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Effect of Aluminium Plate Layers and Electric Current on Pendulum Damping Time

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ABSTRACT

The pendulum is a classic oscillatory system commonly used in physics to study motion and damping phenomena. One notable damping mechanism is electromagnetic damping caused by eddy current induction. This study investigates the effects of varying the number of aluminium plate layers attached to the pendulum and the electric current supplied to a surrounding coil, which generates a magnetic field, on the pendulum damping time. An experimental approach was used by measuring the damping time across different combinations of plate layers and current levels. The data were analyzed to identify the relationship between these variables and the damping behavior of the pendulum. Results indicate a negative exponential relationship between the electric current and damping time, as well as a significant effect of aluminium plate layers on damping efficiency. Increasing the number of aluminium plate layers enhances eddy current induction, resulting in stronger damping forces.

1. INTRODUCTION

Pendulum is one of the dynamic systems that is often used in various studies on mechanics (Wang, 2023). In physics studies, the pendulum is an example of a simple oscillatory system that illustrates various motion phenomena, such as vibration and damping (Zulaikha & Warsono, 2021). As a physical system, the pendulum is also an ideal model for understanding basic concepts such as kinetic and potential energy, conservative forces, and the influence of external forces (Wiranto, 2024). Therefore, the damped oscillation system on the pendulum is interesting to study in more detail, especially related to the factors that affect the damping time on the pendulum (Pili, 2020).

The development of effective and efficient damped oscillation systems requires the use of technology (Dolfo et al., 2016). A deep understanding of the factors that affect the performance of pendulum systems is very important. Several studies have been conducted related to the damping of pendulum motion, one of which is the damping factor due to the magnetic brake system (Pili, 2020). Other research was also carried out related to damping due to eddy currents (Putra et al., 2022).

Eddy currents are used in non-contact braking technologies, such as in maglev trains and high-speed rail vehicles. Eddy currents generated in conductors serve to slow down movement without physical friction (Suwarno, 2016). Damping can occur due to the magnetic field acting on the pendulum (Ghifari et al., 2023). Other factors that work on the damping of pendulum motion include the angular position of the pendulum, the thickness of the magnet, and variations in pendulum length (Noerpamoengkas & Ulum, 2022; Putra et al., 2022; Zarkacy et al., 2023). However, the influence of variations in the number of metallic plate layers as pendulum and the amount of electric current can affect the damping time and dynamic response of the system as a whole has not been fully investigated.

The novelty of this research is focused on exploring the combination of the variable number of metallic plate layers and electric current. The effect of electric current on pendulum systems has been investigated, but studies combining variations in pendulum metal thickness with the magnitude of electric current flowing through copper wire wrapped around iron, and their impact on damping time, remain limited (Budiarto et al., 2022; Wahyuni et al., 2015). The metal used in previous studies was copper (Noerpamoengkas & Ulum, 2022). Aluminium, a metal with different magnetic properties from copper, is used as an alternative material in the study (Firmansyah et al., 2024; Wahyuni et al., 2015). Aluminium shows paramagnetic properties. Paramagnetic materials can be attracted by magnetic fields but with weak strength (Suwarno, 2015). When aluminium is exposed to a changing magnetic field, eddy currents can also form, but the effect is not as strong as in diamagnetic metals such as copper (Suwarno, 2016).

This study aims to examine the effect of the number of aluminium plate layers and the amount of electric current applied to the copper wire winding on the pendulum damping time. These two variables are thought to have an influence on the performance of the pendulum system, especially in determining the time required to reach steady state. This research has the potential and urgency to be applied in the field of applied physics, especially in the development of a more efficient and effective vibration damping system.

2. METHODS

2.1 Research Methods

An experimental method was employed to investigate the effect of aluminium plate layers and electric current on pendulum damping time. The coil used in the setup consisted of an iron core wrapped with copper wire. The independent variables are the number of aluminium plate layers attached to the pendulum and the electric current applied to the coil. The dependent variable is pendulum damping time. The control variables include the distance between the coils, the initial deviation angle, the number of coil turns, and the mass of the pendulum across all variations of aluminium plate layers. The initial deviation angle is set at 10o to ensure harmonic motion (Serway & Jewett, 2014).

