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Determining the Coefficient of Restitution Through the "Bouncing Ball" Experiment using Phyphox

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Abstract

This study aims to determine the restitution coefficient based on the reflected sound from the "bouncing ball" experiment. The experiment used a Phyphox-based smartphone. The produced sound came from a reflection between marble and the floor. Theoretically, the value of the coefficient of restitution is obtained based on the square root of the final height of the object's reflection divided by its initial height. In this study, the determination of the height of the bounce from the "bouncing ball" was measured using the Phyphox application, which was analyzed based on the sound of the bouncing ball and the time interval of the reflection. The results show that the value of the coefficient of restitution for each marble were 0.93, 0.92, and 0.92, while the average error were 0.65%, 0.85%, and 1.43%, respectively. Furthermore, the average error value of the overall measurement is 0.97%. This error is highly dependent on the shape of the object. The rounder a thing is, the higher the level of accuracy will be. In this study, the determination of the coefficient of restitution was carried out in two ways: by comparing the height of the ball's bounce and the time intervals for the *n* and *n*+1 bounce. The value of the coefficient of restitution generated by these methods was identic. Thus, this study had confirmed that the bounce ball experiment using the Phyphox indicated valid data well so that it could be implemented for determining the coefficient of restitution.

Keywords: bouncing ball, coecficient of restitution, Phyphox, smartphone

1 Introduction

The coefficient of restitution is a value that states the level of elasticity of objects in the collision phenomenon. Particularly, the coefficient of restitution is a characterization of the degrees of freedom in the inelastic collision and dimensionless [1]. The value of the coefficient of restitution depends on the ratio of the final height and initial height of the collision particles, which is mathematically expressed by the Equation (1):

$$e = \sqrt{\frac{h_2}{h_1}}. \quad (1)$$

Determining the value of the coefficient of restitution is very useful for developing various sub-fields of physics. The coefficient of restitution has become an essential part of granular hydrodynamics and the kinetic theory of gas [2], [3], computation of granular matter [4], and even in agriculture, especially for the development of agricultural techniques [5]. The coefficient of restitution provides information on the energy lost during the collision process [6]. It could be necessary for dry granular modelling and multi-phase flow models.

Research in determining the value of the coefficient of restitution has been carried out using different techniques. These are determining the coefficient of restitution using a robot and piezoelectric sensor [7], determining the coefficient of restitution using a high-speed camera [6], [8], determining the coefficient of restitution using the double pendulum method [9], determining the coefficient of restitution using high-speed video [10], and others [11]–[14].

One of the experiments that can be used to determine the value of the coefficient of restitution is the "bouncing ball" experiment [15]. A bouncing ball is a bounce event from a ball dropped without initial velocity from a certain height above the earth's surface and hits a particular surface. In the bouncing ball phenomenon, an inelastic collision occurs where the ball will bounce up and until the ball stops at a specific time. The process of

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the bouncing ball illustrates many aspects that could be observed from the principles of mechanics, including the phenomenon of collisions when the ball hits the floor surface [16].

According to the studies that have been carried out, the technique for determining the value of the coefficient of restitution is expensive, complex, and challenging to carry out independently by students. In this study, a cheap and practical technique for determining the coefficient of restitution will be introduced using a smartphone. Generally, using advanced technology in this era, smartphones have been equipped with sophisticated sensors that can support the implementation of science practicums, especially physics. In Addition, this is also supported by the existence of practical support applications that can be downloaded and run freely on smartphones. One application that can be used for physics experiments is the Phyphox.

Several studies using the Phyphox application include research on determining spring constants on spring oscillation events [17], free-fall motion experiments using the stopwatch acoustic feature [18], pendulum motion experiments [19], and others [20], [21]. The value of the coefficient of restitution can be determined by using the Phyphox application, by finding the ratio of the object's speed between two adjacent bounce [22]. In this study, we provide a method to determine the value of the coefficient of restitution of bouncing ball by using Phyphox based on two approaches. The first approach is through the ratio of the height of marbles in two adjacent bounce. While the second approach is through the ratio of time intervals between two adjacent bounce.

2 Research Methodology

In this study, the value of the coefficient of restitution between the marble and the floor would be calculated through the bouncing ball experiment. Based on equation (1), the value of the restitution coefficient could be determined if the initial height and final height of the following bounce process were known. The object used in this study were three marbles with different diameters. The purpose is to evaluate the effect of the size of marble.

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The experiment design is illustrated in Figure 1. The first process was setting the initial height of the marbles using a ruler. It was 15 cm from the floor. The smartphone was placed on the floor in a position close to the bounce of the marbles. To find the value of the bounce marbles' height, a smartphone was installed with the Phyphox. After that, the ball was dropped without initial velocity and allowed to bounce. The sound produced by the marble's bounce would be detected and recorded by the smartphone sensor. Then it would be processed and converted to generate data on interval time, height, and energy of the bounce. Furthermore, the data would be displayed on the smartphone's LCD. The number of bounces produced in this experiment was five times.

