Vibratory Gyro
Skewed Driver and Pick-off Geometry

William S. Watson
Watson Industries, Inc.
Eau Claire, Wisconsin, USA
wsw@watson-gyro.com

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Abstract

This report is based on recent patent applications by Watson Industries, which are available to the industry through licensing. Essentially, Watson Industries has developed several novel new means of applying and extracting signals for vibratory gyros. The method involves using slight skew in alignment 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 node pickoffs. Additionally, the associated circuitry allows independent electrical adjustment of the sense axis alignment and of the isolation of the drive-sensing signal from the rate-sensing signal. 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. Again all of this is done with minimal connections to the gyro mechanism and while preserving symmetry of the drivers.

Test data and analysis of these results 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 improving performance on an existing gyro product. Design improvements include making fewer connections and combining functions to simplify adjustments. Performance is to be improved by improving the tracking between the drive and torquing loops and by improving electrode utilization.

The gyro under consideration is a cylindrical shape, open on one end and a stem for mounting on the other. It uses the oscillation of the rim between two oval shapes as it primary operational mode (see Figure 1). 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 ideally produce signals proportional to the rotation rate.

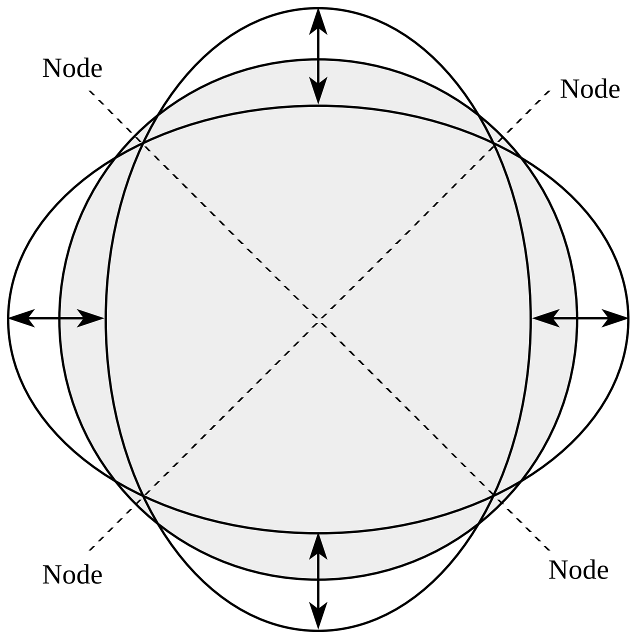

Figure 1. Gyro vibration pattern.

Current Product Example

The gyro to be examined is a piezoceramic cup gyro shown below.

Figure 2. The piezoceramic cup gyro.

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. See Figure 3. The 2 orthogonal node axes have opposite phase signal outputs 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.

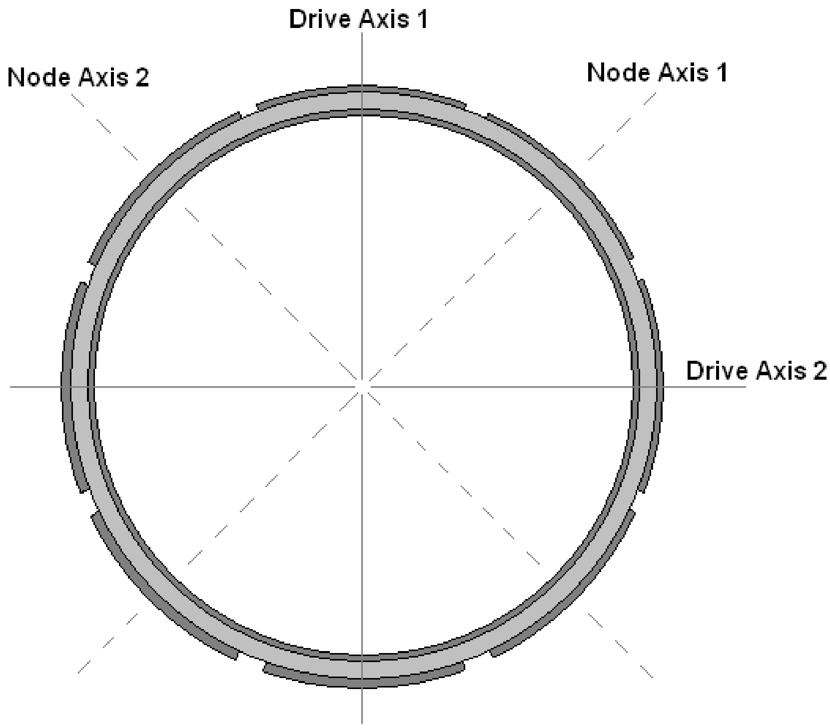

Figure 3. Gyro electrode placement.

The drive axis 1 electrodes (upper and lower) are connected together and 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 connected together and 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 and are used to drive a “torquing” force on the cup as a dedicated and independent function.

This configuration works well and has been commercially available for over a decade. One feature, which has contributed to the success of this product, is that one of the drive electrodes is actually divided into two equal parts. See Figure 4 below.

