BEI SYSTRON DONNER INERTIAL DIVISION
SENSORS & SYSTEMS COMPANY

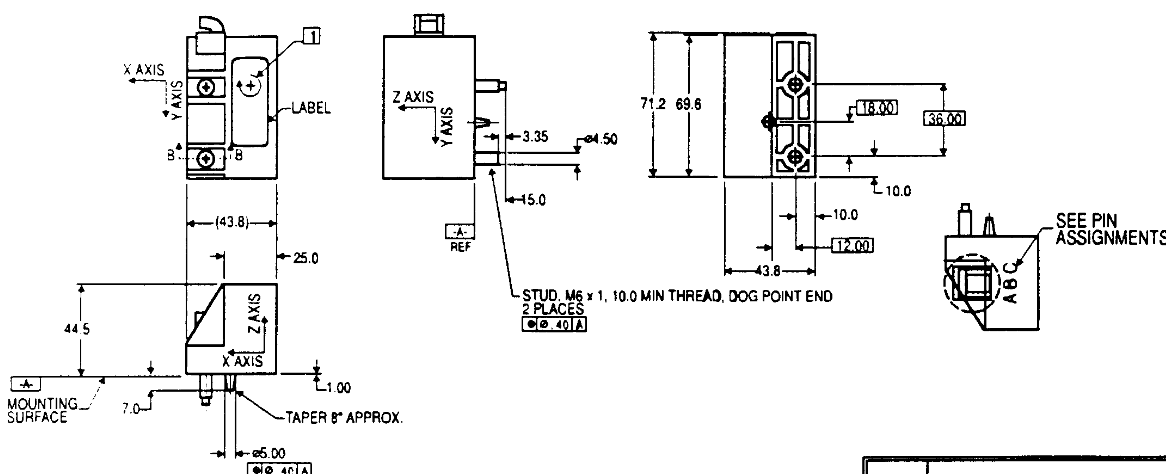
GyroChip®

Solid State Gyroscope

FIRST Project

AQRS-00064-109

PARAMETER	SUMMARY SPECIFICATION
POWER REQUIREMENTS	
Operating Voltage	+5 VDC ±0.25 VDC
Operating Current	20 mA (max.)
PERFORMANCE (typical for 5 Volt input)	
Range*	±64°/sec
Scale Factor*	
Full Range Output	+0.25 to +4.75 VDC
Nominal	35.16 mV/°/sec
Bias*	
Bias at Ambient	+2.50 VDC ±0.5
Bandwidth (90°)	>50 Hz
* Note: Output is ratiometric to supply voltage.	
ENVIRONMENTS	
Operating Temperature	70°F to 90°F
Storage Temperature	-40°F to +185°F
Vibration Operating	1.5 g RMS, 20 to 2,000 Hz
WEIGHT	125 grams max.

