

New iMEMS® Angular-Rate-Sensing Gyroscope

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INTRODUCTION

The new ADXRS150 and ADXRS300 gyros from Analog Devices, with full-scale ranges of 150°/s and 300°/s, represent a quantum jump in gyro technology. The first commercially available surface-micromachined angular rate sensors with integrated electronics, they are smaller—with lower power consumption, and better immunity to shock and vibration—than any gyros having comparable functionality. This genuine breakthrough is possible only because of the Analog Devices proprietary *integrated micro electro-mechanical system* (iMEMS) process, proven by use in millions of automotive accelerometers.

Product Description

Gyroscopes are used to measure *angular* rate—how quickly an object turns. The rotation is typically measured in reference to one of three axes: yaw, pitch, or roll.

Figure 1 shows a diagram representing each axis of sensitivity relative to a package mounted to a flat surface. A gyroscope with one axis of sensitivity can also be used to measure other axes by mounting the gyro differently, as shown in the right-hand diagram. Here, a yaw-axis gyro, such as the ADXRS150 or ADXRS300, is mounted on its side so that the yaw axis becomes the roll axis.

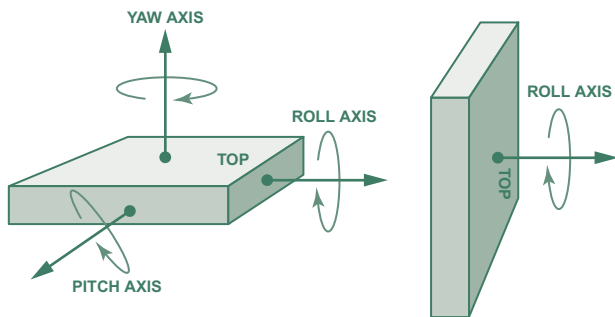


Figure 1. Gyro axes of rotational sensitivity. Depending on how a gyro normally sits, its primary axis of sensitivity can be one of the three axes of motion: yaw, pitch, or roll. The ADXRS150 and ADXRS300 are yaw-axis gyros, but they can measure rotation about other axes by appropriate mounting orientation. For example, at the right: a yaw-axis device is positioned to measure roll.

As an example of how a gyro could be used, a yaw-axis gyro mounted on a turntable rotating at 33 1/3 rpm (revolutions per minute) would measure a constant rotation of 360° times 33 1/3 rpm divided by 60 seconds, or 200°/s. The gyro would output a voltage proportional to the angular rate, as determined by its sensitivity, measured in millivolts per degree per second (mV/°/s). The full-scale voltage determines how much angular rate can be measured, so in the example of the turntable, a gyro would

need to have a full-scale voltage corresponding to at least 200°/s. Full-scale is limited by the available voltage swing divided by the sensitivity. The ADXRS300, for example, with 1.5 V full-scale and a sensitivity of 5 mV/°/s, handles a full-scale of 300°/s. The ADXRS150, has a more limited full-scale of 150°/s but a greater sensitivity of 12.5 mV/°/s.

One practical application is to measure how quickly a car turns by mounting a gyro inside the vehicle; if the gyro senses that the car is spinning out of control, differential braking engages to bring it back into control. The angular rate can also be integrated over time to determine angular position—particularly useful for maintaining continuity of GPS-based navigation when the satellite signal is lost for short periods of time.

Coriolis Acceleration

Analog Devices' ADXRS gyros measure angular rate by means of Coriolis acceleration. The Coriolis effect can be explained as follows, starting with Figure 2. Consider yourself standing on a rotating platform, near the center. Your speed relative to the ground is shown as the blue arrow lengths in Figure 2. 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 (after Gaspard G. de Coriolis, 1792-1843—a French mathematician).

If Ω is the angular rate and r the radius, the tangential velocity is Ωr . So, if r changes at speed, v , there will be a tangential acceleration Ωv . This is half of the Coriolis acceleration. There is another half from changing the direction of the radial velocity giving a total of $2\Omega v$ (see the Appendix). If you have mass, M , the platform must apply a force, $2M\Omega v$, to cause that acceleration, and the mass experiences a corresponding reaction force.

