

Theory of Operation of Angular Rate Sensors

Crossbow uses Micro Electro-Mechanical Sensors (MEMS) designed to measure angular rate in most of our DMU products: IMU, VG, AHRS 300, 400 and 500 Series products.

Crossbow uses Fiber-Optic Gyro (FOG) rate sensors in our IMU700CA, VG700CA and VG700AA products.

Angular rate sensors are used in conjunction with accelerometers to make a dynamic measurement of orientation angle. Angular rate sensors are also used by themselves to track rotational motion.

Angular rate is a rotational speed. It is the motion of a record turning on a record player, a pure rotation.

Angular rate can be specified in various units.

	RPM – rotations per minute	
	deg/s – degrees per second	
	rad/s – radians per second	
1 RPM =	360 deg/60 sec	= 6 deg/s
1 rad/s =	(180 deg/π rad) * 1 rad/s	= 57.3 deg/s

Note that a rate sensor cannot measure an angle or orientation by itself. It only measures rotational motion. We integrate the angular rate over time to get angle as a function of time.

$$q(t) = \int w(t') dt'$$

MEMS Rate Sensors

MEMS sensors are designed to measure angular rate using the Coriolis force. In the 1830's G.G. de Coriolis discovered that an object moving in a rotating frame would cause an observer on the rotating frame to see an apparent acceleration of the object. In other words, if an object is moving in a straight line, and it is subject to a rotation, you will see a deviation from the original straight line. For example, figure 1 shows how an observer on the rotating earth will see apparent accelerations of objects moving perpendicular to the Earth.

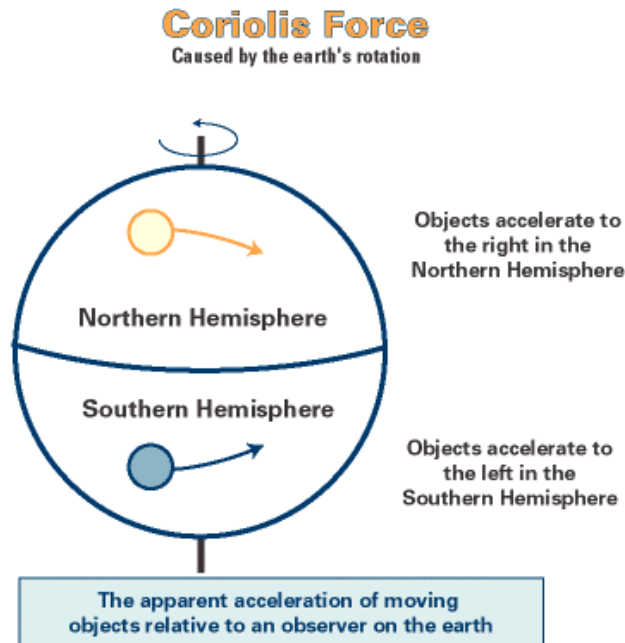


Figure 1. Coriolis Force

The Coriolis Force

The DMU's angular rate gyros generate a Coriolis acceleration by the angular rotation of a vibrating silicon MEMS structure. A change in the direction around one axis of a driving transducer induces a vibration in a detection transducer on another axis. An oscillator circuit is used to control the vibration and signal conditioning circuitry converts measurements to angular rate output and provides an interface to the DMU. In general, the apparent Coriolis acceleration, **A** is given by

$$A = 2\omega V \sin(\phi)$$

where, ω is the angular velocity of the rotating axes relative to a fixed set of axes, **V** is the velocity of the bar, and ϕ is the angle between the vectors ω and **V**. The acceleration is at the right to both ω and **V**. Assuming the vibrating structure has mass *m* and $\sin(\phi, 1)$, the Coriolis force is expressed as,

$$F = 2m\omega V$$

where, **F** is the Coriolis force, *m* is the mass of the sensing element. Notice that the Coriolis force is proportional to ω in the preceding equation. We are assuming the rotation is perpendicular to the motion of the sensing element. The direction of the resulting force is perpendicular to both the rotation and the velocity. This Coriolis force is converted to a voltage by the detector element and signal conditioning circuitry. Since the mass of the structure and the vibration velocity of the bar are both known quantities, the angular velocity ω is easily derived and provided to the DMU.