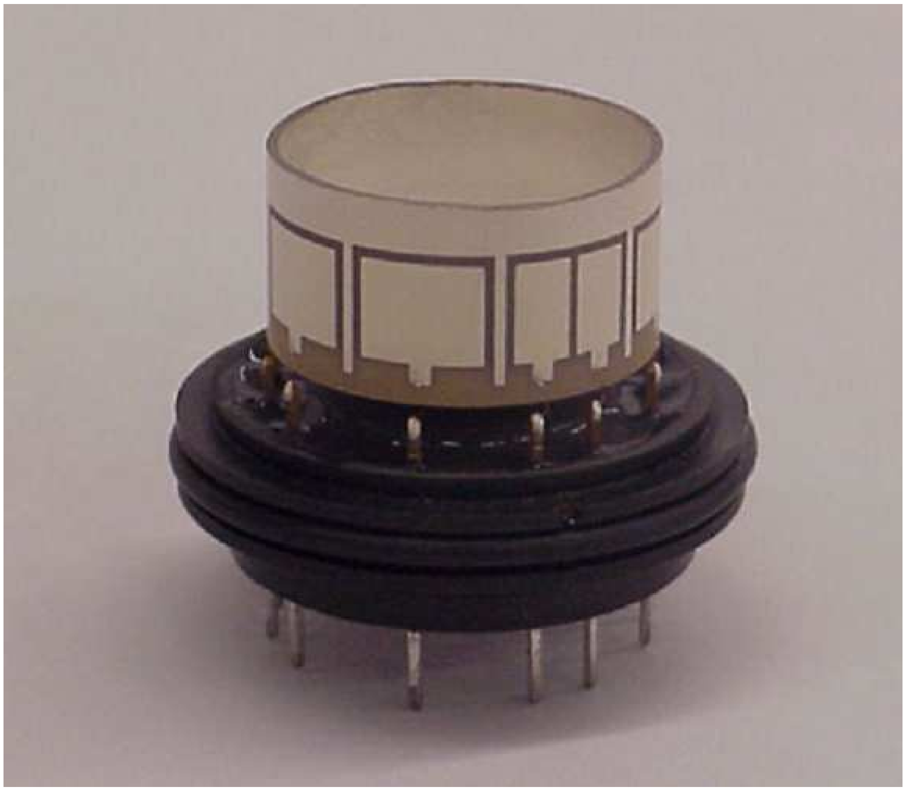

Figure 4. Gyro split electrode.

The function of the split drive electrode is to allow adjustment of the vector of the drive motion. This in turn makes an offset of the node axes. The resulting shift of the rate sense signal is used to adjust the bias of the rate output.

By shifting the amplitude ratio of the drive signal on the two split electrode halves, the axis of the drive motion can be adjusted by almost 3° in either direction. (See Figure 5).

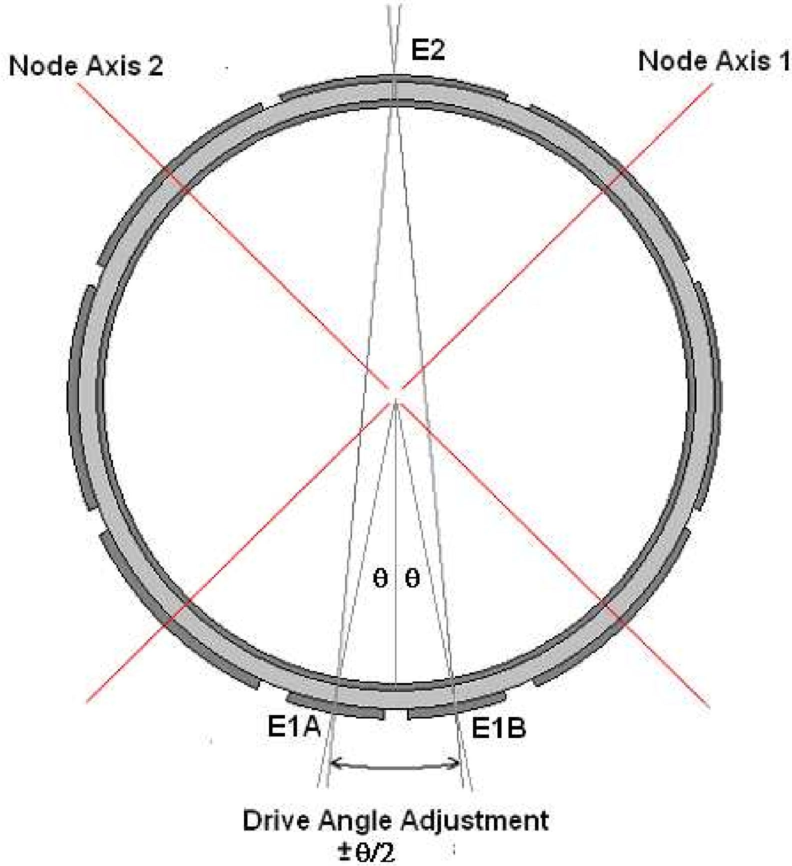

Figure 5. Gyro split electrode geometry.

If $V_{E1A} = V_{E1B} = V_{E2}$, then the $\phi = 0$ and the drive is along the nominal axis. If $V_{E1A} = 2V_{E2}$ and $V_{E1B} = 0$ the drive vector is rotated by $\theta/2$ from the nominal orientation. If $V_{E1B} = 2V_{E2}$ and $V_{E1A} = 0$ the drive vector is rotated by $-\theta/2$ from the nominal orientation. Thus the drive vector can be electronically adjusted by the formula:

$$V_{E2} = (V_{E1A} + V_{E1B})/2$$

$$\phi = \theta\,(V_{E1A} - V_{E1A})/(2V_{E2})$$

Where:

V_{E1A} is the drive voltage on electrode 1A
V_{E1B} is the drive voltage on electrode 1B
V_{E2} is the drive voltage on electrode 2
θ = angle between the centers of E1A or E1B to the axis of symmetry
ϕ is the Drive Vector Angle offset from the nominal

This provides a gyro with typical bias over temperature of ±3°/second and a scale factor over temperature of +1%, -6%. The bias drift is about 1°/hour. Improvements on these properties can be made by re-examining the assumptions that dominated the design.

