Vibratory Gyro
Skewed Pick-Off And Driver Geometry

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BIOGRAPHY

William S. Watson (M'10) Mr. Watson holds a B. S. degree in Aerospace Engineering from The University of Arizona, 1968. He also took graduate studies in Electrical Engineering from the Virginia Polytechnic Institute.

Mr. Watson founded Watson Industries, Inc. in 1980 to provide low cost angular inertial sensors for commercial and industrial use. The company extended its product range to include magnetometers and sensor systems in 1982. Mr. Watson has been the technology leader in the company throughout its existence. He founded Watson Industries Ltd. in England in 1993 to manufacture similar products and to provide engineering support for the European market. He has authored seven professional papers on gyro technology and holds twenty US patents, predominantly in gyro design.

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 a 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 isolation of the drive-sensing signal from the rate-sensing signal.

The improved driver design also allows electrical adjustment of the drive vector. The design additionally provides a means of applying torque drive and quadrature corrections to the gyro on the same drivers as the operational drive. Again all of this is done with minimal connections to the gyro mechanism while preserving symmetry of the drivers.

INTRODUCTION

Gyro design has been dominated by the opinion that the ideal gyro is made of ideal materials (low loss, high mechanical "Q"), maximum symmetry in its geometry, and isolation of the drive and rate sensing functions [1] [2] [3]. These ideal design characteristics are being compromised regularly in the real world to reduce the 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 instead focus on the constructive application of skewed symmetry and combined functions to the gyro mechanism and the system architectures to improve gyro performance.

The 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 enhanced by improving the tracking between the drive and torquing loops and by increasing electrode interface utilization.

The gyro under consideration is a cylindrical shape, open on one end with 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 where, ideally, they will produce signals proportional to the rotation rate.

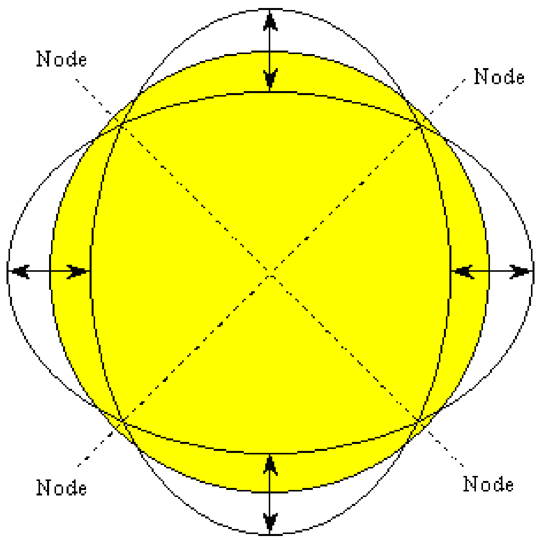

Fig. 1. Primary vibration modes for a cylindrical gyro. Two node axes and two anti-node (or drive) axes are basic to most circular gyro designs.

The system structure typical for a wide range of gyros 1s shown in Figure 2.

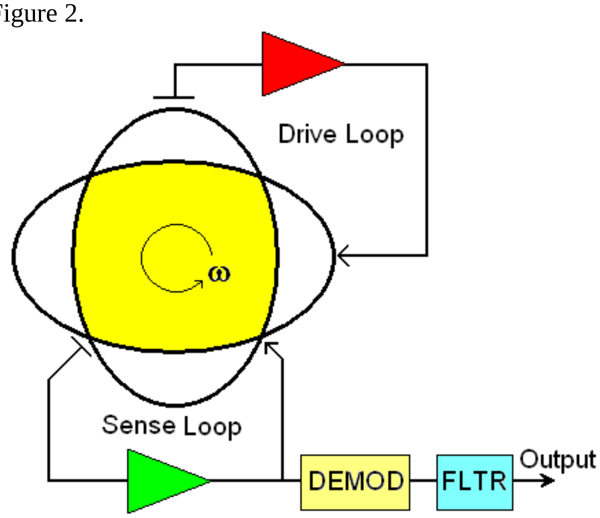

Fig. 2. Typical gyro system. Functional interfaces to the electronics system relies on sensing and driving functions localized to separate node and anti-node axes.

The oscillation drive functions are centered on the anti-node axes and the angular rate sensing functions are centered on the node axes. Rotation is detected when detecting electrodes, which were at the nodes, are moved into the vibrations that were driven on the drive axes. These vibrations are inertial in nature and tend to hold their inertial orientation.

