One-Dimensional Motion Analysis of a Cylinder with a Magnetic Dipole Inside an External Magnetic Field

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Abstract. Electromagnetism has evolved from only a science into an inseparable part of our daily life, nowadays. One kind of benefit of it is the use of magnetic field as an energy source of any physical movements. A motion analysis system was designed and built in this experiment. It consists of a solenoid, two cylinders made from acrylic where magnet chips are inserted within them, and a rail track or container for the cylinders. The goal of this research is to observe and specify the types of motion produced by the cylinder as a response of external magnetic fields from the solenoid. The dependent variables include starting position and starting angle of the cylinder, the amount of magnet chips injected, and the voltage used to supply the solenoids. The motion is a rolling motion, consisting of translational and rotational motions. The rolling motion that we observed is divided into two types, pure and with slipping, while later is divided again into translational and rotational dominance.

1. Introduction
Magnetism plays a big role for the development of human civilization right now. They have been used in many aspects in our life, such as in medical instruments, industries, transportations, chemistry, astrophysics [1]. Einstein classified magnets as a spooky act at a distance to refer the concept that an object could interact without having any physical contact [2, 3]. In 1939, W. Braunbeck succeeded to levitate small graphite beads in a vertical electromagnet [4]. After that breakthrough, a development to move a bigger object with better control system was achieved [5]. The most prominent product of this research is magnetic levitation (maglev), a method by which an object is suspended in the air with no support other than magnetic fields. Maglev has numerous applications in modern science, engineering and technology. Some of them are magnetically levitated trains, the centrifuge of nuclear reactor, heart pump and electromagnetic suspension [6].

The result from literature survey shows that that interactive demonstration of magnetic phenomenon is not much reported in journals as well as in text books [7]. Hence, this work is needed. The aim of the study is to explain the detail motion of a magnetic object caused by an external magnetic field. An experiment was built using an acrylic (PMMA) cylinder inserted by magnet chip(s), a container or a rail for the cylinder and a solenoid, while the apparatus to support the experiment were Vernier magnetometer, LabQuest 2, DC generator, multimeter, electric wires, gorilla pod (phone handle) and mobile camera. Variables considered for the cylinder include linear position \(x_0\), angular position \(\theta_0\) and amount of magnetic chip \(n\) while for solenoid is the voltage \(V\). An image processing software named Tracker had been used for identification and motion classification processes. The tracker works
as a frame separator of a video, enabling us to analyze any physical phenomenon through every frame captured by a video recorder.

2. Experiment Setup

The main observation object of this research is the cylinder which was made from 5 mm acrylic sheets. A hole is created in the middle as a place to contain the magnetic chip(s). The cylinder needs 4 layers of acrylic to cover the chip which has 18 mm in diameter. The layers are glued by a tape. The cylinder is intentionally designed to have a magnetic dipole perpendicular to its shell enabling us to capture the response of magnetic field toward the perfect or imperfect rolling motion. Some dots are put on one of circle surfaces as tracers. Later, those marks will help us to identify the type of motion through a camera and an image processing software. The cylinder containing one magnet chip has a diameter of 21.60 mm and 23.90 mm for those containing two magnet chips.

![Figure 1. The design of cylinder inserted within it by a magnetic chip as its magnetic dipole.](image1.png)

The solenoid in this study is created from a step-down transformer. To make a step-down transformer become a solenoid, we have to cut and remove the primary coil and connect all parts of the secondary coil. After that, we need to remove all I-shaped metal while arrange the E-shaped parts into the same direction. The plates of metal are placed inside the solenoid cavity to amplify the magnitude of the magnetic field. The secondary coil has a diameter of 0.3 mm and 10 m in length. The internal resistance of the coil is 2 Ω. Dimension of the transformer is 18mm x 16 mm x 21 mm. See Figure 2 below.

![Figure 2. The solenoid made from a step-down transformer and its dimension.](image2.png)

A container to keep the cylinder move on track is made by a 2 mm acrylic sheet. It shapes like a railway for the cylinder, with size 204 mm x 27 mm x 12 mm. Markers were drawn on the bottom side every 1 cm. Another acrylic plate also made to measure magnetic field distribution of magnet chip and solenoid.
Figure 3. Acrylic container used to keep the cylinder move one-dimensional. The marks use to help identifying the position and measuring the distribution of magnetic field of the solenoid.

