Measuring the Acceleration of Gravity Using a Smartphone, A4-Papers, and a Pencil

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Abstract

The measurement of the acceleration of gravity, g, is usually conducted in the science laboratory, especially in Physics subject. In contrast to the traditional method using a set of ticker timer, we propose a simple method to determine the magnitude of g using a smartphone, unused A4-sized papers, and a pencil. We use the smartphone application called Phyphox, operating in Timers and Acoustic Stopwatch mode to measure the time between two acoustic events. We then fold unused A4-papers together and put a pencil over them. After that, we flick the folded papers so that the pencil falls down. The first jingle from flicking causes the Acoustic Stopwatch to start whereas the second jingle from hitting of pencil on the floor makes it to stop. Through the measured time read by Acoustic Stopwatch and the height of folded papers, we are able to calculate the average of magnitude of the gravitational acceleration at the 5 different heights via (i) arithmetic mean, (ii) graphing by hand, and (iii) graphing by excel. Based on our observation of a free-falling object, we found that the magnitude of g at Bangkok equals to 9.760 m/s². Comparison with the standard value of 9.783 m/s² measured by the National Institute of Metrology (Thailand), our experimental value for gravity agrees well with the standard value which offers very good accuracy with a percentage of error of about 0.23%. We envisage that this work is not only economical, and can hence be conducted in places with limited access to laboratory tools, but also provides learning opportunities for students in hands-on practicing and data analysis.

Keywords—Gravitational acceleration, laboratory tool, Physics teaching, smartphone.

I. INTRODUCTION

For students enrolled in secondary school, practicing with scientific experiment to understand the truth of nature is an important learning process [1], especially for development of practical skill and scientific reasoning skill [2], [3]. One experiment that all students must conduct is to determine the acceleration of gravity using ticker timer [4], [5]. By attaching one end of the paper strip to the object and another end of that to the carbon paper of ticker timer, later, allowing such object to fall freely under the force of gravity, these cause the needle of ticker timer presses onto the carbon paper and spots as black dots arranged on the paper strip with the time between two adjacent dots equally to 1/50 second. After that, students must record the distance measured between two adjacent dots, and then, calculate the average speed between two adjacent dots. Consequently, for the analysis of experimental results, students are assigned to plot the relationship between the average speed and time, draw a straight line called the line of best fit, and then calculate the slope of the line of best fit in which equals to the magnitude of the gravitational acceleration at the Earth’s surface, together with the percentage of error from the experiment.

Because of the development of technology, smartphones today come with various sensors (such as microphone, camera, thermometer, gyroscope, proximity sensor, digital compass, and barometer, etc.) to facilitate a better user experience [6]. This opens up new perspectives on using smartphones as the laboratory devices [7]. For example, smartphone can be used as an angle meter to read the angle of the ramp tilted relative to the horizontal plane which is useful in reporting the coefficient of friction [8], or it can even be an acoustic stopwatch to count the time taken from start to stop using sound which benefits for measuring the speed of sound in the air [9].

Toward this end, we are therefore interested in utilizing the smartphone as a tool to determine the magnitude of
gravitational acceleration \((g)\), instead of ticker timer. We use the smartphone application called Phyphox, operating in Timers and Acoustic Stopwatch mode to record the time between two acoustic events. We then fold unused A4-papers together and put a pencil over them. After that, we flick the folded papers so that the pencil falls down. The first jingle from flicking causes the Acoustic Stopwatch to start whereas the second jingle from hitting of pencil on the floor makes it to stop. Next, we record the time read from the Acoustic Stopwatch and the height of folded papers after repeating the experiment at least 3 times. Finally, we perform the same procedure at the 5 different heights and calculate the average of magnitude of the gravitational acceleration through (i) arithmetic mean, (ii) graphing by hand, and (iii) graphing by excel. In comparison with the theoretical value of \(g = 9.783 \text{ m/s}^2\) at Bangkok, provided by the National Institute of Metrology (Thailand), we found the experimental values for gravity agree well with the standard value: \(g = 9.713 \text{ m/s}^2, 9.752 \text{ m/s}^2,\) and \(9.760 \text{ m/s}^2\) through the employment of arithmetic mean, graphing by hand, and graphing by excel, respectively, for data analysis.