Because the sensor element must be moving to sense the rotation, MEMS rate sensors are usually physically constructed to be a vibrating structure of some type. The vibration keeps the sensor element moving in a single plane. This also allows the sensor to look for the force signal at the drive frequency of the vibration, which increases the signal-to-noise ratio of the sensor. The sensor element will vibrate perpendicular to the drive vibration. The actual measured signal can be a piezo-electric stress/bending measurement of the vibrating structure, or a variable capacitance measurement.

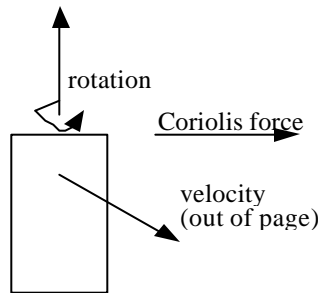


Figure 2. MEMS Vibrating Structure Rate Sensor

The movement of the bar is converted to a voltage by the detector element and signal conditioning circuitry. Since the mass of the bar and the vibration velocity of the bar are both known quantities, the angular velocity is easily derived and provided to the DMU.

Performance of MEMS Rate Sensors

Angular rate gyro accuracy can be characterized by two parameters: scale factor and drift. The scale factor describes the capability of the gyro to accurately sense angular velocity at different angular rates. Scale factor is the parameter that describes the sensitivity of the angular rate sensor in (deg/s)/V. The accuracy of this parameter directly translates into accuracy of the output. This value is used to convert the voltage output from the gyro into an angular rate. System imperfections can cause small variations in the scale

factor. These variations appear as an error in the calibration of the output voltage versus the angular rate. Crossbow calibrates each rate sensor in each DMU to measure this parameter.

Gyro drift characterizes the ability of the gyro to reference all rate measurements to the nominal zero rate output. It appears as an additive term on the gyro output. For example, if the DMU is sitting still, but the rate sensor outputs a value of 0.5 deg/s, this would be a bias drift from the true zero value. Temperature is the biggest effect on bias drift for most MEMS angular rate sensors. Crossbow calibrates an initial value for this parameter at the factory. We can also calibrate the effect of temperature on this parameter. In addition, the DMUs contain a "zeroing" command that will measure the angular rate bias if the DMU is not moving.

Advantages of MEMS Technology

MEMS sensors have all of the advantages of reliable solid-state technology over mechanical gyroscopes.

- No Moving Parts (bearings, parts that have wear)
- Low Power
- Reliability, Long MTBF
- Low Sensitivity to Environmental factors (vibration, shock, acceleration.)

Fiber Optic Gyro (FOG) Rate Sensors

Principles of Operation

The Crossbow DMU-FOG sensor systems contain three fiber optic gyro (FOG) rate sensors and three solid-state micro electro-mechanical (MEMS) accelerometers. The FOG rate sensors operate using a fiber optic ring and a solid-state laser to measure rotation rates using the Sagnac effect, first discovered in 1913. Sagnac discovered that light sent around a closed loop, in two different directions, would show a phase difference between the two beams when the loop is rotated. See figure 3.