Figure 4. Acrylic container used as a tool to measure the distribution of magnetic field of the magnetic chip(s).

To demonstrate interaction of magnetic field, the solenoid is connected to the DC generator directly. The acrylic container is put above the solenoid while the cylinder placed inside the container. When the DC generator is switched on, the current will pass through the coil and the solenoid will generate magnetic field. The magnetic field from solenoid will interact with magnet chip inside the cylinder, so cylinder will move as the response. A mobile camera put right in front of the cylinder to record the motion of the cylinder. This research uses the mobile camera of Infinix Zero 4 which has 16 MP of resolution and 29.97 frame per second of shutter speed. In other words, the video file produced by this camera is a series of photos taken for every 0.03 second. Tracker as an image processing software will analyze all frames created by the camera.

Figure 5. Block diagram of motion analysis experimental set up.
3. Magnetic Fields Distribution

In this research, there are two magnetic field resources used. The first is a ferromagnetic material that generate magnetic dipole of the acrylic cylinder and the second one is a solenoid which generates the external magnetic fields. The measurement of magnetic field distribution is carried out twice for each other, for the ferromagnetic material or magnetic chip through x-axis and y-axis while for solenoid through x-axis (parallel to the surface) and z-axis (perpendicular to the surface).

![Figure 6. Measurement of magnetic fields along the acrylic container using the Vernier magnetometer, parallel to the solenoid surface.](image)

![Figure 7. Measurement of magnetic fields along the acrylic container using the Vernier magnetometer, perpendicular to the solenoid surface.](image)

Both measurements are carried out on certain points, \( x_0 = 0 \) mm, 12.5 mm, 25.0 mm, 35.0 mm and 45.0 mm from the centre point of magnetic chip and for every 1 cm for solenoid from \( x_0 = 0 \) cm, 1 cm until 10 cm. The magnetometer is 7 mm away from the top side of magnet chip and 2 mm from the solenoid during the measurement. For magnetic chips, we measure two variations, \( n = 1 \) and \( n = 2 \) and three for solenoid, \( V = 0.73 \) Volt, \( V = 1.57 \) Volt and \( V = 1.93 \) Volt. The result of measuring magnetic distribution of magnetic chip(s) is shown from Figure 8 until 13 below.
Figure 8. Magnetic field distribution of a magnetic chip \((n = 1)\) along x-axis.

Figure 9. Magnetic field distribution of a magnetic chip \((n = 1)\) along y-axis.

Figure 10. Magnetic field distribution of two magnetic chips \((n = 2)\) along x-axis.
Figure 11. Magnetic field distribution of two magnetic chips \((n = 2)\) along y-axis.

Figure 12. Magnetic field distribution of a magnetic chip along x-axis.

Figure 13. Magnetic field distribution of a magnetic chip along y-axis.

From the data above, we obtain that the number of magnet chips and the amount of voltage given to the solenoid give direct impact for the magnetic field strength, both are directly proportional to each other. At the same time, the position relative to the center is inversely proportional to the magnetic field. The one above the center is largest.
4. Types of Motion

The types of motion are analyzed using some features inside Tracker software called 'Point Mass' and 'Protractor'. The function of 'Point Mass' is to trace the linear position of the cylinder. The tracer could be put automatically or manually, but the manual one gives better precision and accuracy. The tracer is placed on the midpoint of the circle surface of the cylinder captured by the camera. The 'protractor' has the function to measure the change in position angles for each frame. Raw data collected from Tracker would be time in second, linear position in meter, and angular position in degree. Another data needed for the motion analysis is calculated manually. To identify the types of motion, we compare the displacement of the center of mass with the angular position, representing a comparison between translation and rotation motions. If variable \( x_1 \) is used for linear position and \( x_2 \) is used for angular position, mathematical equation from the phenomenon would be:

\[
d\hat{x}_1 = \hat{x}_{n+1} - \hat{x}_n \quad (1)
\]

\[
d\hat{x}_2 = (\theta_{n+1} - \theta_n) \cdot \hat{r} \quad (2)
\]

\[
\Delta d\hat{x} = d\hat{x}_1 - d\hat{x}_2 \quad (3)
\]

We use the IF function of Microsoft Excel to classify the condition of the cylinder (to identify whether the object is moving or not), the direction (to identify the object is moving to left or right), and the types of motion (to identify whether the cylinder has perfect rolling motion or imperfect one, with dominance of either translation or rotation).