The Improvement Process

The assumption that drive motion sensing for amplitude control should be made on the drive axis is the first to be challenged.

Looking at the stresses on the cup from the resonance in figure 6, it can be seen that the joint between the side of the cup and the base of the cup along the drive axis is where the highest stresses exist.

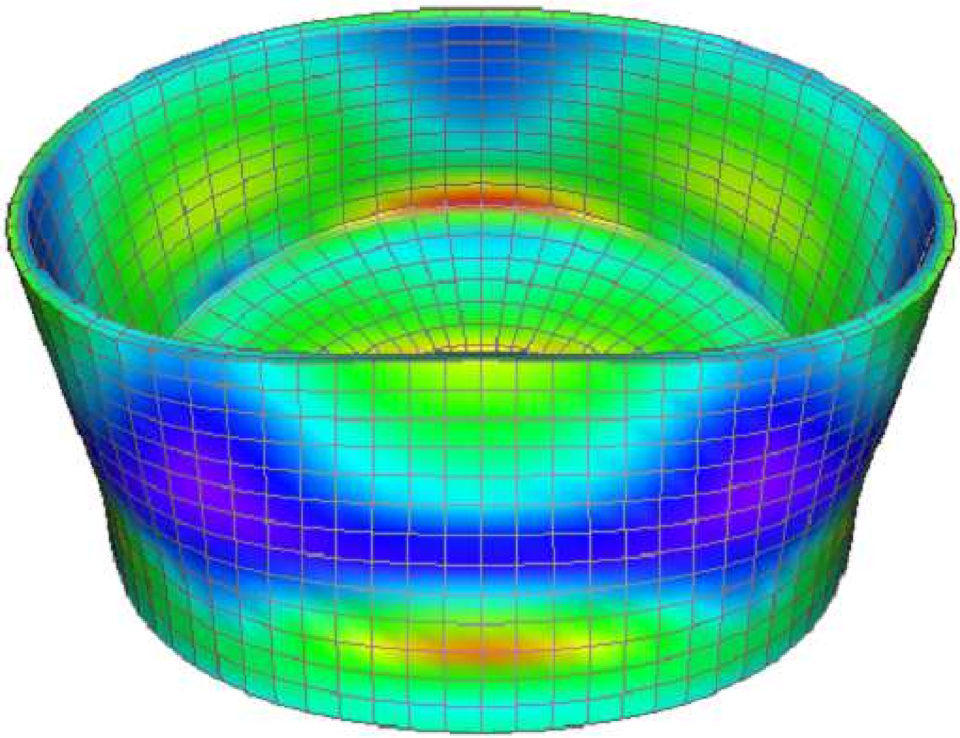

Figure 6. Cup resonance stress pattern.

Looking at the stress and displacement on the drive plane, it is apparent that the highest flexure is at the joint between the side of the cup and the base of the cup also. See Figure 7.

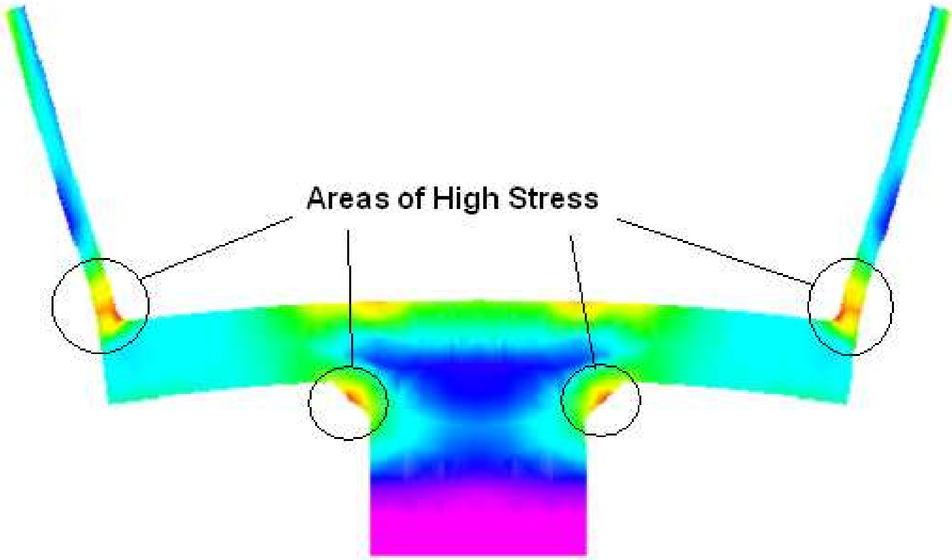

Figure 7. Cup resonance stress pattern and displacement on the drive plane.

This flexure causes localized heating that is small, but significant to the signals of an angular rate. The drive motion sensing at this location receives a very large signal amplitude, but it is not directly related to the signals passed through the angular rate sensing system. Figure 8 shows the stress and displacements on the node plane where the angular rate sensing signals are produced.