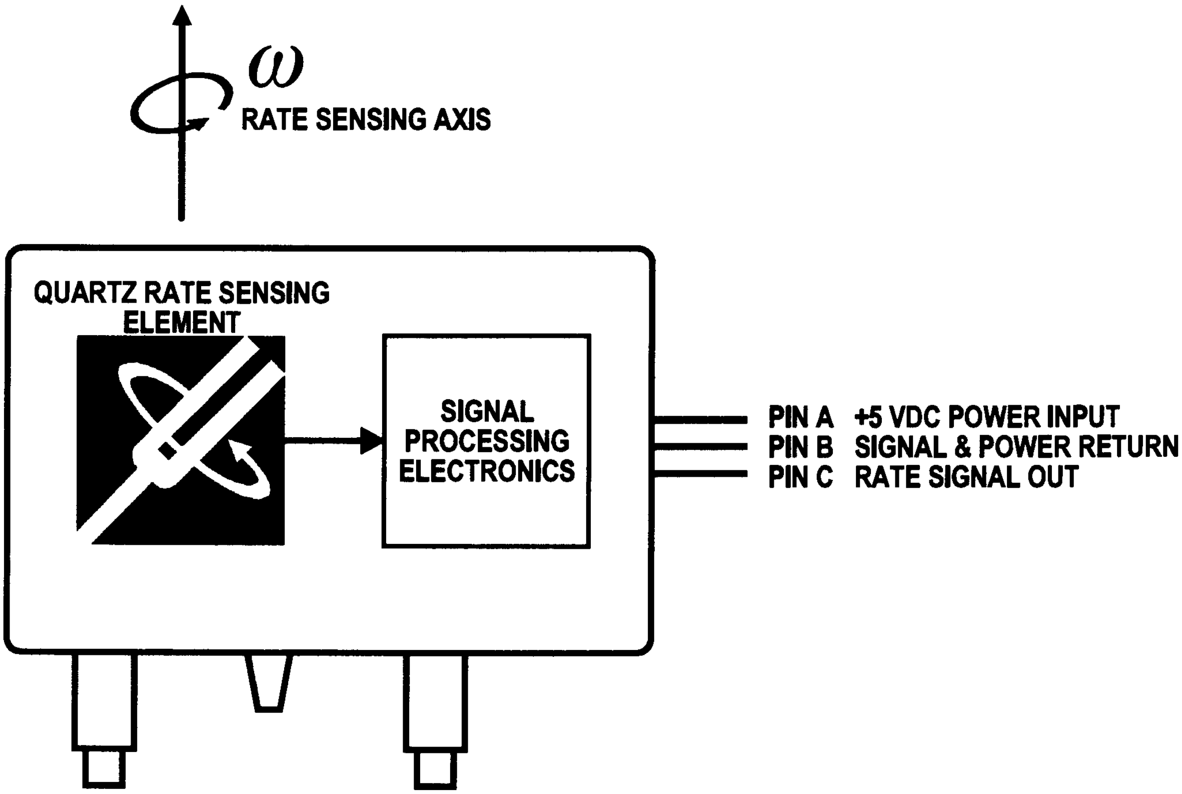


Not Supplied:
Mating Connector Kit (Pioneer Standard)
3 WAY Female – P/N 12064758 (1 ea.)
Terminal Female – P/N 12047767 (3 ea.)

NOTES:
1. ANGULAR RATE APPLIED AS SHOWN SHALL PRODUCE A MORE POSITIVE OUTPUT.
2. DIMENSIONS SHOWN ARE IN MILLIMETERS

Pin	Assignment
A	+5 VDC Input
B	Common
C	Rate Out (1Kohm output impedance)

Systron Donner Inertial Division • 2700 Systron Drive • Concord, California 94518 • Toll Free: (800) 227-1625
Sales: (925) 671-6601 • Customer Service: (925) 671-6499 • FAX: (925) 671-6647
European Business Office (Ashford, England): 44 1303 812778 • FAX: 44 1303 812708



Quartz Rate Sensor
"GyroChip®"

NOT SUPPLIED:
Mating Connector Kit (Pioneer Standard)
3 Way Female - P/N 12064758 (1 ea.)
Terminal Female - P/N 12047767 (3 ea.)

NOTES:

- Rate Sensor Output is ratiometric to input power line voltage over the range of +4.75 to +5.25 VDC.
- Full scale factor rate range is ±64°/sec.
- Output signal is symmetrical about a +2.5 VDC (nominal) bias.
- Output Impedance is 1KΩ or less.

12/98:FIRSTOD.CDR:JSAS

BEI SYSTRON DONNER INERTIAL DIVISION
SENSORS & SYSTEMS COMPANY

A Quartz Rotational Rate Sensor

Based on inertial-sensing principles, the quartz rate sensor provides a simple, reliable measurement of rotational velocity.

The use of a vibrating element to measure rotational velocity by employing the Coriolis principle is a concept that has been around for more than 50 years. In fact, the idea developed long ago out of the observation that a certain species of fly uses a pair of vibrating antennae to stabilize its flight. This sensing technique has been given a practical embodiment: the quartz rate sensor (QRS).

