**PocketLab Voyager: A Flywheel Experiment**

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***Introduction***

A flywheel is a mechanical equivalent to the battery, storing energy for later use. Some of the earliest flywheels date back to potter's wheels and water wheels in mills. Many engines and machines during the Industrial Revolution had flywheels that allowed for smooth and efficient operation. Modern flywheels are used in regenerative braking systems as well as in power plants for storing energy to handle electricity demands during peak usage hours.

With the current growth in interest in flywheels, stemming from concern for the environmental impact of fossil fuel use, flywheels provide a convenient way for storing energy. Because of this, the study of flywheels in the physics curriculum is well worth consideration by teachers. Such a study allows for a careful examination of the principles of conservation of energy, as well as both linear and rotational kinematics.

PocketLab Voyager's ability to collect angular velocity data makes data collection much easier than was required in similar earlier experiments. The experiment of this lesson can be done without the need to purchase an expensive flywheel, as it makes use of a wood disk (from Michaels) as the flywheel. Figure 1 shows the setup use by the author.

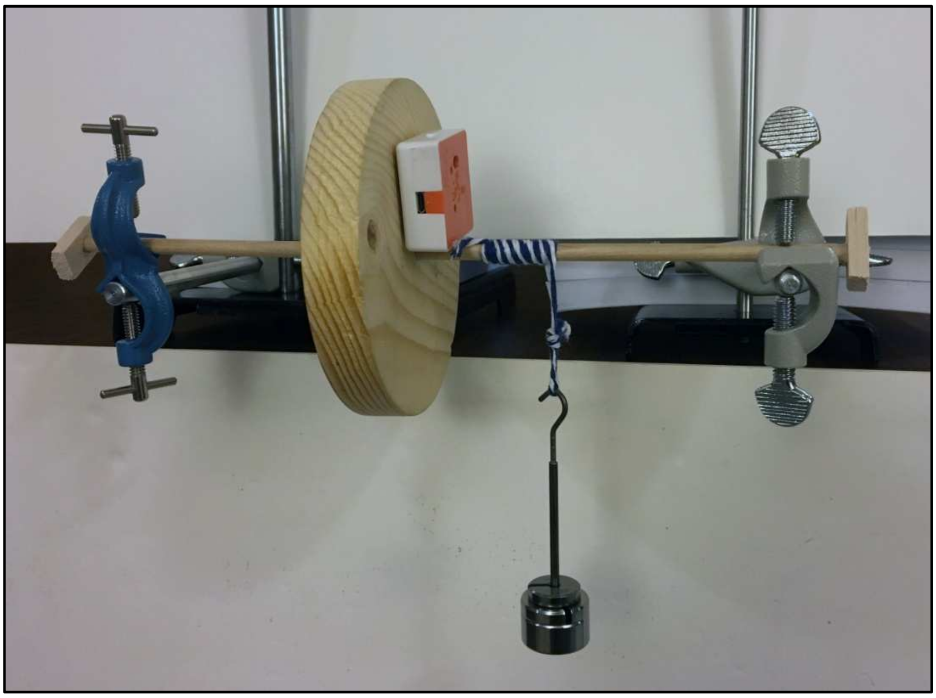

*Figure 1*

A pair of ring stands, two rods, and four clamp holders make up the body of the apparatus. A wooden dowel rod is inserted and centered into a tight hole on the wood flywheel disk. The ends of the dowel rod rest loosely in two clamps so that it can spin easily. A string of known length is wrapped around the dowel rod without overlapping the string. A known mass is attached to a loop at the bottom of the string. Voyager is mounted to the wood flywheel disk with removable mounting tape. The clamp screw on the upper right of Figure 1 is slightly tightened on the dowel rod to keep it from turning.

Voyager is set to record angular velocity data at a rate of 50 points/second. The clamp screw on the upper right of Figure 1 is loosened so that the mass can begin to fall. The mass falls while turning the flywheel one rotation for each turn of the string on the dowel. When the string has completely unwound and releases from the dowel, the wood flywheel continues spinning *from stored mechanical energy* for several seconds, as shown in the video accompanying this lesson. Figure 2 shows an Excel graph of angular velocity vs. time created from the csv file captured from the PocketLab app.