The mechanisms used to drive and to sense these vibrations are usually designed using traditional assumptions from early successful gyros such as the hemispherical resonator gyro (HRG).

The problem is that these driven gyro vibrations are disturbed in their alignment by many things besides the rotations they are intended to measure. This paper addresses alternative and unusual designs of the electrode interfaces and the circuit design required to implement new and improved electrode arrangements.

INITIAL CONCEPT

CURRENT PRODUCT EXAMPLE

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

Fig. 3. Vibrating Structure Gyro. This piezoelectric gyro was a production item made by BAe Systems.

This gyro is made of a solid piezoceramic, precision ground in the shape of a cup with eight electrode areas for driving and sensing. The eight electrodes around the circumference of the cup achieve these basic functions. There are four electrodes for the node axes and four electrodes for the drive axes. See Figure 3. The two orthogonal node axes have opposite phase signal outputs for the rate sense signal, one phase on each axis. The two orthogonal drive axes also have opposite phase for the drive signal, one phase on each axis.

As shown in Figure 4, one electrode area is split in two. 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.

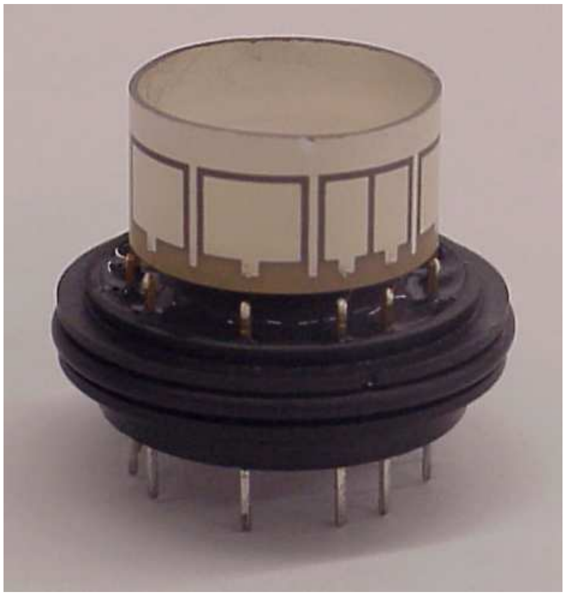

Fig. 4. Split electrode. This exception to the symmetry allows a special adjustment function.

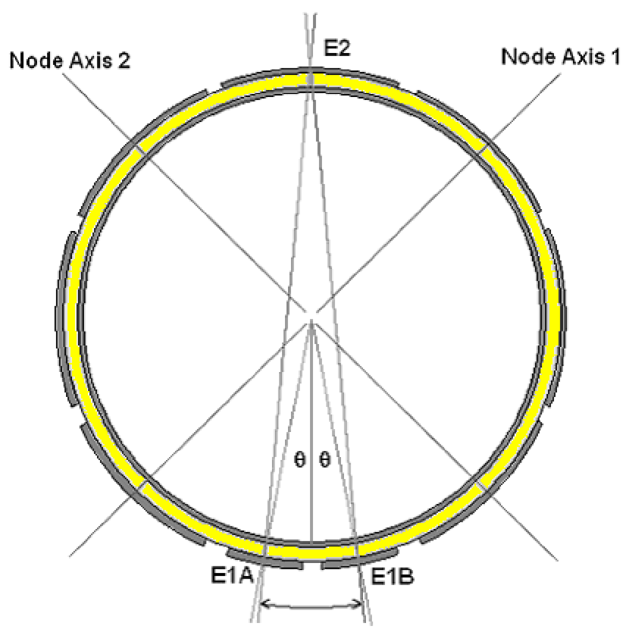

Fig. 5. Split electrode drive geometry. Adjusting the amplitude ratio of the drive voltages on E1A and E1B, the drive vector can be adjusted by ± θ/2.

By shifting the amplitude ratio of the drive signals on the two split electrode halves, the axis of the drive motion can be adjusted by almost 10° in either direction. See Figure 5.

RECONFIGURED GYRO

The first concept tested was to rearrange the functions to provide better utilization of the electrodes. By moving the function of the split electrode from the drive axis to the node axis, it becomes a source of detection for the drive signal and the rate signal. See Figure 6. This frees up the second drive axis electrodes to be used as additional drivers. With four drivers instead of two, the drive function is averaged over twice the area so the influence of any imperfections is cut in half. This increases the stability of the effective drive axes.