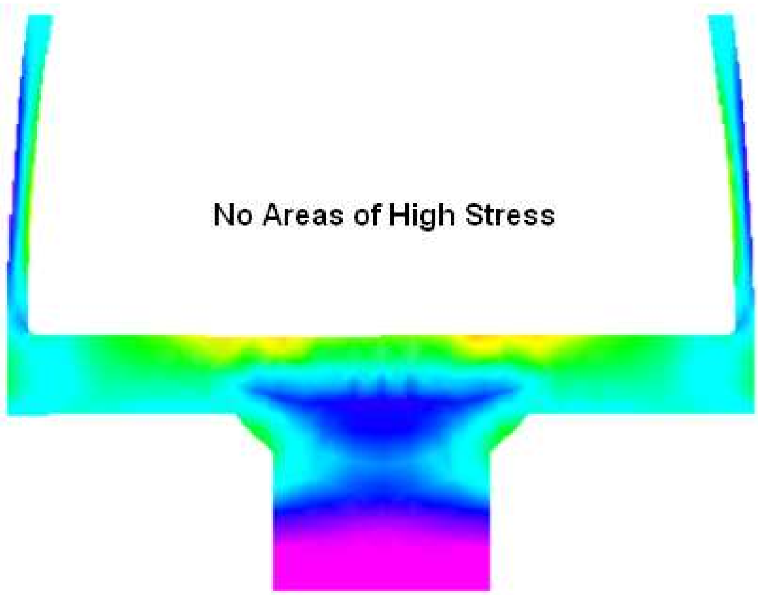

Figure 8. Cup resonance stress pattern and displacement on the node plane.

For signal quality as it relates to the angular rate sensing system, it would be best if the drive motion sensing would be done on the node plane. It is obvious, however, that there is no drive motion detectable right on the node plane by definition. The answer is the drive detection should be done at a small displacement from the nodal plane.

The easiest way to verify this concept is to merely rotate the cup so that the split electrode is across the nodal plane as shown in Figure 9.

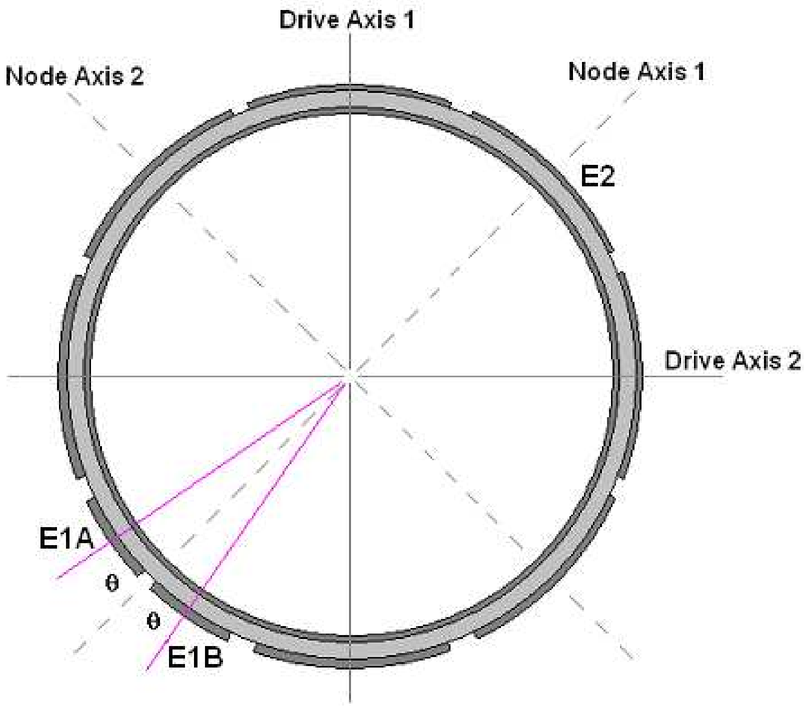

Figure 9. Gyro split electrode in the sense position.

The signals out of this arrangement are:

$S_{E1A} = R_S \cos(\theta) - D_S \sin(\theta) \sim= R_S - D_S\,\theta$

$S_{E2B} = R_S \cos(\theta) + D_S \sin(\theta) \sim= R_S + D_S\,\theta$

Therefore:

$D_S = (S_{E1B} - S_{E1A}) / \theta$

$R_S = (S_{E1A} + S_{E1B}) /2 = S_{E2}$

Where:

S_{E1A} is the sensing signal on electrode 1A
S_{E1B} is the sensing signal on electrode 1B
S_{E2} is the sensing signal on electrode 2
D_S is the drive-sensing signal
R_S is the angular rate-sensing signal
θ is the angle between the centers of E1A or E1B from the nodal plane

In this case, the signal D_S is 30 or 40% of the signal that would be found on the drive axis.

An opportunity is presented by this arrangement because dedicated drive sensing is no longer required. All four electrodes are available for the drive function. The resulting effects from implementing this are:

1) More drive amplitude is available
2) The drive vector angle will be more stable
3) Many more driven harmonics are suppressed

As to the first point, Twice as many electrodes driving will require half as much signal voltage to maintain the same driven amplitude.

For the second point, twice as much electrode area will couple less with individual imperfections of the piezoceramic so that the drive vector will be only half as inclined to be deflected

Finally, the two-electrode drive system allows all even harmonics: two lobes, four lobes, six lobes, etc. etc. Since the drive sense was effectively shorted to ground by the charge amplifier in the two-electrode drive system, odd harmonics are actually encouraged. However, the orthogonal arrangement of four electrodes suppresses odd harmonics and thus allows fewer harmonics.

