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The Sound of G: A Method to Calculate The Acceleration Due to Gravity Using Acoustic Stopwatch

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Abstract

This paper explored to calculate the value of the acceleration due to gravity (g) by using primarily of balloons, mass hanger, an acoustic stopwatch of a smartphone. The acoustic stopwatch used is based on the PhyPhox mobile application. The independent variable was the drop height and the dependent variable is the recorded time. There were seven drop heights and time were recorded for each fall with three repetitions to reduce the error. The computed value of g was comparable to the average value of g of 9.81 m/s and the locally accepted value. The measure value of g is also similar to the findings of various literatures. This proved the ability of the application to measure the drop time with reducing random or systematic errors. The data gathered from this research has proven that simple mobile phone has now tremendous impact in the classroom experiments. The students now can compute g more than visualizing it. The use of an acoustic stopwatch from a mobile phone in a physics experiment can be a great way for students to gain a better understanding of measuring and interpreting data accurately. The app makes it easier for teachers to demonstrate the concept of measurements and how to properly record them by using audio cues from the phone's built-in microphone.

Keywords: acceleration due to gravity, acoustic stopwatch, PhyPhox

INTRODUCTION

One of the most basic competencies in Physics is calculating the acceleration due to gravity (g). This can be done by conducting experiments in free fall, swinging pendulum, Newton's gravitational laws, among others. Usually, the average value g is calculated to be at 9.81 ms^{-1} and since the Earth is not perfectly spherical or uniformly dense, the g may differ from anywhere around the globe (Aron, 2013). This is supported by the Institute of Physics of the United Kingdom by saying that computed g in the region of 10 ms^{-1} is an acceptable one. This means that for every second an object is in free fall, its speed increases by 9.8 meters per second.

This study measured g using the concept of free fall using readily available materials in a standard laboratory. An acoustic stopwatch from a smartphone was used in lieu of standard stopwatch. This acoustic stopwatch called Physical Phone Experiment (PhyPhox) was downloaded freely from the Apple store. The literatures have found g using this same acoustic stopwatch (Sarpudin et al., 2020; Kittiravechote, & Sujarittham, 2020; Anni, 2021; Howard & Meier, 2021; Zhang, Zhang, Chen, Deng, & Zhuang, 2023). However, the method used were different. This study used the sound of the popped balloon as the signal for the acoustic stopwatch. Anni (2021) used sports ball as the free-falling object while Zhang, Zhang, Chen, Deng, & Zhuang (2023) have used steel ball as free-falling object. The sound of the balloon popping may also pique students' curiosity and make them more interested in the experiment. The use of this acoustic stopwatch from a smartphone is to connect to the new vibes of the students.

Furthermore, students are empowered by realizing that there is more power they can do with their smartphone than just mere social media. Using the acoustic stopwatch, it is easier to take multiple readings while performing an experiment, which provides more reliable data than a single reading. The acoustic stopwatch of smartphones allows for quicker and more accurate measurements. This is supported by Hochberg, Becker, Louis, Klein, & Kuhn (2020) who suggest that smartphones in experiments can provide students with enhanced learning experiences and students can easily capture and record data that may prove useful in completing their experiment. Smartphones often have built-in sensors such as accelerometers, gyroscopes, and cameras that can be used for collecting data in science experiments. This can make data collection more efficient and convenient for students (Vijayan, Connolly, Condell, McKelvey, & Gardiner, 2021). This is useful both for developing an understanding of how gravity works as well as giving students hands-on experience with calculating accelerations. Additionally, this experiment allows students to explore the concept of air resistance and its effects on falling objects by varying the types and sizes of dropped objects.

Any free-falling bodies have constant acceleration due to gravity g. The acceleration of free-falling bodies is a measure of how quickly the velocity, or speed, of the body increases as it falls. We can measure this using the simple SUVAT equation where s is displacement, u is initial velocity, v if final velocity, a is the acceleration, and t is time.

$$s = ut + \tfrac{1}{2} gt^2 \qquad (1)$$

Since u = 0 during a free fall:

$$s = \tfrac{1}{2} gt^2 \qquad (2)$$

$$g = 2 \text{ x Gradient} \qquad (3)$$

Equation 2 can be analogized as a y = mx + b in a straight-line equation. Based on equation 2, the y axis is the drop height or displacement (s) while the x-axis is t^2. The graph followed this relationship and if it is true a straight line of best fit is measured with the gradient of g/2. This means that the acceleration due to gravity is computed as gradient times 2.

