Improved Vibratory Gyro
Pick-off and Driver Geometry

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Abstract

This report is based on a recent patent application by Watson Industries. Watson Industries has developed a novel new means of applying and extracting signals for vibratory gyros. The method involves using improved geometry for pickoffs and/or drivers to control the drive and sensing vectors to electrically optimize gyro performance. The main example presented is based on the ceramic cup vibrating structure gyro, but these same principles may apply to almost all other vibrating structure gyro mechanisms.

The improved pickoff design allows both drive sensing and rate sensing to be produced from the same set of pickoffs. Additionally, the associated circuitry allows independent electrical adjustment of both the sense axis alignment and isolation between the drive-sense and rate sense signals. All of this is done with minimal connections to the gyro mechanism and while preserving symmetry of the sensing pickoffs.

The improved driver design also allows electrical adjustment of the drive vector. The design additionally provides a means of applying torque drive to the gyro on the same drivers as the operational drive. Both driver and pickoff design improvements are done with minimal connections to the gyro mechanism while preserving symmetry of drivers and sense pickoffs.

Examples of how these principles may be applied to a wide variety of gyro configurations are provided.

Introduction

Gyro design has been dominated by the opinion that the ideal gyro is made of ideal materials (high mechanical “Q”), maximum symmetry in its geometry, and isolation of the drive and rate sensing functions [1] [2] [3]. These aspirations are being compromised regularly in the real world to reduce cost and complexity of gyros. Now there are some technical reasons to depart from these ideals to improve performance and functionality.

The use of lower Q materials has previously been examined for the considerations of gyro bandwidth and tuning sensitivity [4]. This paper will, therefore, focus on the constructive application of asymmetry and combined functions to the gyro mechanism.

Goals of this effort are to lower product cost while maintaining performance. Design improvements include making fewer connections and combining functions to simplify adjustments.

Current Product Example

The piezoceramic cup gyro can be used an example of how these improvements might be applied. See Figure 1.

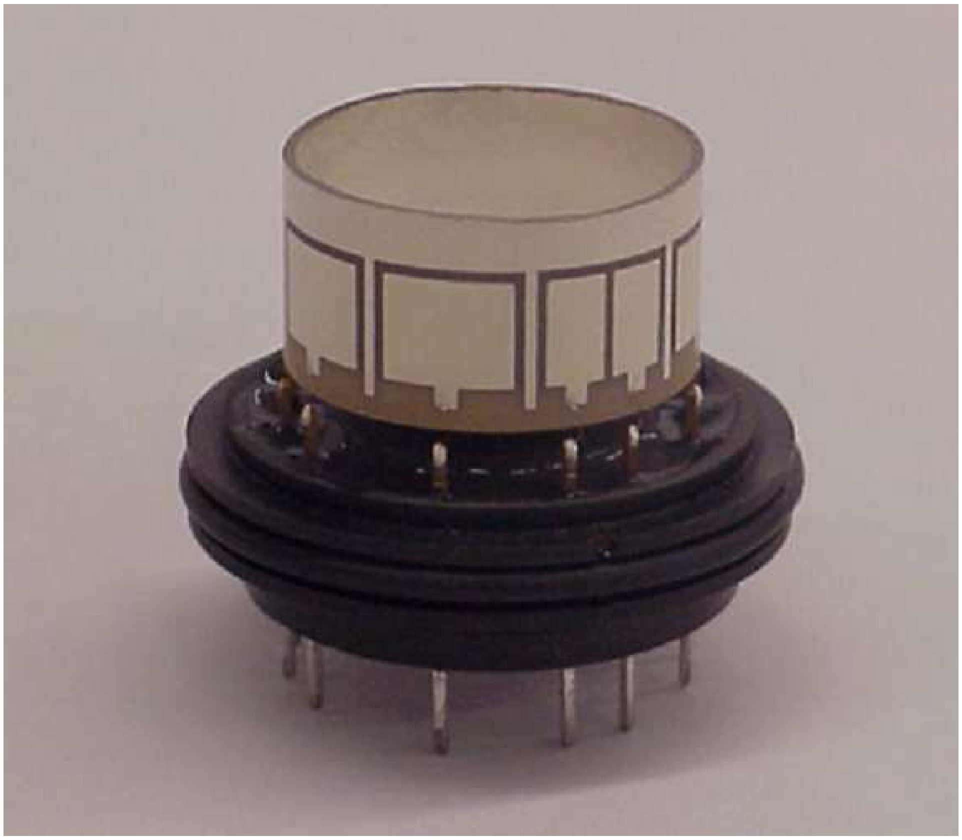

Figure 1. The piezoceramic cup gyro.