Tests have confirmed the improvements cited above. Figure 10 shows a reduction in bias magnitude and an increase in temperature range. Figure 11 shows so shows an extended temperature range with improved scale factor stability.

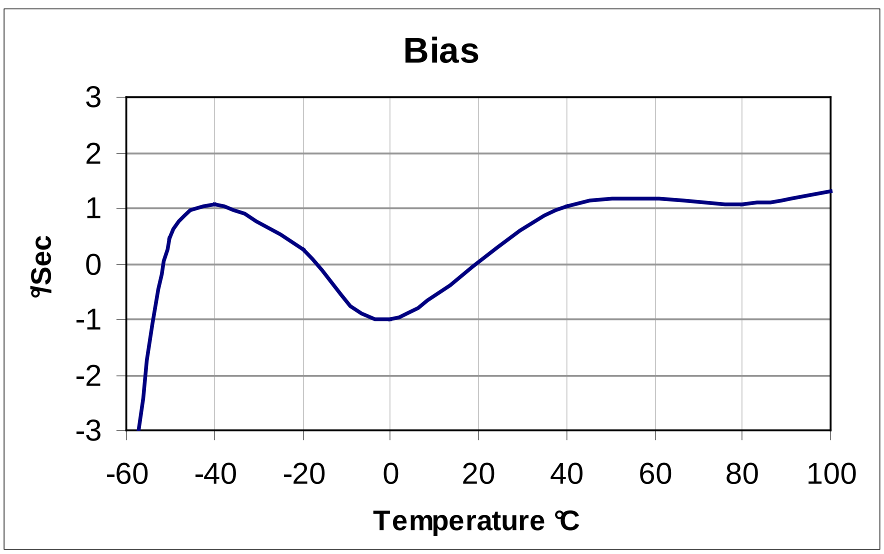

Figure 10. Split electrode bias performance.

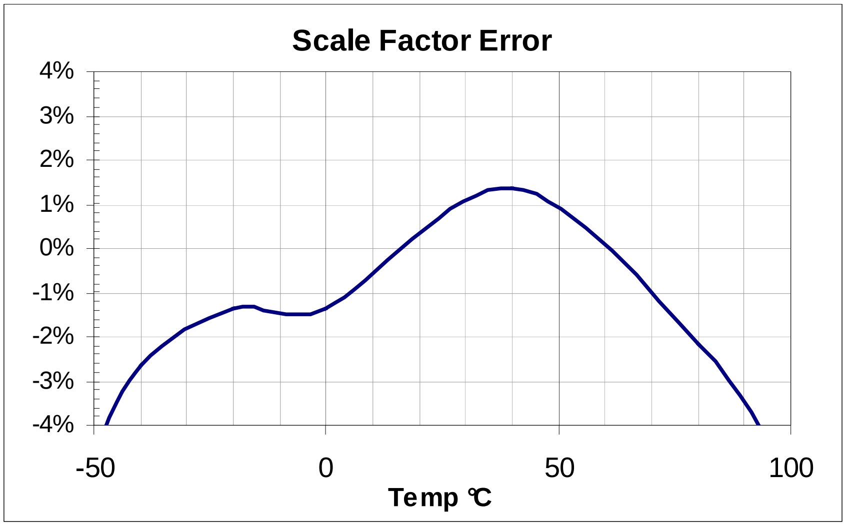

Figure 11. Split sense electrode scale factor performance.

The stability of the drive vector has reduced bias errors and the fact that drive sensing and angular rate sensing share the same electrodes and their variations gives better tracking over temperature. This sharing of sensing electrodes for better tracking is also responsible for the improved scale factor stability.

The next stage in applying these principles would be to establish split electrodes on both ends of the sensing node axis to improve the tracking and sensing area of the drive sensing system. However, this makes a problem in that more connections to the gyro cup which adds to the complexity and cost of the gyro. There is another solution that extends this principle even further while reducing the connections required.

Sense Electrode Skew Implementation

Setting sense electrodes slightly off axis to meet the same effect of the split electrode shown above provides an even better configuration. This skew principle is used on the node axes electrodes shown in Figure 12 below.

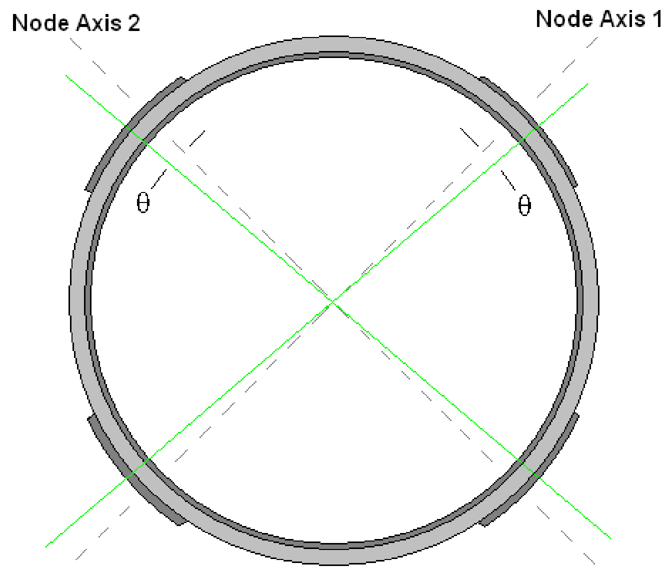

Figure 12. Node axes with skewed electrodes.