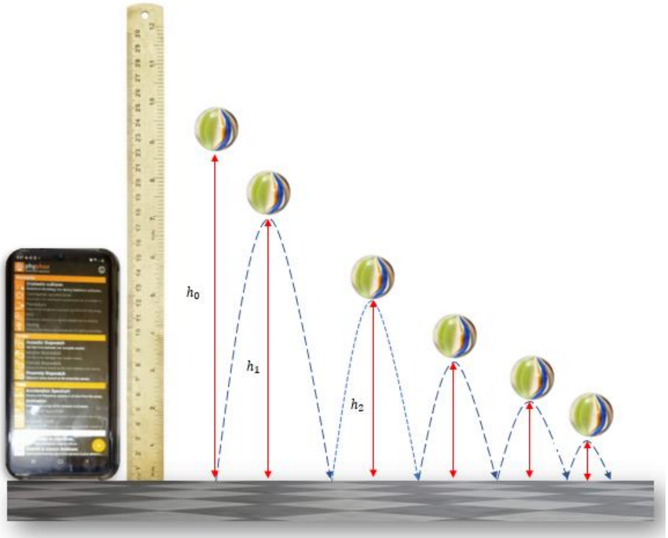

Figure 1. Experiment design in determining the coefficient of restitution

In the next stage, the accuracy of the obtained data needs to be declared because it is related to the error value of a measurement. The smaller the measurement error value, the greater the level of research accuracy. So, it might be stated that the data experiment was valid. The measurement error value is calculated through the Equation (2),

$$error = \left|\frac{m_{standard} - m_{experiment}}{m_{standard}}\right| \times 100\%, \quad (2)$$

where $m_{standard}$ represents the actual value measured through standard measuring instruments and $m_{experiment}$ represents the value displayed by the smartphone.

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The error value was attained from the initial height measurement read by the smartphone compared to the actual height. In this study, the arisen error should be under 2%. Therefore, if the error value is less than 2%, the data collection process could be continued, while others would repeat the experiment process.

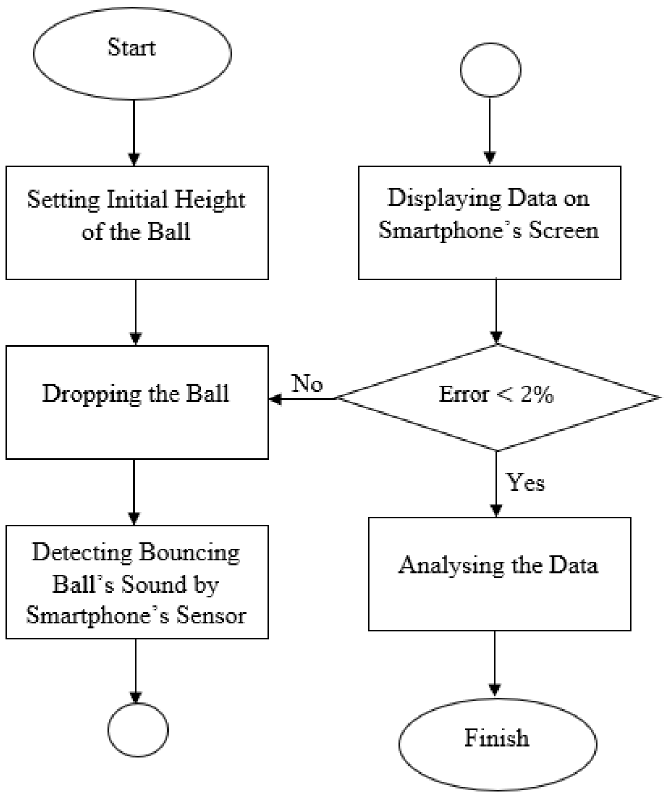

Figure 2. Flowchart of Detecting the coefficient of restitution by Using Phyphox

After determining the error value, the data generated by the smartphone would be analyzed to determine the coefficient of restitution and standard deviations. The calculation of the standard deviation value follows the Equation (3),

$$Ds = \frac{1}{n}\sqrt{\frac{n\sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2}{(n-1}}, \tag{3}$$

where n represents the number of measurements and x_i represents the measurement results in the i^{th} experiment.

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3 Results and Discussion

In this study, three types of marbles with different diameters were used in the experiment. They were labelled with marble 1, having a diameter of 14.1 mm, marble 2, having a diameter of 15.2 mm, and marble 3, having a diameter of 27.4 mm. To obtain the valid data, the experiment was done and repeated five times. The experiment results are shown in Figure 3.

