TECHNICAL ARTICLE

# MEMS GYROSCOPE PROVIDES PRECISION INERTIAL SENSING IN HARSH, HIGH TEMPERATURE ENVIRONMENTS

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## Abstract

There are an increasing number of applications that have a need to gather data from sensors located in very high temperature environments. In recent years there has been considerable progress in semiconductors, passives, and interconnects to enable high precision data acquisition and processing. However, there are still unmet needs for sensors that can operate at temperatures up to 175°C, particularly in the easy to use form factor provided by microelectromechanical systems (MEMS). MEMS sensors often are smaller, lower power, and lower cost than discrete sensor equivalents. In addition, they can also integrate signal conditioning circuitry in the same semiconductor package.

A high temperature MEMS accelerometer—ADXL206—has already been released that provides high precision tilt (inclination) measurements. However, there is still a need for additional degrees of freedom to precisely measure movement of the system in harsh environment applications where the end product can be subjected to severe shock, vibration, and violent motion. This type of abuse can cause undue wear and early failure of the system, incurring high cost in maintenance or downtime.

To meet this need, Analog Devices has developed a new high temperature MEMS gyroscope with integrated signal conditioning, the ADXRS645. This sensor enables precision angular rate (rotation speed) measurement even in the presence of shock and vibration and is rated for temperatures up to 175°C.

## Theory of Operation

MEMS gyroscopes measure angular rate by means of Coriolis acceleration. The Coriolis effect can be explained as follows, starting with Figure 1. Consider yourself standing on a rotating platform, near the center. Your speed relative to the ground is shown as the blue arrow lengths. If you were to move to a point near the outer edge of the platform your speed would increase relative to the ground, as indicated by the longer blue arrow. The rate of increase of your tangential speed, caused by your radial velocity, is the Coriolis acceleration.

If $\Omega$ is the angular rate and $r$ is the radius, the tangential velocity is $\Omega r$. So if r changes at speed v there will be a tangential acceleration $\Omega v$. This is half of the Coriolis acceleration. There is another half from changing the direction of the radial velocity giving a total of $2\Omega v$. If you have a mass (M), the platform must apply a force—$2M\Omega v$—to cause that acceleration, and the mass experiences a corresponding reaction force. The ADXRS645 takes advantage of this effect by using a resonating mass analogous to the person moving out and in on a rotating platform. The mass is micromachined from polysilicon and is tethered to a polysilicon frame so that it can resonate only along one direction.

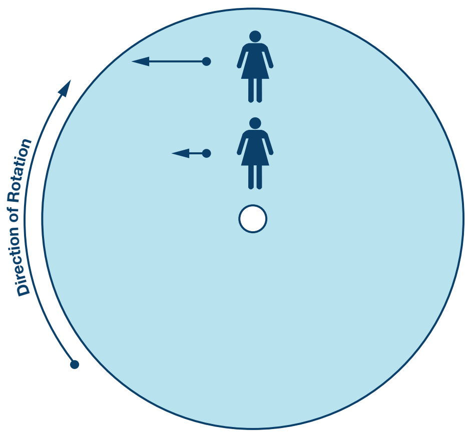


*Figure 1. Coriolis acceleration example. A person moving northward toward the outer edge of a rotating platform must increase the westward speed component (blue arrows) to maintain a northbound course. The acceleration required is the Coriolis acceleration.*

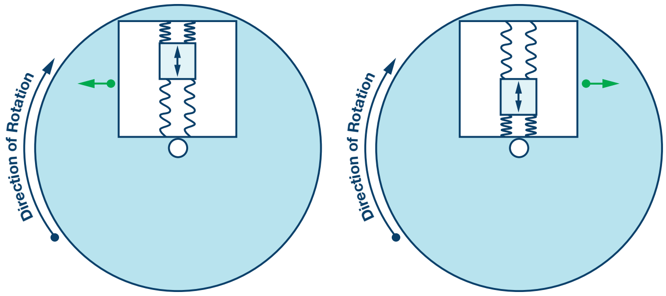


*Figure 2. Demonstration of Coriolis effect in response to a resonating silicon mass suspended inside a frame. The green arrows indicate the force applied to the structure based on status of the resonating mass.*

Figure 2 shows that when the resonating mass moves toward the outer edge of the rotation, it is accelerated to the right and exerts on the frame a reaction force to the left. When it moves toward the center of the rotation it exerts a force to the right, as indicated by the green arrows.

