Physics Education

PAPER • OPEN ACCESS

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To cite this article: Aurelio Agliolo Gallitto *et al* 2025 *Phys. Educ.* **60** 035004

OPEN ACCESS
PAPER
Phys. Educ. 60 (2025) 035004 (8pp)
iopscience.org/ped

Exploring rotations by a modified fidget spinner and a smartphone

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Abstract
We present an educational activity, aimed at the exploration of rotational motion through the use of a modified fidget spinner and a smartphone. We analyze the physics concepts that are involved in the proposed experimental activity, such as angular velocity and moment of inertia, showing that it is possible to transform a well-known popular toy into an opportunity to teach/learn physics concepts, by performing easy and valuable physics experiments in classroom at undergraduate and first-year university laboratory.

Keywords: fidget spinner, rotations, gyroscope, undergraduate laboratory experiments, smartphone physics

1. Introduction

Spinning toys have fascinated humans since ancient times, entertaining children and adults as well [1]: the first clay tops were found in the ancient city of Ur in the Middle East (Iraq), dating from 3500 B.C., and many others have been found on all continents, having shapes most likely noticed in nature; a boy playing with a yo–yo is painted on a Greek vase from 440 B.C., on display at the Altes Museum in Berlin.

A new spinning toy, called *fidget spinner*, has recently been patented in 1997 by the American chemical engineer Catherine Hettinger, which became very popular in 2017. It consists of a steel-ball bearing located in the center of a three-lobed (or multi lobed) flat structure, with weights in the lobes, that can spin almost freely around its central axis. Figure 1 shows a commercial fidget spinner. Thanks to the ball bearing, the lobes spin very fast continuously, so that it keeps spinning for a long period.

Resent research papers have suggested to use a fidget spinner to teach physics concepts [2–8].

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Figure 1. A typical fidget spinner, in which it is shown the steel-ball bearing mounted along its central axis.

Figure 2. Bohnenberger's apparatus of E. Sauerwald, Berlin, 1865. Historical Collection of Physics Instruments, University of Palermo.

Here, we will present new possibilities of the use of this toy in physics classroom at undergraduate and first-year university laboratory. In particular, we discuss a didactic activity concerning the measurements of the angular velocity as a function of time by a smartphone and the analysis of the experimental data to determine the Coulomb friction torque and the drag coefficient, which affect the rotational motion of the system.

To measure the angular velocity, we use the 'gyroscope' tool of the phyphox app [9–11], that provides access to the raw data from the smartphone's gyroscope sensor. The gyroscope was invented in 1817 by the German physicist, mathematician and astronomer Johann Gottlieb Friedrich von Bohnenberger (1765–1831), who devised a machine for demonstrating the peculiarities of the Earth rotation [12, 13]. It was composed by a massive rotating ball, fixed in a hinged mount, providing free rotation of the ball around three mutually perpendicular axes. This mount is now known as 'gimbal' or 'cardanic suspension' from the Italian scientist Gerolamo Cardano (1501–1576), although a similar mechanism was already invented by Philo of Byzantium (ca. 280 B.C. – ca. 220 B.C.) in ancient Greece. Figure 2 shows a Bohnenberger's apparatus built by E. Sauerwald, Berlin, 1865, using a marmoreal glass ball with a diameter of about 6 cm, slightly flattened at the poles, to demonstrate the stability of the Earth's axis, on display at the Historical Collection of Physics Instruments of Palermo University. In 1852, the French physicist Jean Bernard Léon Foucault (1819–1868) coined the term *gyroscope*, for a device used to prove the Earth rotation. Foucault measured the angle of rotation of a gyroscope fixed in space relative to a hinge fixed on the Earth turning from East to West.

Today gyroscope toys are very popular, they are constructed from a small disc-shaped flywheel rigidly fixed on an axis, which can stay up regardless of the direction of flywheel's axis of rotation [14]. It is worth noting that the gyroscope inside smartphones does not use wheel and cardanic suspension (gimbal) like the traditional mechanical ones, it is a micro-electro-mechanical system, a miniaturized gyroscopes. Taking the idea of the Foucault pendulum, the smartphones' gyroscope is based on the Coriolis effect of a vibrating element. The working principle of smartphone's gyroscope sensor is illustrated in the educational video of [15]. The use of the smartphone's gyroscope sensor in physics experiments is widely described in the recent literature [16–22].