This gyro uses the oscillation of the rim between two oval shapes as it primary operational mode (see Figure 2). The nodes see essentially no vibration signal when the gyro is at rest. When the gyro is rotated around its axis of symmetry, the pickoff electrodes that were at the nodes are rotated into the vibration and produce signals proportional to the rotation rate.

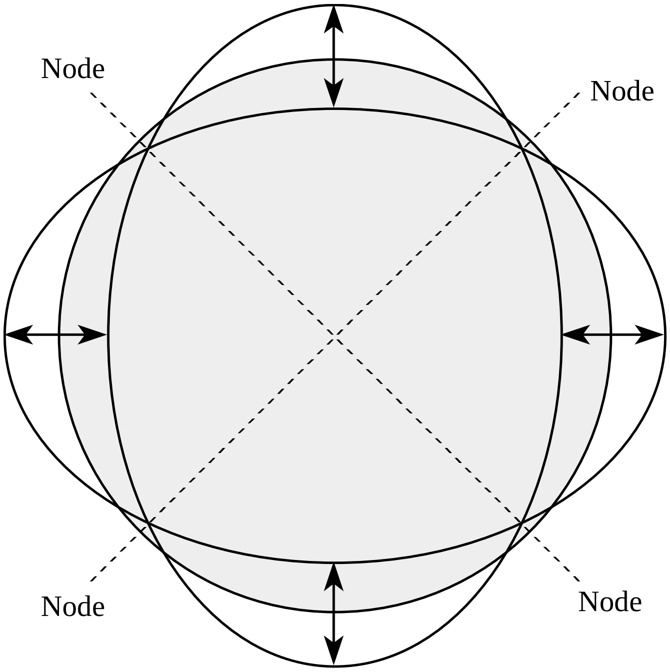

Figure 2. Gyro modes of operation.

The basic functions are achieved by placing 8 electrodes around the circumference of the cup. There are 4 electrodes for the node axes and 4 electrodes for the drive axes. The 2 orthogonal node axes have opposite phase for the rate sense signal, one phase on each axis. The 2 orthogonal drive axes also have opposite phase for the drive signal, one phase on each axis. In this example, however, one electrode on the drive axis is divided (see Figure 3).

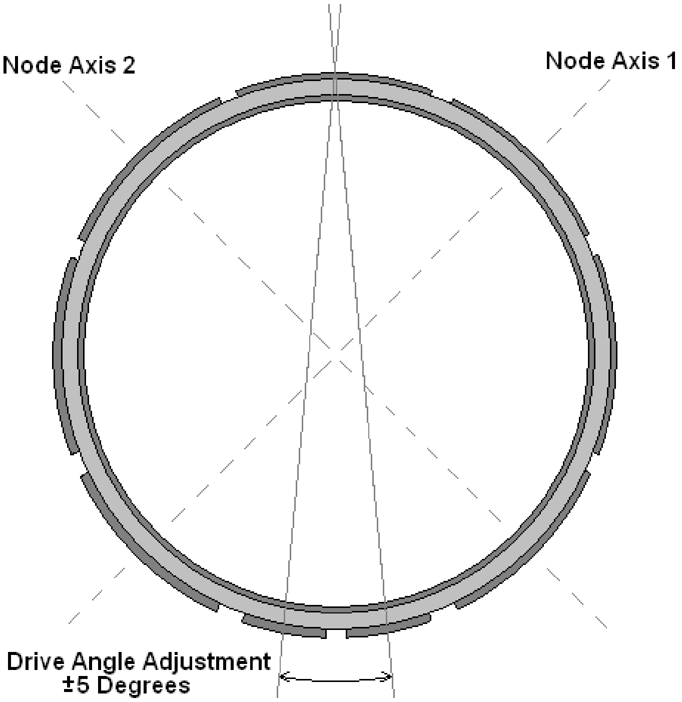

Figure 3. Example of electrode placement.

