Spinning Mass Mechanical Gyroscopes

History of Gyroscopes

In early times, people discovered the spinning top, a toy with a unique ability to balance upright while rotating rapidly. Ancient Greek, Chinese and Roman societies built tops for games and entertainment. The Maori in New Zealand have used humming tops, with specially-crafted holes, in mourning ceremonies. In 14th century England, some villages had a large top constructed for a warming-up exercise in cold weather. Tops were even used in place of dice, like the die in the contemporary fantasy game Dungeons & Dragons.

It was not until the late 18th and early 19th centuries that scientists and sailors began attempting to use spinning tops as a scientific tool. At that time, sailors relied on sextants for navigation, measuring the angle between specific stars and the horizon. This method was limited, however, if choppy seas or fog obscured the true horizon, or clouds obscured the stars.

Serson, an English scientist, noted in the 1740's that the spinning top had a tendency to remain level, even when the surface on which it rested was tilting. He suggested that sailors could use it as an artificial horizon on ships. Unfortunately, when Serson went to sea to test this idea the ship sank and everyone was lost.

A French scientist in the 19th Century, Fleuriais, created a top that was continuously powered by air jets blowing into mini-buckets on the rim of the wheel a process that has been used for thousands of gyros since. The first modern gyroscope was designed in the early 1800s by Johann Gottlieb Friedrich von Bohnenberger, a professor at the University of Tuebingen, Germany. It was made with a heavy ball instead of a wheel, but since it had no scientific application, it faded into history.

In the mid-19th century, the spinning top acquired the name, "gyroscope," though not through its use as a navigation tool. French scientist Leon Foucault had experimented with a long, heavy pendulum in an attempt to observe the rotation of the Earth. The pendulum was set swinging back and forth along the north-south plane, while the Earth turned beneath it.

Foucault corroborated the observation by using a spinning top in a similar manner. He placed a wheel, rotating at high-speed, in a supporting ring in such a way that the axis of the spinning wheel could move independently of the ring. In fact, the supporting ring moved over the course of a day, as it was connected to the surface of the rotating Earth. The axis of the wheel remained pointed in its original direction, confirming that the Earth was rotating in a twenty-four hour period. Foucault named his spinning wheel a "gyroscope," from the Greek words "gyros" (revolution) and "skopein" (to see); he had seen the revolution of the Earth with his gyroscope.

Fifty years later (1898) Austrian Ludwig Obry patented a torpedo steering mechanism based on gyroscopic inertia. It consisted of a little bronze wheel weighing less than 1.5 pounds that was spun by an air jet (like Fleuriais). In the early 20th Century, Elmer A. Sperry developed the first automatic pilot for airplanes using a gyroscope, and installed the first gyrostabilizer to reduce roll on ships. While gyroscopes were not initially very successful at navigating ocean travel, navigation is their predominant use today. They can be found in ships, missiles, airplanes, the Space Shuttle, and satellites.

Basic Principles of Gyroscopes

A Gyroscope is defined as any rotating body that exhibits two fundamental properties: gyroscopic inertia and precession. These properties are inherent in all rotating bodies, including the earth itself.

Gyroscopic Inertia

The rigidity in space of a gyroscope is a consequence of Newton's first law of motion, which states that a body tends to continue in its state of rest or uniform motion unless subject to outside forces. Thus, the wheel of a gyroscope, when started spinning, tends to continue to rotate in the same plane about the same axis in space. An example of this

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tendency is a rifle bullet that, because it spins on itself in flight, exhibits gyroscopic inertia, tending to maintain a straighter line of flight than it would if not rotating.

Rigidity in space can best be demonstrated by a model gyroscope consisting of a flywheel supported in rings in such a way that the axle of the flywheel can assume any angle in space. However, if the model is moved about, tipped, or turned at the will of the demonstrator, the flywheel will maintain its original plane of rotation as long as it continues to spin with sufficient velocity to overcome the friction with its supporting bearings.

Precession

When a force applied to a gyroscope tends to change the direction of the axis of rotation, the axis will move in a direction at right angles to the direction in which the force is applied. This motion is produced jointly by the angular momentum of the rotating body and the applied force. A simple example of precession can be seen in the rolling hoop: to cause the hoop to turn a corner, guiding pressure is not applied to the front or rear of the hoop, as might be expected, but against the top. This pressure, although applied about a horizontal axis, does not cause the hoop to fall over, but to precess about the vertical axis, with the result that the hoop turns and proceeds in a new direction.

The three axis of a gyroscope are called the spin, input, and output axis. The spin axis is the axis that the gyro rotor is rotating. The input axis is the axis about which the rotation of the case of the gyro causes a maximum output. It is normal to the spin axis. The output axis is the axis about which the gimbal is rotating. The pickoff determines the position of the gimbal with respect to the gyro case.

The positive direction of the spin axis is found by wrapping the fingers of the right hand in the direction of the spin rotation. With the thumb of this hand pointing outward at a 90 degree angle, it points in the direction of the positive spin axis or spin vector.