2.2 Tools and Materials

The tools and materials were selected to support the accuracy and consistency of the experiment, particularly in generating and measuring the physical variables involved. The tools and materials used include a power supply as a voltage and current source, two coils made of 1000 turns of copper wire with iron cores, two resistors rated at 10 Ω and 20 W, a multimeter functioning as an ammeter, a breadboard, connecting cables, a stopwatch, an arc frame for consistent pendulum release, pliers, and a ruler. The experimental design is illustrated in Figure 1.

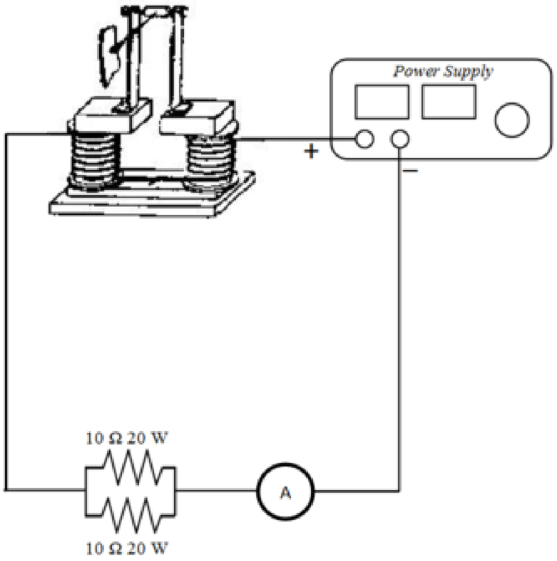

Figure 1. Tool design

2.3 Procedure

The experiment began by installing a pendulum consisting of a single aluminium plate layer. The pendulum was displaced at an angle of 10°, and no electric current was applied to the coil in this initial stage. The time taken for the pendulum to come to a complete stop was recorded. This measurement was repeated ten times to ensure accuracy and consistency.

Subsequent trials were conducted with varying levels of electric current applied to the coil, using the same procedure. The same data collection method was also applied for pendulums consisting of two and three aluminium plate layers. This resulted in a set of data covering different combinations of plate layers and electric current strengths.

2.4 Data Analysis

The recorded damping times from each variation were averaged to obtain representative values. These averages were then analyzed to determine the influence of both the number of aluminium plate layers and the magnitude of the electric current on the pendulum's damping time.

2.5 Equation Analysis

The electric current flowing in the coil will form a magnetic field (Griffiths, 2023). The magnetic field formed can be calculated by equation 1,

$$B = \mu_0 \frac{N}{L} I \tag{1}$$

with B is the magnetic field, μ_0 is the vacuum permeability, N is the number of turns, L is the length of the coil, and I is the electric current flowing in the coil. A conductor that swings in a magnetic field area will experience a change in magnetic flux that causes the appearance of an induced electromotive force in accordance with Faraday's law (Serway & Jewett, 2014). The electromotive force is expressed by equation 2,

$$\varepsilon = -\frac{d\phi}{dt} \tag{2}$$

with magnetic flux $\Phi = BA$, where B is the magnetic field and A is the surface area of the aluminium plate. When a conductor moves in a magnetic field, eddy currents are formed due to the induced electromotive force (Reitz et al., 2009). The eddy currents formed are written as

$$I_e = \frac{\varepsilon}{R} \tag{3}$$

Eddy currents are generally rotational movements in metals that are between two oppositely poled magnets and induce electromotive forces in the metal (Sodano & Bae, 2004). A schematic diagram showing this concept is provided in Figure 2.

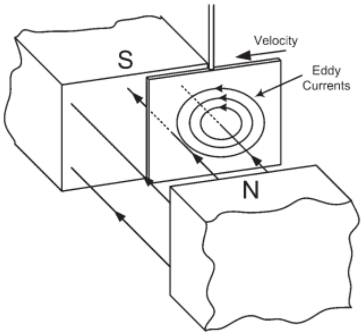

Figure 2. Schematic diagram of a conductor passing through a magnetic field and eddy current generation (Sodano & Bae, 2004)

In Figure 2, the magnetic field is concentrated in the gap between two magnetic surfaces, therefore causing conductors passing through this region to experience magnetic flux changes and induce eddy currents and damping forces (Serway & Jewett, 2014; Sodano & Bae, 2004). The eddy currents formed will generate a magnetic field that opposes the motion of the object, thus creating a damping force (Griffiths, 2023).