THEORY OF OPERATION

To understand how the QRS works requires familiarity with the Coriolis principle. Simply stated, this means that a linear motion within a rotating framework will have some component of velocity that is perpendicular to that linear motion.

The handiest example of the Coriolis effect is that exhibited by wind patterns on Earth. Convection cells in the atmosphere set up a wind flow from the poles toward the equator (with a north-south orientation). The Earth's rotation, however, causes these linear flows to develop a sideways (orthogonal) component of motion. This "bends" the wind from a north-south to an east-west direction. It is the Coriolis effect that creates the east-west "trade winds," and which is responsible for the spirals of clouds observed in satellite photos.

Now let's apply this principle to our rotation sensor. In Figure 1 you can see that the QRS is essentially divided into two sections: drive and pickup.

The drive portion looks and acts exactly like a simple tuning fork. Because the drive tines are constructed of crystalline quartz, it is possible to electrically "ring" this tuning fork. Each fork tine has a mass and an instantaneous radial velocity that changes sinusoidally as the tine moves back and forth. As long as the fork's base is stationary, the momenta of the two tines exactly cancel each other and there is no energy transfer from the tines to the base. In fact, it takes only ~6 μW of power to keep the fork ringing.

As soon as the tuning fork is rotated around its axis of symmetry, however, the Coriolis principle exerts a profound influence on the behavior of this mechanism.

By convention (the "right-hand rule"), the rotational vector ω_i is described by an arrow that is aligned with the axis of rotation. The instantaneous radial velocity of each of the tines will, through the Coriolis effect, generate a vector cross-product with this rotation vector.

The net effect is that each tine will generate a force perpendicular to the instantaneous radial velocity of each of the other tines:

$$F = 2\,m\omega_i \bullet V_r \qquad (1)$$

where:

m = tine mass
ω_i = rotation rate
V_r = radial velocity

Note that this force is directly proportional to the rotation rate, and since the radial velocity of the tines is sinusoidal, the resultant force on each tine is also sinusoidal. Because the radial velocities of the two tines are equal and opposite, the Coriolis forces are equal and opposite, producing an oscillating torque at the base of the drive tine fork that is proportional to the input angular rate.

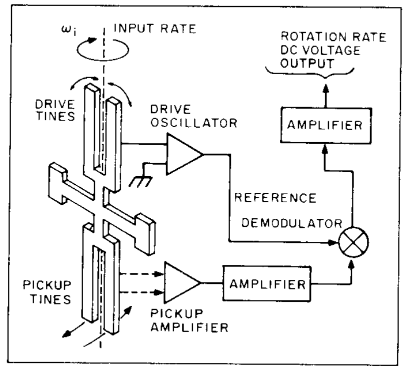


Figure 1. *An oscillating tuning fork senses rotational velocity by using the Coriolis force to translate the linear motion of the tines into an oscillating torque. This torque value is demodulated at the oscillation frequency to generate a DC voltage proportional to the rotation rate input.*

The pickup portion of the QRS now comes into play. The sinusoidal torque variation causes the pickup tines to begin moving tangentially to the rotation and at the same frequency as the drive vibration. Since the forces causing the pickup tines to move are directly proportional to the rotation rate, if there is no rotation the pickup tines will not move. The QRS can therefore truly detect a zero rotation input.

Once the pickup tines are in motion, it is a simple matter to amplify the pickup signal and then demodulate it using the drive frequency as a reference. One additional stage of amplification allows for some signal shaping and produces a DC signal output that is directly propor-

