



Educational Brief

CASSINI SCIENCE INVESTIGATION

The Spinning World of Spacecraft Reaction Wheels

Objective

To demonstrate how reaction wheels (also known as momentum wheels) take advantage of Newton's Third Law to control a spacecraft's orientation.

Time Required: 1 hour

Saturn System Analogy: Cassini's Reaction Wheel Assembly and its use during orbital operations at Saturn

Keywords: Gyroscope, Interplanetary, Momentum, Orientation, Reaction

MATERIALS

- Cassini spacecraft paper model (available through the Cassini web site at <http://saturn.jpl.nasa.gov/cassini/english/teachers/classroom.shtml>); also suitable are paper models of interplanetary spacecraft (available free from NASA at <http://spacelink.nasa.gov>); or commercially made models (an Internet search on "spacecraft models" will provide sources).
- Small battery-powered electric motor (available at discount hobby stores); for example, the 3-volt miniature DC motor available for \$4 at <http://www.ScientificsOnline.com/Products/>
- One or more small wheels (available at hobby shops that carry an assortment of wheels intended for toy cars, airplanes, etc.). *Wheels should be different sizes that can be attached to the motor shaft. Each should weigh a few ounces and be an inch or two in diameter.*

- D-cell battery. *This will provide half of a 3-volt motor's rated performance, which is just about right.*
- About 6 feet of thin wire pair, 28 gauge or so (available at electronics parts stores and hardware stores that carry a wide ranges of wire gauges). *Use stranded rather than solid-conductor wire to provide flexibility. The thinner, longer, and more flexible, the better.*
- Optional: a switch or pushbutton, with a normally open circuit (available from electronics parts stores for a few dollars). *If the switch is not used, the motor is controlled by touching the wire to the battery terminal.*
- Optional: a potentiometer (available from electronics parts stores) or other means to vary the voltage supplied to the motor

Discussion

Most spacecraft require a specific orientation, known as the spacecraft attitude, to do the work we assign the robots. Small rocket engines (control jets) are sometimes used alone, or in combination with other systems. Reaction wheels are used by many interplanetary spacecraft as well as Earth-orbiters such as the Hubble Space Telescope and communications satellites to orient the spacecraft, specifically to point instruments, antennas, or other subsystems at chosen targets.

A spacecraft's reaction wheels are typically a few kilograms to tens of kilograms of mass and are driven by electric motors powered by the spacecraft's electrical power supply. They are managed and controlled by the spacecraft's onboard attitude control computer.

Reaction wheels should not be confused with gyroscopes. Reaction wheels provide the physical means to rotate a spacecraft, based on the principle of angular momentum transfer and Newton's Third Law of action–reaction.

Gyroscopes provide attitude reference information, based on precession and rigidity-in-space principles. As a gyroscope spins, it resists being tipped over. In spaceflight operations, this means that a spinning gyroscope provides a stable reference to a specific direction. This is the principle of “rigidity-in-space.” If a gyroscope is forced to tip, it will tip in a direction 90 degrees from the direction of the push. This is precession. In aircraft, the principle of precession is used in turn indicators to displace a pointer needle left or right of center as the plane makes a turn.

Setup

The experimenter obtains a toy or educational spacecraft model and equips it with a small electric motor with a small wheel attached to its shaft. The assembly is suspended from a support, and the motor is activated. The teacher explains the observed motion of the spacecraft, and relates how real spacecraft use electric power and reaction wheels to manage their pointing attitude.

This demonstration may be done by a presenter in front of an audience, or it may be done by individual experimenters.

To set up the demonstration:

1. Build a model to represent a spacecraft.
2. Attach wires to the motor (soldering is best), and tape the motor to the spacecraft, routing the wire through the spacecraft appropriately. Alternately, make cardboard

pieces shaped like instruments and antennas and tape or glue them to the body of the motor.

3. Suspend the assembly by its wires from a support, so that at least 2 feet of fine wire is between the support and the spacecraft. Align the motor shaft with the supporting wire, that is, straight up and down.
4. For the simplest operation, at the other end of the wire pair attach one conductor to the negative side of the battery, using tape. Prepare to touch the other conductor intermittently to the positive battery terminal.
5. Additional parts will minimize potential electrical circuitry problems. The battery can be placed in a holder. Solder one lead to one motor wire. Solder the other battery holder lead to one end of the switch. Attach the other motor wire to the other side of the switch.
6. Test to make sure the motor and wheel spin when the switch is turned to the on position, imparting a twist to the spacecraft.

Procedure

Suspend the motorized “spacecraft.” Activate the motor and observe the spacecraft. The motor quickly accelerates the wheel's mass, and the reaction from this action imparts a change to the spacecraft's orientation. While the motor continues to run at the same speed, the attitude change is gradually overcome by the force of the twisted supporting wire, returning the spacecraft to its original position or close by. If the reaction to turning the motor on is violent, find a means to reduce the voltage applied to the motor, such as by inserting a potentiometer into the circuit.

Explain that the observed spacecraft motion demonstrates the following:

1. The spacecraft's attitude is changed by changing the angular momentum (the quantity of spin) held by the spacecraft and the wheel.
2. An interfering force (the supporting wire's twist) eventually nulls the result.

Reverse the polarity of the battery, and observe that the motor runs (and the spacecraft rotates) in the opposite direction.



Extension

Add a potentiometer to the circuit. Does the “spacecraft” turn a greater or lesser amount when the motor’s final shaft speed is limited?

Try different wheel masses on the shaft (including no wheel at all). For a constant maximum speed, what rotating mass generates the maximum turn angle?

