CENTRIFUGAL FORCE
Experiment by Ken Cheney

ABSTRACT
Centrifugal force is investigated by experimentally finding the minimum velocity to successfully complete a vertical loop. A mass on a string is timed by photocells to determine the velocity at the top of the loop.

GENERAL
Vertical loops are executed by airplanes, amusement park rides, stunt drivers on motorcycles and are often analyzed in physics problems. If you have been on an amusement park ride that makes a vertical loop you probably wondered if it was really going to work or would you fall out at the top of the circle.

If you did not fall out you might well wonder why you did not. The answer from physics is that you were going in a vertical circle. To produce a circular motion there must be a force toward the center, otherwise you would go in a straight line. At the top of the ride this force is provided by gravity. If gravity exactly matches the force needed for circular motion then you circle neatly and experience no net force at the top.

If the force of gravity is less than the force required for circular motion then the track that the ride moves on provides the extra force.

If the force of gravity is more than the force needed for circular motion then you fall out of the ride and die. This is bad for repeat business so the designers try hard to avoid it happening too often.

THEORY OF THIS EXPERIMENT
One end of a cylinder is attached to a string and rotated in a vertical circle. The minimum velocity the cylinder can have at the top of the circle is the velocity that produces a centrifugal force just equal to gravity. Under these conditions gravity just produces the force required to give circular motion. Any smaller velocity and gravity will cause the cylinder to fall.

Equating centrifugal force and the gravitational force gives:

\[ \frac{mv^2}{R} = mg \]

where:

- \( m \) = the mass of the cylinder
- \( v \) = the velocity of the center of mass of the cylinder
- \( R \) = The distance from the center of rotation to the center of mass of the cylinder
- \( g \) = the acceleration due to gravity
EQUIPMENT

PHOTOCELLS AND LASER

Measuring the velocity is the principle difficulty in this experiment. We will use a photocell and laser to measure the time it takes the cylinder to pass through the laser beam. It is most straightforward to simply measure this time as the cylinder passes the top of its circle.

To minimize the chances of dropping the laser it is best to leave it flat on the table. Adjust the path of the cylinder so that at the top of the path the center of the cylinder breaks the laser beam.

There is a difficulty in finding the diameter of the cylinder as seen by the laser and photocell. The laser beam and photocell are of finite size, the cylinder does not block or unblock the beam instantaneously. This means that the effective diameter of the cylinder is not the same as the physical diameter.

SINGLE BEAM

You can measure the effective diameter of the cylinder by moving it along a scale slowly by hand and marking the points where the timer starts and stops.

DOUBLE BEAM

To produce a larger distance to measure, hence a smaller percent error, you can use two laser beams and measure the time between breaking the first and second beam.

Two laser beams can be easily produced by using two mirrors to fold the beam from your laser so the beam crosses the path of the cylinder twice. Put the laser and photocell on the same table and the mirrors on the next table.

The mirrors are easy to adjust if they are taped to wood blocks.

The effective distance between the beams will differ from the physical distance as discussed above, use the same methods to find the effective distance.

TIMERS: STAND ALONE TIMERS

If you have stand alone timers you must select the function, select pulse or gate. Use the reset button to zero the reading.

The timers often measure a variety of things such as frequency, counts, and time. Select time.

The gate mode times from beam off to beam on. The pulse mode measures the time between two interruptions of the beam. If you are using a single beam select gate. If you are using two beams select pulse.

Practice interrupting the beam with your hand to get a feel for what is happening. In the pulse mode occasionally you get out to synchronization with the timer and need to add a single interruption to get back in synchronization.

TIMERS: COMPUTER BASED TIMING

If you are using a computer for timing plug the photocell into the matching socket on the computer interface.
To decide which timing mode you want (the computer may have a dozen or more modes) look in the manual for a page showing schematically what is timed by each mode. You may want a mode that lets you keep repeating the measurement and remembers the results.

If the computer calculates an average time ignore the average.

ALIGNING THE LASER BEAM WITH THE PHOTOCELLS
The double beam (or even a single beam) can be quite difficult to align. There are two features designed to help you with the alignment.

The photocell housing has a small hole on one side through which is reflected a portion of the laser beam when alignment is correct.

The box holding the socket coming from the computer has lights which go off and on depending on whether the laser beam is detected or not.

GO-NO GO GAUGE
It is impossible to tell by watching whether the string is tight or not. We only want to count the trials where the string is tight. If the string is slack then gravity is greater than centrifugal force.

If you put a small piece of paper above the cylinder at the top position of the cylinder so the cylinder just strikes the paper when the string is tight then you can easily see if the paper is touched or not.

Some people have had good results using the laser beam itself as the go-no go gauge. They placed the beam so it is just broken by the top of the cylinder when the string is tight. Do consider that the distance the top of the cylinder moves is not the same as the distance that the center of mass moves.

PROCEDURE
Arrange the laser and photocells on the table top.
Mount the cylinder so it breaks the laser beam at the top of the circle.
Construct your go-no go gauge.
Remember you want to find out how slow the cylinder can go, not how fast you can throw it or the average velocity.

Practice throwing the cylinder so it revolves as slowly as possible.
Continue throwing looking for the longest time measured. If all times could be trusted you would simply use the longest time that you obtained with a tight string.

It is possible to have blunders. To see if your longest time is reasonable make a histogram of time versus number of occurrences. You’d expect that there would be some occurrences of times shorter than the longest time and a sudden end of longer times. If there are times near your longest time but shorter than you can use your longest time with no qualms.

If you have times for all possibilities up to some time then a long gap followed by a single much longer time than you have reason to be suspicious of the solitary long time.
ANALYSIS

Chose the longest time that you trust, explain clearly why you chose that time. Mark that time on your histogram.

Compare centrifugal force with $mg$ for the velocity corresponding to the time you chose.

Discuss whether your percent error seems reasonable in the light of the expected errors of measurement.