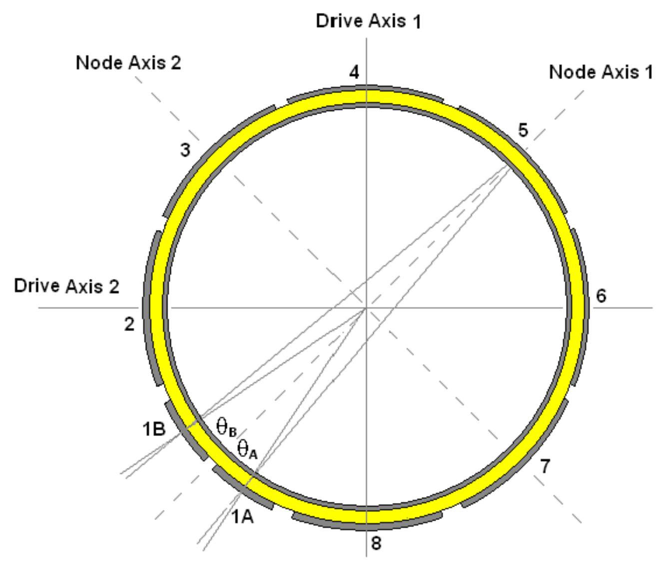

Fig. 6. Split electrode sensing geometry. Rearranging the electrodes provides new opportunities.

In Figure 6, the signals from electrodes 5 and 1A and 1B were added together as the rate sensing signal. The difference of the signals from electrodes 1A and 1B was used as drive motion sensing. The torquing function remained as before, applied to electrodes 3 and 7. The signals from the split electrodes are defined as:

$$V_{1A} = R_S COS\ (2\theta) + D_S SIN\ (2\theta)$$
$$V_{1B} = R_S COS\ (2\theta) - D_S SIN\ (2\theta) \qquad (1)$$

Therefore:

$$R_S \propto V_{1A} + V_{1B} + V_5$$
$$D_S \propto V_{1A} - V_{1B} \qquad (2)$$

Where:
V_{1A} = The output of electrode 1A
V_{1B} = The output of electrode 1B
V_5 = The output of electrode 5
R_S = The rate sensing signal
D_S = The drive motion sensing signal

As expected, an improvement in bias stability over temperature was obtained as shown in Figure 7. The improvement observed was more than a factor of two better than the original design due to increased drive axis stability.

One unexpected effect discovered was the increase of the useful temperature range from –30 °C to +60 °C to more than -40 °C to +85 °C.

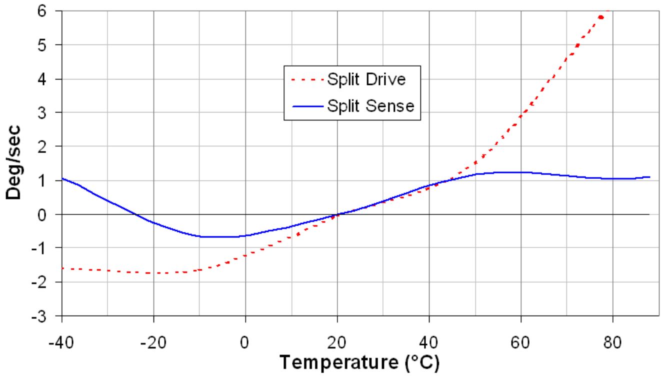

Fig. 7. Bias improvement. Improved drive electrode utilization reduces vibration alignment disturbances for better bias performance.

Another unexpected improvement was found in stability of the scale factor over temperature. See Figure 8. The improvement was a factor of three better than the original design.

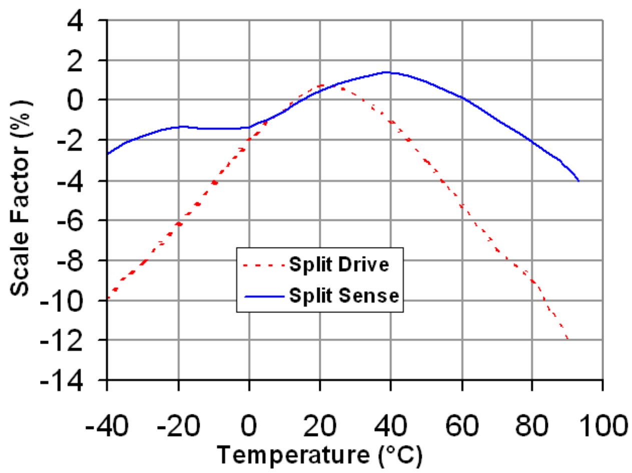

Fig. 8. Scale factor improvement. This is a result of moving the drive sensing away from the high stresses of the drive axis.

