The Atwood machine experiment assisted by smartphone acceleration sensor for enhancing classical mechanics experiments

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Abstract. Newton's second law can be demonstrated by classical mechanical experiments, one of which is using the Atwood machine. Atwood machines consist of two weights suspended by a rope and connected by a pulley. In this study, an Atwood machine experiment was carried out, where the smartphone was placed on one of the loads, so that the vertical acceleration of the motion system could be measured easily using an acceleration sensor. We also consider the effect of pulley rotation which is usually missed from previous studies. By deriving the second law equation of Newton on rotational and translational motion, we can get the relationship between the system acceleration and the gravitational acceleration of the earth. The results of the earth's gravitational acceleration obtained, compared with the results of the experiment using a stopwatch (conventional method), and with the value of the standard earth gravitational acceleration at that place. Earth's gravitational acceleration from the experiment using a smartphone is closer to the standard earth gravitational acceleration value than using a stopwatch. So, in this experiment, the use of a smartphone acceleration sensor contributes to enhance a conventional demonstration of classical mechanics experiments.

1. Introduction

The use of technology for learning is very important today. One of the technologies that can be used for learning physics, especially for practicum is a smartphone [1,2] and air track [3]. In today's smartphones, there are many supporting features for physics practicum, namely sensor technology such as sound, light, acceleration, and gyroscope sensors [4-7]. In addition, there is also a camera with good resolution for motion video recording purposes. In the mechanics experiment, the feature that is widely used is the acceleration sensor, for example it used in momentum, impulse, and oscillation experiments [8-10]. Apart from utilizing sensors, smartphone applications are also widely used for mobile physics learning [11,12].

One of the mechanical experiments that is often carried out at school and elementary level in college is the Atwood machine. The Atwood machine can be used to demonstrate Newton's second law. Currently, there has not been much use of acceleration sensors on smartphones for Atwood machine experiment. Even though the use of an acceleration sensor allows the acquisition of experimental data to be more practical than using classic tools such as a stopwatch. Researches related to this topic were carried out by Monteiro et al [13] and Lopez et al [14], but in that studies it had not considered pulley rotation, so the researches were only translational motion. For this reason, this study wants to improve...
this by considering the effect of pulley rotation. It also shows the practicality of using smartphones in complex experimental situations. This research is also expected to be able to offer the use of acceleration sensors on smartphones to improve classical mechanics experiment at colleges or schools.

2. Methods
In this study, we used an Atwood machine set-up consisting of a pulley with a mass \( m_p = 56.45 \) grams, smartphone with a mass \( m_s = 189.22 \) grams, and loads of varying mass \( m \) from 70.00 grams to 120.00 grams (10.00 gram intervals). The Atwood machine setup has been arranged as shown in Figure 1.

![Figure 1. Experiment set up of Atwood machine](image1)

![Figure 2. Display example of acceleration measurement using Phyphox application](image2)

Because the mass of the smartphone was greater than the mass of the load, in this motion system, the smartphone would move down with a certain acceleration. This acceleration would be recorded by the acceleration sensor on a smartphone using the Phyphox application. An example of the display of acceleration measured by a smartphone using the Phyphox application was shown in Figure 2. If seen from Figure 2, there are 3 phases, namely preparation, movement, and after movement, then system acceleration was measured from the average acceleration in the movement phase. The experiment was carried out with 6 variations of the load mass \( m \) from 70.00 grams to 120.00 grams with the addition of 10.00 grams for each variation, so that we will get 6 curves of acceleration versus time. After getting the acceleration value of the system, then we calculated the Earth's gravitational acceleration \( g \) which was obtained from equation 1. Equation 1 was obtained from deriving second Newton's law by considering the rotation of the pulley with a moment of inertia \( I = \frac{1}{2} m_p r^2 \) (\( r \) is radius of the pulley) [15].

\[
a = \left( \frac{m_s - m}{m_s + m + \frac{1}{2} m_p} \right) g \tag{1}
\]

As a comparison, we also measured the acceleration of the system in this Atwood machine experiment by the classical way using a stopwatch. When the smartphone moves down, we measured the travel time \( t \) for the vertical distance \( y = 1.00 \) m. Assuming the initial velocity of the smartphone was zero, the acceleration of the system with this method was obtained by equation 2. Next, then we calculated the Earth's gravitational acceleration with equation 1.

\[
a = \frac{2y}{t^2} \tag{2}
\]
3. Results and Discussion

The results of measuring the system acceleration using the acceleration sensor on a smartphone are shown by the acceleration versus time curve in Figure 3.