The split plate pair (lower) and the electrode on the opposite side (upper) are the only driven electrodes used. These electrodes are dedicated to producing the drive motion as an independent function.

The other drive axis electrodes (left and right) are used for drive motion sensing to feed back automatic gain control (AGC) as a control of drive amplitude. These electrodes are dedicated to sensing the drive motion as an independent function and are not available to drive the cup oscillations.

The electrodes on Node Axis 1 are connected together and are used to produce the rotation rate signal as a dedicated and independent function. Likewise, the electrodes on Node Axis 2 are connected together, but they are used to drive a “torquing” force on the cup as a dedicated and independent function.

To use the split plates, the average of the voltages on the two split plates is set to equal the voltage on the upper electrode. By adjusting the ratio of the voltages on the split plates, the vector of the driven oscillation is adjusted by up to 5 degrees in either direction. This is used to compensate for misalignment of the electrodes. This is used for static alignment, not for active torque adjustments. These split plates add complexity that has consequences. There are more connections to be made on the cup, the plates have slightly less effective area and cup symmetry is disturbed.

These split plates are used to allow an electrical solution for electrode printing errors. These and other errors could also be corrected to some degree by using corrective signals from other sensors such as thermistors, or by using EEPROM correction tables or by limiting performance such as using a reduced temperature range. All of these error compensation systems have limitations on their effectiveness. They also increase cost by requiring extra testing and adjustment.

The torque function involves sensing a rotation rate from the Node Axis 1 electrodes, processing that information and driving the cup through the Node Axis 2 electrodes. The torquing signal polarity is set to fight the existing node vibrations and the gain in signal processing is used to set a bandwidth for the overall response of the gyro. This can also be used to control quadrature signals in the sensing system.

Improved Geometry

This proposed changes the approach to the above problems by combining functions where appropriate thus allowing more functionality with less complexity. Adding a small amount of skew or misalignment to the drive electrodes accomplishes the first step in this solution. See Figure 4.

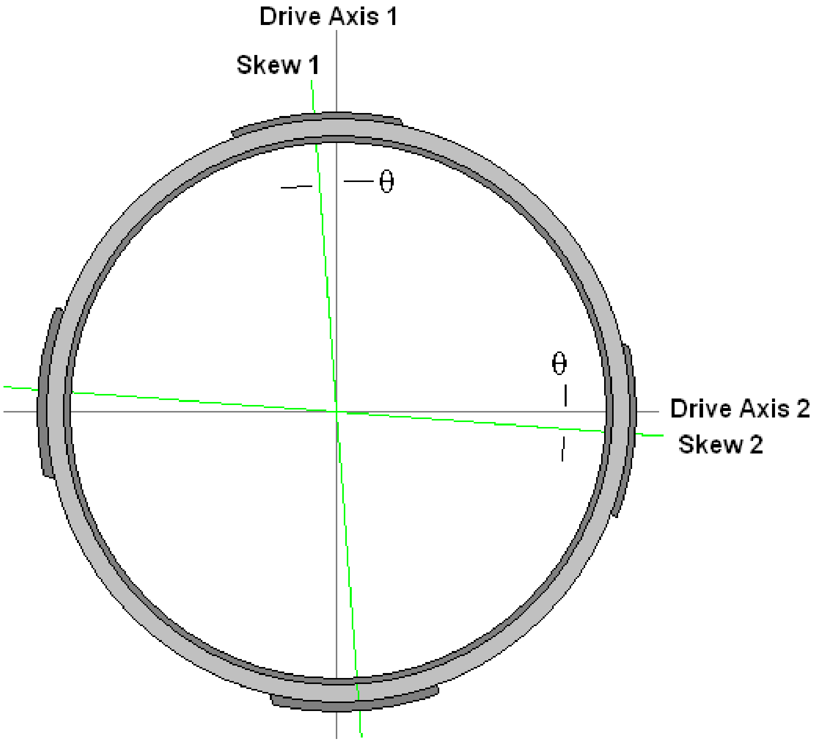

Figure 4. Skewed Drive Electrodes.

In this configuration, all 4 drive axis plates are used to drive the gyro oscillations. This allows more oscillation amplitude for a higher signal to noise ratio and better control of the mode of oscillation. If only the electrodes of one driver axis are used, then most even numbered harmonics (fundamental, 2, 4, 6, 8....) are equally encouraged. When the electrodes of both drive axes are used, with the axes in opposing phase, then fewer harmonics are encouraged (fundamental, 4, 8, 16....).

