Experiment 6: Torque and Rotational Equilibrium

Introduction

When an object is either stationary or is moving with constant velocity (that is, in a straight line at constant speed), we say it is in **translational equilibrium**. By Newton's First Law of Motion, the net force on the object must be zero.

However, a net force of zero can still cause an object to rotate. Imagine holding the opposite sides of a wheel with your two hands, and pushing/pulling the two sides in opposite directions. The wheel begins to rotate. We call the "rotational effectiveness" of a force the **torque** produced by the force. The net torque can be non-zero even though the net force is zero, and the net torque can be zero even though the net force is non-zero.

When an object is either not rotating, or is rotating with constant angular speed, we say it is in **rotational equilibrium**. In this experiment, you will find out what condition the net torque on an object must satisfy in order for the object to be in rotational equilibrium.

Apparatus

Your apparatus is a meter stick that has weights hanging from it at various points, and balances horizontally on a pivot. The weights hang from clamps so that you can slide them back and forth easily along the meter stick. Also, the pivot point is on a clamp that you can loosen and slide along the meter stick.

Preliminary Measurements

First, you need to measure the masses of the meter stick and the clamps. There are two kinds of clamps. One kind does not have a wire hanger, and is used to mount the meter stick on the pivot. You should have one of these clamps. Measure its mass. The other kind of clamp has a wire hanger, and is used for hanging weights on the meter stick. You should have three of these clamps. Measure their total mass together and divide by three to get the average mass for each clamp.

Slide the clamp that does **not** have the wire hanger onto the meter stick, near the center, and put its little metal fingers on the support stand. The screw that tightens the clamp should be on the **underside** of the meter stick. Adjust the position of the clamp until the meter stick balances (which is almost impossible if you have the screw on top of the clamp, by the way!), and then tighten the screw. Read off the position of the clamp on the meter stick, using the indicator at the middle of the clamp, and call it x_0.

Case I: Two Known Masses

Hang mass m_1 = 100.0 g at 15.0 cm on the meter stick, that is, 15.0 cm from the zero end of the meter stick. Hang a second mass, m_2 = 200.0 g, on the other side of x_0. Adjust its position so that the apparatus balances and is therefore in rotational equilibrium. Record the masses and their positions, in kilograms and meters, respectively.

Add the mass of the hanger to each mass to get the total mass hanging at each point, and calculate the **weight**, $W = mg$, of each mass, in newtons. These are the forces that act on the meter stick and try to make it rotate vertically around the pivot.

The distance of each force from the pivot is called the **lever arm** of the force. (Some books call it the **moment arm.**) Calculate it for each force, from the positions of the masses and the pivot.

For each mass, the product of the weight and the lever arm is called the **torque**. It's positive if it tries to make the meter stick rotate counterclockwise, negative if clockwise. Compare the **magnitudes** of the two torques (that is, ignore any minus signs) by calculating the percent difference.

Case II: Three known masses

With the meter stick still pivoting at the original x_0, hang m_1 = 100.0 g at 30.0 cm and m_2 = 200.0 g at 70.0 cm. Hang m_3 = 50.0 g at the location which places the system in equilibrium. Record data and carry out calculations similar to Case I. Find the net counterclockwise torque and the net clockwise torque, and the percent difference in their magnitudes.

A General Rule

Based on how the clockwise and counterclockwise torques compare in Cases I and II, can you come up with a general rule for how they should compare ideally (that is, in the absence of random experimental errors)? In such an ideal situation, what should the **net torque** be, treating counterclockwise as positive and clockwise as negative?

To test your general rule, use it to **predict** the position at which you should hang m_3 = 50.0 g , in order to achieve equilibrium if m_1 = 100.0 g is at 20.0 cm and m_2 = 200.0 g is at 60.0 cm. Then set it up and **measure** the actual position at which you have to hang m_3. Calculate the percent error.

Case III: Unknown Mass—the Balance Principle

A laboratory balance uses the method of torques to compare an unknown mass with a known mass. This part of the procedure illustrates the balance principle.

With the meter stick still pivoting at x_0, hang an unknown mass m_1 at 10.0. Suspend m_2 = 200.0 g on the other side of the pivot point and adjust its position to reach equilibrium.

Using your general rule, **predict** the value of the unknown mass, then **measure** it on the balance scale and calculate the percent error.

Case IV: Meter Stick with One Mass

Suspend m_1 = 100.0 g at the zero end of the meter stick. Move the meter stick in the support clamp until the system is in equilibrium. Record the new support position as x_0' in your data tables.

Since the meter stick is in equilibrium, there must be a torque produced by a force acting on the meter stick on the side opposite the new balance point from the hanging mass. This force is in fact the weight of the meter stick itself. For the purpose of calculating the torque, **the weight of the meter stick can be considered as if it were a single force acting at the center of mass of the meter stick**. To test this:

Consider all of the mass of the meter stick to be concentrated at its center of gravity, x_0. Use the total mass of the meter stick as m_2. Calculate the lever arms of the two forces (the weight of the hanging mass and the weight of the meter stick) relative to the new balance point, x_0'. Compute the magnitudes of the clockwise and counterclockwise torques and compare their percent difference as before.

Questions

1. How can a large force can produce little or no torque, and a small force produce a large torque?

2. In order to keep the meter stick and hanging masses from falling to the table, the support must exert an upward force on the meter stick, whose magnitude is equal to the sum of all the downward forces. Why do we not include this “support force” in our torque calculations?

3. A uniform meter stick is at rotational equilibrium when 220 g is suspended at 5.0 cm, 120 g is suspended at 90, and the support stand is placed at the 40 cm mark. What is the mass of the meter stick?