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Moment of inertia analysis of rigid bodies using a smartphone magnetometer

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Abstract
This study reports the experimental results of the measurement and analysis of the moment of inertia (MOI) of rigid bodies using a smartphone magnetometer. The MOI apparatus comprises a spiral spring, stand, deviation scale, and vibration counter. The magnetometer application used on the smartphone is the Physics Toolbox Sensor Suite. The magnet, which is placed on top of the MOI apparatus, rotates with the rigid body, and the smartphone magnetometer is used to detect the magnetic field values. We experimentally determine the relationship between the magnetic field and time. The time function is used to analyse the oscillation period of the rigid bodies, which comprise a solid cylinder, solid sphere, solid cone, and solid circular disc. The oscillation periods are proportional to the radii of the rigid bodies. This experience will trigger student interest in conducting related experiments.

1. Introduction

Over the past several years, smartphone technology has developed rapidly, pervading various sectors, including education. Smartphones can be used as a teaching medium because various basic and advanced physics experiments can be easily performed using sensors available on smartphones. The use of these sensors has enabled the development of inexpensive, high-quality, reliable instruments. Smartphone sensors have been successfully utilised to analyse various physical phenomena. For example, acceleration sensors have been used for analysing radial acceleration [1], simple pendulum phenomena [2], and free-fall motion [3]. Magnetometer sensors have been used to measure the value of the acceleration of gravity (g) using a magnetic pendulum [4]. Recent studies have reported that smartphone magnetometer sensors can measure and analyse the average speed of a moving car [5] and the magnetic field produced by a coil carrying current [6].

In this study, we utilised a smartphone-based magnetometer sensor to measure and analyse the moment of inertia (MOI) of a rigid body. Although the measurement of an object's MOI is a standard physics laboratory activity, the use of magnetometer sensors on smartphone devices in experiment is fairly new and can be of interest

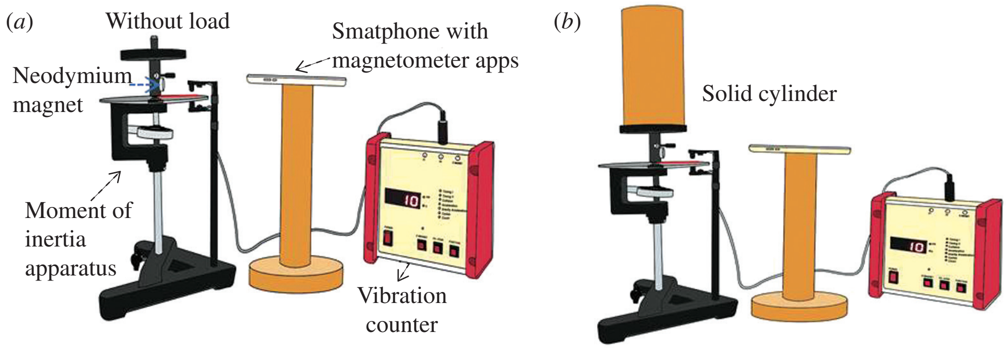

Figure 1. Schematic of the MOI analysis using a smartphone magnetometer. (a) Without load, and (b) with solid cylinder.

to students. We expect the use of smartphones as instructional media to trigger the interest of students, provide motivation for laboratory work, and enable students to perform experiments by themselves.

2. Experimental methods

2.1. Analytical approach

The oscillation of a physical system can be expressed as [7, 8]:

$$I\frac{\mathrm{d}^2\theta}{\mathrm{d}t^2}+k\theta=0, \tag{1}$$

where I is the MOI of the rigid body against the rotary axis. k is the spiral spring constant of the MOI apparatus, t is the time, and θ is the deviation. From equation (1), a standard analysis reveals that the period (T) of torsional oscillations is given by

$$T=2\pi\sqrt{\frac{I}{k}}. \tag{2}$$

From equation (2), we can determine the moment of self-inertia (I_0) using the MOI apparatus, by measuring the self-period (T_0) of the MOI apparatus, that is,

$$I_0=\frac{k}{4\pi^2}T_0^2. \tag{3}$$

If the rigid body is attached to the MOI apparatus and is rotated, the oscillation period (T) can be expressed as

$$T^2=\frac{4\pi^2}{k}\left(I+I_0\right). \tag{4}$$

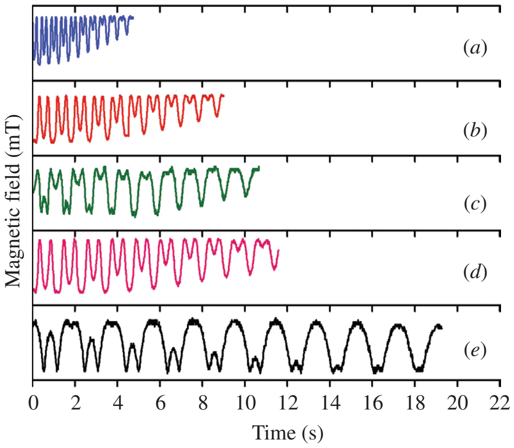

Figure 2. Magnetic fields (a) without load, (b) solid cylinder, (c) solid sphere, (d) solid cone, and (e) solid circular disc.

