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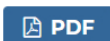


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## Local Gravitational Acceleration through Experimental and Simulative Approaches on Physical Pendulum

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### ABSTRACT

Accuracy in measuring local gravitational acceleration remains a challenge due to the limitations of conventional experimental approaches and the influence of dynamic system conditions. Furthermore, few studies have integrated numerical simulation methods to enhance precision in the context of nonlinear oscillatory motion. This study aims to conduct an in-depth analysis of the dynamics of a damped physical pendulum and to evaluate the accuracy of local gravitational acceleration measurements by integrating experimental methods with numerical simulations. This is a quantitative study employing a quasi-experimental design. The research subject consisted of a single set of physical

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# Local Gravitational Acceleration through Experimental and Simulative Approaches on Physical Pendulum

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## ABSTRAK

Ketelitian dalam pengukuran percepatan gravitasi lokal masih menghadapi tantangan akibat keterbatasan pendekatan eksperimental konvensional dan pengaruh kondisi dinamis sistem. Selain itu, belum banyak kajian yang mengintegrasikan pendekatan simulasi numerik untuk meningkatkan akurasi dalam konteks gerak osilasi nonlinier. Penelitian ini bertujuan untuk menganalisis secara mendalam dinamika bandul fisis teredam serta mengevaluasi akurasi pengukuran percepatan gravitasi lokal dengan mengintegrasikan metode eksperimen dan simulasi numerik. Penelitian ini merupakan penelitian kuantitatif dengan desain eksperimen semu. Subjek penelitian terdiri atas satu set alat bandul fisis berupa batang logam homogen, tanpa melibatkan partisipan manusia. Data diperoleh melalui pengukuran periode osilasi menggunakan stopwatch digital berakurasi tinggi dan pengukuran panjang efektif menggunakan roll meter. Instrumen divalidasi melalui prinsip fisika klasik dan uji konsistensi hasil. Simulasi numerik dilakukan menggunakan metode Runge-Kutta orde 4 (ODE45). Analisis data meliputi analisis deskriptif kuantitatif, komparatif, dan evaluasi kesalahan relatif serta identifikasi ketidakpastian. Hasil penelitian menunjukkan bahwa nilai percepatan gravitasi hasil eksperimen mendekati nilai teoritis dengan tingkat kesalahan relatif yang rendah. Disimpulkan bahwa integrasi pendekatan eksperimen dan simulasi memberikan pemahaman yang lebih komprehensif terhadap dinamika bandul dan akurasi pengukuran gravitasi lokal. Implikasi dari penelitian ini adalah perlunya penerapan model dinamis yang lebih kompleks untuk mendukung pengukuran presisi di berbagai bidang seperti geofisika, teknik, dan pendidikan.

## ABSTRACT

Accuracy in measuring local gravitational acceleration remains a challenge due to the limitations of conventional experimental approaches and the influence of dynamic system conditions. Furthermore, few studies have integrated numerical simulation methods to enhance precision in the context of nonlinear oscillatory motion. This study aims to conduct an in-depth analysis of the dynamics of a damped physical pendulum and to evaluate the accuracy of local gravitational acceleration measurements by integrating experimental methods with numerical simulations. This is a quantitative study employing a quasi-experimental design. The research subject consisted of a single set of physical pendulum apparatus in the form of a homogeneous metal rod, with no human participants involved. Data were collected by measuring the oscillation period using a high-accuracy digital stopwatch and the effective length using a roll meter. Instruments were validated based on classical physics principles and result consistency tests. Numerical simulations were performed using the fourth-order Runge-Kutta method (ODE45). Data analysis included quantitative descriptive analysis, comparative analysis, relative error evaluation, and uncertainty identification. The results showed that the experimental gravitational acceleration value closely approximated the theoretical value, with a low relative error. It is concluded that integrating experimental and simulation approaches provides a more comprehensive understanding of pendulum dynamics and improves the accuracy of local gravity measurements. The findings imply the need for more complex dynamic models to support precision measurements in various fields such as geophysics, engineering, and education.

## 1. INTRODUCTION

Gravitational acceleration refers to the quantity that describes an object's velocity changes when it falls freely toward Earth's center due to gravitational pull (Pacala & Pili, 2023; Salim et al., 2022). On Earth's surface, gravitational acceleration is typically around  $9.8 \text{ m/s}^2$ , indicating that the velocity of a freely falling object increases by approximately 9.8 meters per second (Dwiatmoko & Dzulkifli, 2019; Shi et al., 2021; Subhan et al., 2022). However, this value varies depending on geographic location. For instance, in

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equatorial regions such as Indonesia, the average gravitational acceleration value is generally slightly lower, around  $9.78 \text{ m/s}^2$  (Medellu et al., 2023; Meena, 2019). Understanding local gravitational acceleration is crucial in various fields, including geodesy (for determining Earth's shape and size), aviation (for calculating flight paths and ensuring aircraft stability), geophysics (to study subsurface structures and mass distribution, enabling natural resource exploration and disaster mitigation), and civil engineering (for calculating structural loads of buildings and bridges) (Pacala & Pili, 2023; Yanti et al., 2020). One classical method for measuring gravitational acceleration is the physical pendulum experiment (Wang et al., 2022; Yuningsih et al., 2020). A physical pendulum consists of a rigid body suspended from a fixed pivot point, allowing it to oscillate freely under the influence of gravity. Unlike a mathematical pendulum that modeled as a point mass attached to a massless string, a physical pendulum exhibits a non-uniform mass distribution. As a result, the pendulum's period depends not only on the length of the suspension string but also on the distance between the pivot point and the object's center of mass (Dwiatmoko & Dzulkifli, 2019; Monteiro et al., 2020). Despite its practical applications, physical pendulums have inherent limitations. A primary limitation is the assumption that no external forces, aside from gravity, act on the system. In practice, however, external forces such as air resistance and damping inevitably influence the pendulum's oscillatory motion, leading to discrepancies between the measured and actual values of gravitational acceleration (Jatmiko, 2022; Rangkuti et al., 2019; Salim et al., 2022; Subhan et al., 2022).

To address these limitations, a comparative study is necessary between experimental results from physical pendulums and numerical simulation methods. Numerical simulations provide reliable data comparisons and enable a deeper analysis of factors influencing measurement outcomes, such as damping effects that are challenging to quantify experimentally. These simulations offer a more accurate representation of the oscillatory motion of physical pendulums and improve our understanding of their behavior. In the experimental method, the distance of the pivot point to the center of mass varies, and the time required for several oscillations is precisely measured. The oscillation period obtained is then used to calculate the gravitational acceleration value and its uncertainty. Meanwhile, in numerical simulation, the approach involves modeling the motion of a physical pendulum by utilizing differential equations that describe the system's dynamics. Thus, numerical simulation allows the analysis of the influence of various variables, such as damping on the period and the gravitational acceleration value. The factors that influence the oscillatory motion of the pendulum can be identified by comparing the simulation results with the experimental results. Accordingly, the primary objective of this study is to accurately measure local gravitational acceleration by employing a combined approach of experimental methods and numerical simulation using a physical pendulum system. The study also aims to analyze the influence of damping coefficients and initial angular displacements on the oscillatory dynamics of the system. In addition, it seeks to evaluate the reliability of the numerical model by comparing simulation results with experimental data and theoretical values, as well as to identify potential sources of uncertainty that may affect the measurement outcomes, both from experimental and computational perspectives. Through this approach, the research is expected to contribute significantly to the advancement of understanding in nonlinear oscillatory motion and to improve the accuracy of gravitational acceleration measurements, particularly in the geographical context of Indonesia.