Figure 3. The experimental setup with a smartphone fixed, by an expanded-PVC support, to the fidget spinner, standing horizontally on three adjustable legs. A sign on all lateral sides of the PVC support indicates the central axis.

2. Measuring the angular velocity

To experimentally investigate the time dependence of the rotational motion, we have modified a fidget spinner to use it in a 'reverse mode', that is the lobes are used as fixed feet and the smartphone rotates with the central ring of the ball bearing. The smartphone is fixed to a home-made expanded-PVC support, by elastic rubber loops, which in turn is fixed to the inner ring of the spinner's ball bearing. The spinner and the support are thus positioned as horizontally as possible by three adjustable legs fixed onto the lobes, as shown in figure 3. We use the simple spatial configuration where the system can spin almost freely around its vertical central axis that coincides with the z-axis of the smartphone.

To measure the angular velocity of the spinning smartphone, we have used the gyroscope tool of the phyphox app, which gives the data from the smartphone's gyroscope sensor, at regularly spaced time intervals of about 0.002 s. This sensor measures the angular velocity, ω, of the smartphone in rad s^{-1} with a resolution of about 6×10^{-4} rad s^{-1} and a time accuracy of about 2.4×10^{-3} s, which are characteristics of the specific sensors integrated into the smartphone used and are provided by the phyphox app.

We have measured the angular velocity of the spinning smartphone as a function of time, for different initial angular velocities, ω_0, after having lubricated the bearing and adjusted the length of the legs to position the smartphone as horizontally as possible by using the 'inclination' tool of the phyphox app. The results are reported in figure 4. As one can see from the graph, $\omega(t)$ regularly decreases with time. For all the values of ω_0 we have investigated, the spinner shows a similar behavior. The small oscillations observed at lower velocity values probably could be due to a not perfect horizontal disposition of the smartphone, which implies a rotation around a slight tilted axis with respect to the vertical one, and to a non-homogeneous distribution of the mass of the smartphone, which implies that the center of mass does not correspond to the geometrical center of the rotating system.

3. Mathematical modelling of decelerated rotation

Looking for a didactic model to explain the time dependence of the angular velocity of the rotating smartphone, we apply the Newton's second law for the rotational motion:

$$M = I\alpha \,, \tag{1}$$

where M is the resulting resistive torque acting on the system, α the angular acceleration and I the moment of inertia of all the rotating parts, i.e. the smartphone, support, and bearing's inner ring. In

