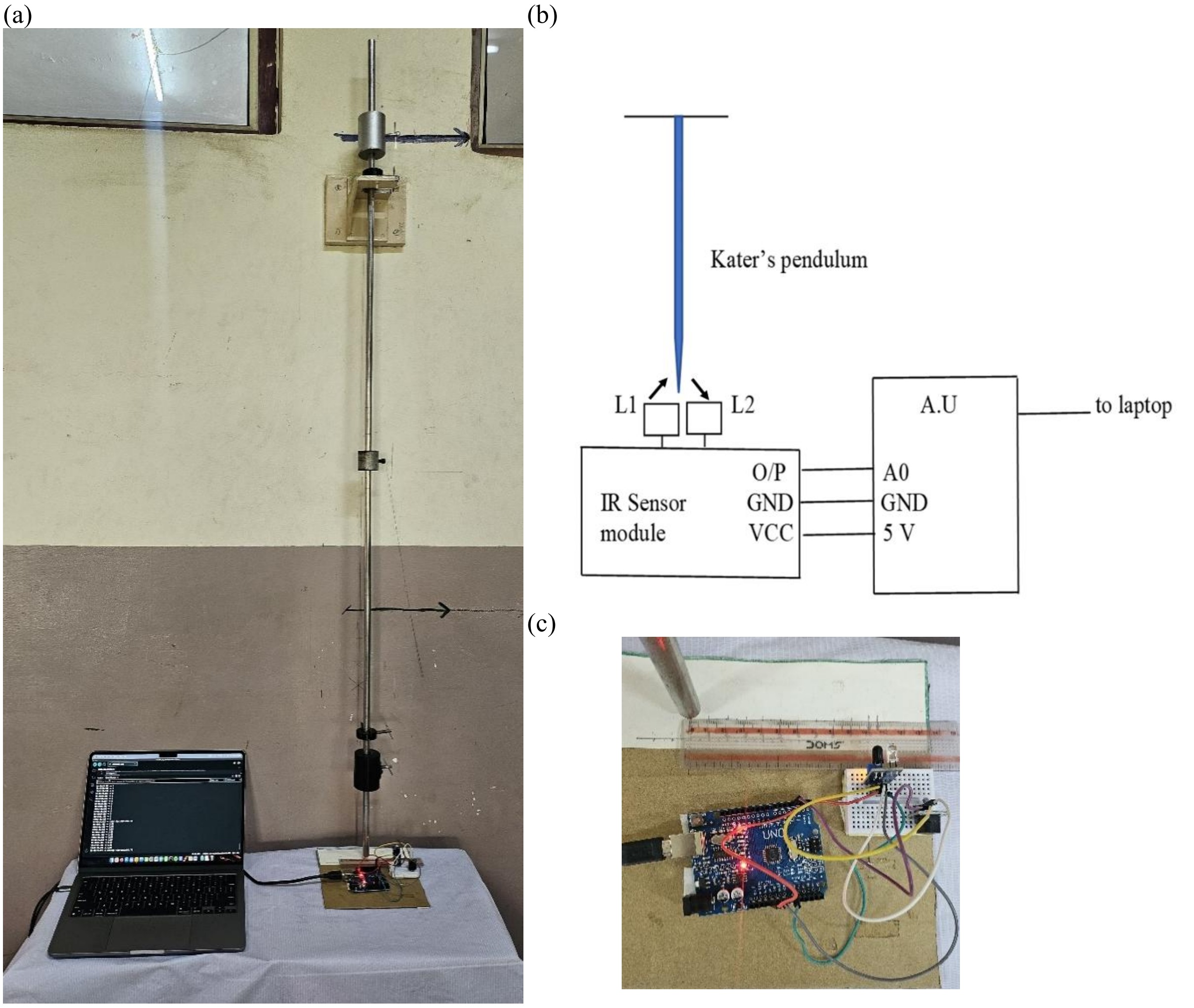

Figure 1. (a) The experimental arrangement of Kater's pendulum is depicted along with Arduino interface to PC. (b) Schematic (c) Arduino setup of Pendulum Experiment with electronic interface. L1, L2: IR Sensors, A.U: Arduino Uno3, O/P: output of IR module

2.1 Measuring Procedure

To record the time instants at which the IR sensor detects Kater's pendulum, we first set a mean position at 5 cm on the scale. Now, the pendulum is displaced by 5 cm from its mean position and then released. Each time the pendulum passes through the IR sensor, the buzzer beeps and count increments by unity. When the pendulum passes the IR sensor module 41 times, the output from Arduino stops automatically. Using the recorded time instants, the Arduino code calculates the average time period of oscillations.