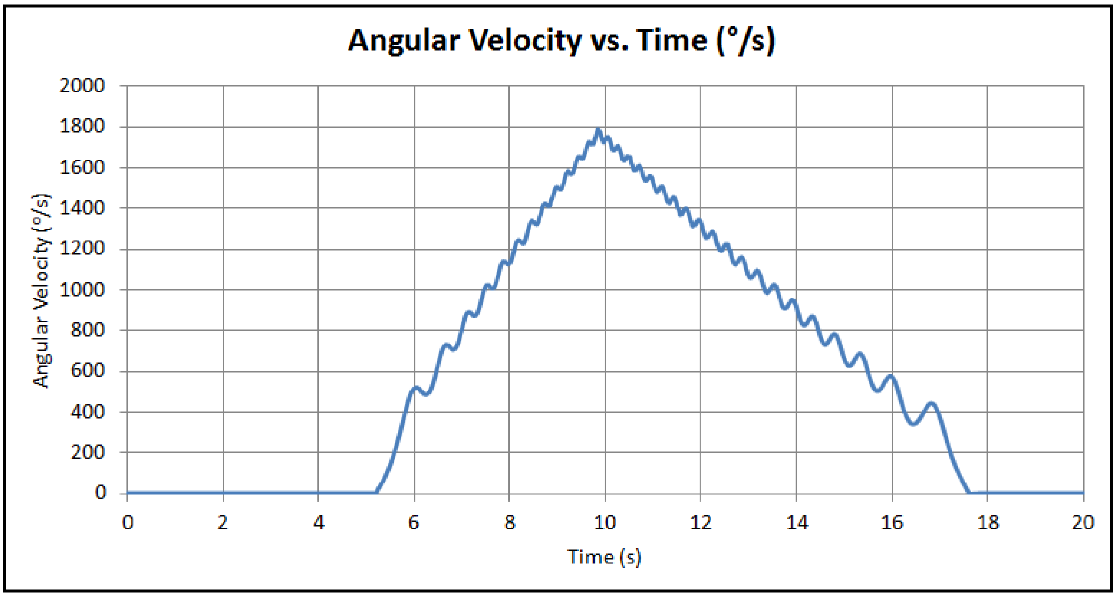


*Figure 2*

The mass falls about 5 seconds, from 5 to 10 seconds, causing the angular acceleration of the flywheel to increase with an envelope that appears to be linear. After the string unwinds and releases from the dowel rod, the wood flywheel continues to spin for about 8 additional seconds, from 10 to 18 seconds, with gradually decreasing angular velocity until it stops. The "blips" in the angular velocity graph are due to the slight irregular weighting of the flywheel, caused by the attached Voyager. These blips are actually very helpful, as they provide an easy way to determine the number of rotations of the flywheel both before and after the string has released.

By making appropriate angular velocity measurements on the above graph as well as measuring parameters such as the length of the string, the radius of the axle and mass of the falling weight, it is possible to determine the moment of inertia of the flywheel. This can be accomplished through an analysis involving conservation of energy, as described in the next section of this document. Students can also compare this moment of inertia to the theoretical moment of inertia of a disk about its axis, and attempt to explain any differences.

*Flywheel Conservation of Energy Analysis**

The gravitational potential energy, *mgh*, of the hanging mass is converted into three major components, as a result of its fall:

| | |
|---|---|
| $rotKE_{flywheel}$ | rotational kinetic energy of the flywheel |
| $tranKE_{hanging\ mass}$ | translational kinetic energy of the hanging mass |
| $W_{friction}$ | work required to overcome the frictional torques of bearings and air resistance while rotating the flywheel apparatus ***one time*** |

where

*m* = the mass of the weight hanging on the string
*g* = the acceleration of gravity
*h* = the length of the string.

If *n* is the number of rotations of the flywheel axis while the string is attached and falling, *I* is the moment of inertia of the flywheel apparatus, and *v* is the velocity of the hanging mass at the instant the string has just completely unwound and is released, then conservation of energy tells us that:

$$mgh = ½I\omega^2 + ½mv^2 + nW_{friction}$$

If we assume that $W_{friction}$ is independent of time, then all of the rotational kinetic energy of the flywheel apparatus immediately after the string is released is eventually used up in overcoming bearing friction and air resistance:

$$NW_{friction} = ½I\omega^2,$$

where *N* is the number of flywheel rotations after the string has unwound but before the flywheel comes to rest.