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. This is the rate range for an open loop system, but the same applies to the transients of a closed lop system.

For example, if the gyro cup rate bandwidth on the node axes is 100Hz and the maximum rotation rate is 100° per second, the lag o f the vibration vector skew would be 0.16°.

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

Where:

ϕ is the angle of lag in due to rotation rate

γ is the precession constant (= 1 for this example [5])

R_R is the maximum rotation rate

B_W is the rate bandwidth on the node axis

The graph of Figure 13 represents this formula for a rotation rate of one degree per second for a wide range of rates, drive frequencies and damping.

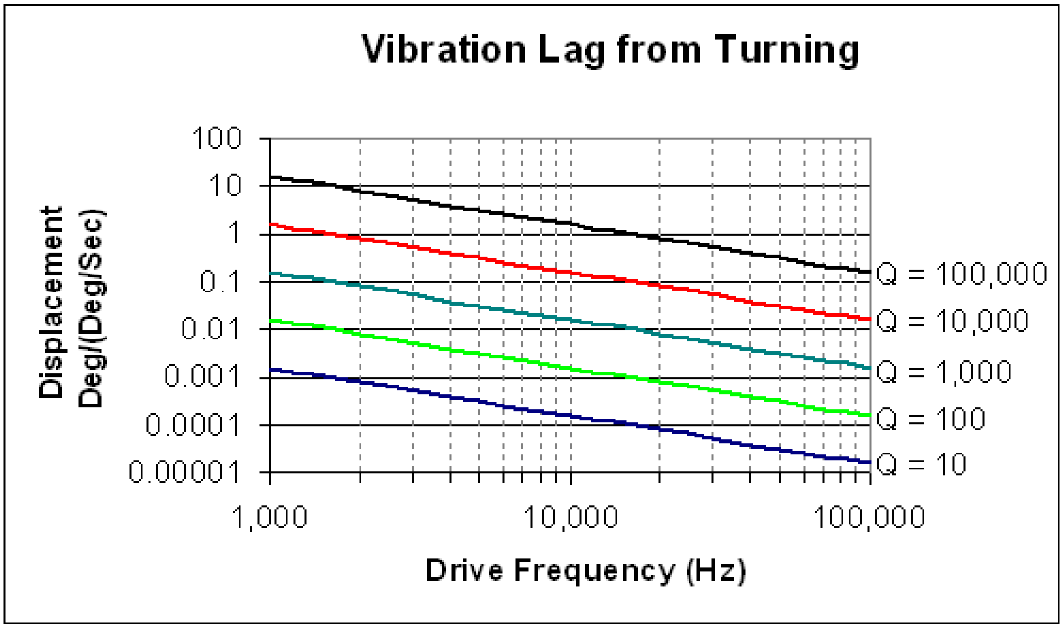

Figure 13. Skew sensing circuitry

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.

$$S_1 = -R_S - D \operatorname{Sin}(2\theta)$$
$$S_2 = R_S - D \operatorname{Sin}(2\theta)$$

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
R_S = signal from an angular rate input.

These signals can be combined:

$$S_2 – S_1 = 2 R_S = \text{The rate sensing signal.}$$

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.

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

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 14 below.

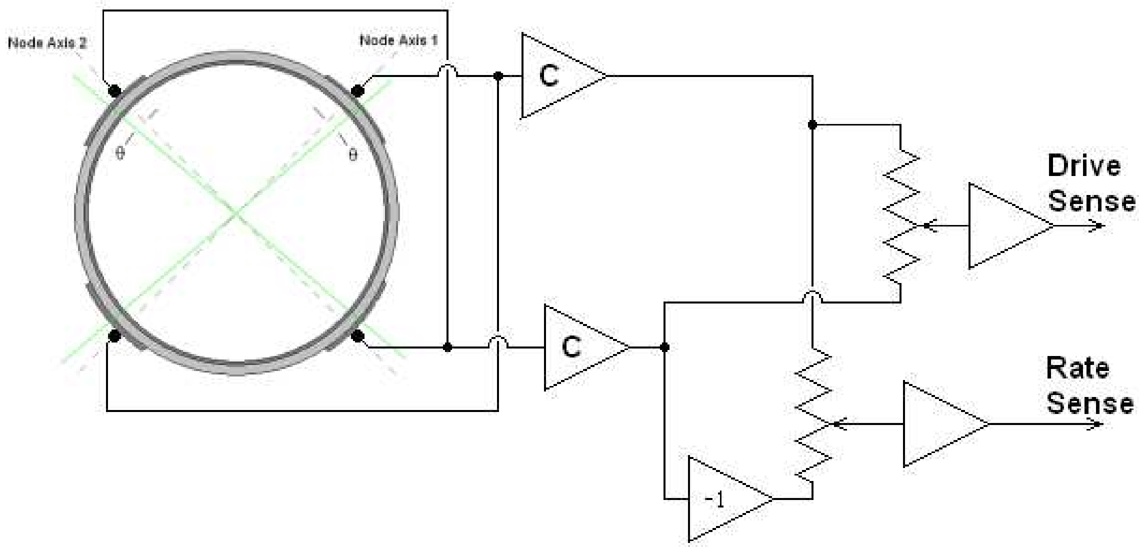

Figure 14. Skew sensing circuitry

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, and 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 and more stable alignment.