## 2. METHOD

This study employs a quantitative approach with a quasi-experimental design, combining direct measurements through physical experimentation and numerical modeling via computer-based simulation (Hambali et al., 2020; Husni, 2020; Rajab et al., 2025). The primary objective is to accurately determine the local gravitational acceleration and to examine the effects of initial deviation angle and damping coefficient on the oscillatory dynamics of a physical pendulum system (Medellu et al., 2023; Salim et al., 2022). The experimental subject consists of a single physical pendulum apparatus, constructed from a homogeneous metal rod of specific dimensions and mass, which serves as the main instrument for data collection. No human participants are involved in this study; thus, all data collection is instrument-based and relies on physical measurements (Bangun et al., 2022; Mintjelungan et al., 2024). The distance from the pivot point to the center of mass of the homogeneous metal can be varied between two different lengths ( $a_1$  and  $a_2$ ) and it is measured by a roll meter. The time required to swing with an initial deviation angle ( $\theta_0$ ) of  $10^\circ$  for two different pivot points is measured using a digital stopwatch with an accuracy of 0.01 seconds three times to minimize errors. The average period for each pivot point ( $T_1$  and  $T_2$ ) is calculated from the time data obtained. Using the calculated period, the value of gravitational acceleration and its efficiency can be determined. The selection of a relatively small deviation angle in this physical pendulum experiment is generally based on the assumption that at a small deviation angle, the sine value of the angle ( $\sin \theta$ ) can be approximated by the angle value in radians ( $\theta$ ) ( $\sin \theta = \theta$ ) (Azahra et al., 2024; Bocresion, 2023). This

approach allows us to achieve the pendulum's motion equation into a simple harmonic motion equation. To account for the damping effect that is not measured in the experiment, the differential equation describing the motion of the physical pendulum is modified by adding a damping term as a mathematical model to describe the swing motion. The parameters used in the simulation include the effective swing length, damping coefficient, and compression acceleration (Bagus et al., 2024; Ekoputri et al., 2023).

Numerical simulations are performed using MATLAB software to obtain numerical solutions to this mathematical model. The simulation results are then compared with experimental data to validate the model. The differential equation describing the motion of the physical pendulum is solved numerically using the Runge-Kutta method, specifically with the ODE45 function, to obtain numerical solutions for the position and angular velocity of the swing as a function of time. The swing period from the simulation is calculated by finding the time difference between two consecutive cut points of the position curve. From the span period obtained from the simulation, the value of the simulated gravitational acceleration can be calculated. Simulations are performed with various values of the damping coefficient and initial swing angle to explore the effects on both the swing period and the shape of the position curve. Next, the gravity values obtained from experiments and simulations are compared with electromagnetic values to verify the accuracy of the simulation models and experimental methods and identify distance sources.

### 3. RESULT AND DISCUSSION

#### Result

##### Experimental Results

The experimental method aims to determine the value of Earth's gravitational acceleration using the principle of a physical pendulum. In this study, a physical pendulum with two variations of pivot points on a hollow homogeneous metal rod was used. The observed swing periods were recorded for multiple trials, and gravitational acceleration values were calculated using Equation (1).

$$T = 2\pi \sqrt{\frac{k_0^2 + a^2}{g \cdot a}} \tag{1}$$

where:

- T = swing period (seconds)
- k<sub>0</sub> = radius of gyration to the center of mass (cm)
- a = distance of the pivot point to the center of mass (cm)
- g = Earth's gravitational acceleration (cm/sec)

In the experimental method, an approach is taken based on the assumption that the pendulum swing has a small amplitude thus the restoring force acting on the pendulum is proportional to its deviation. With this assumption, complex nonlinear equations of motion can be simplified into linear equations that are easier to solve. In addition, a more straightforward formula is obtained to calculate the swing period by ignoring factors such as friction and assuming the pendulum's mass is concentrated at one point. From equation (1), by taking point A<sub>1</sub> as the pivot point whose swing period is T<sub>1</sub> and pivot point A<sub>2</sub> (on the opposite side of point A<sub>1</sub>) whose swing period is T<sub>2</sub>, the equation of the relationship between the period and the acceleration of gravity (Equation 2) and the uncertainty of the acceleration of gravity (Equation 3) is obtained.

$$\frac{\pi^2}{g} = \frac{T_1^2 + T_2^2}{8(a_1 + a_2)} + \frac{T_1^2 - T_2^2}{8(a_1 - a_2)}$$

$$g = \frac{4\pi^2(a_1^2 - a_2^2)}{a_1 T_1^2 - a_2 T_2^2} \tag{2}$$

$$\Delta g = \left[ \frac{8\pi^2 a_1 \Delta a_1 + 8\pi^2 a_2 \Delta a_2}{4\pi^2(a_1^2 - a_2^2)} + \frac{2a_1 T_1 \Delta T_1 + 2a_2 T_2 \Delta T_2 + T_1^2 \Delta a_1 + T_2^2 \Delta a_2}{(a_1 T_1^2 - a_2 T_2^2)} \right] g \tag{3}$$

In the experimental method, the swing period can be measured for several effective pendulum lengths by varying the distance between the pivot point and the center of mass of the rod and calculating the time required to swing. The swing period data is then used to calculate the Earth's gravitational acceleration value. Table 1 shows the distance from the pivot point to the center of mass and the measured swing times for 20 oscillations.

**Table 1.** Results of Measuring the Distance of the Pivot Point (A) and the Time Required to Swing Using the Experimental Method

Distance of pivot point A from the center of mass (cm)	Swing Angle	Swing Time (seconds)		
		Time for 20 swings (repetition 1)	Time for 20 swings (repetition 2)	Time for 20 swings (repetition 3)
a1: 57.5 ± 0.02	10°	35.0	35.0	35.0
a2: 47.5 ± 0.02	10°	33.5	33.5	33.5

The experiment was conducted in a closed room with a relatively stable temperature to minimize the influence of environmental factors. The time data obtained did not show any variation, indicating a relatively good level of measurement precision. Furthermore, the time data was analyzed using the average method and its uncertainty. By applying equations (1) and (2), the value of gravitational acceleration and its uncertainty are obtained based on the experimental results of  $g \pm \Delta g = (967.91 \pm 6.52) \text{ cm/s}^2$ . When compared to the theoretical value of local gravitational acceleration, which is  $978 \text{ cm/s}^2$ , there is a difference that can be calculated through the percentage error to understand the difference between the experimental and theoretical results.

$$\text{Percentage difference} = \left( \frac{|g_{theory} - g_{experiment}|}{g_{theory}} \right) \times 100\% \approx 1.03\%$$

### Simulation Results

To complement the experimental findings, numerical simulations were conducted using MATLAB with the fourth-order Runge-Kutta method (ODE45) which implements a method to solve differential equations that describe the dynamics of a physical pendulum. This simulation was carried out for various initial deviation angles ranging from 5° to 30°. In each iteration of the initial angle, simulations were carried out for a range of damping coefficient values ( $b$ ) from 0 (no damping) to 1 (high damping) with an interval of 0.1. The initial angle was converted from degrees to radians for calculation at each iteration. The simulation's initial angular velocity ( $\omega_0$ ) was set at zero, considering that the pendulum was initially at rest. This means the pendulum is only given an initial push as a deviation angle ( $\theta_0$ ) without any initial angular velocity. Important parameters in the simulation include the simulation period, the length of the pivot point to the center of mass, and the radius of gyration, which explain the distribution of the pendulum mass. After obtaining the angular position data  $\theta$  from the simulation, the swing period is determined by identifying the peaks in the data using the *findpeaks* function. The simulation period obtained is then used to calculate the simulated gravitational acceleration value based on equation (4).