If *r* is the radius of the flywheel axle, then the velocity *v* of the hanging mass after falling the distance *h* is given by the equation $v = \omega r$, and we have:

$$mgh = ½I\omega^2 + ½m\omega^2r^2 + n(½I\omega^2)/N$$

If this last equation is solved for the moment of inertia *I*, we obtain our final equation:

$$I = \frac{Nm}{n+N}\left(\frac{2gh}{\omega^2} - r^2\right)$$

Before the existence of Voyager, one would have to count the number of windings of the string on the axle to obtain *n*, count the number of rotations of the flywheel *N* before it stops, note the time required for the *N* rotations in order to obtain the *average* angular velocity, and then double this to get the angular velocity at the instant that the string leaves the axle. With Voyager, the values of *n*, *N*, and *ω* can simply be found by information contained in the angular velocity vs. time graph!

* http://vlab.amrita.edu/?sub=1&brch=74&sim=571&cnt=1

***Results***

For the experiment run shown in Figure 1, we find that $n$ = 13, $N$ = 20, and $\omega$ = 1788 °/s (or 31.2 rad/s). Other measured values were: $h$ = 0.46 m, $r$ = 0.00325 m, and $m$ = 0.08 kg. These measurements in turn give the moment of inertia $I$ as 0.000292 kg-m$^2$.

With the mass M of the flywheel *by itself* measured as 0.132 kg, and its radius R being 0.063 m, then its moment of inertia $MR^2/2$ (the moment of inertia of a solid disk about it axis) should be 0.000262 kg-m$^2$. There is an 11% difference between our experimental value for $I$ and the theoretical value.

***Angular Velocity Exceeding Voyager's Gyroscope Range***

You may find that the angular velocity will exceed Voyager's gyroscope range of 2000 °/s, particularly if the length of the string is long enough to produce a large number of rotations of the axle. You can recognize exceeding the range by a horizontal line at 2000 °/s, as shown in Figure 3. The graph was obtained by importing data from the PocketLab app *csv* file into Vernier's Logger *Pro*® software. The analysis could also be done with standard spreadsheets, though it might take a little more time.

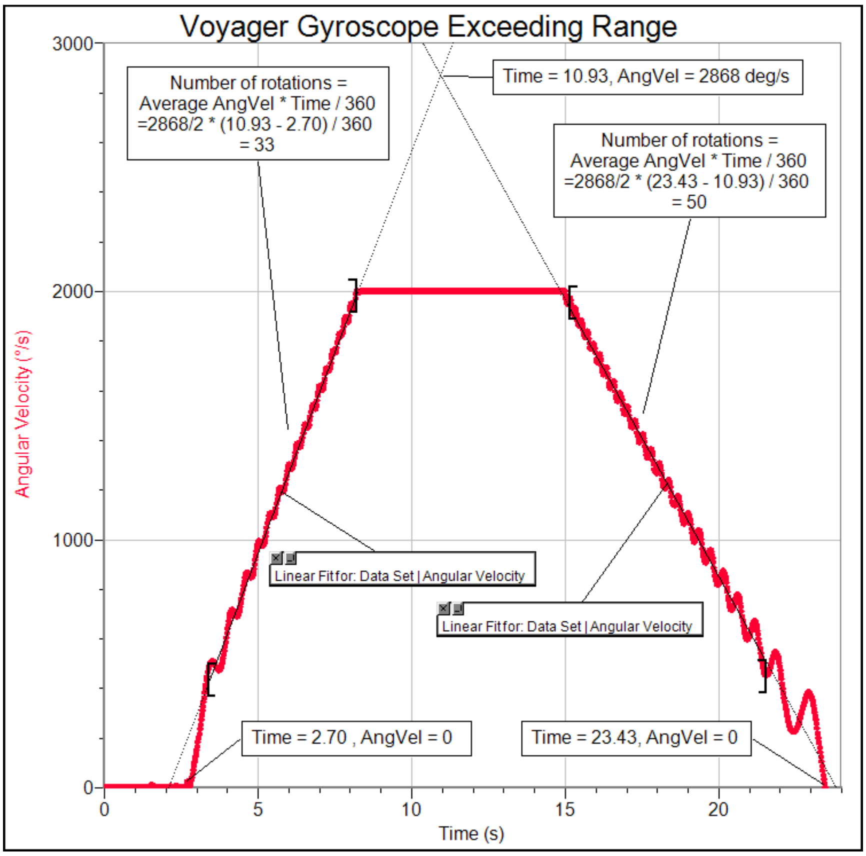


*Figure 3*

All that you need to do is perform a linear fit on the "blip" lines and then extrapolate them until they meet. This will provide you with the angular velocity $\omega$ required for the analysis. Then to determine the number of rotations $n$ and $N$, simply follow the procedure outlined in Figure 3.