Moreover, the objectives of this study are to calculate the acceleration due to gravity using an acoustic stopwatch of smartphone; to determine the absolute uncertainty of the measured value of g; and to calculate the percent error of various value of g based on the literature and its average value.

METHOD

The materials and equipment were set-up as shown in Figure 1. The independent variable of this experiment is the drop height while the dependent variable will be the time. A meter rule is used to measure the drop height. There was a total of 7 drop heights. The time was measured using the acoustic stopwatch of PhyPhox (Staacks et al., 2018). The mass of the hanger, the size of balloon, type of mobile phone used, and the environmental conditions were kept constant. The doors of the room and window were closed to reduce the effect of the air resistance. A total of three repetitions were made per drop height. The average of these three measurements of time were taken. The average can reduce the random error on the smartphone.

Since the time from the acoustic stopwatch is repetitive, there is an uncertainty which will be measured as half the range of the data (Nagwa, 2023). To maintain the sound received by the PhyPhox application, the type of smartphone utilized is the same. In this experiment it is an iPhone 13. Generally, iPhones have more advanced noise cancellation and echo reduction for phone calls, as well as improved audio quality for both music playback and making/receiving calls. Android phones may not have the same levels of noise cancellation as iPhones but make up for it with more robust customization options, allowing users to make adjustments to their audio (Saliba, Al-Reefi, Carriere, Verma, Provencal, & Rappaport, 2017). The threshold frequency of the device is set at 0.1 auditory unit and the minimum delay is kept at 0.1s.

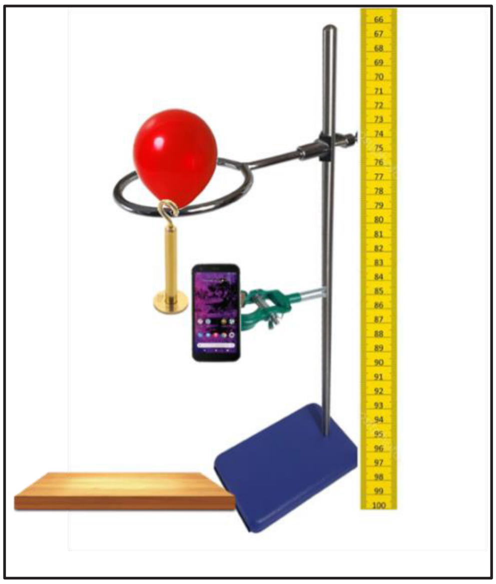

Figure 1. The experimental Set-up. These are composed of balloon, mass hanger, retort stand, c-clamp, iron ring, wooden bench, meter rule, and smartphone

A retort-stand with a total height of 187 meters was steadily posted parallel to the classroom's wall. An iron ring and C-clamp were connected to it. Seven drop heights were marked by a sticky paper. The smartphone was connected to the C-clamp while the balloon was placed on the iron ring. The mass hanger is connected to the fixed opening of balloon. At least 21 balloons are expected to be used but total of 25 balloons were used for this experiment. There were times that the mass hanger hit the clamped boss so this was not considered.

The balloon was pinched using a pin. The sound signature of the popped balloon served as the start for the acoustic stopwatch of PhyPhox in the smartphone to record the time. As the mass hanger hit the wooden bench, this marked the end for the time recording for the acoustic stopwatch. There were three repetitions of time recording for each drop height and an average was taken. This is done in order to reduce the uncertainty in time.

Once all the data were gathered, a graph of drop height in the y-axis and t^2 in the x-axis was created. If there is a straight-line graph then the relationship is true. A percentage uncertainty on the computed g and the graph was calculated. The computed g was compared to the g in the literature by using percent error. The uncertainty on the computed g was calculated using error propagation in division.

RESULTS AND DISCUSSION

A total of three repetitions of time (t) were made per drop height were recorded. The average of these t was used to compute the t^2 which is the x-axis of the graph. Since the data on time was repetitive, the error was computed as half the range (Pearson Education, 2023).