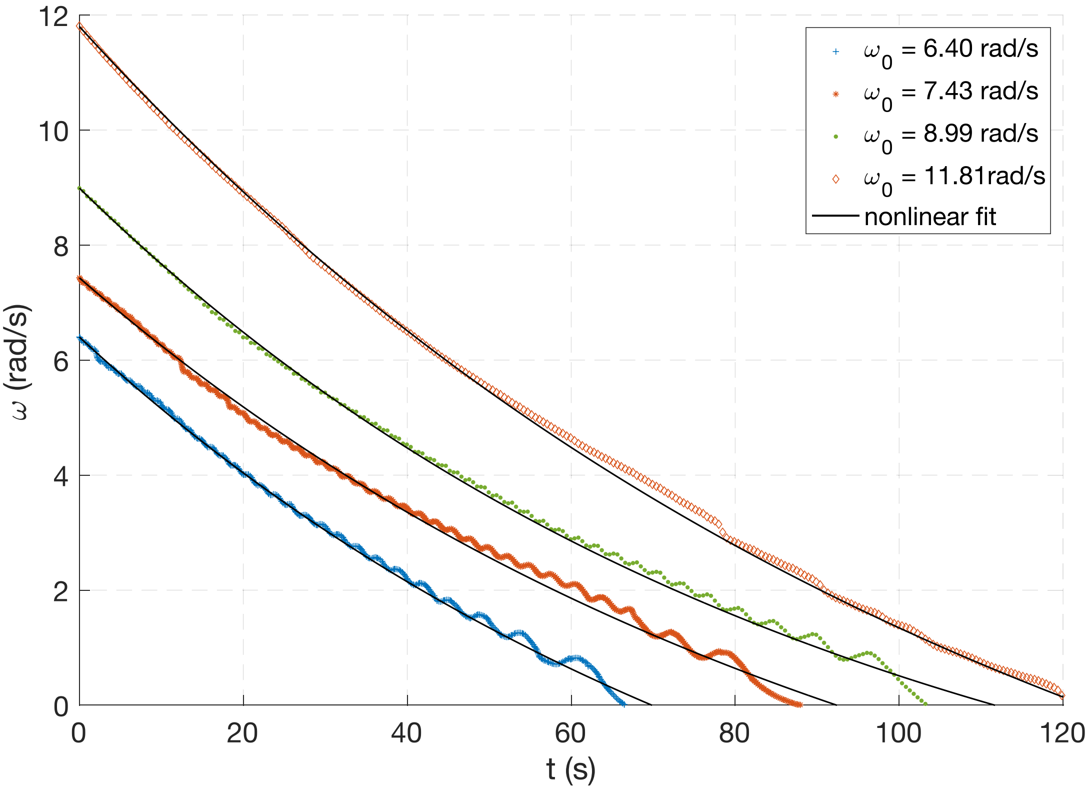

Figure 4. Component of the angular velocity along the z-axis as a function of time for different initial angular velocities. Symbols are experimental data; continuous lines are theoretical curves obtained as explained in the text.

our case, it is reasonable to suppose that the resulting resistive torque, M, is the sum of two components: the Coulomb friction torque, M_0, that is a constant torque at any velocity, and the drag torque, M_ω, that is a velocity-dependent friction torque. M_ω takes into account all the contributions to the drag torque that depend on the relative velocity. For didactic purposes, M_ω can be considered directly proportional to the angular velocity as $M_\omega = -\beta\omega$, where β is the drag coefficient that takes into account the air viscous drag and the velocity-dependent friction of the bearing as experimental observed [5, 7, 8]. The existence of the Coulomb friction torque is supported by the fact that $\omega(t)$ decreases to zero regularly with time, as shown in figure 4.

To calculate the moment of inertia, I, we approximate all the rotating parts as an homogeneous rectangular plate of total mass m, having the dimensions of the smartphone, respectively $a = (76 \pm 2)\,\text{mm}$ and $b = (166 \pm 2)\,\text{mm}$, whose rotation axis is along the z-direction, passing through the central axis of the rotating system. The estimated uncertainty of a and b takes into account the roundness of the smartphone's edges. The total mass of all rotating parts is $m = (263.0 \pm 1.0)\,\text{g}$, whose uncertainty is negligible with respect to that of the smartphone's dimensions. It is worth noting that the moment of inertia of the smartphone can be also measured by a direct method by using the smartphone as the mass of a rotating system [22] or of an oscillating compound pendulum [3, 23].

$$I = \frac{m}{12}\left(a^2 + b^2\right) = (7.3 \pm 0.4) \times 10^{-4}\,\text{kg}\,\text{m}^2 . \quad (2)$$

From equation (1), one obtains:

$$-M_0 - M_\omega = I\alpha \quad \Rightarrow \quad -M_0 - \beta\omega = I\frac{\text{d}\omega}{\text{d}t}\,, \quad (3)$$

Table 1. Values of β and M_0 obtained from the curves that best fit the experimental data.

$\omega_0\,(\mathrm{rad\,s^{-1}})$	$\beta\,(\mathrm{N\,m\,s})$	$M_0\,(\mathrm{N\,m})$
6.40	8.10×10^{-6}	4.43×10^{-5}
7.43	7.42×10^{-6}	3.54×10^{-5}
8.99	7.99×10^{-6}	3.00×10^{-5}
11.81	6.36×10^{-6}	3.93×10^{-5}

then

$$\frac{\mathrm{d}\omega}{\mathrm{d}t} + \frac{\beta}{I}\omega + \frac{M_0}{I} = \frac{\mathrm{d}\omega}{\mathrm{d}t} + \frac{\beta}{I}\left(\omega + \frac{M_0}{\beta}\right) = 0\,. \tag{4}$$