To measure the Coriolis acceleration, the frame containing the resonating mass is tethered to the substrate by springs at 90° relative to the resonating motion, as shown in Figure 3. This figure also shows the Coriolis sense fingers that are used to sense displacement of the frame through capacitive transduction in response to the force exerted by the mass.

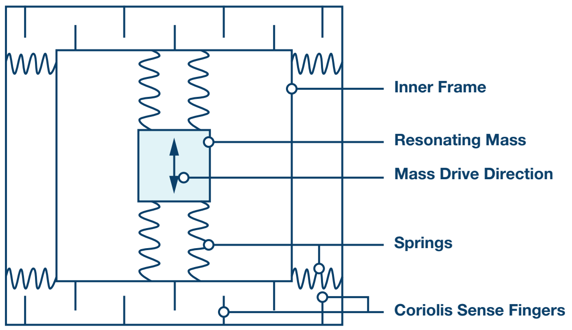


*Figure 3. Schematic of the gyroscope's mechanical structure.*

Figure 4, which shows the complete structure, demonstrates that as the resonating mass moves and as the surface to which the gyroscope is mounted rotates, the mass and its frame experience the Coriolis acceleration and are translated 90° from the vibratory movement. As the rate of rotation increases, so does the displacement of the mass and the signal derived from the corresponding capacitance change. It should be noted that the gyroscope may be placed anywhere on the rotating object and at any angle, so long as its sensing axis is parallel to the axis of rotation.

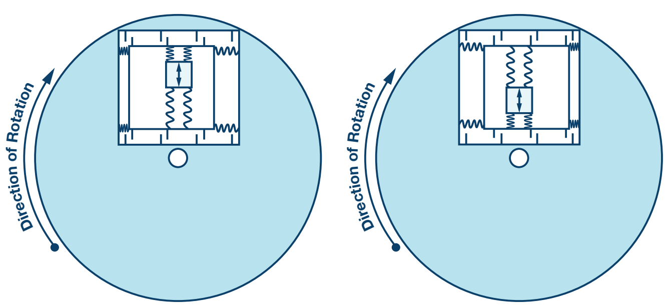


*Figure 4. The frame and resonating mass are displaced laterally in response to the Coriolis effect.*

## Capacitive Sensing

ADXRS645 measures the displacement of the resonating mass and its frame due to the Coriolis effect through capacitive sensing elements attached to the resonator, as shown in Figure 4. These elements are silicon beams interdigitated with two sets of stationary silicon beams attached to the substrate, thus forming two nominally equal capacitors. Displacement due to angular rate induces a differential capacitance in this system.

In practice, the Coriolis acceleration is an extremely small signal, producing fractions of Angstroms of beam deflection and corresponding capacitance changes on the order of zeptofarads. Therefore, it is extremely important to minimize cross sensitivity to parasitic sources such as temperature, package stress, external acceleration, and electrical noise. This is achieved partially by situating the electronics, including amplifiers and filters, on the same die as the mechanical sensor. However, it's more important to make differential measurements as far down the signal chain as possible and correlate the signal with the resonator velocity, especially to deal with the effects of external acceleration.