$$g_{sim} = \frac{4\pi^2 k^2}{T_{sim}^2 d} \tag{4}$$

where

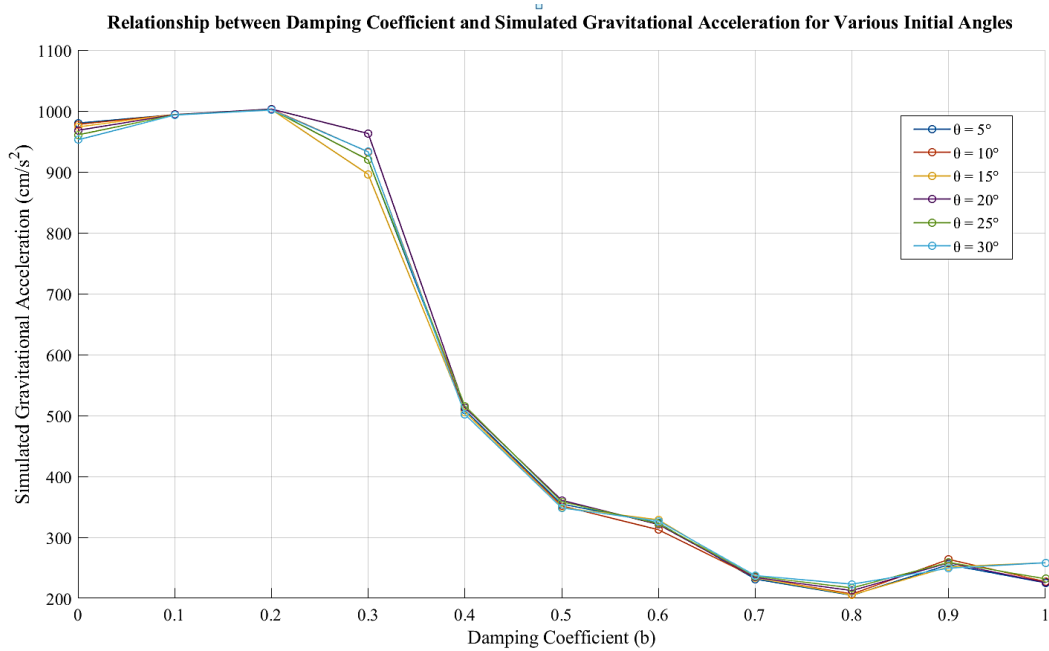
$g_{sim}$  = simulated gravitational acceleration (cm/s<sup>2</sup>)

$T_{sim}$  = simulated swing period (seconds)

$k$  = radius of gyration of the two pivot points (cm)

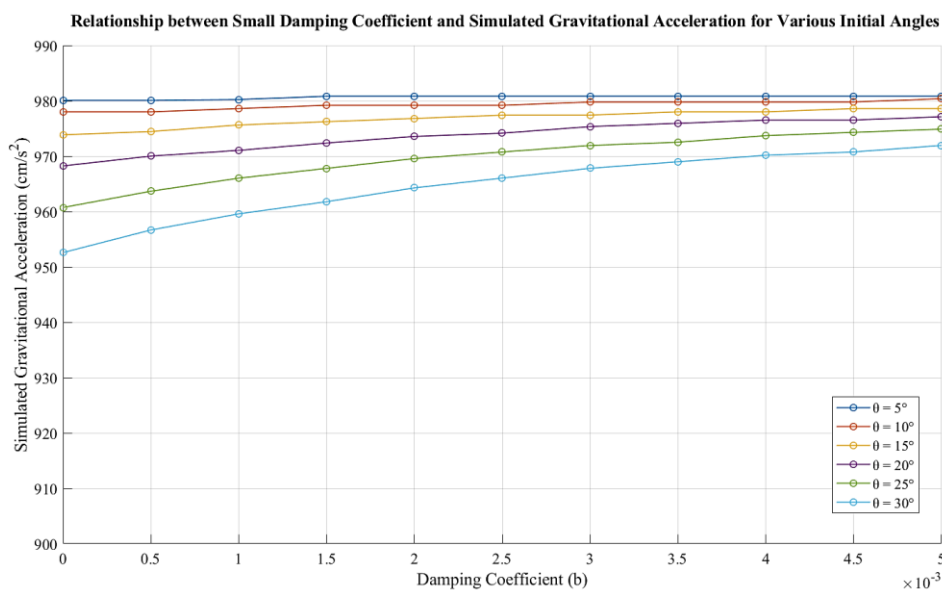
$d$  = average distance of the pivot point to the center of mass (cm)

Conducting simulations for various combinations of initial angles and damping coefficients yields a comprehensive dataset of gravitational acceleration values. This dataset is then compared with the theoretical value of local gravitational acceleration to evaluate the accuracy of the simulation model. For each combination of parameters, the percentage difference between the simulated and theoretical values is calculated. The key findings indicate that for small damping coefficients, ranging from 0 to 0.3, the simulated gravitational acceleration remains stable and closely aligned with the theoretical value. However, as the damping coefficient increases to 0.5 or higher, the gravitational acceleration decreases significantly, reflecting the characteristics of non-linear pendulum behavior. [Figures 1](#) and [Figure 2](#) illustrate the relationship between damping coefficients and simulated gravitational acceleration at various angles.



**Figure 1.** Relationship Between Damping Coefficient and Simulated Gravitational Acceleration for Various Initial Swing Angles

Figure 1 illustrates the correlation between the damping coefficient ( $b$ ) and the simulated gravitational acceleration across different initial angles ( $\theta$ ). At low damping coefficients (0 to 0.3), the simulated gravitational acceleration remains stable and closely matches the theoretical value (978 cm/s<sup>2</sup>). However, beyond , gravitational acceleration begins to decrease significantly across all angles. This indicates that higher damping levels strongly influence pendulum dynamics, leading to deviations from ideal simple harmonic motion. As the damping coefficient increases, especially at values around 0.5 and above, the lines representing each angle begin to converge, indicating that the influence of increased damping becomes dominant. The simulated gravitational acceleration decreases consistently, reaching values around 300 cm/s<sup>2</sup> at a damping coefficient 0.9. This trend highlights the limitations of simple harmonic motion approximations in high-damping conditions, requiring a nonlinear approach to accurately model pendulum behavior.



**Figure 2.** Relationship Between Small Damping Coefficient and Simulated Gravitational Acceleration for Various Initial Swing Angles

Figure 2 shows the relationship between small damping coefficients ( $0$  to  $5 \times 10^{-3}$ ) and simulated gravitational acceleration for various swing angles. In the small damping range, the data show that the simulated gravitational acceleration tends to be stable and close to the theoretical value of about  $978 \text{ cm/s}^2$ , especially for small angles such as  $5^\circ$  and  $10^\circ$ . The acceleration value is almost unchanged, indicating that the damping effect in this range is very minimal, and the pendulum behavior is close to simple harmonic oscillation. Although there is a slight increase in the simulated gravitational acceleration with an increasing damping coefficient, the change is not significant, indicating that the impact of small damping is not enough to change the dynamics of the pendulum drastically. However, the nonlinearity effect dominates at large angles, causing a significant deviation from the standard gravity value. The simulated results confirm that for small damping values and low initial angles, the pendulum behaves in accordance with simple harmonic motion. However, at higher damping coefficients and larger angles, deviations occur due to dominant non-linear effects. These findings align with previous theoretical expectations regarding the transition from linear to non-linear motion in damped pendulum systems. The measurement results of fulcrum distance (a) and swing time by the experimental method are presented in Figure 3.