Scott D. Orlosky and Harold D. Morris, Systron Donner, a BEI Electronics Company

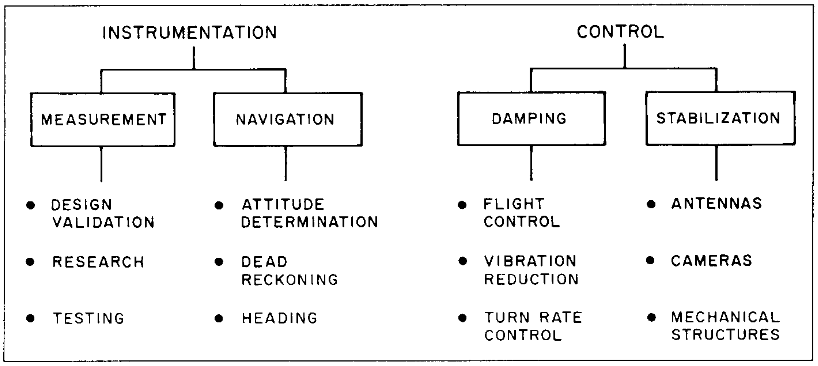


Figure 2. *A variety of instrumentation and control applications can benefit from rotational velocity as a means of improving designs, adding navigational capability to autonomous vehicles, and damping out unwanted motions of control surfaces or gimballed platforms.*

tional to the input angular rate. All of the electronics are fairly simple, and can be contained within the same package as the sensing element.

CONSTRUCTION

The QRS is fabricated from a wafer of single-crystal, synthetically grown quartz. The material's piezoelectric properties are particularly stable over temperature and time. Quartz exhibits a high modulus of elasticity and therefore can be made to ring very precisely with a high Q (quality factor). In addition, quartz can be worked by using conventional wet chemical etch production techniques similar to those favored by the semiconductor industry for producing chips.

APPLICATIONS

Until recently, the most common rotation sensors based on the principles of inertial mechanics were spring-restrained spinning-wheel gyroscopes. These tend to be large and heavy, and to consume large quantities of power. They also tend to wear out after only a few thousand hours of operation and so cannot be used continuously for long periods of time. Their use has been restricted to highly specialized applications such as in military aircraft and missiles, where the short mission times and availability of maintenance personnel made their use practical. By contrast, QRS technology, with its MTBF >100,000 hours and the low cost of ownership, is attractive to industrial and commercial customers as well. QRS applications fall into two broad categories: open-loop, or instrumentation applications; and closed-loop, or control applications (see Figure 2).

INSTRUMENTATION

These applications involve either instrumenting a structure for purposes of determining its rates of rotational motion (measurement), or processing that information in real time to generate information about orientation (navigation). Typical examples of rotational velocity measurement include instrumenting vehicles for crash studies, determining dynamics of specific platforms (e.g., boats, trains, robots, or even human beings), and environmental measurements such as earthquakes and wave motions.

Measurement. One key element in measurement system design is to determine the peak rotational velocities involved to ensure that an instrument with the proper range is used. If the selected range of the QRS is too low, the output will be clipped and valuable information will be lost.

A fairly straightforward way to determine the correct range requirement is to establish two parameters: the frequency of movement of the structure to be instrumented; and the peak angular displacement of that movement. Let's assume that we want to determine the dynamics of a vehicle's body roll while it takes a turn. The body roll motion can be described as:

$$\theta = A \cdot \sin(2\pi \cdot F_n \cdot t) \text{ in degrees} \qquad (2)$$

where:

A = amplitude of movement
F_n = frequency of movement

The parameter of interest for measuring angular velocity is the change in angular position with time, or (dθ/dt). Taking the derivative of the above equation:

$$(d\theta/dt) = A \cdot 2\pi \cdot F_n \cdot \cos(2\pi \cdot F_n \cdot t) \qquad (3)$$

Let's assume that the natural frequency of the vehicle suspension system is 6 Hz, and the peak body roll is 10°. By substituting these into Equation 3:

$$(d\theta/dt) = 10 \cdot 2\pi \cdot 6 \cdot \cos(2\pi \cdot 6 \cdot t) = 377 \cdot \cos(37.7 \cdot t)°/s \qquad (4)$$

Since the cosine term has a maximum value of 1, the peak rotational velocity is 377°/s. So even a seemingly benign environment, a 10° roll at 6 Hz, generates fairly high peak rotational velocities.

Navigation. Navigation applications are becoming increasingly interesting for the QRS, expecially in light of the availablity of GPS receivers at a reasonable cost. In principle, by reading the output from the rotation sensor (rotational velocity) and integrating this output over time, it is possible to determine the sensor's angular displacement. A QRS can be used for sensing vehicle yaw as part of a navigation package (see Figure 3).