## Vibration Rejection

Ideally a gyroscope would be sensitive only to rotation rate and nothing else. In practice, all gyroscopes have some sensitivity to acceleration due to asymmetry of their mechanical designs and/or micromachining inaccuracies. In fact, there are multiple manifestations of acceleration sensitivity—the severities of which vary from design to design. The most significant are usually sensitivity to linear acceleration (or *g* sensitivity) and vibration rectification (or $g^2$ sensitivity) and can be severe enough to completely swamp the rated bias stability of the part. The output of some gyroscopes swings from rail to rail when the rate input is beyond the rated measurement range. Other gyroscopes have a tendency to lock up when exposed to shocks as small as a few hundred *g*. These gyroscopes are not damaged by the shock, but they no longer respond to rate and need to be power cycled to restart.

The ADXRS645 employs a novel approach to angular rate sensing that makes it possible to reject shocks of up to 1000 *g*—it uses four resonators to differentially sense signals and reject common-mode external accelerations that are unrelated to angular motion. The top and bottom resonator pairs in Figure 5 are mechanically independent and they operate antiphase. As a result, they measure the same magnitude of rotation but give outputs in opposite directions. Therefore, the difference between the sensor signals is used to measure angular rate. This cancels nonrotational signals that affect both sensors. The signals are combined in the internal hardwiring ahead of the preamplifiers. Thus, extreme acceleration overloads are largely prevented from reaching the electronics—thereby allowing the signal conditioning to preserve the angular rate output during large shocks.

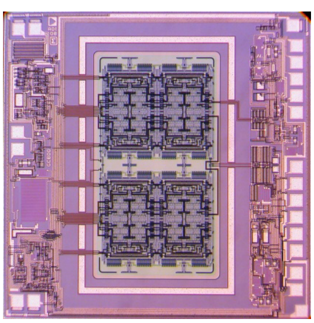

*Figure 5. Quad differential sensor design.*

## Sensor Implementaion

A simplified schematic of the gyroscope and associated drive and sense circuitry is shown in Figure 6.

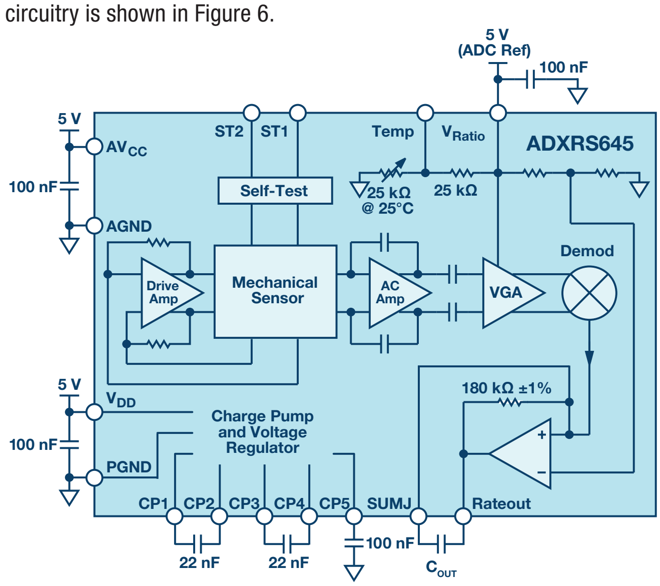


*Figure 6. Block diagram of the integrated gyroscope.*

The resonator circuit senses the velocity of the resonating mass, amplifies, and drives the resonator while maintaining a well controlled phase (or delay) relative to the Coriolis signal path. The Coriolis circuitry is used to detect the movement of the accelerometer frame with downstream signal processing to extract the magnitude of the Coriolis acceleration and produce an output signal consistent with the input rotation rate. In addition, a self-test function checks the integrity of the entire signal chain including the sensor.

## Application Example

One of the harshest environments for electronics is arguably encountered in the oil and gas downhole drilling industry. These systems utilize a multitude of sensors to better understand the motion of the drill string below the surface, optimize operations, and prevent damage. The drill rate of rotation measured in RPM is a key metric that the drill operator needs to know at all times. Traditionally this has been calculated from magnetometers. However, magnetometers are subject to interference from ferrous materials present in the drill casing and the surrounding borehole. They also must be housed in special, nonmagnetic drill collars (housings).