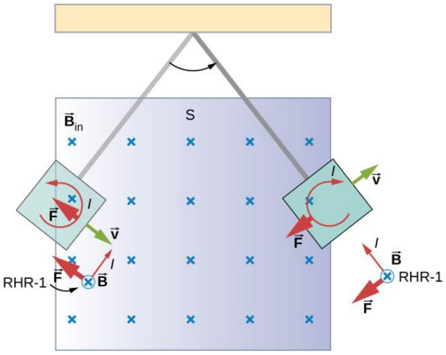

Figure 3. A view of the direction of the magnetic force in the countercurrent rotation with motion on a metal pendulum passing between the magnetic poles (Janzen, 2018)

Based on Figure 3 as the plate moves out of the plane on the right side, the magnetic flux decreases, resulting in a clockwise eddy current. These current experiences a force towards the left, which in turn inhibits the motion of the plate. A similar analysis can be applied when the plate swings from the right to the left direction, where its motion remains damping both when entering and leaving the plane (Janzen, 2018). The direction of the damping force is always opposite to the direction of the pendulum motion (Suwarno, 2015).

The magnitude of the eddy current is formulated to depend on the magnitude of the magnetic field B and the speed v (Chen et al., 2019). If a conductor of length l moves in a magnetic field B with speed v, the flux change occurs due to a change in position, so the induced voltage can be written as

$$\varepsilon = Blv \tag{4}$$

From equations 3 and 4, the magnitude of the eddy current that occurs is formulated by

$$I_e = \frac{Blv}{R} \tag{5}$$

The damping force is the Lorentz force generated by eddy currents formed in a conductor interacting with a magnetic field (Thornton & Marion, 2004). Mathematically, eddy currents interact with the magnetic field of the winding to cause a Lorentz force as a damping force expressed by

$$F = I_e Bl \tag{6}$$

by entering equations 1 and 5,

$$F = \frac{{\mu_0}^2 N^2 l^2}{L^2 R} I^2 v \tag{7}$$

This damping force causes damping that is proportional to the speed of the object's motion (Serway & Jewett, 2014). From equation 7, it can be written

$$F = kv \tag{8}$$

with k as the damping constant then

$$k = \frac{{\mu_0}^2 N^2 l^2}{L^2 R} I^2 \tag{9}$$

The presence of damping causes the motion to slow down as illustrated in Figure 4.

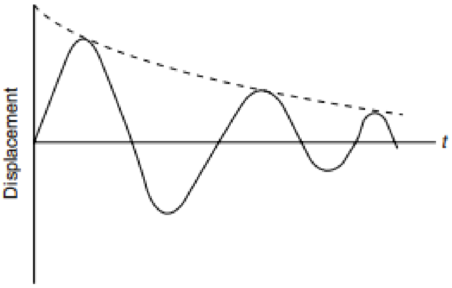

Figure 4. Damped oscillatory motion (Pain, 2005)

In a pendulum system with mass m subjected to electromagnetic damping force, the total force acting on the body follows Newton's second law with the equation of motion

$$m\frac{dv}{dt} = -F \tag{10}$$

can be written as

$$m\frac{dv}{dt} = -kv \tag{11}$$

The equation is integrated,

$$\int_{v_0}^{v}\frac{dv}{v} = -\frac{k}{m}\int_0^t dt \tag{12}$$

to

$$\ln\left(\frac{v}{v_0}\right) = -\frac{k}{m}t \tag{13}$$

so that the equation is

$$v = v_0 e^{-\frac{k}{m}t} \tag{14}$$

The equation of motion with electromagnetic damping follows an exponential model (Pain, 2005; Tipler, 2001). The data obtained is then processed in the form of a graph of the relationship between damping time and the amount of electric current flowing in the coil so that an equation is needed to determine the relationship between damping time and the amount of electric current. Equation 13 is modified into

$$\ln\left(\frac{\alpha v_0}{v_0}\right) = -\frac{k}{m}t \tag{15}$$

where α is the fraction of velocity at a time compared to the initial velocity,

$$\ln(\alpha) = -\frac{k}{m}t \tag{16}$$

to

$$t = -\frac{\ln(\alpha)}{k}m \tag{17}$$

Thus, it can be expressed by the equation

$$t = -\frac{\ln(\alpha)}{I^2}m\frac{L^2R}{{\mu_0}^2N^2l^2} \tag{18}$$

From equation 18, the relationship between damping time and electric current is obtained in a non-linear.

$$t \propto \frac{1}{I^2} \tag{19}$$

The damping time is inversely proportional to the square of the electric current.