The flow chart of the program for detecting the oscillations is shown in Figure 2 (Arduino code is shown in the Appendix).

The flowchart explanation:

1. Initialization.
2. When carry on is true, then the Arduino board reads further;
3. when carryon=false, returns nothing.
4. Arduino reads signals from A_0.
5. If analog voltage <0.8(low), there is an increment of 1; else, the result would be printed as 5.
6. Now, if the mean position pass>40, then the time period would be calculated; else, the Arduino rereads the pin A_0.

The program determines the average time period for the given set of oscillations. Each oscillation is depicted on the serial plotter, as shown in Figure 4, from which we can infer that the oscillations were of equal amplitudes and frequency. Time interval data sets for 20 oscillations are recorded on a serial monitor, and the average time period is determined.

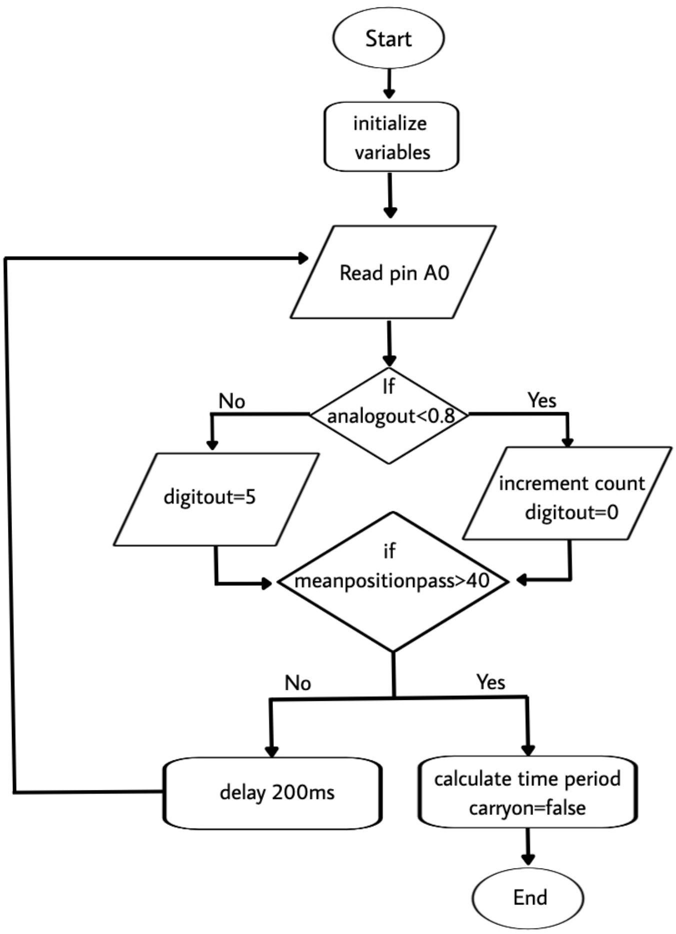

Figure 1. Flow Chart of the program written for the measurement

When we 'run' the above code, the following data of table 1 is generated on the serial monitor. In this table, we recorded the instants at which the pendulum passed over the mean position for a specified number of times. From this, the periods of oscillation are determined, and their mean is calculated by the program. Denoting, t_i=Instants of Time at mean position, i=1, 2, 3…, $T=t_{(2*i+1)}-t_{(2*i-1)}$ = time-periods for 20 oscillations.

Table 1. Observations of time period with respect to time instants recorded

t_i	**5.1**	5.8	**6.6**	7.41	**8.21**	9.01	**9.81**	10.61	**12.21**	14.01	**14.81**	15.61	**16.41**
T			**1.5**		**1.61**		**1.6**		**2.4**		**2.6**		**1.6**
t_i	17.21	**18.02**	18.82	**20.42**	22.22	**23.02**	23.82	**24.62**	25.42	**26.22**	27.02		
T		**1.61**		**2.4**		**2.6**		**1.6**		**1.6**			
t_i	**28.02**	28.83	**29.63**	30.43	**31.23**	32.03	**32.83**	33.63	**34.43**	35.23	**36.24**	37.04	**38.64**
T	**1.8**		**1.61**		**2.6**		**1.6**		**1.6**		**1.81**		**1.6**
t_i	39.44	**40.24**	41.04	**41.84**									
T		**1.6**		**1.6**									

Average time-period=1.847 s

In the Arduino menu tools, the serial plotter facility is available for recording events. One can opt to use this for visualizing oscillations as shown in Figure 4. On the y-axis is the digital voltage, which suffers a vertical dip from high to low when the pendulum gets past the mean position. An advantage of using a serial plotter is that one can identify and select the 'good' data for analysis.