Analysis showed that the environment of the drive-sensing signal when taken on the drive axis is significantly different from that of the node axis region. In the split drive configuration, the drive flexure produced local heating and work softening of the cup material (see Figure 9). As a result, the drive-sensing signal, which is used to regulate the amplitude of the signals that migrate to the rate sensing system, is dissimilar to the rate sensing signal. They do not track in gain, so the scale factor of the system is degraded.

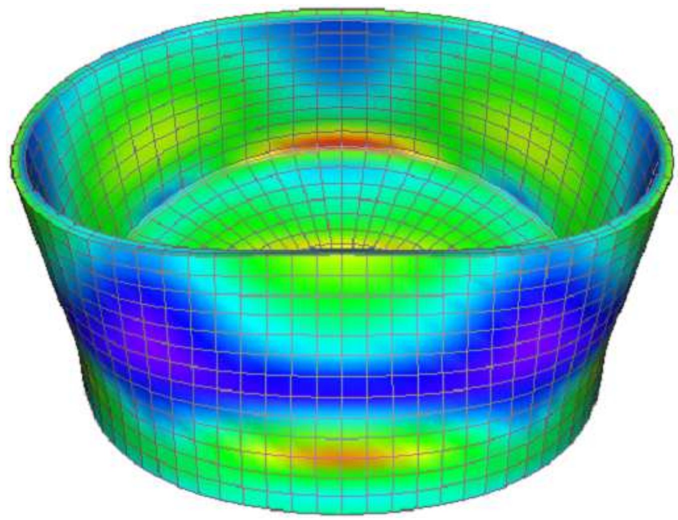

Fig. 9. Stress patterns of the vibrating cup. Flexure and local heating change the drive axis interface from the node axis interface.

EXTENDED CONCEPT

SENSING SYSTEM

It is essential that angular rate sensing should be based at the node axes and the results above indicate that the drive sensing should also be in proximity of the node axes. Applying both functions as above could be done with four sets of uniformly distributed split electrodes, but this would require many more connections. Another approach is to have one electrode per node in opposing pairs with each pair skewed in opposite directions as shown in Figure 10.

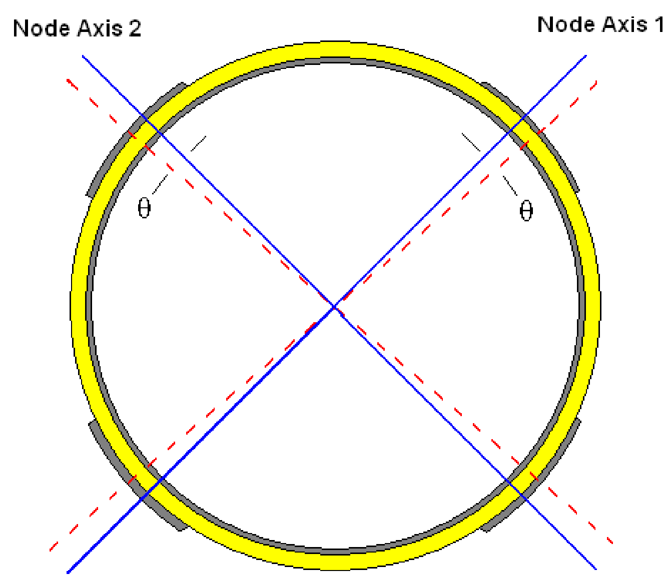

Fig. 10. Skewed sensing. Symmetry is maintained about both drive axes.

The signals from such an electrode arrangement can be trigonometrically defined as follows:

$$V_1 = D_S\,SIN\,(2\theta) + R_S\,COS\,(2\theta)$$
$$V_2 = D_S\,SIN\,(2\theta) - R_S\,COS\,(2\theta) \qquad (3)$$

Where:
V_1 = The output of electrodes on node axis 1
V_2 = The output of electrodes on node axis 2

Then for small angles:

$$V_1 \approx 2\theta D_S + R_S$$
$$V_2 \approx 2\theta D_S - R_S \qquad (4)$$

Then:

$$R_S \approx (V_1 - V_2)/2$$
$$D_S \approx (V_1 + V_2)/(4\theta) \qquad (5)$$

These equations are true in principle, but in a real world of tolerances and misalignment, errors will contaminate the isolation between the drive sense and rate sense signals. To compensate for this, adjustment is added to the system by tweaking the gain of the output of the electrodes as shown in Figure 11.