Drive Electrode Skew Implementation

Adding a small amount of skew or controlled misalignment to the drive electrodes accomplishes more functionality with less complexity. See Figure 15.

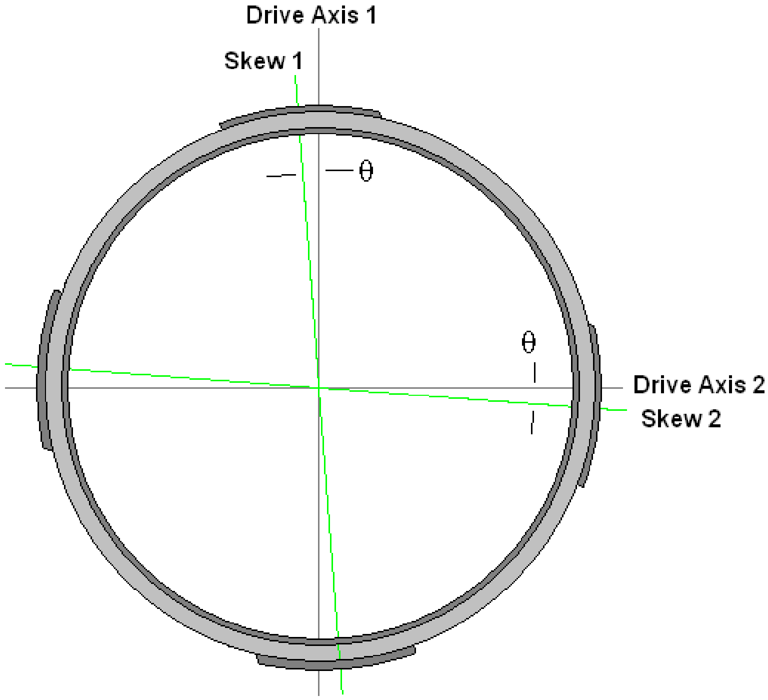

Figure 15. Skewed Drive Electrodes.

In this configuration, all 4 drive axis plates are used to drive the gyro oscillations. As with the split sense electrode configuration, 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, 2, 6, 10....).

The skew adds to this the 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 and temperature effects.

Another advantage is that the same material and structure is used to make drive motion as is used to make torque motion. 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 torque drive as well.

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 [6]:

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

Where:

ϕ = the vibration pattern lag 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

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:

Drive Skew: $\theta \sim 2\phi$

For wide bandwidth gyros, this skew may not be much and might be buried in the tolerance errors of the manufacturing system. For a 100°/second range and 100 Hertz bandwidth, the calculated value of θ is 0.16°. This is too small to hold in some constructions.

The drive circuitry needed to actively torque this system is shown in Figure 16.

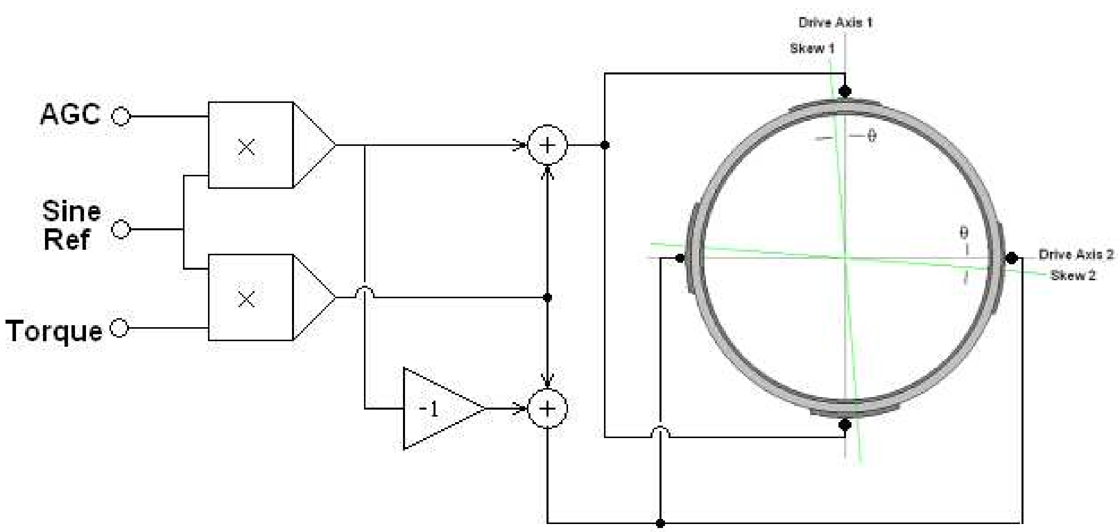

Figure 16. Skew drive plate electronics.

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

$V_{D1} = V_T * \mathrm{Sin}(\omega) + V_C * \mathrm{Sin}(\omega)$

$V_{D2} = V_T * \mathrm{Sin}(\omega) - V_C * \mathrm{Sin}(\omega)$

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 $-\phi$ 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 $+\phi$ from the nominal orientation. Thus the drive vector can be electronically adjusted by the formula:

$$D\phi = -\phi * V_T / V_C$$

Where:

$D\phi$ is the Drive Vector Angle from the nominal

Implementation

These principles have been confirmed in a piecewise manner so far, but products are now in process to establish a complete product, trademarked as Pro Gyro™. Figure 17 shows the resonator built to these requirements. It has 6° of drive skew and 2° of sense skew.

Figure 17. Skew electrode pattern

This cup has been assembled into its supporting circuit as shown below in Figure 18 and finally as a final assembly in Figure 19.