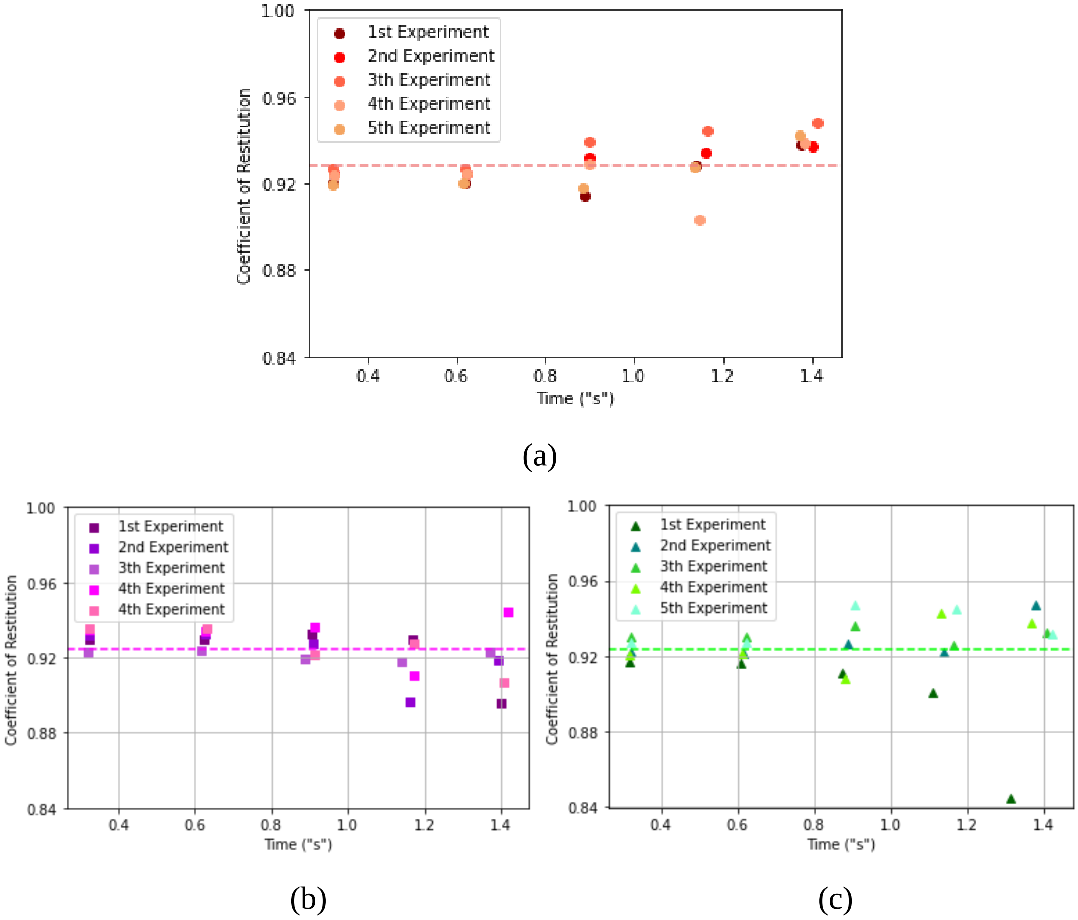

Figure 3. The experiment results of the coefficient of restitution for (a) marble 1, (b) marble 2, and (c) marble 3

Figure 3 shows the bounce ball experiment results using marble with various diameters. The initial height of the marble is set at 15 cm from the floor. In this experiment, the

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coefficient of restitution for marble 1 was 0.90 to 0.95, while for marble 2, the coefficient of restitution was 0.90 to 0.94, as well as the coefficient of restitution for marble 3 was in the range of 0.84 to 0.95. The dash line in each figure indicate the average value of the coefficient of restitution. The average value of the three marbles respectively are 0.9282, 0.9247, and 0.9237. Based on equation (2), average error value of the three marbles respectively are 0.65%, 0.85%, and 1.43%, respectively. Moreover, the average coefficient of restitution for collisions in this experiment was displayed in Table 1.

Analytical calculation

The coefficient of restitution is a significant empirical parameter in any physical modelling where there is energy loss caused by particle collisions [23]. One of the essential factors that influence the factor determining the value of the restitution coefficient is the velocity value immediately after the n^{th} reflection [24],

$$v_n = v_0 e^n, \tag{4}$$

where v_0 is the velocity of the ball just before the collision. The time interval between adjacent collisions (n^{th} to $(n+1)^{th}$) is expressed by the Equation (5),

$$T_n = \frac{2v_n}{g}$$
$$T_n = \frac{2v_0 e^n}{g}$$
$$T_n = T_0 e^n. \tag{5}$$

where g is the gravitational acceleration and $T_0 = 2v_0/g$. Then, from the equation 5, it could be obtained that the coefficient of restitution could also be determined through the time interval of the bouncing ball,

$$e^n = \frac{T_n}{T_0}. \tag{6}$$

Time interval (T_n) of bouncing marble was show in Figure 4.