\[
\text{Condition} = \begin{cases} 
|d\hat{x}_1| + |d\hat{x}_2| \leq 0.0001 & \rightarrow \text{motionless} \\
|d\hat{x}_1| + |d\hat{x}_2| > 0.0001 & \rightarrow \text{move} 
\end{cases} 
\]

\[
\text{Direction} = \begin{cases} 
|d\hat{x}_1| + |d\hat{x}_2| \leq 0.0001 & \rightarrow \text{motionless} \\
|d\hat{x}_1| + |d\hat{x}_2| > 0.0001, d\hat{x}_1 < 0 & \rightarrow \text{move to the left}; \\
|d\hat{x}_1| + |d\hat{x}_2| > 0.0001, d\hat{x}_1 > 0 & \rightarrow \text{move to the right}; 
\end{cases} 
\]

\[
\text{Condition} = \begin{cases} 
|d\hat{x}_1| + |d\hat{x}_2| \leq 0.0001 & \rightarrow \text{motionless}; \\
|\Delta d\hat{x}| \leq 0.0005 & \rightarrow \text{perfect rolling}; \\
d\hat{x}_1 > d\hat{x}_2 & \rightarrow \text{translation dominance}; \\
d\hat{x}_1 < d\hat{x}_2 & \rightarrow \text{rotation dominance} 
\end{cases} 
\]

We use threshold value 0.0001 to eliminate error created by Tracker, usually from \( 1 \cdot 10^{-7} \) until \( 1 \cdot 10^{-5} \). While error value 0.0005 is used as the tolerance value of the camera, which is around 1/12 of the circumference of the cylinder. This research uses two different variations for each dependent variable, \( x_0 = 1 \) cm (1 cm to the left) and \( x_0 = 2 \) cm, \( \theta_0 = 90^\circ \) and \( \theta_0 = 180^\circ \), number of magnetic chip \( n = 1 \) and \( n = 2 \), voltage supplied for solenoid \( V = 1.52 \) Volt and \( V = 3.12 \) Volt. As the reference we use the experiment data from \( x_0 = 2 \) cm, \( \theta_0 = 90^\circ \), \( n = 2 \), and \( V = 1.52 \) Volt. The data from the identification process could be explained by the following figures.
Figure 14. Linear position of cylinder through time ($x_0 = 2$ cm, $\theta_0 = 90^\circ$, $n = 2$, $V = 1.52$ Volt).

Figure 15. Angular position of cylinder through time ($x_0 = 2$ cm, $\theta_0 = 90^\circ$, $n = 2$, $V = 1.52$ Volt).

Figure 16. The variety of the cylinder’s motion through time ($x_0 = 2$ cm, $\theta_0 = 90^\circ$, $n = 2$, $V = 1.52$ Volt).

Blue indicates the translational dominance of translation, yellow indicates the rotational dominance of rotation, while green means perfect rotation or translation and rotation have same magnitude.
Figure 17. The variety of the cylinder’s motion through time \((x_0 = 1 \text{ cm}, \theta_0 = 90^\circ, n = 2, V = 1.52 \text{ Volt})\).

Figure 18. The variety of the cylinder’s motion through time \((x_0 = 1 \text{ cm}, \theta_0 = 180^\circ, n = 2, V = 1.52 \text{ Volt})\).

Figure 19. The variety of the cylinder’s motion through time \((x_0 = 1 \text{ cm}, \theta_0 = 90^\circ, n = 1, V = 1.52 \text{ Volt})\).

Figure 20. The variety of the cylinder’s motion through time \((x_0 = 1 \text{ cm}, \theta_0 = 90^\circ, n = 1, V = 3.12 \text{ Volt})\).

5. Conclusion

The number of magnetic chip(s) arranged in parallel and the voltage supplied for the solenoid are directly proportional to magnetic field generated by them at the same distance. The external magnetic field from the solenoid leads the cylinder with dipole magnet to roll, as the result of interaction of the
magnetic field. The initial angular position (theta) will affect the direction of the movement, based on the polarity created by magnetic chip(s) and solenoid. The external magnetic field pushes the magnetic chip(s) to adjust its polarity to reach the lowest potential. Initial linear position, number of magnetic chips, and the voltage of solenoid directly affect the motion, especially the swing frequency of the cylinder and the amplitude. All of them are inversely proportional to the frequency.

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