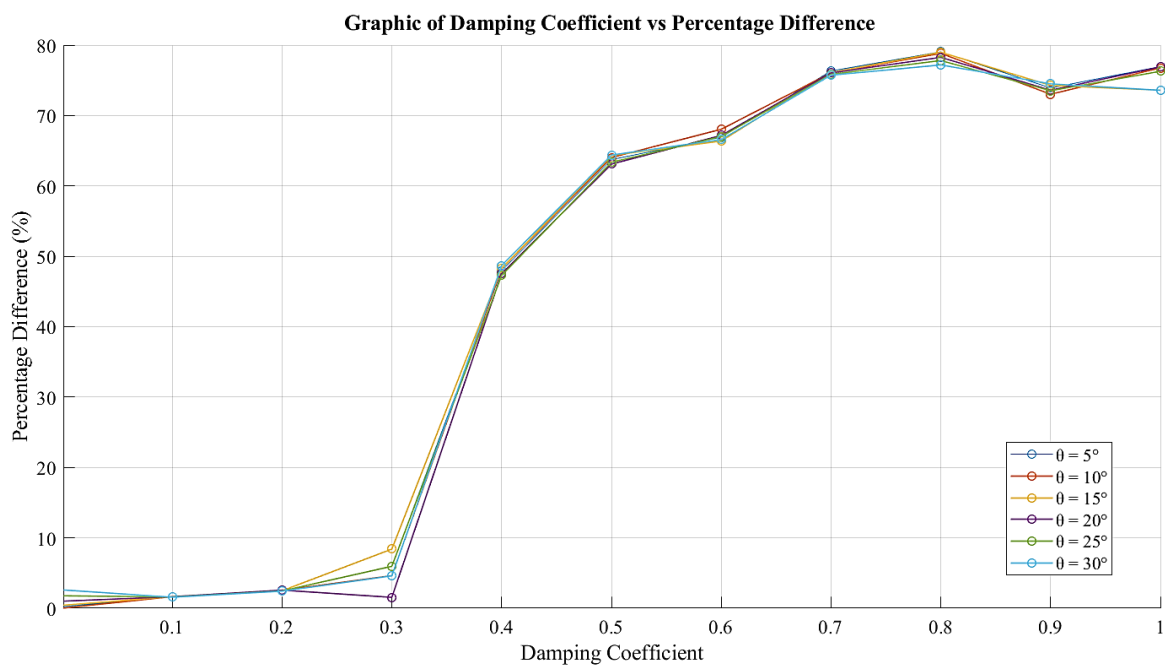


Figure 3. The Percentage Difference between the Simulated and Theoretical Values is Calculated for Each Combination of Parameters

Figure 3 provides a detailed analysis of the percentage difference between the simulated and theoretical gravitational acceleration values for various damping coefficients and initial angles. At low damping coefficients (from 0 to approximately 0.3), the percentage difference remains minimal (around 0 to 10%), which indicates that the system behaves linearly and that damping has minimal impact on gravitational acceleration calculations. However, beyond  $b \geq 0.3$ , the percentage difference rises sharply, exceeding 50% at higher damping coefficients ( $b \geq 0.5$ ). This behavior highlights the transition from linear to nonlinear dynamics in the pendulum system. At larger initial angles ( $\theta \geq 20^\circ$ ), the percentage difference becomes more pronounced even at lower damping coefficients, as observed in the error analysis where deviations increase with larger amplitude. This indicates that nonlinearity dominates the system's behavior, leading to greater deviations from theoretical predictions. The convergence of percentage differences for various angles at higher damping coefficients suggests that damping effects overpower the influence of initial angles, creating a uniform trend across conditions.

### Discussion

The experimental results show a gravitational acceleration value of  $967.91 \pm 6.52 \text{ cm/s}^2$ , which deviates by 1.03% from the theoretical value of  $978 \text{ cm/s}^2$ . This discrepancy can be attributed to measurement uncertainties, including errors in measuring the effective length of the pendulum and the period of oscillation (Braza, 2020; Nst, 2024). Although variations in results are inevitable, this percentage error remains within an acceptable range for laboratory experiments. The consistency of repeated swing time measurements indicates a relatively high level of precision (Adlim et al., 2020; Taherdoost, 2021). The

simulation results provide deeper insights into pendulum dynamics, particularly under non-ideal conditions. These findings underscore the importance of considering damping effects and nonlinearities when modeling pendulum dynamics. The observed trends align with findings that assert damping may trigger chaos in pendulum motion. Similarly, the dominance of non-linear effects at large angles has been emphasized, and it has been further demonstrated through Fourier analysis that the contribution of higher harmonic components becomes increasingly significant as the oscillation amplitude grows (Hinrichsen, 2020; Medellu et al., 2023; Meena, 2019). Moreover, the rotational dynamics of a forced-damped nonlinear pendulum reveal that damping can induce extreme rotational events, deviating significantly from standard thresholds (Asmorowati et al., 2023; Juharna et al., 2022; Monteiro et al., 2020; Subhan et al., 2022). These numerical results highlight a sudden expansion in chaotic attractors due to internal crises, reinforcing the impact of damping in triggering chaotic behavior. The findings from this study align with prior research that emphasizes the necessity of nonlinear numerical approaches to capture the full dynamics of damped pendulum motion. A successful application of the Finite Element Method (FEM) to solve the nonlinear pendulum equation with damping forces by transforming the problem into a boundary value problem further supports the importance of incorporating nonlinear effects in pendulum models, particularly at higher damping coefficients and large oscillation angles. These comparisons validate the study's findings and reinforce the need for more complex models in high-damping scenarios (Hafez, 2022; Wang et al., 2022).

The study results show that although the physical pendulum method can provide accurate results at small angles and low damping, it faces significant limitations at large and high damping. Addressing these conditions, it requires a more complex, nonlinear approach to effectively capture the dynamics of pendulum systems under nonlinear and damped conditions (Bocresion, 2023; Braza, 2020; Faux & Godolphin, 2019; Hinrichsen, 2020). Nevertheless, this model provides valuable insights into understanding the effects of damping and initial angle on the dynamics of a pendulum system and shows the potential for using numerical simulations to explore nonlinear phenomena in damped oscillatory systems. This study contributes to the field by combining experimental and numerical methods to analyze physical pendulum dynamics. The integration of MATLAB simulations with experimental data offers a robust framework for understanding damping and non-linearity effects. However, this research faced certain limitations. The experimental setup was constrained to a restricted angle range of 30° or less, which limited the ability to explore more extreme non-linear behavior. Moreover, the environmental conditions modeled in the simulations were simplified and did not account for real-world complexities such as air resistance or temperature fluctuations. Despite these constraints, The results emphasize the importance of precise experimental setups and advanced simulation models for gravitational acceleration measurements. Looking ahead, future studies could benefit from broadening the range of initial angles and damping coefficients to better probe extreme non-linear regimes. Additionally, incorporating real-world variables like air resistance would further enhance the realism and applicability of the models.