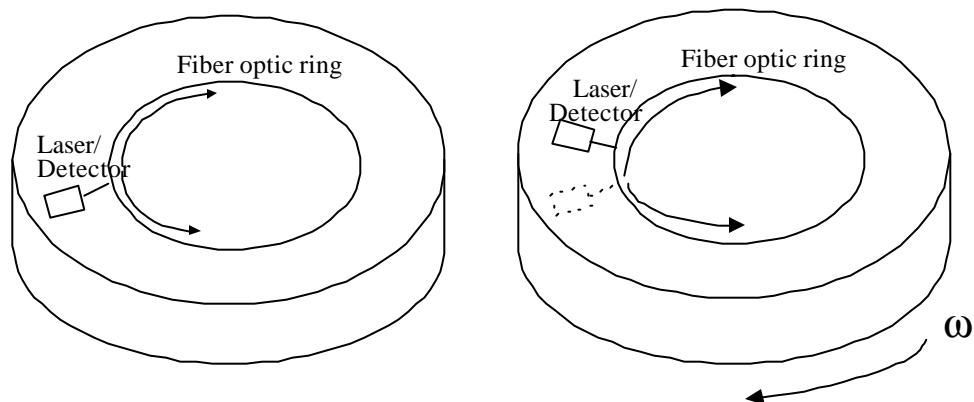


Figure 3. A Fiber-Optic Gyro (FOG) Rate Sensor

The laser supplies a beam of light that is perfectly in phase. When you split a beam of light, and then recombine it, you will get interference. Where the light remains in phase, you will get constructive interference, which makes a bright spot; where the light is out of phase, you get destructive interference, which makes a dark spot. See figure 4. The phase difference in the FOG sensor is caused by differences in path length traveled by each beam. If the FOG sensor is rotated, the laser/detector moves a tiny amount. This shortens the distance one beam of light travels, and lengthens the distance the other beam of light

travels. When the two beams are recombined, they will form an interference pattern that depends on the rotation rate.

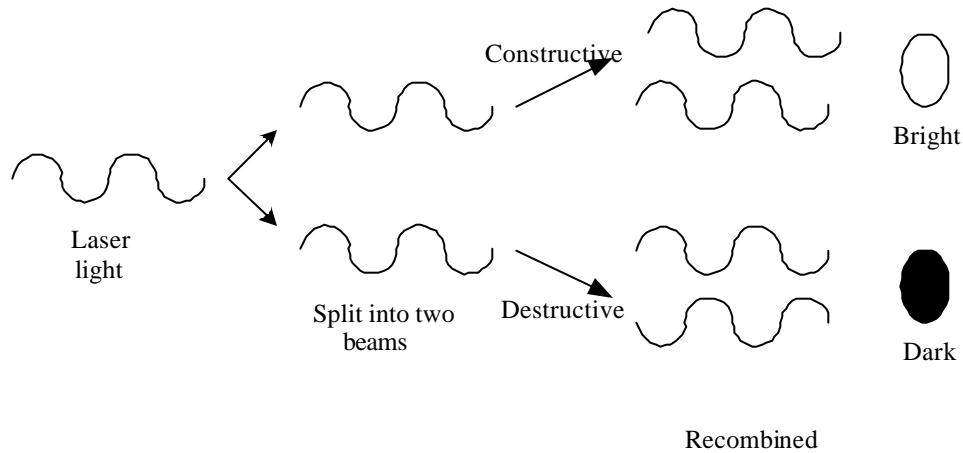


Figure 4. Constructive and Destructive Interference

The Sagnac Effect

The Sagnac Effect utilizes the physical principle that the speed of light is constant. Two beams of laser light are sent in opposite directions around a ring. Because the speed of the laser light is constant, the motion of the optic ring itself, the laser, and the detector, have no effect on the individual light beams. An interference effect is created when the two counter-rotating laser beams are recombined at the detector. Imagine a FOG sensor that is rotating clockwise as seen from the top. A solid-state laser creates a single laser beam. The laser light is split into two beams, one going clockwise, and one counter-clockwise. After traveling through the fiber optic loops, the laser beams are recombined at the detector. The beam going clockwise will have to travel a little farther in going from the laser to the detector, because the detector has rotated away from it some; the beam going counterclockwise travels a little less from the laser to the detector because the detector has rotated into it. The difference in distance traveled creates a phase shift between the two beams. The Sagnac phase shift, ΔS , can be calculated as

$$\Delta S = 8\pi n A \omega / c \lambda$$

where, A is the cross-sectional area enclosed by the fiber optic coil, n is the number of turns of the optical fiber around the ring, ω is the angular rotation around the sensitive axis, c is the speed of light, and λ is the laser light wavelength. Because n , A , c and λ are all known, the FOG sensor can translate a measured ΔS into the angular rotation rate ω .

FOG rate sensors have extremely low levels of bias drift with time or temperature. Solid-state laser diodes provide a very stable source of laser light at a constant frequency. This translates into very stable operation.

Advantages of FOG Technology

FOG sensors have all of the advantages of reliable solid-state technology over mechanical gyroscopes.

- No Moving Parts
- High Stability over Time
- High Stability over Temperature
- Reliability, Long MTBF
- Low Sensitivity to Environmental factors (vibration, shock, acceleration)