![Figure 3. Acceleration versus time curve from measurement results using acceleration sensor](image)

After we observe Figure 1, if the load mass gets bigger, the system acceleration will be smaller. This is in accordance with equation 1. Changes in system acceleration due to variations in load mass \( m \) also cause smartphone travel time to change for the same distance. From the curve in Figure 1, we can calculate the system acceleration and the Earth's gravitational acceleration as shown in Table 1. Using statistical rules, we obtain the Earth's gravitational acceleration \( g = (9.79 \pm 0.03) \text{ m/s}^2 \). Figure 3 also shows that the use of an acceleration sensor on a smartphone can capture quantitative data features in school physics experiments (16).

| \( m \) (gram) | \( m_p \) (gram) | \( m \) (gram) | \( a \) (m/s²) | \( g \) (m/s²) |
|---------------|----------------|---------------|--------------|-------------|
| 189.22        | 56.45          | 70.00         | 4.08         | 9.84        |
| 189.22        | 56.45          | 80.00         | 3.58         | 9.75        |
| 189.22        | 56.45          | 90.00         | 3.16         | 9.79        |
| 189.22        | 56.45          | 100.00        | 2.76         | 9.82        |
| 189.22        | 56.45          | 110.00        | 2.36         | 9.75        |
| 189.22        | 56.45          | 120.00        | 2.01         | 9.80        |

While the results of the measurement of the acceleration of the motion system and the acceleration of the earth's gravity in an experiment using a stopwatch are shown in Table 2. From Table 2, we get the \( g = (9.57 \pm 0.14) \text{ m/s}^2 \).

If we compare the error value of Earth's gravitational acceleration between experiment using an acceleration sensor and a stopwatch, the results from the experiment using the acceleration sensor is more precise. This result show that the use of acceleration sensors for mechanics practicum produce in
more precise experimental results [16,17]. So that the use of an acceleration sensor produces good performance in terms of data acquisition and is also practical in its implementation [14]. According to Vogt and Kuhn [18], Earth’s gravitational acceleration is measured using an acceleration sensor on a smartphone provide a sufficient level of accuracy for learning in school.

Table 2. Calculation result of system acceleration and the Earth’s gravitational acceleration for Atwood experiment using stopwatch

| m (gram) | y (m) | t (second) | a (m/s²) | g (m/s²) |
|---------|-------|------------|----------|----------|
| 70.00   | 1.00  | 0.71       | 3.97     | 9.57     |
| 80.00   | 1.00  | 0.76       | 3.46     | 9.43     |
| 90.00   | 1.00  | 0.80       | 3.13     | 9.68     |
| 100.00  | 1.00  | 0.87       | 2.64     | 9.40     |
| 110.00  | 1.00  | 0.92       | 2.36     | 9.77     |
| 120.00  | 1.00  | 1.01       | 1.96     | 9.56     |

Next, we compare the value of the Earth's gravitational acceleration obtained from the two experimental methods above with the reference value of the Earth's gravitational acceleration at the experimental place from direct measurements using the Phyphox application. Figure 4 is display of direct measurement of the Earth’s gravitational acceleration using the Phyphox application which shows the value of \( g = 9.80 \text{ m/s}^2 \). From these results, we get the argument that \( g \) value generated from the Atwood machine experiment using an acceleration sensor is more accurate because it is closer to the reference value of \( g \).

Figure 4. Direct measurement of Earth's gravitational acceleration reference using Phyphox application

Apart from the precise measurement results, the Phyphox application options used in this study also have several advantages, namely being able to present kinematics concepts to students directly and wirelessly, providing analyzed data to a smartphone screen or desktop computer [19]. But on the other hand, the use of smartphones in mechanic labs is quite risky if the smartphone falls during the experiment [16]. So, if Atwood’s equipment does not allow for a smartphone to be attached, then the use of the classic method with a stopwatch is recommended. Even though in fact the use of smartphones
for learning is currently very suitable because the world is in a pandemic era that demands online learning [20].

4. Conclusion
The Atwood machine experiment assisted by the acceleration sensor on the smartphone obtained more precise and accurate results than using the classic method with a stopwatch. Data acquisition also took place practically and easily. This argument indicates that in the next the use of smartphones can enhance classical mechanics experiments in schools and colleges. But it is necessary to consider the risk of falling the smartphone during the experiment. One technique that can be recommended is to install a soft base under the Atwood machine to avoid collisions between the floor and the smartphone when it falls.

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