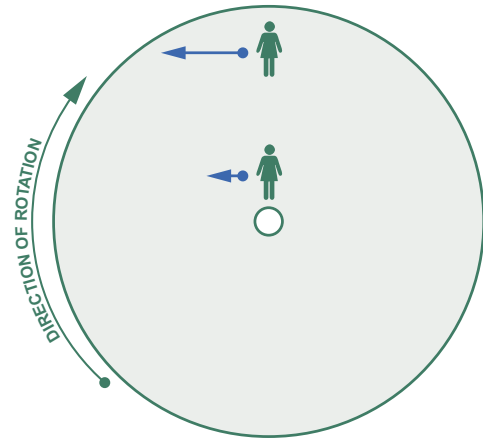


Figure 2. Coriolis acceleration example. A person moving northward toward the outer edge of a rotating platform must increase the westward speed component (blue arrows) to maintain a northbound course. The acceleration required is the *Coriolis acceleration*.

The ADXRS gyros take 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.

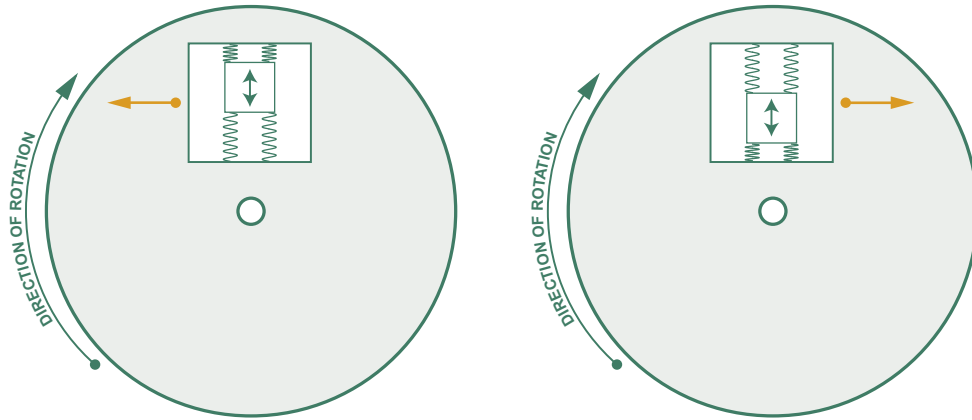


Figure 3. Demonstration of Coriolis effect in response to a resonating silicon mass suspended inside a frame. The orange arrows indicate the force applied to the structure, based on status of the resonating mass.

Figure 3 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 orange 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 4. This figure also shows the Coriolis sense fingers that are used to capacitively sense displacement of the frame in response to the force exerted by the mass, as described further on. If the springs have a stiffness, K , then the displacement resulting from the reaction force will be $2 \Omega v M / K$.

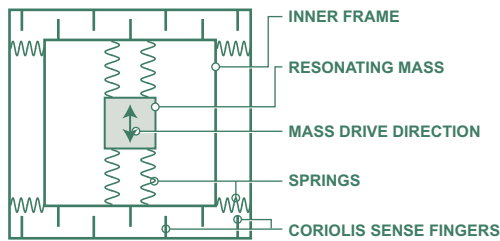


Figure 4. Schematic of the gyro's mechanical structure.

Figure 5, which shows the complete structure, demonstrates that as the resonating mass moves, and as the surface to which the gyro is mounted rotates, the mass and its frame experience the Coriolis acceleration and are translated 90° from the

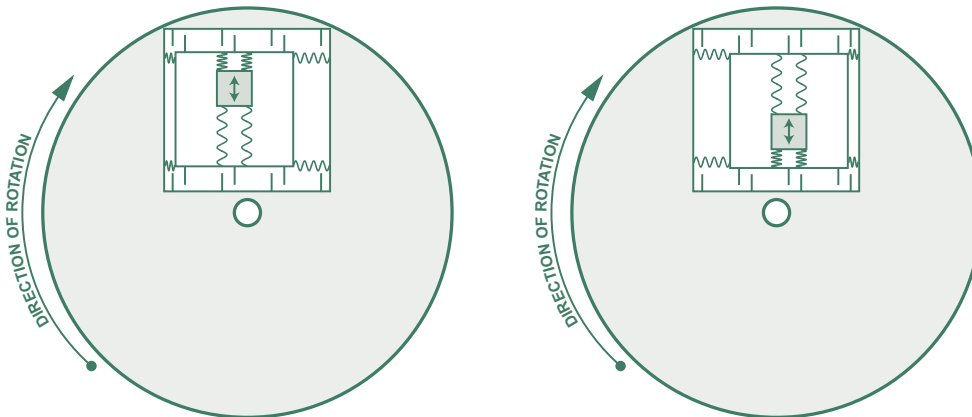


Figure 5. The frame and resonating mass are displaced laterally in response to the Coriolis effect. The displacement is determined from the change in capacitance between the Coriolis sense fingers on the frame and those attached to the substrate.

