Photogate sensor for compound physical pendulum experiments

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Abstract. Instructional instruments play an important role in support students’ learning through the active learning approach. This research proposes a compound physical pendulum experiment using a photogate sensor. The sensor was set up to determine the frequency of an object vibrating back and forth using the application of an Arduino board. The designed sensor can measure the frequency in a range of 0.001-1000 Hz, which can be simply used for demonstration the harmonic motion in physics laboratories. Here, the compound physical pendulum used consists of a disk of radius 4.80 ± 0.05 cm and mass 420.00 ± 0.01 g, fixed at the end of a rod of mass 125.00 ± 0.01 g and length 53.00 ± 0.05 cm. The experimental result shows a strong agreement with the theoretical calculation of the physical pendulum equation with only 2.5% difference. The low-cost photogate sensor made of an Arduino microcontroller can be one beneficial option for physics small to large classrooms.

1. Introduction

In physics classrooms, we try to use simple teaching and learning materials, but high accuracy both for demonstrations and doing the experiment. With a progress of electronics and technologies, several modern devices are developed for science teaching and learning including an Arduino board. The Arduino is low-cost, a reliable system, acquires data at a fast rate and can be used to measure dynamic variables with reasonable precision in experiments. Currently, an Arduino board is more popularly utilized in physics classes [1-5]. Applications of Arduino for a harmonic motion and related physics topics are such as an experimental investigation of Hooke’s law, and a spring’s constant of a mass-spring system in simple harmonic motion [3]. Moreover, a work of Wong and colleagues in 2015 reported the highest success rate of building correct models after using the Arduino board, which is better than the Lego Mindstorms NXT and smartphones [1].

In this study, we select to use the Arduino board and its photogate sensor to measure the frequency of a compound physical pendulum. Its results will be programmed and displayed on an LCD monitor. This instrument integrated with an interactive demonstration (or an experiment) can be used to enhance students’ learning about a vibration of a compound physical pendulum.
2. Apparatus and method

2.1. Arduino board
Arduino (UNO) is a microcontroller board based on the ATmega328P. It comprises 14 digital input/output pins (6 of them can be used as PWM outputs), 6 analog inputs, a 16 MHz quartz crystal, a USB connection, a power jack, an ICSP header and a reset button. It contains necessary components to support the microcontroller and is easy to connect to a computer via a USB cable or power it with an AC-to-DC adapter (or battery) to start. The Arduino (UNO) can be programmed with the Arduino Software (IDE).

2.2. Reflective IR sensor (TCRT5000L)
TCRT5000L are reflective IR sensors which include an infrared emitter (wavelengths 950 nm) and a phototransistor in a leaded package to block visible light. Its operate range is within > 20 % relative collector current: 0.2 mm to 15 mm. Examples of IR sensor applications are a position sensor for shaft encoder and a detector of reflective materials (i.e., papers, IBM cards, magnetic tapes and so on). Limit switch for mechanical motions in videocassette recorder (VCR) and general purpose - wherever space is limited.

2.3. Experimental setup of a compound physical pendulum
The compound physical pendulum used consists of a disk of radius \( R = 4.80 \pm 0.05 \) cm and mass \( m_2 = 420.00 \pm 0.01 \) g, fixed at the end of a rod of mass \( m_1 = 125.00 \pm 0.01 \) g and length \( l = 53.00 \pm 0.05 \) cm. As shown in figure 1(b), a distance from the rotation axis to the disk \( h = 51.40 \pm 0.05 \) cm and the thick of the disk \( L = 0.80 \pm 0.05 \) cm.

![Arduino board and LCD displays](image1)
![Experimental setup for measuring the frequency of the compound physical pendulum](image2)

**Figure 1.** (a) Experimental setup for measuring the frequency of the compound physical pendulum, (b) Structure of the pendulum used in this study.