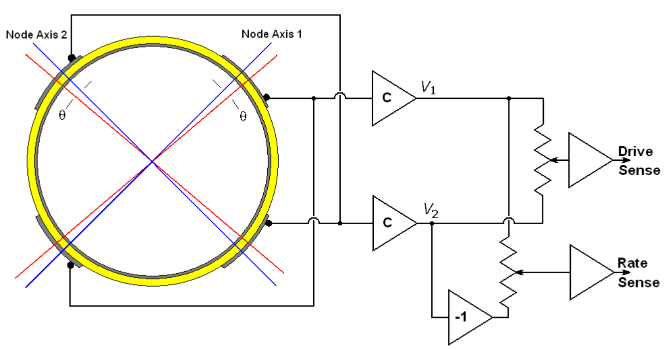

Fig. 11. Skewed sensing system. Rate sense and drive sense are adjusted to make them orthogonal.

The sense skew angle used has two main considerations. First, the drive sense signal needs to be reasonably small so that environmental variations affecting each electrode slightly differently will not unreasonably disturb the rate sensing signal. Some compromise is already being made along these lines in that current designs use a node-sensing electrode larger than zero width for sensitivity. The two extreme edges of such an electrode would have a nearly equal drive-sensing signal; the amplitude would be proportional to the sine of twice the angle from the node and opposite polarity. The two edge signals virtually cancel each other out leaving the rate-sensing signal essentially free of the drive-sense signal. Since four electrodes are utilized, the removal of some of the electrode on one edge of each electrode can be afforded without harming overall sensitivity. The result is merely moving the cancellation of the drive-sense edge signals to the electronics where the balance can now be adjusted optimally.

The second consideration is the integrity of the drive-sense signal. The drive-sense signal needs to be larger than the rate-sense signal such that errors in balance do not allow the rate-sense signal to harm performance of the drive system. The exact optimal skew depends on the gyro configuration and specifications and is to be done in coordination to the drive system.

DRIVE ELECTRODE SKEW IMPLEMENTATION

Much like the sensing system, skew can be used to make the drive electrodes multifunctional and more efficient. See Figure 12.

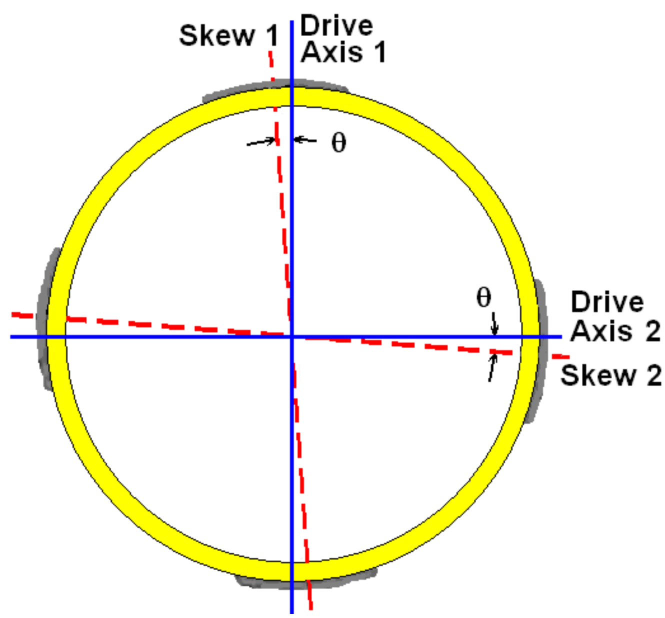

Fig. 12. Skewed drive electrode geometry. Symmetry is maintained about both node axes.

In this configuration, all four drive axis electrodes are used to drive the gyro oscillations. As with the split sense electrode configuration, this allows more oscillation amplitude per drive voltage for a higher signal to noise ratio and better control of the mode of oscillation. If only the electrodes of one drive axis are used, then most even numbered harmonics (2, 4, 6, 8...node axes) are equally encouraged. When the electrodes of both drive axes are used, with the axes in opposing phase, then fewer harmonics are encouraged (2, 6, 10.... node axes).