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 gyro 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. The above explanation is intended to give an intuitive sense of the function and has been simplified by the placement of the gyro.

Capacitive Sensing

ADXRS gyros measure 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 Figures 4, 5, and 6. These elements are silicon beams inter-digitated 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. If the total capacitance is C and the spacing of the beams is g , then the differential capacitance is $2 \Omega v M C / g K$, and is directly proportional to the angular rate. The fidelity of this relationship is excellent in practice, with nonlinearity less than 0.1%.

The ADXRS gyro electronics can resolve capacitance changes as small as 12×10^{-21} farads (12 zeptofarads) from beam deflections as small as 0.00016 Angstroms (16 femtometers). The only way this can be utilized in a practical device is by situating the electronics, including amplifiers and filters, on the same die as the mechanical sensor. The differential signal alternates at the resonator frequency and can be extracted from the noise by correlation.

These sub atomic displacements are meaningful as the *average* positions of the surfaces of the beams, even though the individual atoms on the surface are moving randomly by much more. There are about 10^{12} atoms on the surfaces of the capacitors, so the statistical averaging of their individual motions reduces the uncertainty by a factor of 10^6 . So why can't we do 100 times better? The answer is that the impact of the *air molecules* causes the structure to move—although similarly averaged, their effect is far greater! So why not remove the air? The device is not operated in a vacuum because it is a very fine, thin film weighing only 4 micrograms; its flexures, only 1.7 microns wide, are suspended over the silicon substrate. Air cushions the structure, preventing it from being destroyed by violent shocks—even those experienced during firing of a guided shell from a howitzer (as demonstrated recently).

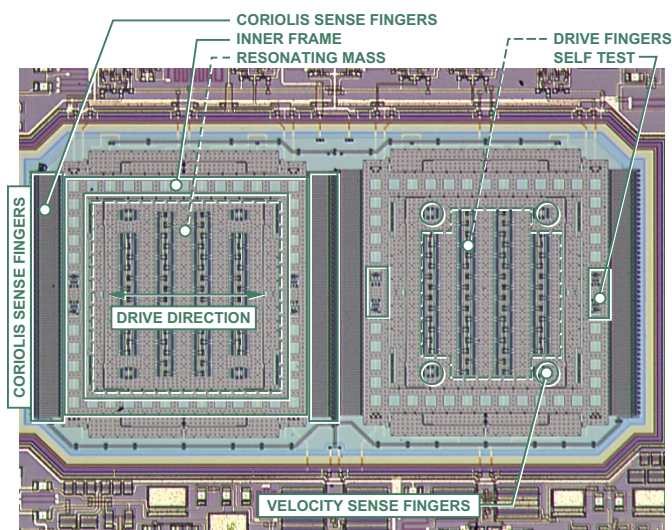


Figure 6. Photograph of mechanical sensor. The ADXRS gyros include two structures to enable differential sensing in order to reject environmental shock and vibration.

Features

Integration of electronics and mechanical elements is a key feature of products such as the ADXRS150 and ADXRS300, because it makes possible the smallest size and cost for a given performance level. Figure 7 is a photograph of the ADXRS die.

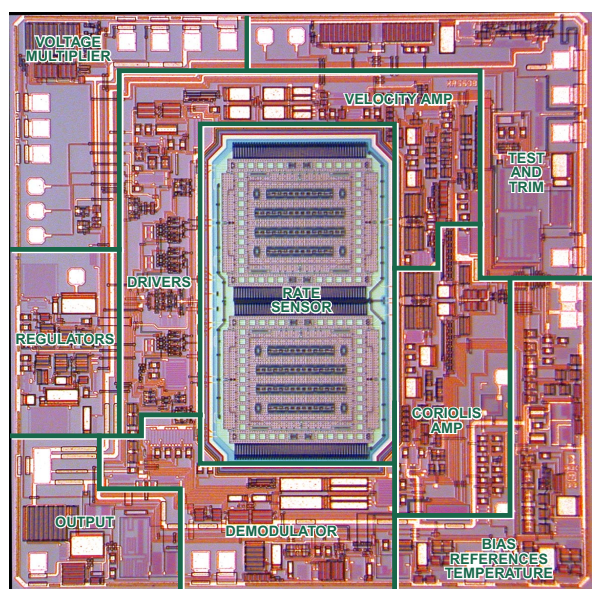


Figure 7. Photograph of ADXRS gyro die, highlighting the integration of the mechanical rate sensor and the signal conditioning electronics.