#### 4. CONCLUSION

Based on the results of the study, it can be concluded that the experimental and simulation methods applied to the physical pendulum system are capable of reliably measuring gravitational acceleration under ideal conditions. This approach has proven to be sufficiently accurate for practical purposes, with measurements closely aligning with the theoretical values for the local region. The simulation results indicate that at low damping levels, the gravitational acceleration remains stable and consistent with theoretical predictions, suggesting that damping effects within this range are minimal and the system behaves similarly to simple harmonic motion. However, under higher damping conditions, significant deviations from theoretical values occur, accompanied by the emergence of nonlinear motion characteristics. These findings imply that the simple harmonic motion model is valid only under controlled, ideal conditions and becomes inadequate in scenarios involving large angular deviations or high damping. Therefore, to achieve higher accuracy under such conditions, the application of more complex nonlinear models is required.

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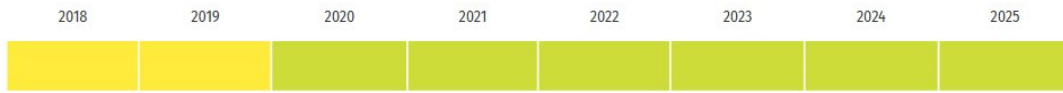
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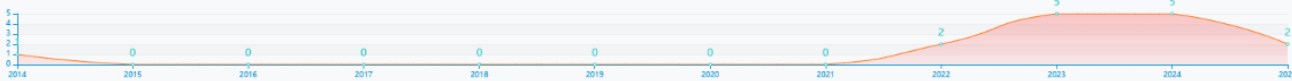
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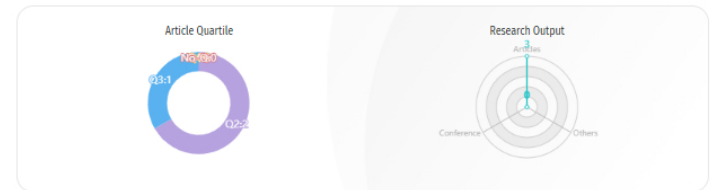
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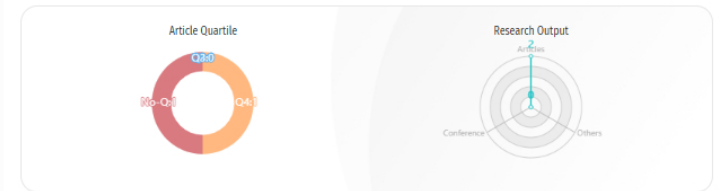
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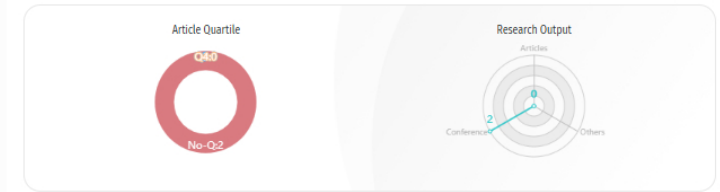
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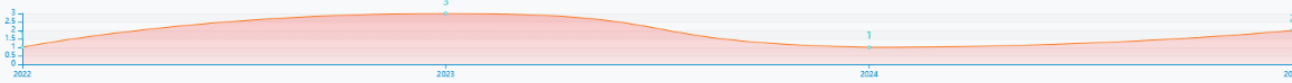
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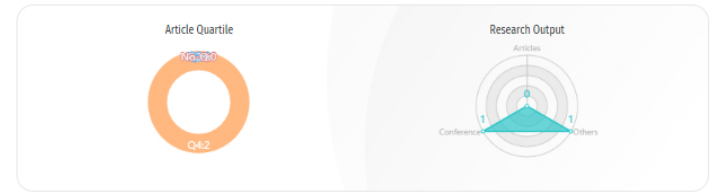
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# Local Gravity Paper

*by Ika Wahyu Utami*

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## Local Gravitational Acceleration through Experimental and Simulative Approaches on Physical Pendulum

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### ABSTRAK

Ketelitian dalam pengukuran percepatan gravitasi lokal masih menghadapi tantangan akibat keterbatasan pendekatan eksperimental konvensional dan pengaruh kondisi dinamis sistem. Selain itu, belum banyak kajian yang mengintegrasikan pendekatan simulasi numerik untuk meningkatkan akurasi dalam konteks gerak osilasi nonlinier. Penelitian ini bertujuan untuk menganalisis secara mendalam dinamika bandul fisis teredam serta mengevaluasi akurasi pengukuran percepatan gravitasi lokal dengan mengintegrasikan metode eksperimen dan simulasi numerik. Penelitian ini merupakan penelitian kuantitatif dengan desain eksperimen semu. Subjek penelitian terdiri atas satu set alat bandul fisis berupa batang logam homogen, tanpa melibatkan partisipan manusia. Data diperoleh melalui pengukuran periode osilasi menggunakan stopwatch digital berakurasi tinggi dan pengukuran panjang efektif menggunakan roll meter. Instrumen divalidasi melalui prinsip fisika klasik dan uji konsistensi hasil. Simulasi numerik dilakukan menggunakan metode Runge-Kutta orde 4 (ODE45). Analisis data meliputi analisis deskriptif kuantitatif, komparatif, dan evaluasi kesalahan relatif serta identifikasi ketidakpastian. Hasil penelitian menunjukkan bahwa nilai percepatan gravitasi hasil eksperimen mendekati nilai teoritis dengan tingkat kesalahan relatif yang rendah. Disimpulkan bahwa integrasi pendekatan eksperimen dan simulasi memberikan pemahaman yang lebih komprehensif terhadap dinamika bandul dan akurasi pengukuran gravitasi lokal. Implikasi dari penelitian ini adalah perlunya penerapan model dinamis yang lebih kompleks untuk mendukung pengukuran presisi di berbagai bidang seperti geofisika, teknik, dan pendidikan.

### ABSTRACT

Accuracy in measuring local gravitational acceleration remains a challenge due to the limitations of conventional experimental approaches and the influence of dynamic system conditions. Furthermore, few studies have integrated numerical simulation methods to enhance precision in the context of nonlinear oscillatory motion. This study aims to conduct an in-depth analysis of the dynamics of a damped physical pendulum and to evaluate the accuracy of local gravitational acceleration measurements by integrating experimental methods with numerical simulations. This is a quantitative study employing a quasi-experimental design. The research subject consisted of a single set of physical pendulum apparatus in the form of a homogeneous metal rod, with no human participants involved. Data were collected by measuring the oscillation period using a high-accuracy digital stopwatch and the effective length using a roll meter. Instruments were validated based on classical physics principles and result consistency tests. Numerical simulations were performed using the fourth-order Runge-Kutta method (ODE45). Data analysis included quantitative descriptive analysis, comparative analysis, relative error evaluation, and uncertainty identification. The results showed that the experimental gravitational acceleration value closely approximated the theoretical value, with a low relative error. It is concluded that integrating experimental and simulation approaches provides a more comprehensive understanding of pendulum dynamics and improves the accuracy of local gravity measurements. The findings imply the need for more complex dynamic models to support precision measurements in various fields such as geophysics, engineering, and education.