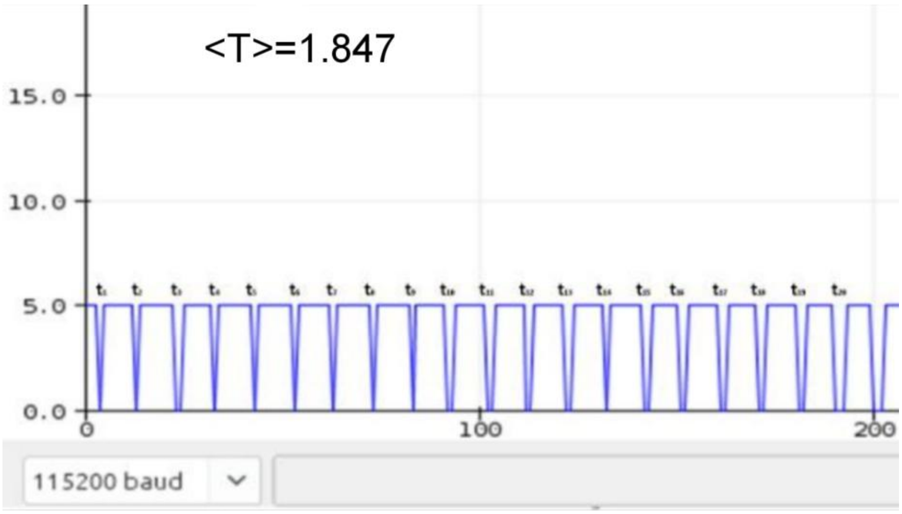

Figure 3. The output of a pendulum generated using IR sensors with Arduino, and then the data was captured on a serial plotter

3. RESULTS AND DISCUSSION

We performed the pendulum experiment in the usual manner by using a steel rod 150 cm long with two movable knife-edges A and B on either side, as shown in Figure 4.

The pendulum is made to oscillate for a fixed number of oscillations about the knife edges A and B. The position of the A is fixed throughout the experiment, while we change the position of B in steps of 2 or 4 cm away from the center of the rod and keep finding the time-period of oscillations about each of the pivots placed at distances lA and lB from CG. For each set of oscillations, the value of 'g' is determined by using the formula.

$$g = \frac{8\pi^2}{\frac{T_A^2+T_B^2}{l_A+l_B}+\frac{T_A^2-T_B^2}{l_A-l_B}} \qquad \dots (7)$$

where T_A and T_B are periods of oscillations about A and B, respectively, and l_A and l_B are the lengths between the pivot positions A and B from the position of CG on the bar, respectively.

The first aim of the experiment is to find the lengths l_A and l_B for which the period of oscillations is almost equal.

We measured the time-periods of oscillations about A and B positions of the knife-edges by keeping the position of edge A fixed and the position of B variable. The observations recorded for average periods over 20 oscillations are shown in Table 2.

Based on these observations, a plot of T_B versus l_B is shown in Figure 6, which agrees well with the earlier reported [3]. The Fig 5 below shows the position of the wedge B at which the time-period T_B is equal to the time-period about wedge A. From this position of the wedges, we can determine the value of 'g'.

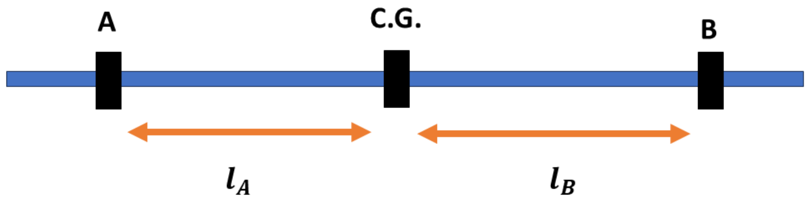

Figure 4. The pivoting wedges A and B of Kater's pendulum

Table 2. Time-period TB about knife-edge at B, lB: position of knife-edge at B from C.G.