The skew allows adjustment of the driven oscillation vector. The ratio of the drive voltages for each drive axis is used to adjust drive vector between the two skew angles. This can be used for static alignment or for torquing that vector. If torquing is the objective, the skew will have to be more than enough to overcome the relative shift in the oscillation pattern due to the maximum rotation rate.

The relative shift angle desired can be calculated from the operational parameters. The rate signal vibrations spatially lag the driven vibrations since the sense signals die out with the “Q” of the resonant system. The time it takes these vibrations to die out is the time constant of the sense system and is proportional to the inverse of the bandwidth of the gyro mechanism. The relative shift angle is the amount of rotation that is maintained in one time constant. An equation for the preferred shift angle is then [5]:

$$\phi = \gamma * R_R / (2 * \pi * B_W)$$

Where:

ϕ = the shift angle

γ = the precession constant (= 1 for this example [6])

R_R = the maximum rotation rate range

B_W = the bandwidth of the rate response

For example, if the gyro rate bandwidth is 100Hz and the maximum rotation rate is 200 degrees per second, the skew would be 0.32 degrees.

The skew angle desired needs to be large enough to not require too much drive voltage from the system, thus not risking errors from saturation. A good multiplier would be 2 so that the drive axis that has increased voltage would only be 1.5 times the nominal voltage:

$$\text{Drive Skew: } \theta \sim 2\phi$$

Note that symmetry is maintained in this approach around both Node Axes.

The drive circuitry needed to actively torque this system is shown in Figure 5.

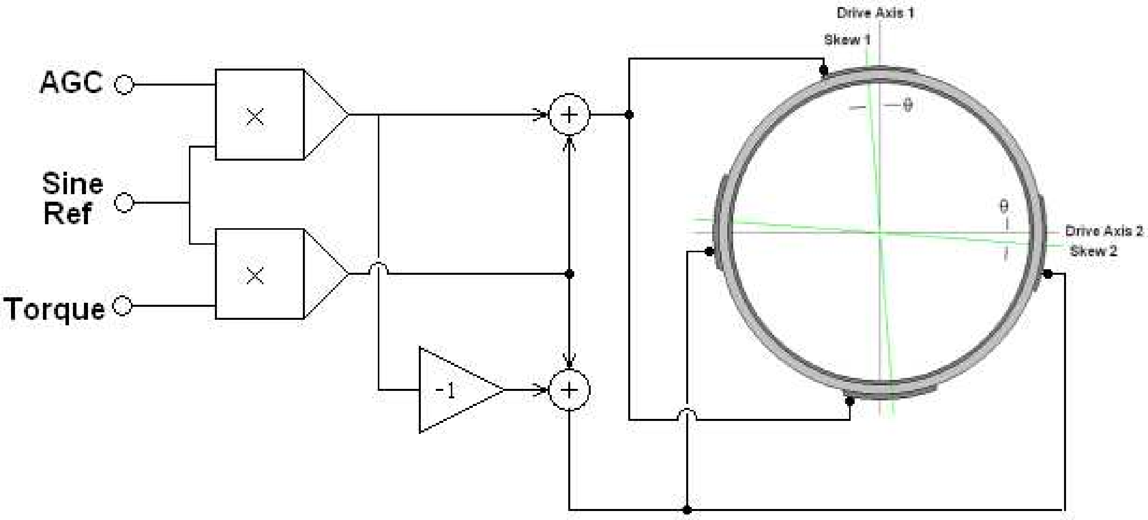

Figure 5. Skew drive plate electronics.