### 1. INTRODUCTION

Gravitational acceleration refers to the quantity that describes an object's velocity changes when it falls freely toward Earth's center due to gravitational pull (Pacala & Pili, 2023; Salim et al., 2022). On Earth's surface, gravitational acceleration is typically around  $9.8 \text{ m/s}^2$ , indicating that the velocity of a freely falling object increases by approximately 9.8 meters per second (Dwiatmoko & Dzulkifli, 2019; Shi et al., 2021; Subhan et al., 2022). However, this value varies depending on geographic location. For instance, in

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equatorial regions such as Indonesia, the average gravitational acceleration value is generally slightly lower, around  $9.78 \text{ m/s}^2$  (Medellu et al., 2023; Meena, 2019). Understanding local gravitational acceleration is crucial in various fields, including geodesy (for determining Earth's shape and size), aviation (for calculating flight paths and ensuring aircraft stability), geophysics (to study subsurface structures and mass distribution, enabling natural resource exploration and disaster mitigation), and civil engineering (for calculating structural loads of buildings and bridges) (Pacala & Pili, 2023; Yanti et al., 2020). One classical method for measuring gravitational acceleration is the physical pendulum experiment (Wang et al., 2022; Yuningsih et al., 2020). A physical pendulum consists of a rigid body suspended from a fixed pivot point, allowing it to oscillate freely under the influence of gravity. Unlike a mathematical pendulum that modeled as a point mass attached to a massless string, a physical pendulum exhibits a non-uniform mass distribution. As a result, the pendulum's period depends not only on the length of the suspension string but also on the distance between the pivot point and the object's center of mass (Dwiatmoko & Dzulkifli, 2019; Monteiro et al., 2020). Despite its practical applications, physical pendulums have inherent limitations. A primary limitation is the assumption that no external forces, aside from gravity, act on the system. In practice, however, external forces such as air resistance and damping inevitably influence the pendulum's oscillatory motion, leading to discrepancies between the measured and actual values of gravitational acceleration (Jatmiko, 2022; Rangkuti et al., 2019; Salim et al., 2022; Subhan et al., 2022).

To address these limitations, a comparative study is necessary between experimental results from physical pendulums and numerical simulation methods. Numerical simulations provide reliable data comparisons and enable a deeper analysis of factors influencing measurement outcomes, such as damping effects that are challenging to quantify experimentally. These simulations offer a more accurate representation of the oscillatory motion of physical pendulums and improve our understanding of their behavior. In the experimental method, the distance of the pivot point to the center of mass varies, and the time required for several oscillations is precisely measured. The oscillation period obtained is then used to calculate the gravitational acceleration value and its uncertainty. Meanwhile, in numerical simulation, the approach involves modeling the motion of a physical pendulum by utilizing differential equations that describe the system's dynamics. Thus, numerical simulation allows the analysis of the influence of various variables, such as damping on the period and the gravitational acceleration value. The factors that influence the oscillatory motion of the pendulum can be identified by comparing the simulation results with the experimental results. Accordingly, the primary objective of this study is to accurately measure local gravitational acceleration by employing a combined approach of experimental methods and numerical simulation using a physical pendulum system. The study also aims to analyze the influence of damping coefficients and initial angular displacements on the oscillatory dynamics of the system. In addition, it seeks to evaluate the reliability of the numerical model by comparing simulation results with experimental data and theoretical values, as well as to identify potential sources of uncertainty that may affect the measurement outcomes, both from experimental and computational perspectives. Through this approach, the research is expected to contribute significantly to the advancement of understanding in nonlinear oscillatory motion and to improve the accuracy of gravitational acceleration measurements, particularly in the geographical context of Indonesia.

## 2. METHOD

This study employs a quantitative approach with a quasi-experimental design, combining direct measurements through physical experimentation and numerical modeling via computer-based simulation (Hambali et al., 2020; Husni, 2020; Rajab et al., 2025). The primary objective is to accurately determine the local gravitational acceleration and to examine the effects of initial deviation angle and damping coefficient on the oscillatory dynamics of a physical pendulum system (Medellu et al., 2023; Salim et al., 2022). The experimental subject consists of a single physical pendulum apparatus, constructed from a homogeneous metal rod of specific dimensions and mass, which serves as the main instrument for data collection. No human participants are involved in this study; thus, all data collection is instrument-based and relies on physical measurements (Bangun et al., 2022; Mintjelungan et al., 2024). The distance from the pivot point to the center of mass of the homogeneous metal can be varied between two different lengths ( $a_1$  and  $a_2$ ) and it is measured by a roll meter. The time required to swing with an initial deviation angle ( $\theta_0$ ) of  $10^\circ$  for two different pivot points is measured using a digital stopwatch with an accuracy of 0.01 seconds three times to minimize errors. The average period for each pivot point ( $T_1$  and  $T_2$ ) is calculated from the time data obtained. Using the calculated period, the value of gravitational acceleration and its efficiency can be determined. The selection of a relatively small deviation angle in this physical pendulum experiment is generally based on the assumption that at a small deviation angle, the sine value of the angle ( $\sin \theta$ ) can be approximated by the angle value in radians ( $\theta$ ) ( $\sin \theta = \theta$ ) (Azahra et al., 2024; Bocresion, 2023). This

approach allows us to achieve the pendulum's motion equation into a simple harmonic motion equation. To account for the damping effect that is not measured in the experiment, the differential equation describing the motion of the physical pendulum is modified by adding a damping term as a mathematical model to describe the swing motion. The parameters used in the simulation include the effective swing length, damping coefficient, and compression acceleration (Bagus et al., 2024; Ekoputri et al., 2023).

Numerical simulations are performed using MATLAB software to obtain numerical solutions to this mathematical model. The simulation results are then compared with experimental data to validate the model. The differential equation describing the motion of the physical pendulum is solved numerically using the Runge-Kutta method, specifically with the ODE45 function, to obtain numerical solutions for the position and angular velocity of the swing as a function of time. The swing period from the simulation is calculated by finding the time difference between two consecutive cut points of the position curve. From the span period obtained from the simulation, the value of the simulated gravitational acceleration can be calculated. Simulations are performed with various values of the damping coefficient and initial swing angle to explore the effects on both the swing period and the shape of the position curve. Next, the gravity values obtained from experiments and simulations are compared with electromagnetic values to verify the accuracy of the simulation models and experimental methods and identify distance sources.

### 3. RESULT AND DISCUSSION

#### Result

##### Experimental Results

The experimental method aims to determine the value of Earth's gravitational acceleration using the principle of a physical pendulum. In this study, a physical pendulum with two variations of pivot points on a hollow homogeneous metal rod was used. The observed swing periods were recorded for multiple trials, and gravitational acceleration values were calculated using Equation (1).

$$T = 2\pi \sqrt{\frac{k_0^2 + a^2}{g \cdot a}} \tag{1}$$

where:

- T = swing period (seconds)
- $k_0$  = radius of gyration to the center of mass (cm)
- a = distance of the pivot point to the center of mass (cm)
- g = Earth's gravitational acceleration (cm/sec)

In the experimental method, an approach is taken based on the assumption that the pendulum swing has a small amplitude thus the restoring force acting on the pendulum is proportional to its deviation. With this assumption, complex nonlinear equations of motion can be simplified into linear equations that are easier to solve. In addition, a more straightforward formula is obtained to calculate the swing period by ignoring factors such as friction and assuming the pendulum's mass is concentrated at one point. From equation (1), by taking point  $A_1$  as the pivot point whose swing period is  $T_1$  and pivot point  $A_2$  (on the opposite side of point  $A_1$ ) whose swing period is  $T_2$ , the equation of the relationship between the period and the acceleration of gravity (Equation 2) and the uncertainty of the acceleration of gravity (Equation 3) is obtained.

$$\frac{\pi^2}{g} = \frac{T_1^2 + T_2^2}{8(a_1 + a_2)} + \frac{T_1^2 - T_2^2}{8(a_1 - a_2)}$$

$$g = \frac{4\pi^2(a_1^2 - a_2^2)}{a_1 T_1^2 - a_2 T_2^2} \tag{2}$$

$$\Delta g = \left[ \frac{8\pi^2 a_1 \Delta a_1 + 8\pi^2 a_2 \Delta a_2}{4\pi^2(a_1^2 - a_2^2)} + \frac{2a_1 T_1 \Delta T_1 + 2a_2 T_2 \Delta T_2 + T_1^2 \Delta a_1 + T_2^2 \Delta a_2}{(a_1 T_1^2 - a_2 T_2^2)} \right] g \tag{3}$$

In the experimental method, the swing period can be measured for several effective pendulum lengths by varying the distance between the pivot point and the center of mass of the rod and calculating the time required to swing. The swing period data is then used to calculate the Earth's gravitational acceleration value. Table 1 shows the distance from the pivot point to the center of mass and the measured swing times for 20 oscillations.