The ADXRS150 and ADXRS300 are housed in an industry-standard package that simplifies users' product development and production. The ceramic package—a 32-pin ball grid-array, (BGA)—measures 7 mm wide by 7 mm deep by 3 mm tall. It is at least 100 times smaller than any other gyro having similar performance. Besides their small size, these gyros consume 30 mW, far less power than similar gyros. The combination of small size and low power make these products ideally suited for consumer applications such as toy robots, scooters, and navigation devices.

Immunity to Shock and Vibration

One of the most important concerns for a gyro user is the device's ability to reliably provide an accurate angular rate-output signal—even in the presence of environmental shock and vibration. One example of such an application is automotive rollover detection, in which a gyro is used to detect whether *or not* a car (or SUV) is rolling over. Some rollover events are triggered by an impact with another object, such as a curb, that results in a shock to the vehicle. If the shock saturates the gyro sensor, and the gyro cannot filter it out, then the airbags may not deploy. Similarly, if a bump in the road results in a shock or vibration that translates into a rotational signal, the airbags might deploy when not needed—a considerable safety hazard!

As can be seen in Figures 6 and 7, the ADXRS gyros employ a novel approach to angular rate-sensing that makes it possible to reject shocks of up to $1,000g$ —they use two resonators to differentially sense signals and reject common-mode external accelerations that are unrelated to angular motion. This approach is, in part, the reason for the excellent immunity of the ADXRS gyros to shock and vibration. The two resonators in Figure 6 are mechanically independent, and they operate anti-phase. As a result, they measure the same magnitude of rotation, but give outputs in opposite directions. Therefore, the difference between the two sensor signals is used to measure angular rate. This cancels non-rotational signals that affect both sensors. The signals are combined in the internal hard-wiring ahead of the very sensitive 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. This scheme requires that the two sensors be well-matched, precisely fabricated copies of each other.

SUMMARY

Analog Devices has used its iMEMS process to achieve a breakthrough with the development of the World's first fully integrated angular rate sensor. Integration yields a revolution in reliability, size, and price. The result is a gyro that is suited for a much wider range of applications than previously thought possible or affordable. The device's low power and small size will benefit small consumer and industrial products that run on batteries, such as toys, scooters, and portable instruments. The tremendous immunity to shock and vibration benefits automotive and other applications that are subject to harsh environmental conditions.

Looking forward, it is possible to exploit the iMEMS process and gyro design techniques to achieve even higher levels of integration. Just as Analog Devices has developed dual-axis accelerometers, it will be possible to produce multi-axis gyroscopes. It will even be possible to integrate both accelerometers and gyros on a single die. The resulting inertial measurement unit would enable even tiny vehicles to be stabilized and navigated autonomously. ▶

APPENDIX

Motion in 2 dimensions

Consider the position coordinate, $z = re^{i\theta}$, in the complex plane. Differentiating with respect to time, t , the velocity is

$$\frac{dz}{dt} = \frac{dr}{dt} \epsilon^{i\theta} + ir \frac{d\theta}{dt} \epsilon^{i\theta}$$

the two terms are the respective radial and tangential components, the latter arising from the angular rate. Differentiating again, the acceleration is

$$\frac{d^2z}{dt^2} = \left[\frac{d^2r}{dt^2} \epsilon^{i\theta} + i \frac{dr}{dt} \frac{d\theta}{dt} \epsilon^{i\theta} \right] + \left[i \frac{dr}{dt} \frac{d\theta}{dt} \epsilon^{i\theta} + ir \frac{d^2\theta}{dt^2} \epsilon^{i\theta} - r \left(\frac{d\theta}{dt} \right)^2 \epsilon^{i\theta} \right]$$

The first term is the radial linear acceleration and the fourth term is the tangential component arising from angular acceleration. The last term is the familiar centripetal acceleration needed to

constrain r . The second and third terms are tangential and are the Coriolis acceleration components. They are equal, respectively arising from the changing direction of the radial velocity and from the changing magnitude of the tangential velocity. If the angular rate and radial velocities are constant,

$$\frac{d\theta}{dt} = \Omega \text{ and } \frac{dr}{dt} = v$$

then

$$\frac{d^2z}{dt^2} = i2\Omega v \epsilon^{i\theta} - \Omega^2 r \epsilon^{i\theta}$$

where the angular component, $i\epsilon^{i\theta}$, indicates a tangential direction in the sense of positive θ for the Coriolis acceleration, $2\Omega v$, and $-\epsilon^{i\theta}$ indicates towards the center (i.e., *centripetal*) for the $\Omega^2 r$ component.