The h vs t^2 was plotted using the MS Excel for automatic computation of the gradient or slope. This can also be computed by drawing vertical and horizontal lines forming a right triangle with the line of best fit as the longest side or hypotenuse. From Figure 2 the gradient is 488.85 cms^{-2}, Based on equation 2, the g is two multiplied by the gradient, hence g is equal to 977.77 cms^{-2} or 9.78 ms^{-2}. This value is near to the average value of g which is 9.81 ms^{-2}. This proved that this method using the acoustic stopwatch can measure g with accuracy.

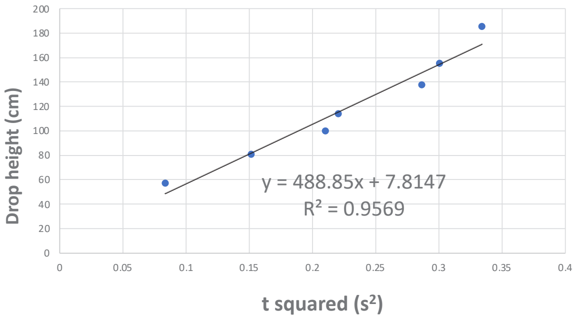

Figure 2. The drop height (h) against the t^2 with a line of best fit. The gradient is 488.85 cms^{-2}.

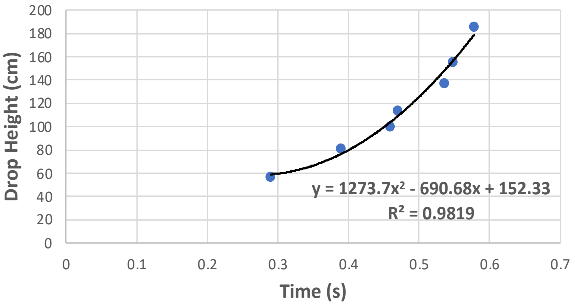

Figure 3. The graph of drop height against time showing a curved line. The gradient is velocity and in free fall the object is falling at constant acceleration

How much is the accuracy of the measure value of g? The percentage error is a measure of accuracy (Montoye, Mitrzyk, & Molesky, 2017). The percentage error is calculated by subtracting the measured value from the actual value and then dividing it by the actual value and multiplying by 100. The percent error of the computed value of g, in this experiment, is 0.418% which is a very low error. A low percent error indicates a high level of accuracy in the measurement or calculation. It suggests that there is minimal discrepancy between the measured value and the true value (Byju's, 2023). This value is lower compared to the percent error found by Kittiravechote & Sujarittham (2020) and lower from the study of Anni (2021). The h vs t was also plotted to verify the relationship. Theoretically, the graph should follow an x2 graph. The gradient of figure 3 is velocity which is proportional to acceleration given a constant time. In this premise, the graph is not straight line since the object falling is accelerating at constant acceleration due to gravity. As shown in Figure 3, the curve line followed this relationship. The measured time was repeated three times to reduce the random error coming from additional minor noises in the laboratory and systematic error coming from the acoustic stopwatch itself. It was observed that there was variation on the measured value of t over the three repetition as shown in Table 1.

Table 1. The time and time squared as linked to the seven drop heights.

No	height (cm)	t_1 (s)	t_2 (s)	t_3 (s)	average t (s)	t^2 (s^2)
1	185.5	0.58	0.576	0.578	0.578	0.334
2	155.5	0.524	0.578	0.543	0.548	0.301
3	137.5	0.538	0.528	0.54	0.535	0.287
4	114	0.47	0.49	0.449	0.47	0.221
5	100	0.468	0.493	0.415	0.459	0.21
6	81	0.39	0.388	0.39	0.389	0.152
7	57.3	0.287	0.298	0.283	0.289	0.084

The uncertainty on the g was calculated by using an error propagation for division. This can be expressed as a = bc^{-1} or

$$\left|\frac{\Delta b}{b}\right| = \left|\frac{\Delta c}{c} + \frac{\Delta a}{a}\right| \qquad (4)$$