The formulas for the drive vector that this circuit implementation are:

$$V_{D1} = V_T * \text{Sine}(\omega) + V_C * \text{Sine}(\omega)$$

$$V_{D2} = V_T * \text{Sine}(\omega) - V_C * \text{Sine}(\omega)$$

Where:

V_{D1} is the Drive Voltage on Drive Axis 1
V_{D2} is the Drive Voltage on Drive Axis 2
V_C is the Automatic Gain Control Voltage
V_T is the Torquing Voltage Signal
ω is the Drive Reference Frequency

If $V_T = V_C$, then $V_{D2} = 0$ and the drive is along Skew 1 and the drive vector is rotated by $-\theta$ from the nominal orientation. But if $V_T = -V_C$, then $V_{D1} = 0$ and the drive is along Skew 2 and the drive vector is rotated by $+\theta$ from the nominal orientation. Thus the drive vector can be electronically adjusted by the formula:

$$D_\theta = -\theta * V_T / V_C$$

Where:

D_θ is the Drive Vector Angle from the nominal

Application to Node Axes

Another way to use this skew principle is with the node axes electrodes (see Figure 6). The skew angle required is proportional to the relative shift, ϕ, in the oscillation pattern due to the maximum rotation rate. A reasonable skew angle would allow the drive sense signal to equal the rate sense signal at the maximum rotation rate ($\theta \sim \phi$).

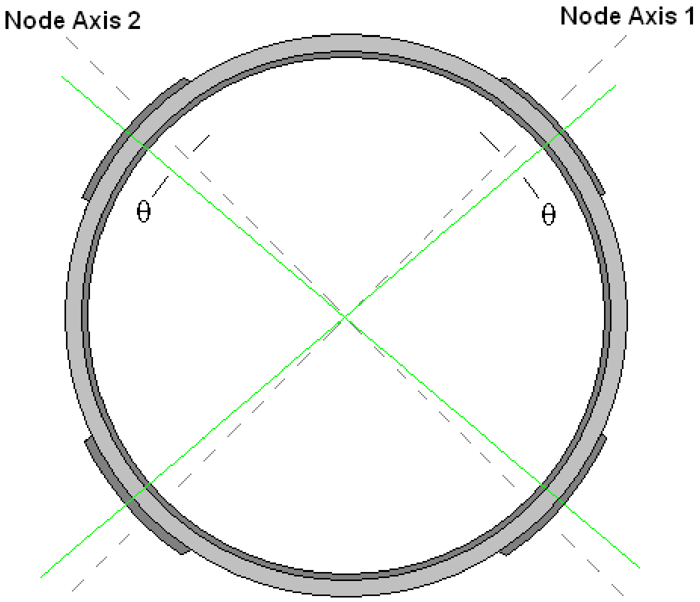

Figure 6. Node axes skewed electrodes.

The signal produced on the sense electrode is proportional to the vibration amplitude at its location. At the node and at rest, this is zero. With the electrode at the drive axis, the signal is that of the full drive vibration. In between these extremes the signal is proportional to the sine of a geometric constant times the angle from the node. In this case (having two node axes) the constant is 2.

$$S_1 = D\ \mathrm{Sine}(2\theta) + DK$$
$$S_2 = D\ \mathrm{Sine}(2\theta) - DK$$

Where:

S_1 = signal from the first sense electrode axis
S_2 = signal from the second sense electrode axis
D = signal for the electrode at the drive axis
θ = skew angle
DK = signal from an angular rate input.

These signals can be combined:

$S_1 - S_2 = 2DK$ = The rate sensing signal.

This can also find the drive motion amplitude by using the common mode of these signals. By adding these two signals as common mode, the rate signal can be nulled for pure drive sensing without adding to the number of connections.

$S_1 + S_2 = 2D(\mathrm{Sine}(2\theta))$ = The drive motion sensing signal.

The two sense electrode axes will not be perfectly aligned in a practical product. The solution is to make slight adjustments in the gain balance between the two sense outputs to compensate the alignment errors. Doing this separately for the rate sense signal and the drive sense signal, they can both be optimized.

The circuit configuration to make use of the sense skew is shown in figure 7 below.