By solving equation (4), one obtains:

$$\omega(t) = \left(\omega_0 + \frac{M_0}{\beta}\right)\mathrm{e}^{-\frac{\beta}{I}t} - \frac{M_0}{\beta}\,. \tag{5}$$

From equation (5), one can deduce that the motion stops when $\omega(t) = 0$, after a time interval t_1, which is obtained by imposing $\omega(t_1) = 0$ and it is given by:

$$t_1 = \frac{I}{\beta}\ln\left(\frac{\omega_0 + M_0/\beta}{M_0/\beta}\right) = \frac{I}{\beta}\ln\left(1 + \frac{\beta\omega_0}{M_0}\right). \tag{6}$$

From equation (6), one has that when $\omega_0 \sim 2M_0/\beta$, the stopping time t_1 is:

$$t_1 \approx \frac{I}{\beta}\ln(3)\,,\ \text{that is}:\quad t_1 \sim \frac{I}{\beta}\,. \tag{7}$$

Therefore, from equation (7) and by using the values of the stopping time, $t_1 \sim 100\,\mathrm{s}$, and $\omega_0 \sim 10\,\mathrm{rad\,s^{-1}}$, taken from the curves of figure 4, one obtains $\beta \sim I/t_1 \sim 7\times10^{-6}\,\mathrm{N\,m\,s}$ and $M_0 \sim \omega_0\beta/2 \sim 3.5\times10^{-5}\,\mathrm{N\,m}$, which we use as initial parameter for the fitting of the experimental data. Figure 4 shows the expected curves obtained by equation (5) for different initial velocities ω_0. In the table 1 are listed the values of β and M_0 obtained from the curves that best fit the experimental data by a non-linear least-squares fitting method.

Since one expects that β and M_0 do not depend on the value of ω_0, from the values obtained by fitting the experimental curves for different ω_0, one can estimate the average values of β and M_0 and their uncertainty: $\beta = (7.5 \pm 0.4)\times10^{-6}\,\mathrm{N\,m\,s}$ and $M_0 = (3.7 \pm 0.3)\times10^{-5}\,\mathrm{N\,m}$. The expected $\omega(t)$ curves for different initial angular velocities are shown in figure 5.

It is worth noting that analogous results have been obtained by using another fidget spinner. Moreover, they are qualitatively in agreement with the results reported in [5, 7], obtained by using similar spinners. Furthermore, since the β value obtained by the non-linear fit agrees with that previously obtained by using the values of the stopping time and the moment of inertia, equation (7) may provides a direct qualitative estimation of β, at least in this range of values of ω_0.

4. Discussion and conclusion

The resulting resistive torque M, acting on the system, has been supposed be the sum of two components: the Coulomb friction torque, M_0, that is independent of the velocity, and the drag torque, M_ω, that is a velocity-dependent friction torque. M_ω takes into account all the contributions to the drag torque that depend on the angular velocity. As experimentally observed by Somogyi *et al* [8], in the investigation of the rotational motion of the fidget spinner at the atmospheric pressure and at the lower pressure of 17 kPa, there is a significant braking effect in vacuum that may indicate that friction of bearings is also velocity dependent. For didactic purposes, M_ω can be considered directly proportional to the relative angular velocity as $M_\omega = -\beta\omega$, where the drag coefficient β takes into account both the air viscous drag and the velocity-dependent friction of the bearing [5, 7, 8]. The dependence of the resistive torque on the angular velocity can be also experimentally observed from the slope of the ω-vs.-t curves of figure 4, for $t \to 0$. This slope corresponds to the initial angular acceleration, which is given by equation (1) replacing M with $M_0 + M_\omega$. Although we have only four curves, the results we have obtained agree with a linear dependence of the resistive torque on the angular velocity. However, further investigation is necessary to better clarify this point.