II. THEORY

Free fall is an example of a vertical motion with constant acceleration. Free-falling object is not only limited to releasing object in the hand, but also included in throwing up and down. This is because as soon as the object moves away from the hand, there is only the force of gravity exerted on it. Although the air resistance takes place along the motion, it might be negligible at a position near the earth's surface.

The rate of speed’s change of free-falling object is defined as the gravitational acceleration which is denoted by the symbol of \(\ddot{g} \). For simple calculation, the magnitude of \(\ddot{g} \) is equivalent to 9.8 \(\text{ m/s}^2\). However, \(\ddot{g} \) in practical depends on the location of mensuration, e.g., the magnitude of \(\ddot{g} \) at London and Bangkok is reported as 9.812 and 9.783 \(\text{ m/s}^2\), respectively [10].

As mentioned before, free fall is one-dimensional motion under constant acceleration. Accordingly, the equation of motion is

\[
s = ut + \frac{1}{2} at^2,
\]

where the parameters \(s, u, t, \) and \(a\) are, respectively, the distance, the initial speed, the time, and the acceleration. If the experiment is designed by dropping the object \((u = 0)\) at a certain height \((H)\) under the gravity \((g)\), the equation is reduced to

\[
H = \frac{1}{2} gt^2.
\]

As shown by the above equation, through the measurement of the height and the time of travel for free-falling object, we are able to determine the acceleration of gravity.

III. METHOD

A. Materials and equipment

The necessary materials and equipment composed of 1 smartphone with Phyphox application, 1 pencil or pen, 4 sheets of unused A4-sized papers, 1 tape or glue, 1 scissors, and 1 ruler or tape measure or meter stick. A calculator, a graph paper, and a computer with excel program are optional for data analysis.

B. Procedure

The experiment is conducted as follows. Folding A4-sized papers together into a shape that the pencil can be placed on as shown in Fig. 1. Opening the Phyphox application, selecting the Timers mode, and then choosing the Acoustic Stopwatch function. Adjusting the threshold with a value in between 0.3 to 0.5 a.u. Pressing the Play button shown by the triangle symbol (the time appears 0.000 s). Flicking the folded paper so that the pencil falls down as shown in Fig. 2. The first jingle from flicking causes the Acoustic Stopwatch to start whereas the second jingle from hitting of pencil on the floor makes it to stop. Recording the time read from the Acoustic Stopwatch and the height of folded papers after repeating the experiment at least 3 times. Performing the same procedure again at the 5 different heights. Finally, calculating the average of magnitude of the gravitational acceleration through (i) arithmetic mean, (ii) graphing by hand, and (iii) graphing by excel.
Fig. 1. Setting the height of free fall experiment using the unused A4-sized papers folded into various shapes that the pencil or pen can be placed on.

Fig. 2. Time series of the free fall experiment

C. Data analysis

Arithmetic mean of the gravitational acceleration is determined from the average value of $g$ at the 5 different heights as
Each height must follow the equation of motion as
\[ g = \frac{2H}{t^2}. \]  
(4)

Likewise, to find the average value of \( g \) using the graph, this can be done by plotting the relationship between height in meter (Y-axis) and squared time in second\(^2\) (X-axis). The line of best fit from all data results in a straight line that passes through the origin with its slope of half of the magnitude of \( g \), in other word, \( g \) is equally to twice of the slope.

Furthermore, to enhance the efficiency of our analysis, we use the excel program to interpret the data and provide the line of best fit with its corresponding linear equation. We noted that after generating the graph with scatter plot, we find the line of best fit from the following commands: Layout, Analysis, Trendline, More Trendline Options, choose Linear, tick Set Intercept = 0.0, and tick Display Equation on chart.

Finally, to estimate the percentage of error, this can be obtained from the equation,
\[ \text{Error} \%(\%) = \left| \frac{g_{\text{Experiment}} - g_{\text{Theory}}}{g_{\text{Theory}}} \right| \times 100\%, \]  
(5)

where \( g_{\text{Theory}} \) represents the magnitude of the gravitational acceleration at Bangkok which equals to 9.783 m/s\(^2\) [10].