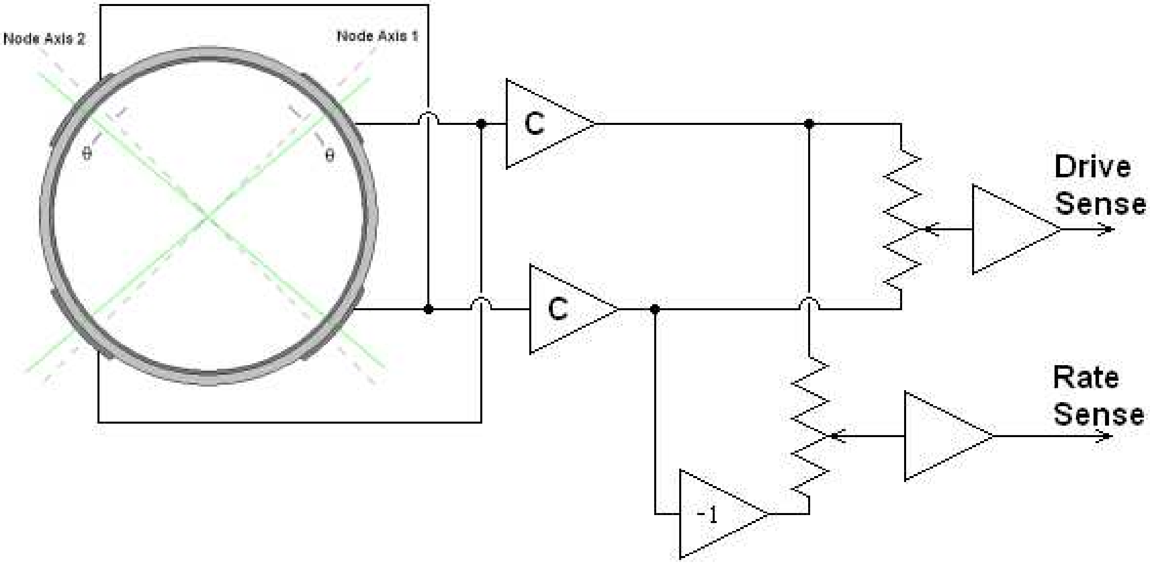

Figure 7. Skew sensing circuitry

To make the drive sense signal independent from the rate sense signal, adjust drive sense to cancel rate signal and adjust rate sense to cancel drive signal.

The advantages for the skewed sense electrodes are an optimized rate sense signal, an optimized drive sense signal, fewer electrode connections for simplicity and greater symmetry for better resonance performance.

The fact that the same electrodes are used to sense rotation rates and drive amplitude means that the gains of both functions will track exactly and the open loop gain will be constant within the limits of the AGC system. Also note that all 4 electrodes are used to produce each sense signal such that twice the signal from the previous design is produced, thus a larger signal to noise ratio.

Application to Other Gyros

These principles can be applied to other gyro configurations such as the silicon ring type, tuning fork type gyros and several others. The requirements to use this method for drive skew is that more than one node must exist. Two or more nodes are required so that the redirected drive energy of one node can be compensated by an equal and opposite action at the other node. However sensing skew will work on gyros with one node such as a tuning fork gyro.

One silicone ring configuration is shown in Figure 8 below. To use this concept, the driving sensing elements (using capacitive or magnetic driving and/or sensing) would be skewed from the ideal orientation by small angles producing the same functions and advantages as shown above.