Beyond simple RPM measurement, there is increasing interest in understanding the motion of the drill string or drilling dynamics to optimally manage parameters such as the amount of force applied, rate of rotation, and steering. Poorly managed drilling dynamics can result in high vibration and extremely erratic motion of the drill leading to longer drilling times to the target zone, premature failure of equipment, difficulty in steering the bit, and damage to the well itself. In extreme cases equipment can be broken and left in the well, which then must be retrieved at a very high cost.

One especially harmful type of motion resulting from poor management of drilling parameters is known as stick-slip. Stick-slip is a phenomenon where the drill bit gets stuck, but the top of the drill string continues to rotate. While the bit is stuck, the bottom of the drill string winds up until it builds enough torque to break loose, often violently. When this happens, a large spike in rotation rate occurs at the drill bit. Stick-slip tends to occur cyclically and can last over a long period of time. A typical RPM response from stick-slip is shown in Figure 7. Because the drill string at the surface continues to rotate normally, the drilling operators often are unaware that this damaging phenomenon is happening downhole.

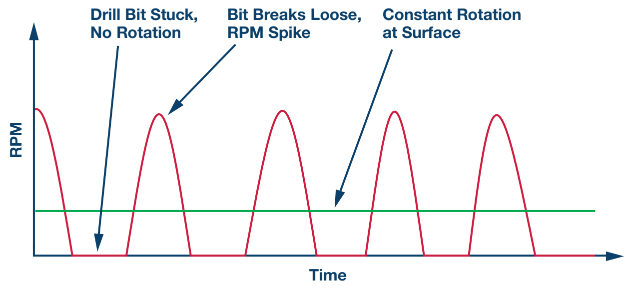


*Figure 7. Examples of a stick-slip cyclic RPM profile.*

A critical measurement for this application is an accurate, high sample rate measurement of the rotation speed near the drill bit.  A gyroscope such as the vibration rejecting ADXRS645 is ideally suited for this task because the measurement is decoupled from any linear movement of the drill string. Rotation rate calculated from magnetometers is subject to noise and error when there is high vibration and erratic motion. A gyroscope-based solution gives an instantaneous answer for rotation speed and is not dependent on zero crossings or other algorithms that can be affected by shock and vibration.

In addition, the gyroscope-based circuit is smaller and requires fewer components than a fluxgate magnetometer solution, which requires multiple magnetometer axes and additional drive circuitry. Signal conditioning is integrated into the ADXRS645. Supporting high temperature ICs to sample and digitize the gyroscope analog output are available in low power, low pin count packages. A 175°C rated gyroscope circuit with digital output can be realized with the simplified signal chain shown in Figure 8. A full reference design for the data acquisition circuit is available at www.analog.com/cn0365.

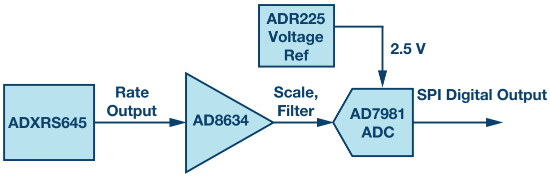


*Figure 8. 175°C rated gyroscope digital output signal chain.*

## Summary

This article presented the first MEMS gyroscope rated for high temperature 175°C operation—ADXRS645. This sensor enables precision angular rate measurements in harsh environment applications, rejecting the influence of shock and vibration. The gyroscope is supported by a portfolio of high temperature ICs to acquire the signal for processing. For more information on Analog Devices high temperature products, please go to www.analog.com/hightemp.

## About the Author

Jeff Watson [jeffrey.watson@analog.com] is a systems applications engineer in the Instrumentation, Aerospace and Defense business unit at Analog Devices, focusing on high temperature applications. Prior to joining ADI, he was a design engineer in the downhole oil and gas instrumentation industry and off-highway automotive instrumentation/controls industry. Jeff received his bachelor's and master's degrees in electrical engineering from Penn State University.

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