l_B (m)	0.1	0.14	0.18	0.22	0.24	0.26	0.28	0.32	0.36	0.38	0.42	0.44	0.46	0.5
T_B(s)	2.66	2.28	2.08	1.96	1.92	1.88	1.85	1.83	1.81	1.8	1.8	1.8	1.81	1.82

l_B (m)	0.54	0.58	0.62	0.66	0.68	0.7
T_B(s)	1.84	1.87	1.89	1.92	1.93	1.95

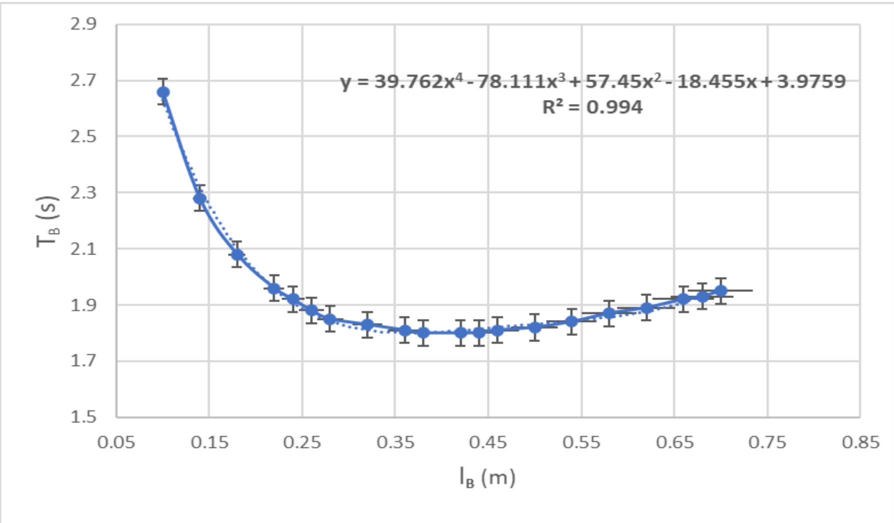

Figure 5. The variation of time-period with a change in the length from C.G. to wedge B. l_A = 0.70 m, l_B = 0.23m, and $T_A \approx T_B$ = 1.93 s

Using the values of distances of the wedges A and B from the position of CG are l_A =70 cm, l_B =23 cm, and T_A~T_B =1.93 s from expression 1, we obtain.

$$g \approx \frac{8\pi^2}{\frac{T_A^2+T_B^2}{l_A+l_B}} \quad \ldots (8)$$

Substituting the values of time-periods for l_A+ l_B =93 cm, we obtain the value of 'g' as 9.85 m/s^2.

To conclude, in this work, we have been able to achieve reasonable success in completely automating the process of experimenting. The possibility of obtaining spurious observations exists when the experiment is conducted near room windows or in a very bright environment. Additionally, care must be taken to ensure the pendulum's bottom tip passes near the IR Sensor. In this experiment, the standard deviation and variance of the recorded time periods are 0.45 and 0.2, respectively. Precision refers to the consistency or repeatability of measurements.

Several recent studies support the findings of this research regarding the effectiveness of Arduino microcontrollers and non-contact sensors in pendulum experiments. Mulyadi et al. [26] demonstrated that an Arduino-based proximity sensor system for mathematical pendulum harmonic motion achieved an error rate of less than 1% in measuring gravitational acceleration, while Fauzi et al. [27] reported up to 99% accuracy using a combination of ultrasonic and infrared sensors. Bachtiar and Ermawati [28] also confirmed the feasibility and effectiveness of infrared sensor–based pendulum practical tools in physics learning, with very high validity and effectiveness scores. Furthermore, a digital approach through the *Pendulum Tracker* based on computer vision [29], [30] provided an alternative method for real-time oscillation tracking with strong accuracy. Thus, the results of this study are consistent with previous findings but offer novelty through the integration of infrared sensors as a non-contact detection system with Arduino, enabling real-time visualization of oscillations. This novelty not only enhances measurement accuracy but also provides a more interactive learning experience. The implications of this research are significant, as it offers a modern, low-cost, and replicable experimental tool that can enrich physics education practices, support STEM-based laboratory development, and foster technology-integrated learning in the digital era.

4. CONCLUSION

The acceleration due to gravity was determined as 9.85 m/s² in Delhi using an Arduino-based measurement. We can assert that some traditional methods of conducting experiments can be modified and replaced by microcontroller-based techniques. The automation process will help students connect hardware to the physical experiment through software, which offers better control and reliability. Experiments like a simple pendulum and bar pendulum in various modes, where the time period needs to be measured for further analysis, can benefit from this approach. The present study can assist in achieving more accurate measurements.

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