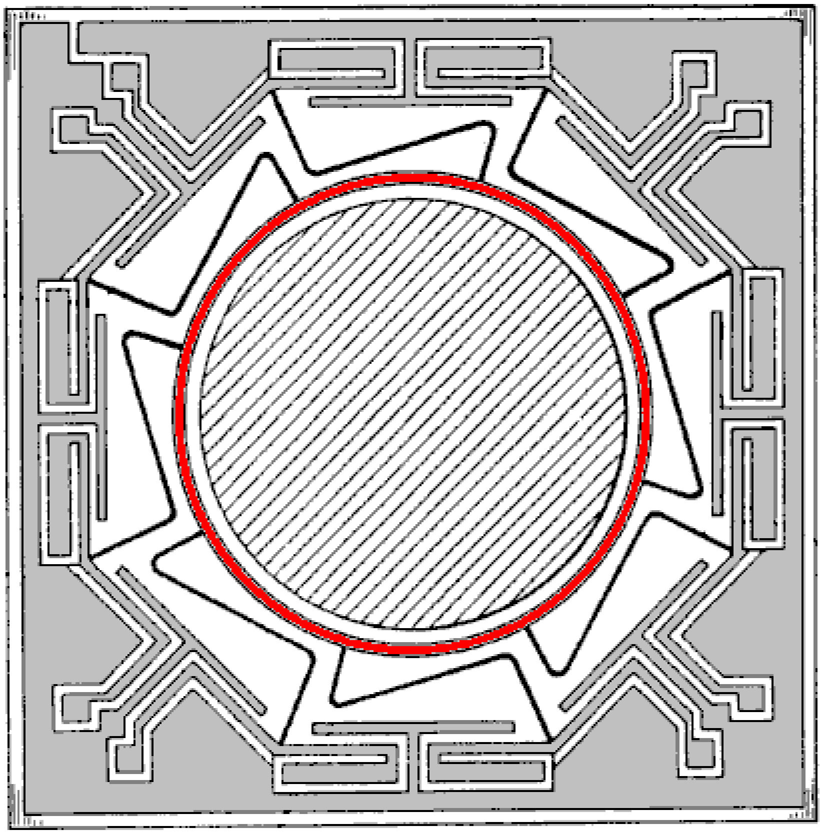

Figure 8. Ring gyro configuration

These skew principles can be used for tuning fork gyros (Figure 9) by adapting the sense mechanism to allow a measured portion of drive motion signal to be added to the rate sense signal as previously shown. As before, the pickoff signals are separately processed for mixing. One requirement is that the resonant frequency of the driven fork oscillations and the rate sensing response are substantially the same.

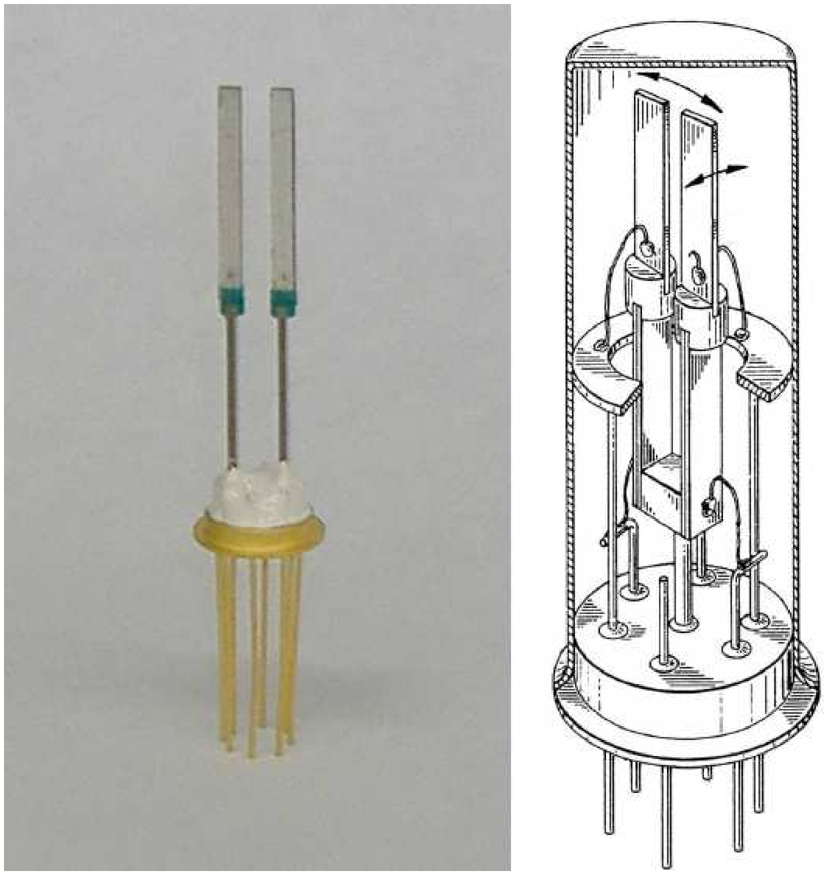

Figure 9. Tuning fork gyros

The tuning fork configuration, see Figure 9, has only one node at the base. As such the drive cannot use the skew features that are used on cups and rings. The two elements at the base are driven by an AC voltage to resonate in opposition as shown as a dotted arrow below. This diagram is a top view of the sense elements.

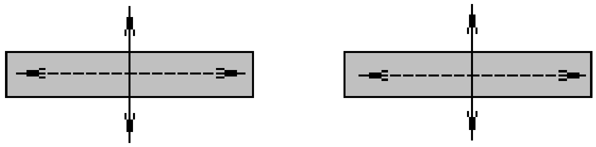

Figure 10. Traditional tuning fork vibration pattern

If the sense elements are skewed slightly, without any skew on the drive elements, the drive vector remains aligned in opposition. The sensitive axes of the sensing, however, are not aligned and will pick up a portion of the drive oscillation along with the signal from rotation rates.