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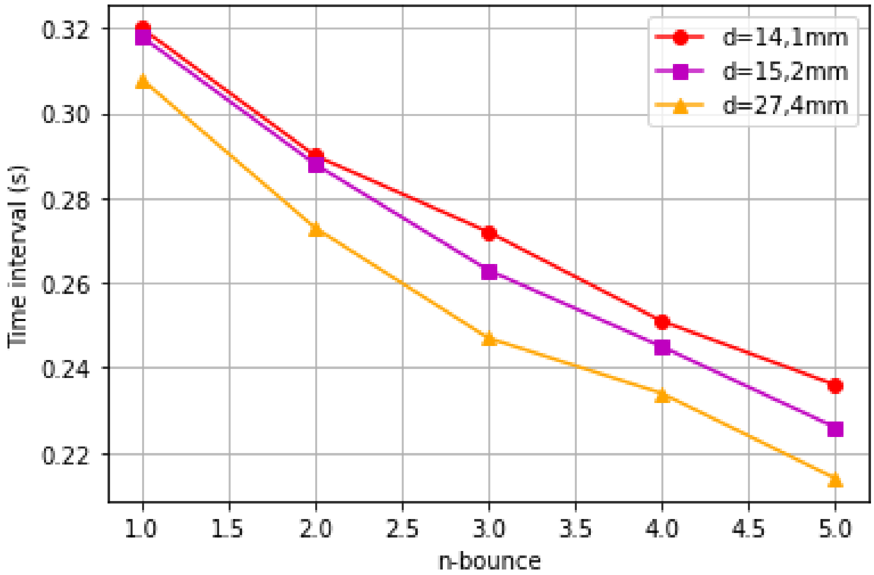

Figure 4. The time interval vs *n*-bounce for each marble

From Figure 4, it is obtained that for marble 1, when $n = 1$, then the value of $h = 0{,}1497\ m$, dan $T_n = 0{,}322s$. So, substituting those data to T_0, it could be determined the coefficient of restitution,

$$T_0 = (2v_0/g)$$
$$T_0 = \left(2\sqrt{2gh}/g\right)$$
$$T_0 = \left(\sqrt{\frac{8h}{g}}\right)$$
$$T_0 = \left(\sqrt{\frac{8(0{,}1497m)}{9{,}8\ m/s^2}}\right)$$

$$T_0 = 0{,}3496s, \qquad (7)$$

Thus, for $n = 1$ the coefficient of restitution of marble 1 is

$$e^1 = \frac{0{,}322s}{0{,}3496\ s}$$

$$e_1 \approx 0{,}92. \qquad (8)$$

The coefficient of restitution of marble 2 dan marble 3 could be found by applying the same method. Those are $e_2 \approx 0{,}93$ and $e_3 \approx 0{,}92$.

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The last step in this study was comparing values of the coefficient of restitution. The purpose was to see the validity of the data between the experimental and analytical methods. The data is shown in Table 1.

Table 1. Comparison of the coefficient of restitution between analytical and experimental method

Marble	**Coefficient of Restitution**	
	Experimental	**Analytical**
d1 = 14,1 mm	$e \approx 0{,}93$	$e \approx 0{,}92$
d2 = 15,2 mm	$e \approx 0{,}92$	$e \approx 0{,}93$
d3 = 27,4 mm	$e \approx 0{,}92$	$e \approx 0{,}92$

Table 1 shows that the coefficient of restitution between the experiment and analytical approach is not the same but very identic. Many factors could cause this. The measurement of the restitution coefficient value is highly dependent on the shape and material of the object, the level of surface roughness of the reflection, the level of sphericity of the thing, and the measurement error. However, the small measurement error may cause a shift in energy to the translational or rotational components [23]. Furthermore, since there was no change in the coefficient of restitution for three kinds of marble, it could be stated that there is no effect from the diameter of the marble to determine the coefficient of restitution. Thus, this study confirmed that bounce ball experiment using the Phyphox indicates valid data well so that it could be implemented to determine the coefficient of restitution.

4 Conclusion

This research has succeeded in determining the coefficient of restitution. The method was cheap and practical through the phenomenon of bouncing balls and smartphones integrated with the Phyphox application. The value of the coefficient of restitution for each marble was 0.93, 0.92, and 0.92, while the average error was 0.65%, 0.85%, and 1.43%, respectively. Moreover, the average error value of the overall measurement is 0.97%. This error is highly dependent on the shape of the object. The rounder an object is, the higher the level of accuracy will be. In this study, the determination of the coefficient of restitution was carried out in two ways: by comparing the height of the

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