SYSTEM COMPONENTS

Anti-Aliasing Filter. Because a computer interface requires the use of an analog-to-digital (A/D) converter, the output from the QRS becomes part of a sampled data stream. In order to prevent aliasing of the output, a filter must be used with the corner frequency usually set at 1/4 to 1/2 of the sampling frequency.

A/D Converter. The A/D conversion should be carried out immediately after anti-aliasing since this puts the converter close to the QRS and reduces the overall noise of the system, yielding the most stable results. A 12-bit converter is generally adequate. The sample frequency should be appropriate for the system, but typical values range from 100 Hz to 1000 Hz.

Bandpass Filter. This filter is tailored to the specific application. When the sensor is used as part of a head-mounted display for a virtual reality application, for example, it is not necessary to track very small, high-frequency head movements because they may simply be part of the normal jostling associated with interactive game playing. Only larger, definite head swings need attention.

Similarly, low-frequency variations in the QRS output, which are usually associated with changes in environmental temperatures or warm-up, are not meaningful tracking information and should be rejected.

These two scenarios determine the lower and upper ranges of the bandpass filter. A reasonable starting point would be to choose upper and lower corner frequencies of 0.1 Hz and 10 Hz.

Integrator. This is where the angular velocity information is turned into angular position. Since the initial conditions are indeterminate at start-up, it is recommended that a reset capability be included. This allows you to initialize the integrator to zero or some known position at startup.

The portion of the platform that is to be measured must usually be held very steady during startup so that the initial conditions represent as closely as possible a true "zero input" state. Any residual error at startup will cause the apparent output from the integrator to drift.

One method to reduce the startup error is to average the input to the integrator for a few seconds during the initialization sequence, and then subtract this average value to establish the zero point.

As a practical matter, it is virtually impossible to measure the "pure" rotational velocity without introducing or reading some error at the same time. This accumulation of errors means that over time, the true angular position and the calculated angular position will diverge. The sensor output may not be drifting, but the apparent calculated angle is.

The rate of this divergence is determined by a variety of factors including: how well the initial conditions are established; the accuracy of the alignment of the sensor to the true axis of rotation; the quantization errors of the signal (if it has been digitized); and the stability of the environment in which the measurement is being done.

For most practical applications, therefore, the QRS is used only for short-term navigation. In order to prevent these incremental errors from growing too large, the common practice is to periodically update, or correct, the calculated angle

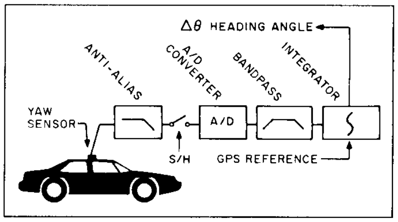


Figure 3. *By combining the quartz rotation sensor (QRS) with a fixed reference such as a GPS receiver, a complete navigation system can be created for an automobile. Attention to signal processing design as well as to blending the GPS reference signal produces a system that can cope with extended GPS blackouts.*

through the use of a fixed, external reference as shown in Figure 3.

The reference selected will depend on the situation; examples include a GPS signal, a corner-cube with optical line-of-sight, or an encoded magnetic signal. In fact, the combination of dead reckoning between fixed reference updates is a nearly ideal means of navigation through a variety of dynamic environments.

This method has been used for autonomous delivery robots in hospitals, automated forklifts in warehouses, and emergency vehicles deployed in urban environments.

CONTROL

To employ the QRS in control applications requires an understanding of how it works as part of a system. The typical system model takes into account the magnitude and phase relationships of the sensor response.