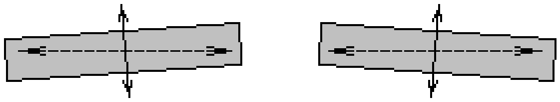

Figure 11. Skewed tuning fork vibration pattern

Subtracting the left element signal from the right element signal will produce a maximum rate signal and cancel the drive signal (gain adjustment will give correct this balance for sensor variations). Adding the two element signals will produce a maximum drive-sensing signal and cancel the rate signal. This is just like the cup and ring configurations in use.

$S_1 = D\ \mathrm{Sine}(\theta) + DK$

$S_2 = D\ \mathrm{Sine}(\theta) - DK$

Where:

S_1 = signal from the first sense electrode axis

S_2 = signal from the second sense electrode axis

D = signal for the electrode at the drive axis

θ = skew angle

DK = signal from an angular rate input.

$S_1 - S_2 = 2DK$ = The rate sensing signal.

$S_1 + S_2 = 2D(\mathrm{Sine}(\theta))$ = The drive motion sensing signal.

MEMS gyros using two oscillating plates moving in opposition can be used with the skew design in much the same way as the tuning fork. This configuration in is current form is shown in Figure 12.

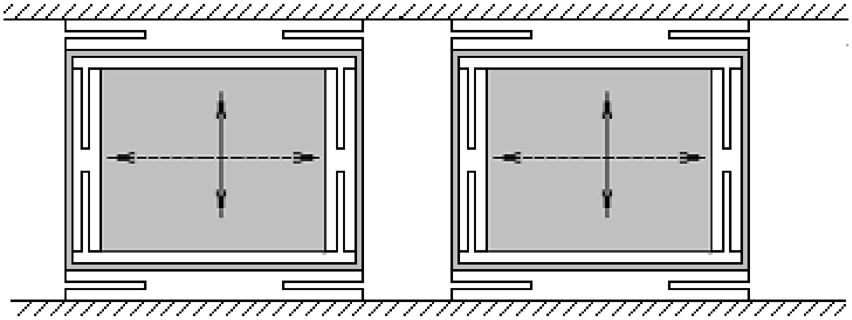

Figure 12. Traditional MEMS gyro vibration pattern

The two plates are driven in linear opposition as shown as the dashed arrow below. The drive mechanism is usually electrostatic attraction/repulsion rather than piezoelectric effects. Traditionally, the sensing mechanism is made as orthogonal as possible in order to get the most pure rate-sensing signal. However, the drive-sensing signal then requires some additional mechanism to be made.

With a skewed sensing system, as in Figure 13, the drive is still made in linear opposition, but the skewed sense mechanism is used to produce both rate sensing and drive sensing.

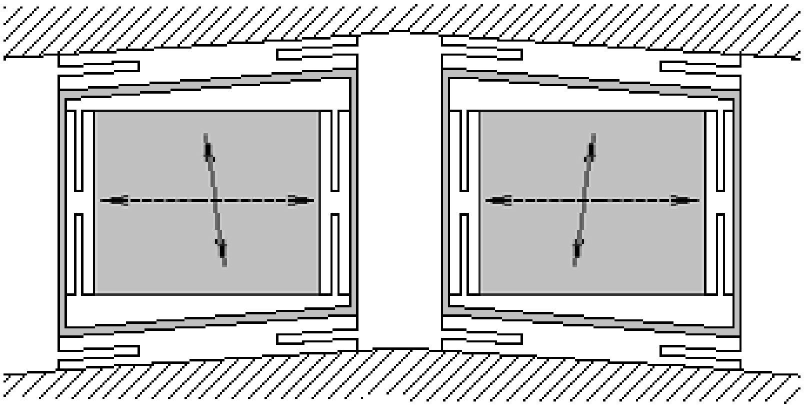

Figure 13. Skewed MEMS gyro vibration pattern

Conclusions

Moving away from total orthagonality in drive and sense mechanisms for a solid state rate gyro can improve signal levels, offer additional means of adjustability, reduce connections, and simplify torquing.

An important feature of this is that the same material and structure is used to detect drive motion as is used to detect rate response. If the material has variations from temperature or age or any other effect, the AGC correcting the drive amplitude and frequency will exactly correct the rate signal as well.

References

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