**Table 1.** Results of Measuring the Distance of the Pivot Point (A) and the Time Required to Swing Using the Experimental Method

Distance of pivot point A from the center of mass (cm)	Swing Angle	Swing Time (seconds)		
		Time for 20 swings (repetition 1)	Time for 20 swings (repetition 2)	Time for 20 swings (repetition 3)
a <sub>1</sub> : 57.5 ± 0.02	10 <sup>0</sup>	35.0	35.0	35.0
a <sub>2</sub> : 47.5 ± 0.02	10 <sup>0</sup>	33.5	33.5	33.5

The experiment was conducted in a closed room with a relatively stable temperature to minimize the influence of environmental factors. The time data obtained did not show any variation, indicating a relatively good level of measurement precision. Furthermore, the time data was analyzed using the average method and its uncertainty. By applying equations (1) and (2), the value of gravitational acceleration and its uncertainty are obtained based on the experimental results of  $g \pm \Delta g = (967.91 \pm 6.52) \text{ cm/s}^2$ . When compared to the theoretical value of local gravitational acceleration, which is  $978 \text{ cm/s}^2$ , there is a difference that can be calculated through the percentage error to understand the difference between the experimental and theoretical results.

$$\text{Percentage difference} = \left( \frac{g_{\text{theory}} - g_{\text{experiment}}}{g_{\text{theory}}} \right) \times 100\% \approx 1.03\%$$

**Simulation Results**

To complement the experimental findings, numerical simulations were conducted using MATLAB with the fourth-order Runge-Kutta method (ODE45) which implements a method to solve differential equations that describe the dynamics of a physical pendulum. This simulation was carried out for various initial deviation angles ranging from 5° to 30°. In each iteration of the initial angle, simulations were carried out for a range of damping coefficient values (b) from 0 (no damping) to 1 (high damping) with an interval of 0.1. The initial angle was converted from degrees to radians for calculation at each iteration. The simulation's initial angular velocity ( $\omega_0$ ) was set at zero, considering that the pendulum was initially at rest. This means the pendulum is only given an initial push as a deviation angle ( $\theta_0$ ) without any initial angular velocity. Important parameters in the simulation include the simulation period, the length of the pivot point to the center of mass, and the radius of gyration, which explain the distribution of the pendulum mass. After obtaining the angular position data  $\theta$  from the simulation, the swing period is determined by identifying the peaks in the data using the *findpeaks* function. The simulation period obtained is then used to calculate the simulated gravitational acceleration value based on equation (4).

$$g_{\text{sim}} = \frac{4\pi^2 k^2}{T_{\text{sim}}^2 d} \tag{4}$$

where

- $g_{\text{sim}}$  = simulated gravitational acceleration (cm/s<sup>2</sup>)
- $T_{\text{sim}}$  = simulated swing period (seconds)
- $k$  = radius of gyration of the two pivot points (cm)
- $d$  = average distance of the pivot point to the center of mass (cm)

Conducting simulations for various combinations of initial angles and damping coefficients yields a comprehensive dataset of gravitational acceleration values. This dataset is then compared with the theoretical value of local gravitational acceleration to evaluate the accuracy of the simulation model. For each combination of parameters, the percentage difference between the simulated and theoretical values is calculated. The key findings indicate that for small damping coefficients, ranging from 0 to 0.3, the simulated gravitational acceleration remains stable and closely aligned with the theoretical value. However, as the damping coefficient increases to 0.5 or higher, the gravitational acceleration decreases significantly, reflecting the characteristics of non-linear pendulum behavior. Figures 1 and Figure 2 illustrate the relationship between damping coefficients and simulated gravitational acceleration at various angles.

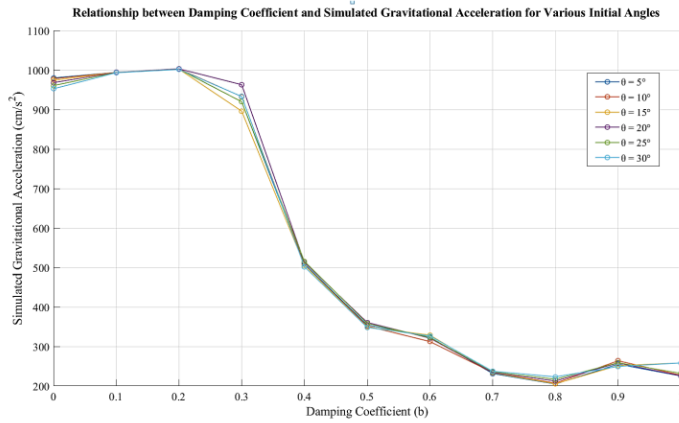


Figure 1. Relationship Between Damping Coefficient and Simulated Gravitational Acceleration for Various Initial Swing Angles

Figure 1 illustrates the correlation between the damping coefficient ( $b$ ) and the simulated gravitational acceleration across different initial angles ( $\theta$ ). At low damping coefficients (0 to 0.3), the simulated gravitational acceleration remains stable and closely matches the theoretical value ( $978 \text{ cm/s}^2$ ). However, beyond , gravitational acceleration begins to decrease significantly across all angles. This indicates that higher damping levels strongly influence pendulum dynamics, leading to deviations from ideal simple harmonic motion. As the damping coefficient increases, especially at values around 0.5 and above, the lines representing each angle begin to converge, indicating that the influence of increased damping becomes dominant. The simulated gravitational acceleration decreases consistently, reaching values around  $300 \text{ cm/s}^2$  at a damping coefficient 0.9. This trend highlights the limitations of simple harmonic motion approximations in high-damping conditions, requiring a nonlinear approach to accurately model pendulum behavior.