3. RESULT AND DISCUSSION

Based on the design of the research tool shown in Figure 1, the complete set of instruments used for data collection is arranged as illustrated in Figure 5. In the experimental setup, the pendulum was constructed using aluminium plates, and an electric current was applied to an iron core wrapped with copper wire to generate a magnetic field. Variations in pendulum mass were introduced through different numbers of aluminium plate layers, as presented in Figure 6.

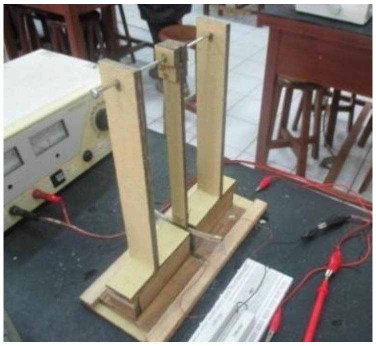

Figure 5. Research tool setup

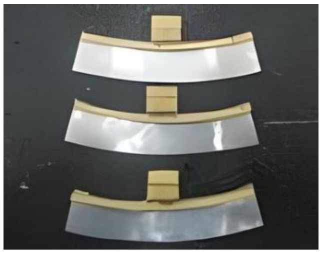

Figure 6. Variation of aluminium plate layers

The collected data shows that as the electric current in the coil increases, the pendulum damping time decreases. These findings are summarized in Table 1. The damping time was shortest when the current was highest and when the pendulum used three aluminium plate layers.

Table 1. Experimental data on pendulum with varying aluminum plate layers

No.	Electric current (A)	Average damping time (s)		
		1 layer	2 layers	3 layers
1.	0	24.24	24.22	24.23
2.	0.025	23.49	23.34	22.71
3.	0.050	21.50	21.13	21.09
4.	0.075	20.36	20.29	20.40
5.	0.100	19.64	19.16	19.47
6.	0.125	18.70	18.31	18.21
7.	0.150	18.52	17.84	16.78
8.	0.175	17.71	17.29	15.75
9.	0.200	17.08	17.18	15.35
10.	0.225	16.35	16.41	14.54
11.	0.250	15.56	15.22	13.43

This dataset was further analyzed to plot the relationship between damping time and electric current strength, as shown in Figure 7. The analysis, based on Equation 19, reveals that the damping time is inversely proportional to the square of the electric current. The graph for each variation in the number of aluminium plate layers demonstrates a non-linear decrease in damping time with increasing electric current. The trend follows a negative exponential curve, where initial increases in current result in a rapid decrease in damping time, but the effect becomes less pronounced at higher current values.