The input axis, also called the torque axis, also uses the right hand rule. If the fingers of the right hand are wrapped in the direction of the applied force, the thumb will point in the direction of the torque vector. The applied force will cause the spin axis to move into the torque axis rotating the gimbal about the output axis or precession axis.

Again the right hand can be helpful in demonstrating these relationships. Arrange your thumb, index and middle fingers into the three quadrature axis. Assume that your thumb is pointing in the direction of the spin vector and that your index finger is pointing in the direction of the torque vector. Keep your fingers rigidly in this configuration.

When you try to rotate your thumb (spin vector) into your index finger (torque vector) your hand (the gyro) moves around your middle finger (precession axis) just the way the actual gyro does. In addition, the middle finger points in the direction of the precession vector. This is also known as the law of gyroscopic precession.

Types of Spinning Mass Gyros

There are two basic types of single axis, spinning mass gyros. A rate gyro which is an open loop system and a rate integrating gyro which is a closed loop version of the rate gyro.

The Rate Gyro

If a gyro is subjected to any angular rate, a torque about the quadrature axis will be developed. A torque input produces an angular rate output (torque in – precession out) and an angular rate input produces a torque output (precession in – torque out). The rate in – torque out relationship is the basis of the rate gyro.

The spinmotor is mounted in a gimbal that is attached to the gyro case by a torsion bar on one end and a precision bearing at the other end. The torsion bar limits the rotation of the gimbal. The gimbal turns about the output axis in response to a rotation about the input axis. This effect is a consequence of the property of precession. When the gyro is turned about the input axis, the direction of angular momentum is changed of the same angle. This variation of angular momentum will create a torque on the gyroscope wheel in accordance with Newton's law. This torque will act on the gimbal that will rotate about the output axis of an angle proportional to the input velocity.

Rate gyros are liquid filled to provide damping for the correct dynamic response and to protect the gimbal against shock and vibration. The damping is a function of fluid viscosity which varies with temperature. Rather than control the temperature of the fluid, which acts as an interfering input, many gyros use mechanical damping compensators. The principle of damping compensation is based on the method of opposing inputs to correct the effect of temperature. One method of providing a mechanical damper is to make the components different materials with different coefficients of expansion. This will close down the gap between the gimbal and the case of the gyro as the viscosity of the fluid reduces with increasing temperature.

The pickoff used in rate gyroscopes is an electromagnetic system that can determine the position of the gimbal with respect to the case of the gyro. The system called a microsyn, consists of a toothed rotor on the gimbal and a stator attached to the case. The stator contains an excited winding and a pickup winding on each leg of stator lamination stack. The excited winding sets up fluxes which couple into the pickup winding. When the rotor is at 0 position, the voltage induced in the pickup winding cancel out. As the rotor is rotated from the 0 position, the voltage induced in one set of windings decreases. The voltages induced in the other set of windings increases. A net voltage is obtained at the output, whose magnitude is proportional to the amount of rotation and whose phase is proportional to the direction of rotation.

The most common spring restraint used in a rate gyroscope is a torsion bar. The full scale rate of the gyro is determined by the diameter of the torsion bar. The larger the diameter, the more gyroscopic torque is require for a given amount of twisting. For high sensitivity the torsion bar stiffness should be small. The weaker the torsion bar, the more it twists and the larger the output signal. But at the same time the input axis must stay as close as possible from the reference position to prevent the gyro to sense rotation about an axis normal to the desired input axis. This effect of sensitivity to an axis other than the input axis is called cross-coupling error. Therefore, stiff torsion bars are usually preferred as they can also increase the bandwidth (meaning that the gyro can measure higher frequency input signals) and protect the gyro against shock and vibration.

Rate Integrating Gyros

In a rate integrating gyro (RIG), the spring is removed and replaced with a high precision ball bearing. The restraint in this type of gyro is the damping fluid. When a torque is developed about the gimbal axis due to an angular rate about the input axis, the gimbal begins to rotate about the gimbal or output axis. The only thing resisting the rotation of the gimbal is the damping fluid. The resistance to the gimbal rotation depends directly upon the viscosity of the damping fluid and the velocity with which the gimbal rotates.

In the RIG, an angular velocity about the input axis causes the gimbal to move with some angular velocity about the output axis, and the gimbal angular velocity about the output axis will always be directly proportional to the angular velocity about the input axis. If the gimbal is moving about the gimbal axis with an angular velocity directly related to the rate about the input axis, then in any given amount of time, the total angle through which the gimbal rotates will be directly proportional to the total angle through which the gyro rotates about the input axis. Therefore, with a pickoff we can measure how far the gyro has rotated about the input axis.

Integration is a mathematical term for summing up. If we sum up bits of angular velocity over a time span, we get the total angle traveled. In the RIG, the angular velocity about the input axis is summed up (or integrated) about the output axis. The gimbal axis puts out a signal proportional to the integral of the input axis velocity.

A RIG also contains an electrical torquer which precesses the gimbal until the pickoff signal goes back to zero or null. The RIG operates in a closed loop system where the pickoff output drives a servo amplifier that supplies current to the torquer. The gyro output then is not the pickoff angle but the amount of current supplied to the torquer. The current coming from the servo is proportional to the torque acting on the gimbal.

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