IV. RESULT AND DISCUSSION

The time of free-falling object recorded by the Acoustic Stopwatch at the 5 different heights as well as the corresponding magnitude of acceleration of gravity from (4) are presented in Table 1.

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Squared Time (s(^2))</th>
<th>Height (m)</th>
<th>Acceleration of Gravity (m/s(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.397</td>
<td>0.158</td>
<td>0.755</td>
<td>9.557</td>
</tr>
<tr>
<td>0.352</td>
<td>0.124</td>
<td>0.660</td>
<td>10.645</td>
</tr>
<tr>
<td>0.345</td>
<td>0.119</td>
<td>0.576</td>
<td>9.681</td>
</tr>
<tr>
<td>0.302</td>
<td>0.091</td>
<td>0.397</td>
<td>8.725</td>
</tr>
<tr>
<td>0.218</td>
<td>0.048</td>
<td>0.239</td>
<td>9.958</td>
</tr>
</tbody>
</table>

In order to evaluate the magnitude of the gravitational acceleration measured by a smartphone, we analyze the experimental result with the 3 different methods as follows.

A. Calculation of \( g \) via arithmetic mean

Through (3) and (5), the magnitude of acceleration of gravity identified in the previous section is averaged and becomes 9.713 m/s\(^2\) with 0.72% of error compared with standard value of 9.783 m/s\(^2\).

B. Calculation of \( g \) via graphing by hand

The averaged magnitude of acceleration of gravity from experiment is obtained through graphing data by hand, as shown in Fig. 3. Plotting the relationship between height in meter (Y-axis) and squared time in second\(^2\) (X-axis) gives a linear line of best fit. The slope of the straight line is approximately 4.876 m/s\(^2\) which results in the magnitude of the gravitational acceleration of 9.752 m/s\(^2\). The measured value of \( g \) is thus within 0.32% of the theoretical quantity.
Fig. 3. Obtaining the averaged magnitude of acceleration of gravity (g) using the graphing data by hand. The plot between height (Y-axis) and squared time (X-axis) shows a linear line of best fit with its slope (or gradient) of half of the magnitude of g.

C. Calculation of g via graphing by excel

To enhance the analysis effectiveness, the averaged magnitude of acceleration of gravity is further deduced from graphing using excel. As shown in Fig. 4, the dependence of the height on the squared time performs the linear relationship with its corresponding equation,

\[ y = 4.8801x \]  \hspace{1cm} (6)

This provides the magnitude of the gravitational acceleration of 9.760 m/s$^2$. Comparison of the experimental value with our measure displays an accuracy of 0.23%.

Fig. 4. Enhancing the effectiveness of data analysis to determine the magnitude of the gravitational acceleration (g) via graphing by excel. The result shows that the measured value of the magnitude of g is twice of the slope and becomes 9.760 m/s$^2$ with 0.23% of error.

As shown in the data analysis with 3 methods that composed of arithmetic mean, graphing by hand, and graphing by excel, the magnitude of the acceleration of gravity are found to be 9.713 m/s$^2$, 9.752 m/s$^2$, and 9.760 m/s$^2$, respectively. Compared to the theoretical value of g at Bangkok (9.783 m/s$^2$), three experimental results
give the accuracy of 0.72%, 0.32%, and 0.23% which implied that our method is suitable for classroom experiment to measure the gravitational acceleration with high accuracy. To this end, we highlight our work for determining the gravitational acceleration using smartphone which is simple to conduct for students.

V. Conclusion

In this paper, we propose a simple method to measure the acceleration of gravity based on the observation of a free-falling object using the smartphone instead of the usually employed with ticker timer. Regarding the best of our experimental result, the magnitude of the gravitational acceleration at Bangkok is found to be 9.760 m/s², this method offers very good accuracy, with a percentage of error of about 0.23%. Our experimental value for gravity agrees well with the standard value in which reported as 9.783 m/s² measured by the National Institute of Metrology (Thailand). We envisage the advantage of this experiment that it is not only economical, and can hence be conducted in places with limited access to laboratory tools, but also provides learning opportunities for students in hands-on practicing and data analysis.

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References