Following equation 3, this leads to

$$\left|\frac{\Delta g}{g}\right| = \left|\frac{\Delta G}{G}\right| \qquad (5)$$

Substituting 9.78 ms^{-2} for g, 0.002 cms^{-2} or 0.00002 ms^{-2} for G, and 0.00019 cms^{-2} 0.0000019 ms^{-2} for the ΔG. The Δg is obtained to be ±0.93 ms^{-2}. This study reports the value of the acceleration due to gravity as (9.78 ± 0.93) ms^{-2}. In Uzbekistan, the value of g is reported and acceptable as 9.80 ms^{-2} on a free online gravitational acceleration calculator. This tool requires a user to input the latitude and elevation of the experiment's location. The experiment's value of g is similar to the data found by Kittiravechote and Sujarittham (2020) whom recorded g at (9.760 ± 0.23) ms^{-2}. The method used by Kittiravechote and Sujarittham (2020) is a bit different. They used A4 folded papers and pen as materials and the experiment was conducted in Thailand. In addition, White, Medina, Román, and Velasco (2007) reported the value of g to be (9.776 ± 0.005) ms^{-2} however the method was different since they used digital audio recording computer. The g computed by Bara, Mako, Eku, and Pau (2021) was 10 ms^{-2} but again the method is different and was conducted in Indonesia. The study of Tiili and Suhonen (2020) found that g in their local place is 9.67 ms^{-2} without reporting the uncertainty on their calculation.

From the related literature cited, there is now an additional knowledge provided by this experiment with regards to a method of measuring the acceleration due to gravity. The data acquired by this research is comparable to the literatures and the standard value of the country where the study was conducted. Although errors may persist but it is a grim reality of any experiment. The difference of the result of this experiment from the literatures cited is attribute to the method used, materials used, location of the experiment, and the environmental condition. In total, the value of g that will be measured will truly be different.

Furthermore, the future positive effect of this experiment to the students is undeniable. It can provide them with a more accessible and accurate way to measure and record data of the time of fall, allowing them to complete the experiment faster and analyze their results faster. using smartphones also make it easier for students to collaborate with each other on experiments as supported by Kittiravechote and Sujarittham (2020) and Bara, Mako, Eku, & Pau (2021). This collaborative process can potentially lead to innovative insights and applications that would not be possible using regular instruments (Glăveanu, Ness, Wasson, & Lubart, 2019).

On the other hand, there are some drawbacks associated with smartphone use in experiments including: increased distraction from non-related activities or applications, potential for data accuracy issues if not monitored properly, and a lack of physical interaction/manipulation when experimenting with large objects (Felisoni & Godoi, 2018). Hence it is now on the part of the teacher to facilitate the class experiment properly and make use students are at pace and on time with the objectives of the experiment.

Using a mobile phone and an acoustic stopwatch to measure acceleration due to gravity can provide a hands-on opportunity for students in the classroom to develop a better understanding of physics and science concepts. With this activity, students can measure the acceleration of an object falling from rest under the influence of gravity, which can help them visualize the forces at work. Additionally, through practicing taking accurate measurements with a stopwatch, they can gain valuable experience with precision measurement and timing. Furthermore, by calculating their own results in conjunction with applying their knowledge of average acceleration due to gravity, they will be able to apply theory to hands-on experiments.

CONCLUSION

The value of the acceleration due to gravity that this paper came up indicates that acoustic stopwatch from PhyPhox is indeed a very good tool in reducing the random error which is common in big time delay when using a standard stopwatch. The experimental setup used in this paper is clearly recommended for classroom experiments. It can indeed catch the attention and motivation of the students based on the experience of the experimenter. The acoustic stopwatch from a mobile phone appeared to offer a viable option for measuring acceleration due to gravity in a classroom environment. However, this is for further studies. It is recommended to use more faster smartphone to reduce more the time delay. This paper used 0.1s time delay, with the use of more advanced smartphone this can be further reduced. For those who will use this method, make sure to use heavier mass hanger because there were moments that the end signal for the stopwatch was not audible to the smartphone. Instead of a wooden bench, a metal bench is recommended since it can produce louder sound than a wooden bench. Be careful as well not to hit anybody when the mass hanger is falling down.

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