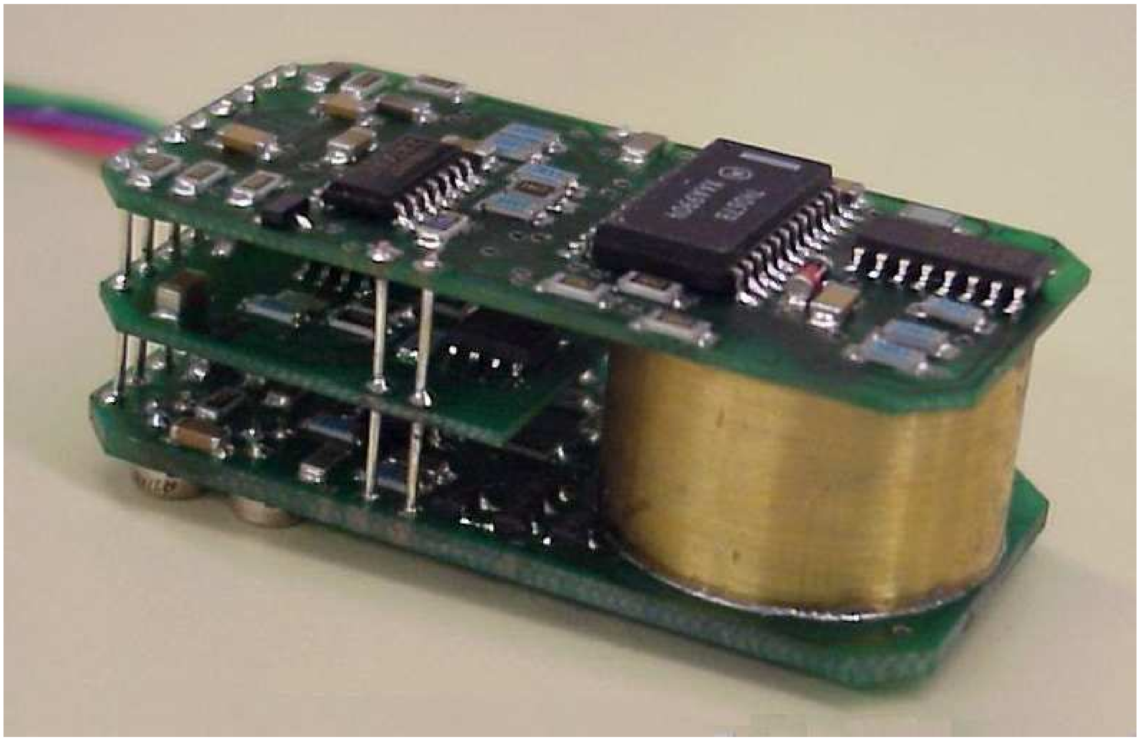

Figure 18. Pro Gyro™ assembly.

Figure 19. Pro Gyro™ product.

Application to Other Gyros

These principles can be applied to other gyro configurations such as the silicon ring type and others. One silicone ring configuration is shown in Figure 20 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.

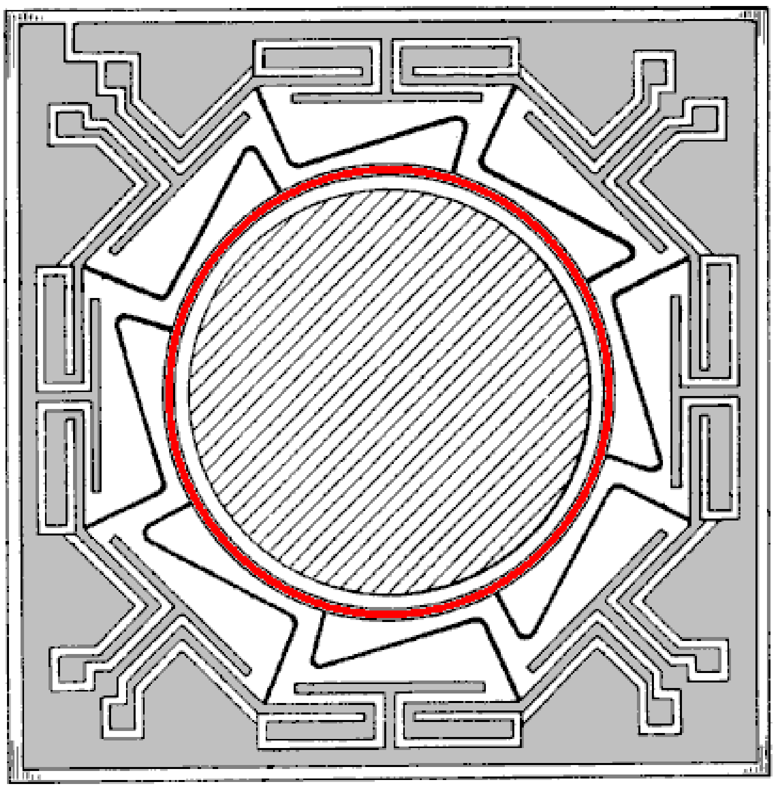

Figure 20. Ring gyro configuration

Conclusions

Moving away from total orthagonality in drive and sense mechanisms for a solid state rate gyro can improve signal fidelity, offer additional means of adjustability, reduce errors, reduce complexity 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.

Likewise, the same material and structure is used to make drive motion as is used to make torque motion. 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 torque drive as well.

References

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