The pendulum suspended on a stand is made to swing back and forth through a small angle in order to approximate as a simple harmonic motion. Its frequency was detected by the reflective IR sensor through Vcc (Supply voltage), GND (Ground) and Data (Signals), which connected to 5V, GND and D11 (Digital input channel 11) of the Arduino board. The Arduino board read times in active-HIGH and LOW states of digital input channel 11 that receives from the IR sensor. The collected times were calculated and converted to the frequency of the pendulum. Its flow chart was shown in figure 2. The control sequence was programmed with the Arduino Software (IDE) and displayed the results via the LCD monitor.
2.4. Theoretical frequency calculation of the compound physical pendulum

For a simple harmonic motion of the physical pendulum, its frequency \( f \) can be expressed by equation (1):

\[
\frac{1}{2\pi} \sqrt{\frac{Mgd_{CM}}{I_{support}}} = f
\]

where, \( M \) is a total mass of the system and \( g \) is the gravitational acceleration. We substituted \( g = 9.78095 \text{ m/s}^2 \) as identified by Ref. [6] at Prince of Songkla University, Thailand. \( d_{CM} \) is the distance between the rotation axis to the center of mass. The position of the center of mass of this compound physical pendulum can be calculated using the center of mass equation. We estimated that it is a uniform rod, as well as uniform disk. \( I_{support} \) is the moment of inertia of the system, where \( I_{support} = I_1 + I_2 \). \( I_1 \) is the moment of inertia of a uniform rod \( m_1 \) about the point of the suspension \( (I_1 = \frac{1}{3}m_1l_1^2) \). \( I_2 \) is the moment of inertia of a uniform disk \( m_2 \) about the point of the suspension, which is estimated by using the parallel-axis theorem, \( I_2 = I_{CM} + m_2 \left(h + \frac{L}{2}\right)^2 \). We considered the disk \( m_2 \) as a solid cylinder with the central diameter axis, where \( I_{CM} = \frac{1}{4}m_2 R^2 + \frac{1}{12} m_2 L^2 \) [7-8].

3. Results and discussion

In our apparatuses, \( d_{CM} = 46.00 \pm 0.05 \text{ cm}, I_1 = 0.01170 \pm 0.00002 \text{ kg\cdotm}^2, I_2 = 0.1129 \pm 0.0003 \text{ kg\cdotm}^2, I_{support} = 0.1246 \pm 0.0003 \text{ kg\cdotm}^2 \) and \( M = 545.00 \pm 0.02 \text{ g} \). Therefore, the theoretical frequency \( (f_{cal}) \) of this compound physical pendulum is about \( 0.706 \pm 0.003 \text{ s}^{-1} \). In another way, the average frequency

![Diagram](image-url)
of the pendulum detected by the photogate sensor of the Arduino board \((f_{ex})\) is 0.724 ± 0.005 s\(^{-1}\). It shows about 2.5\% difference between the two obtained frequencies. Sources of the difference may occur from an underestimated calculation of \(d_{CM}\) of the used rod with a curved end (shown in figure 1(b)) as the straight rod and the contact areas between the curved end of the rod and the stand are not the stationary pivot point, as well as not frictionless as mentioned in the theory [9]. This may generate an inconsistent swing of the pendulum in the experiment, and affect the average value \(f_{ex}\) detected by the photogate sensor. Results of using this sensor in a physics lecture class to interactive demonstrate the concept of a simple harmonic motion of a compound physical pendulum showed that most students were engaged in this activity. Firstly, we asked students to compute \((f_{cal})\) of the pendulum. They have a chance to reorganize idea about the physics concepts involving frequency of a physical pendulum, position of a center of mass, moment of inertia of an object and the parallel-axis theorem. After that, we explained how the photogate sensor works. Finally, we made the pendulum swing in a small angle, measured its frequency \((f_{ex})\) and displayed on the screen in front of the class. Students and the instructors also discussed physics concepts, results and limitations of the sensor. Some students volunteered to swing the pendulum in different directions. Some were interested more in Arduino board microcontroller and electronics devices. Overall, this led to more interactive lecture classroom.

4. Conclusion
This paper presents the applications of the Arduino board and its photogate sensor to investigate the frequency of a compound physical pendulum. The results indicated a high accuracy of the detected data compared with the theoretical one. Moreover, the Arduino microcontroller is low-cost and can be programmed using an open source programming language. The functionalities of systems of the Arduino platform can easily modified in order to fit the specific educational needs of the instructors. It will be advantageous to students in both physics lecture classes and laboratories.

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