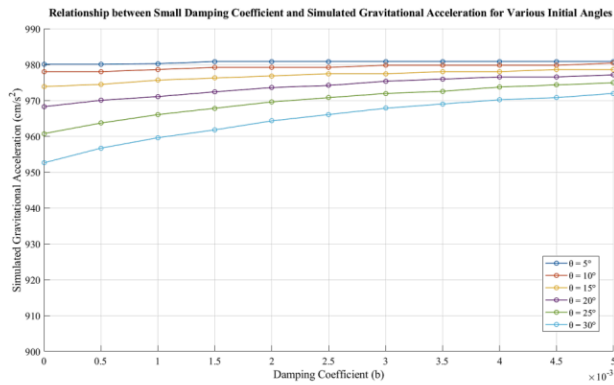


Figure 2. Relationship Between Small Damping Coefficient and Simulated Gravitational Acceleration for Various Initial Swing Angles

Figure 2 shows the relationship between small damping coefficients ( $0$  to  $5 \times 10^{-3}$ ) and simulated gravitational acceleration for various swing angles. In the small damping range, the data show that the simulated gravitational acceleration tends to be stable and close to the theoretical value of about  $978 \text{ cm/s}^2$ , especially for small angles such as  $5^\circ$  and  $10^\circ$ . The acceleration value is almost unchanged, indicating that the damping effect in this range is very minimal, and the pendulum behavior is close to simple harmonic oscillation. Although there is a slight increase in the simulated gravitational acceleration with an increasing damping coefficient, the change is not significant, indicating that the impact of small damping is not enough to change the dynamics of the pendulum drastically. However, the nonlinearity effect dominates at large angles, causing a significant deviation from the standard gravity value. The simulated results confirm that for small damping values and low initial angles, the pendulum behaves in accordance with simple harmonic motion. However, at higher damping coefficients and larger angles, deviations occur due to dominant non-linear effects. These findings align with previous theoretical expectations regarding the transition from linear to non-linear motion in damped pendulum systems. The measurement results of fulcrum distance (a) and swing time by the experimental method are presented in Figure 3.

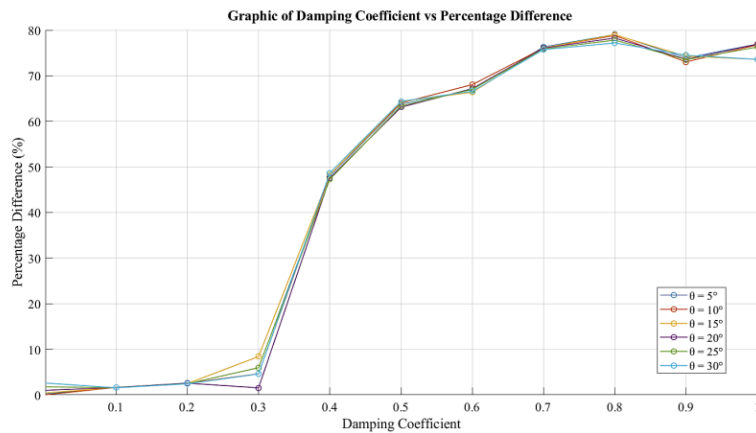


Figure 3. The Percentage Difference between the Simulated and Theoretical Values is Calculated for Each Combination of Parameters

Figure 3 provides a detailed analysis of the percentage difference between the simulated and theoretical gravitational acceleration values for various damping coefficients and initial angles. At low damping coefficients (from 0 to approximately 0.3), the percentage difference remains minimal (around 0 to 10%), which indicates that the system behaves linearly and that damping has minimal impact on gravitational acceleration calculations. However, beyond  $b \geq 0.3$ , the percentage difference rises sharply, exceeding 50% at higher damping coefficients ( $b \geq 0.5$ ). This behavior highlights the transition from linear to nonlinear dynamics in the pendulum system. At larger initial angles ( $\theta \geq 20^\circ$ ), the percentage difference becomes more pronounced even at lower damping coefficients, as observed in the error analysis where deviations increase with larger amplitude. This indicates that nonlinearity dominates the system's behavior, leading to greater deviations from theoretical predictions. The convergence of percentage differences for various angles at higher damping coefficients suggests that damping effects overpower the influence of initial angles, creating a uniform trend across conditions.

**Discussion**

The experimental results show a gravitational acceleration value of  $967.91 \pm 6.52 \text{ cm/s}^2$ , which deviates by 1.03% from the theoretical value of  $978 \text{ cm/s}^2$ . This discrepancy can be attributed to measurement uncertainties, including errors in measuring the effective length of the pendulum and the period of oscillation (Braza, 2020; Nst, 2024). Although variations in results are inevitable, this percentage error remains within an acceptable range for laboratory experiments. The consistency of repeated swing time measurements indicates a relatively high level of precision (Adlim et al., 2020; Taherdoost, 2021). The

simulation results provide deeper insights into pendulum dynamics, particularly under non-ideal conditions. These findings underscore the importance of considering damping effects and nonlinearities when modeling pendulum dynamics. The observed trends align with findings that assert damping may trigger chaos in pendulum motion. Similarly, the dominance of non-linear effects at large angles has been emphasized, and it has been further demonstrated through Fourier analysis that the contribution of higher harmonic components becomes increasingly significant as the oscillation amplitude grows (Hinrichsen, 2020; Medellu et al., 2023; Meena, 2019). Moreover, the rotational dynamics of a forced-damped nonlinear pendulum reveal that damping can induce extreme rotational events, deviating significantly from standard thresholds (Asmorowati et al., 2023; Juharna et al., 2022; Monteiro et al., 2020; Subhan et al., 2022). These numerical results highlight a sudden expansion in chaotic attractors due to internal crises, reinforcing the impact of damping in triggering chaotic behavior. The findings from this study align with prior research that emphasizes the necessity of nonlinear numerical approaches to capture the full dynamics of damped pendulum motion. A successful application of the Finite Element Method (FEM) to solve the nonlinear pendulum equation with damping forces by transforming the problem into a boundary value problem further supports the importance of incorporating nonlinear effects in pendulum models, particularly at higher damping coefficients and large oscillation angles. These comparisons validate the study's findings and reinforce the need for more complex models in high-damping scenarios (Hafez, 2022; Wang et al., 2022).

The study results show that although the physical pendulum method can provide accurate results at small angles and low damping, it faces significant limitations at large and high damping. Addressing these conditions, it requires a more complex, nonlinear approach to effectively capture the dynamics of pendulum systems under nonlinear and damped conditions (Bocresion, 2023; Braza, 2020; Faux & Godolphin, 2019; Hinrichsen, 2020). Nevertheless, this model provides valuable insights into understanding the effects of damping and initial angle on the dynamics of a pendulum system and shows the potential for using numerical simulations to explore nonlinear phenomena in damped oscillatory systems. This study contributes to the field by combining experimental and numerical methods to analyze physical pendulum dynamics. The integration of MATLAB simulations with experimental data offers a robust framework for understanding damping and non-linearity effects. However, this research faced certain limitations. The experimental setup was constrained to a restricted angle range of 30° or less, which limited the ability to explore more extreme non-linear behavior. Moreover, the environmental conditions modeled in the simulations were simplified and did not account for real-world complexities such as air resistance or temperature fluctuations. Despite these constraints, the results emphasize the importance of precise experimental setups and advanced simulation models for gravitational acceleration measurements. Looking ahead, future studies could benefit from broadening the range of initial angles and damping coefficients to better probe extreme non-linear regimes. Additionally, incorporating real-world variables like air resistance would further enhance the realism and applicability of the models.

#### 4. CONCLUSION

Based on the results of the study, it can be concluded that the experimental and simulation methods applied to the physical pendulum system are capable of reliably measuring gravitational acceleration under ideal conditions. This approach has proven to be sufficiently accurate for practical purposes, with measurements closely aligning with the theoretical values for the local region. The simulation results indicate that at low damping levels, the gravitational acceleration remains stable and consistent with theoretical predictions, suggesting that damping effects within this range are minimal and the system behaves similarly to simple harmonic motion. However, under higher damping conditions, significant deviations from theoretical values occur, accompanied by the emergence of nonlinear motion characteristics. These findings imply that the simple harmonic motion model is valid only under controlled, ideal conditions and becomes inadequate in scenarios involving large angular deviations or high damping. Therefore, to achieve higher accuracy under such conditions, the application of more complex nonlinear models is required.

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