Teaching and learning physics by using smartphones in introductory physics laboratory has recently received significant attention

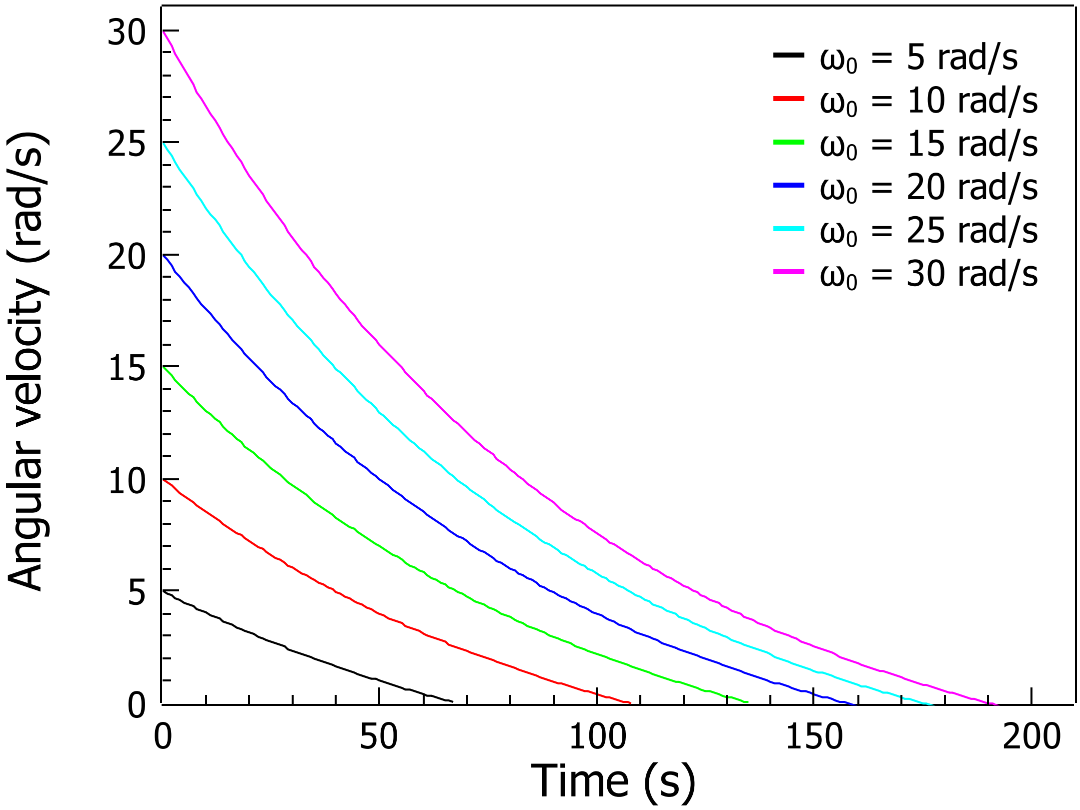

Figure 5. Expected angular velocity as a function of time for different initial angular velocities obtained by equation (5) with $\beta = 7.5 \times 10^{-6}$ N m s and $M_0 = 3.7 \times 10^{-5}$ N m.

since modern smartphones, equipped with built-in sensors supported by appropriate software, offer the possibility of designing low-cost physics laboratories by using smartphones instead of expensive devices [10, 11, 22, 24–38]. The use of the smartphone in physics experiments provides a precious educational resource for active learning [25, 26, 31] and contributes to stimulate students' interest in physics [31, 33]. For the aforementioned expectations, the phyphox app possesses the necessary requirements to achieve these purposes, since it offers many features and is free to download [10, 11]. Phyphox provides the opportunity to bring physical equipment into the hands of every student at all times during the lesson, promoting interactive learning [11]. Moreover, it allows students to conduct experiments as homework and to plan their own research, particularly, in a distance learning context [29].

In conclusion, we have devised a simple apparatus by modifying a fidget spinner to experimentally investigate the time dependence of the rotational motion by the smartphone's gyroscope sensor. From the fit of the experimental data with the analytic solution of the Newton motion equation, we have determined the Coulomb friction torque and the drag coefficient that affect the motion of the system. Simple models of this rotating system can be easily built by students, actively engaging them in discussion about rotational-dynamics topic. This educational activity can be done in an introductory physics laboratory, moreover it allows students to acquire skills in data-analysis techniques.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://sites.unipa.it/griaf/download/.

Acknowledgments

The authors thank Marcello Mirabello for technical support.

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Received 13 November 2024, in final form 14 February 2025
Accepted for publication 25 February 2025
https://doi.org/10.1088/1361-6552/adba33

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