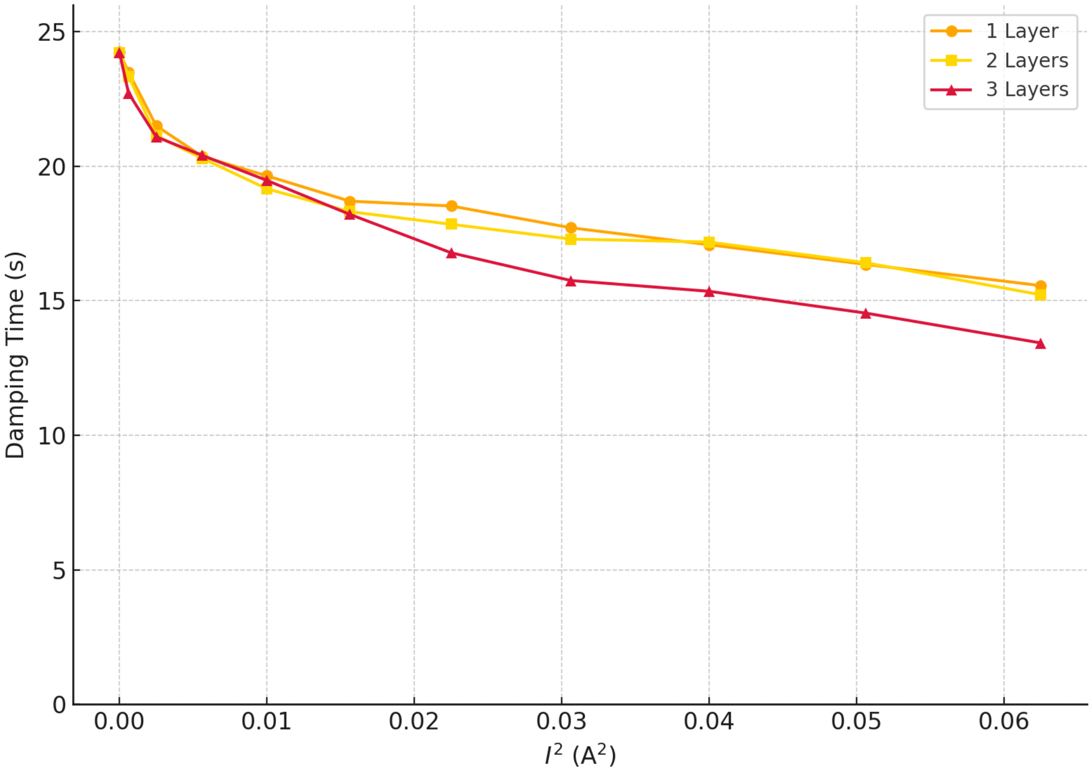

Figure 7. Graph of the relationship between I^2 and damping time for the variation of aluminum plate layers

Additionally, Figure 7 indicates that the damping time decreases with each additional aluminium plate layer. The pendulum with three layers recorded a significantly shorter damping time compared to those with one or two layers.

The observed pattern in the damping time is closely related to the eddy current damping mechanism, where a magnetic field interacts with a conductive metal to produce a damping force (Ghifari et al., 2023). As the aluminium pendulum swings through the magnetic field generated by the coil, changes in magnetic flux induce eddy currents within the plate, according to Faraday's Law (Reitz et al., 2009; Serway & Jewett, 2014). These eddy currents interact with the magnetic field, producing a Lorentz force that opposes the motion of the pendulum and acts as a damping force (Griffiths, 2023; Suwarno, 2015; Thornton & Marion, 2004).

The magnitude of this damping force depends on the magnetic field strength, which in turn is controlled by the electric current flowing through the coil. As the current increases, the magnetic field becomes stronger, inducing larger eddy currents and resulting in stronger damping. This aligns with earlier studies involving aluminium rods and swinging discs, which demonstrated similar damping effects in the presence of magnetic fields (Griffiths, 2023; Suwarno, 2015).

The exponential behavior of the damping time can be attributed to the fact that eddy current damping is dependent on the velocity of the moving conductor. At higher speeds, larger eddy currents form and produce stronger damping forces. As the pendulum slows down, the damping force diminishes, leading to exponential rather than linear deceleration (Thornton & Marion, 2004).

Furthermore, the results confirm that increasing the number of aluminium plate layers enhances the damping effect. A greater number of layers increases the surface area interacting with the magnetic field, thereby allowing more eddy currents to be induced (Griffiths, 2023; Putra et al., 2022). However, this enhancement is subject to limitations. When magnetic field saturation or resistive losses occur, further increases in layers or current may no longer significantly improve the damping force (Fahriani et al., 2019; Sa'adah et al., 2020).

Thus, both the electric current and the number of aluminium plate layers play critical roles in determining the efficiency of eddy current damping. The negative exponential trend observed in the graph supports the theoretical model and highlights the non-linear nature of this damping mechanism.

4. CONCLUSION

Based on the results of the study, it can be concluded that the damping time of the pendulum is inversely proportional to the amount of electric current applied to the coil. This relationship is non-linear and follows a negative exponential pattern. Increasing the electric current causes a significant decrease in damping time, but the effect gets smaller at larger currents. Increasing the number of aluminum plate layers accelerates the damping time because the larger surface area increases the eddy current induction and the resulting damping force. Further research suggestions are to add variations in the number of layers to determine the damping effect that occurs whether it continues to increase or begins to decrease due to resistance and magnetic field saturation effects. In addition, it can also find out more information related to the optimal limit of the aluminum layer before the saturation effect occurs. The results have potential applications in applied physics, particularly in the development of more efficient and effective vibration damping systems.

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