Extrapolate by thinking, or further refining the demonstration:

1. To rotate the spacecraft one way, you begin to rotate the wheel the other way. Once you have accelerated the wheel to a constant rotation rate and it continues spinning, the spacecraft will not continue to twist, unless some other force is applied (such as the force the wire’s twist imparts in the demonstration).
2. If you had three motorized wheels, each of them mounted orthogonally, you could control the spacecraft’s rotation in any direction.

In space operations, interfering forces, such as the twisting wire in the demonstration, are minimal. This allows reaction wheels to work very efficiently in controlling and maintaining a spacecraft’s desired attitude. What forces, both internal and external to the spacecraft, might interfere with attitude maintenance? Example answers include atmospheric drag, pressure of sunlight, magnetic torque, and reaction wheel bearing friction.

If a spacecraft is orbiting close enough to a planet with an atmosphere and it has an appendage like a long boom, that boom can be a source of drag (force) on the spacecraft and cause the spacecraft to rotate. This is analogous to dragging an oar through the water to turn a boat.

Solar photon pressure acting on spacecraft surfaces can act to rotate the spacecraft (like the twist imparted by the supporting wire in the demonstration). Solar photon pressure is

analogous to wind affecting a weather vane. A weather vane rotates into the breeze because of the pressure of the wind. Similarly, solar photons exert a pressure on the spacecraft.

Another interfering force is the gravity gradient. Portions of a spacecraft closer to a planet are attracted slightly more by the planet’s gravity than are portions that are farther away.

Consider: if you were to keep adding energy to the wheel in this demonstration, you could overcome more and more of the “interfering” force that the supporting wire makes evident. Of course, continuing to do this would eventually mean the motor would have to be going unacceptably fast.

Because of momentum built up in a spacecraft’s reaction wheels due to these “interfering” forces, a spacecraft periodically has to slow down its reaction wheels. But to do so without changing the spacecraft’s attitude in an undesired way, the spacecraft has to use thrusters (or some other means, like magnetic torquers) to brace itself and “hold still” in space. These events are called “reaction wheel desaturation maneuvers” or simply “desats.”

Education Standards

A visit to the URL <http://www.mcrcel.org> yielded the following standards and included benchmarks that may be applicable to this activity.

Science Standards

10. Understands forces and motion.

LEVEL 1 (GRADES K-2)

Knows that the position and motion of an object can be changed by pushing or pulling.

LEVEL 2 (GRADES 3-5)

Knows that when a force is applied to an object, the object either speeds up, slows down, or goes in a different direction.



Knows the relationship between the strength of a force and its effect on an object (e.g., the greater the force, the greater the change in motion; the more massive the object, the smaller the effect of a given force).

LEVEL 4 (GRADES 9-12)

Knows that laws of motion can be used to determine the effects of forces on the motion of objects (e.g., objects change their motion only when a net force is applied; whenever one object exerts force on another, a force equal in magnitude and opposite in direction is exerted on the first object; the magnitude of the change in motion can be calculated using the relationship $F = ma$, which is independent of the nature of the force).

Technology Standards

4. Understands the nature of technological design.

LEVEL 2 (GRADES 3-5)

Knows constraints that must be considered when designing a solution to a problem (e.g., cost, materials, time, space, safety, scientific laws, engineering principles, construction techniques, appearance, environmental impact, what will happen if the solution fails).

Evaluates a product or design (e.g., considers how well the product or design met the challenge to solve a problem; considers the ability of the product or design to meet constraints), and makes modifications based on results.

LEVEL 3 (GRADES 6-8)

Implements a proposed design (e.g., organizes materials and other resources, plans one's work, makes use of group col-

laboration when appropriate, chooses suitable tools and techniques, works with appropriate measurement methods to ensure accuracy).

Evaluates the ability of a technological design to meet criteria established in the original purpose (e.g., considers factors that might affect acceptability and suitability for intended users or beneficiaries; develop measures of quality with respect to these factors), suggests improvements, and tries proposed modifications.

LEVEL 4 (GRADES 9-12)

Evaluates a designed solution and its consequences based on the needs or criteria the solution was designed to meet.

5. Understands the nature and operation of systems.

LEVEL 1 (GRADES K-2)

Knows that when parts are put together, they can do things that they couldn't do by themselves.

LEVEL 2 (GRADES 3-5)

Knows that when things are made up of many parts, the parts usually affect one another.

Understands the relationships between elements (i.e., components, such as people or parts) in systems.

Teachers — Please take a moment to evaluate this product at http://ehb2.gsfc.nasa.gov/edcats/educational_brief. Your evaluation and suggestions are vital to continually improving NASA educational materials. Thank you.



Student Worksheet — The Spinning World of Spacecraft Reaction Wheels

Procedure

A battery-powered motor is suspended by its wires such that the rotating shaft is oriented vertically, parallel to the wires and the force of gravity. Wheels of different sizes (and alternatively, none at all) are attached to the shaft one at a time and the motor is activated.

When the motor is activated, the shaft (+wheel) turns and the motor body also turns. Does the motor body turn in the same direction as the shaft rotates? State Newton's Law that explains this.

With respect to when the motor is first switched on, when does the motor body turn the most?

What happens if the polarity of the electricity feeding the motor is switched?

Using wheels of different size (with fixed motor speed), observe the amount the motor body turns with each. With which wheel does the motor body turn more? Is wheel diameter or mass the important parameter, or is a combination of both?

If available, use resistors or a potentiometer to vary the shaft rotation speed. Does the motor body turn more with higher or lower shaft speed? Why?