Damping. The ability to accurately measure rotational velocity opens up new possibilities for control of structures. One of the most useful types of

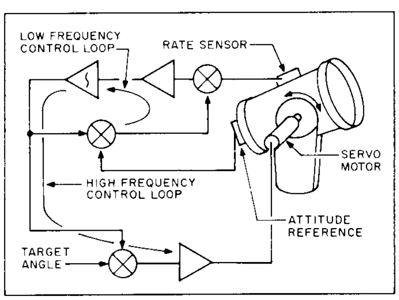


Figure 4. *As part of an attitude control system for a mobile telescope, the QRS can be combined with a simple tilt sensor to provide both absolute pointing accuracy as well as stability. Rapid motions are compensated for in the high-frequency control loop, while the low-frequency control loop provides a vertical reference to gravity.*

control applications is to damp out the resonant behavior of mechanical systems. Very few mechanical systems produce pure linear motion—most machines have parts that rotate or pivot. Aircraft, land vehicles, and ships are governed by means of roll, pitch, and/or yaw controls. By monitoring and controlling these motions it is possible to provide active roll damping on ships, remove "Dutch roll" from aircraft flight, reduce body roll on a car as it takes a turn, or damp out end-effector shake in an industrial robot.

Stabilization. This is a special instance of closed-loop control—stabilization—in which the item being controlled is intended to remain stationary even during movement of the platform to which it is attached. It is important that the QRS be tightly coupled mechanically to the object to be controlled, usually a camera or an antenna on a multi-axis gimbal. This gimbal mechanism must have no mechanical resonances in the bandwidth of the servo-control loop.

The system designer must take into account the transfer function of the system servo-loop and ensure enough phase margin to prevent oscillation. Because it is often necessary to independently move the camera or antenna, a commandable DC offset must be included in the control loop to allow an operator to rotate and point the camera in the gimbal. This method has been used successfully to stabilize antennas aboard ships and land vehicles, as well as cameras aboard helicopters and survey airplanes.

An example of such an application is shown in Figure 4. Here, the QRS is used as part of a servo-control loop to provide an absolute pointing angle in attitude as well as image stability for a mobile telescope.

For simplicity it is assumed that the telescope is mounted on a platform that can rotate only in attitude, and that the control mechanism is therefore an attitude control system only. The principle described can be applied to the other axes of rotation.

Refer first to the high-frequency control loop portion of Figure 4. Assume that this circuit is designed to operate at 10 Hz, which is a typical value for a servo control. Let's further assume that the telescope has a rotational inertia J =

12 slug-ft^2.

Since: $\omega_n^2 = K_s/J$
then: $K_s = (10 \bullet 2 \bullet \pi)^2 \bullet 12$
$= 47{,}300$ ft-lb./rad (5)

where:

ω_n = corner frequency of servo-loop
K_s represents the servo stiffness

The preceding implies that an external torque of 10 ft-lb. will allow a movement of only 10/47,300 = 0.0002 rad, or 0.7 arc-min.

Now let's look at the low-frequency control loop portion of Figure 4. This will act as a vertical reference unit and ensure that the absolute pointing angle of the telescope matches the commanded (or target) angle. To accomplish this, a stable, long-term attitude reference must be provided.

For most systems, gravity does the job quite nicely. A simple tilt sensor is always referenced to local gravity, and over a fairly narrow range it will behave linearly. To avoid coupling-in any high-frequency movements that are, by definition, not gravity related, this reference is part of a control loop with a time constant of typically 100 s. This allows the attitude reference to closely follow the typical platform motions you might find on most common mobile platforms, i.e., ships, trains, or planes.

In general, the loop will incorporate a proportional and differential control element that does not appear in the figure.

SUMMARY

A new type of sensor has been developed that can add significantly to the capabilities of engineers and designers alike. Based on inertial-sensing principles, the quartz rate sensor provides a simple, reliable measurement of rotational velocity that can be used to instrument structures in new ways and gain a more in-depth insight into designs; to aid in short-term navigation of autonomous mobile platforms; and to allow for improved methods of stabilizing structures.

Scott D. Orlosky is Director for Commercial Business and Harold D. Morris is Chief Scientist, Systron Donner Inertial Division, a BEI Electronics Company, 2700 Systron Dr., Concord, CA 94518; 510-671-6601, fax 510-671-6647.