Table 1. Determination of T for different objects.

Objects	$10T$ (s)	T (s)
Without load	4.619	0.4619
Solid cylinder	8.688	0.8688
Solid sphere	10.007	1.0007
Solid cone	11.383	1.1383
Solid circular disc	19.456	1.9456

[a] Periods were calculated by dividing the 10-peaks time by 10.

By substituting equation (3) into equation (4), the MOI of the rigid body (I) attached to the MOI apparatus can be written as

$$I=\left(\frac{T^2}{T_0^2}-1\right)I_0. \tag{5}$$

Table 2. Moments of inertia of the rigid bodies.

Rigid body	Mass (kg)	Radius (cm)	Equation [8]	MOI (I) I (theoretical) (kg cm^2)	I (experimental-smartphone magnetometer) (kg cm^2)
Solid cylinder	0.500	4.00	$I = \frac{1}{2}mR^2$	4.00	4.20
Solid sphere	0.500	5.55	$I = \frac{2}{5}mR^2$	6.16	6.11
Solid cone	0.500	7.30	$I = \frac{3}{10}mR^2$	7.99	8.39
Solid circular disc	0.500	10.65	$I = \frac{1}{2}mR^2$	28.4	27.7

[a] Substituting the values of k and T_0 into equation (3) gives a value of I_0 of 1.65×10^{-4} kg m^2.

2.2. Experimental setup and measurements

The MOI apparatus (PMK 380) and objects (a solid cylinder, solid sphere, solid cone, and solid disk) were obtained from Pudak Scientific (Bandung, Indonesia). The MOI apparatus used in this study comprises a series of devices containing two parts: the foot part, which is the base for the stand, and the body part. The body part comprises an iron bar to hold the test objects and a spiral spring to allow the objects to oscillate. The dimensions of the MOI apparatus (length × width × height) are 180 mm × 190 mm × 300 mm. The spiral spring constant (k) of the MOI apparatus is 0.0306 N · m/rad.

An Android smartphone with a magnetometer sensor (Physics Toolbox Sensor Suite) was used to determine the magnitude of the magnetic field. The magnetic field data are recorded from the entire magnetic field detected by the smartphone magnetometer. A schematic of the MOI analysis of rigid bodies using the smartphone magnetometer is depicted in figure 1. The number of oscillations was set to 10, using the vibration counter in the cycles function key. The magnetic field peak and time are determined when the apparatus completes one oscillation each with and without the rigid body (cylinder, sphere, cone, or circular disc).

The magnetic peak value represents the position of the magnet at one oscillation. The variation of magnetic field value ($\mathbf{B}$) with time (t), shown by the output of the magnetometer sensor, was used to determine the oscillation period (T). The time function was used to determine the self-period (T_0) (without load) and the oscillation period (T) (with load), which are important variables in analysing an object's MOI. The MOIs of the cylinder, sphere, cone, and circular disc were analysed using equation (5).

3. Results and discussion

In the experiments, we measured the MOIs for a solid cylinder, sphere, cone, and circular disc using the smartphone magnetometer. Magnets were placed under the test object parallel to the smartphone magnetometer to simplify the detection of the magnetic field around it. The smartphone magnetometer detects the magnetic field value (100 mT), as shown in figure 2. One full oscillation produces two peaks of the magnetic field at different times. The peak position and the second time are selected as the initial data for analysis. It is observed that the magnetic field peak and the time function of the solid sphere and solid circular disc follow the same pattern.

The periods of the magnetic field variations for the apparatus without load (T_0) and with load (T) were obtained from the $\mathbf{B}$–t graphs (see figure 2 and table 1). The results were used to calculate the MOIs (I) in table 2. As can be clearly seen, the larger the radius of the object, the larger the MOI.

4. Conclusions

We successfully used a smartphone magnetometer application (Physics Toolbox Sensor Suite) and MOI apparatus to record magnetic fields and time functions for rigid bodies. The time function is used to analyse the oscillation periods of each rigid body to enable determination of the MOI values. The performed experiments were found to be sufficiently suitable and consistent with the theory. We believe that the use of the smartphone as a learning medium will ignite the interest of students, motivating them to conduct their own experiments.

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