If the drive voltage were applied to only skew axis 1 electrodes (V_{D1} SIN(ωt)) the vibration pattern would be displaced counterclockwise by the angle θ. Likewise, drive voltage on skew axis 2 electrodes (V_{D2} SIN(ωt)) would displace the vibration pattern clockwise by the angle θ. Remembering the drive axis 2 polarity is opposite from drive axis 1, the vibration pattern displacement (D) follows this equations:

$$D = \theta \frac{(V_{D1} + V_{D2})}{(V_{D1} - V_{D2})} \quad (6)$$

This is embodied in Figure 13 as a system of drive controlled by the system automatic gain control (AGC) and the torquing signal (T).

$$Drive_1 = V_{D1} SIN(\omega t) = (T + AGC) SIN(\omega t)$$
$$Drive_2 = V_{D2} SIN(\omega t) = (T - AGC) SIN(\omega t) \quad (7)$$

Therefore:

$$D = \theta \frac{T}{AGC} \quad (8)$$

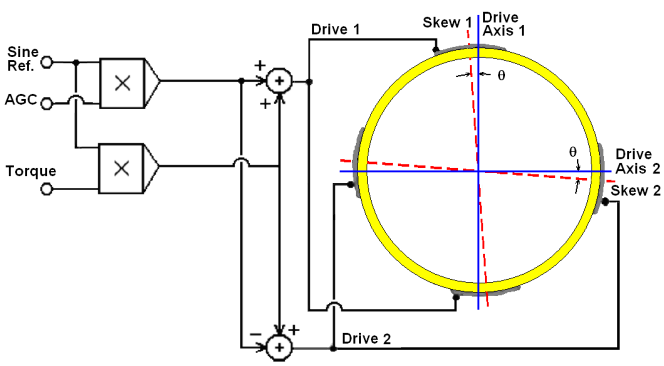

Fig. 13. Skewed drive system. Electronic signal mixing makes more effective use of the electrodes.

The appropriate amount of drive axis skew depends on the maximum rate range and the properties of the gyro mechanics. As an example, consider the example in the Initial Concept Section above. This device has a bandwidth (B_W) of 100 Hz. With a maximum angular rate (R_{MAX}) of 500 °/s, the maximum driven vibration displacement is:

$$D_{MAX} = \gamma \frac{R_{MAX}}{2\pi B_W} = \frac{500\ °/s}{638\ rad\ /\ s} = 0.8° \quad (9)$$

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

A working example of this is shown in Figure 14. The figure is a piezoceramic cup with active patches skewed 6° for drive and 2° for sensing.

Fig. 14. An example of skewed electrode placement. The drive electrodes are skewed by 6° and the smaller node electrodes are skewed by 2°.

Because some over range is appropriate and because such a small angle is at best difficult to maintain in light of tolerances, a higher skew angle is appropriate.

QUADRATURE ADJUSTMENT SYSTEM

The overall system resonance will be roughly the average of the natural frequencies of the two drive axes such as is shown in Figure 15, below. If left as is, this mistuning would produce a quadrature signal at the rate-sensing signal [6]. This is compensated by detecting this quadrature in the rate sensing and feeding a quadrature phase signal to the dedicated torquing electrodes, thus actively correcting any mistuning over a wide range of conditions.

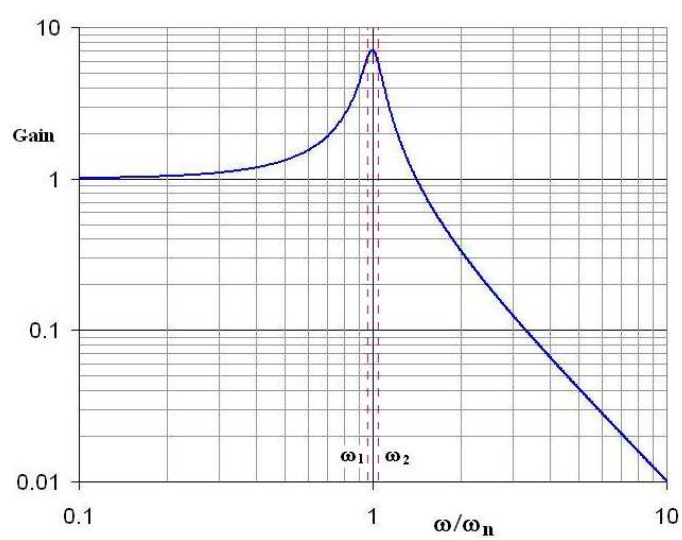

Fig. 15. Gyro resonance amplitude response. A resonant system can be driven off its natural frequency with some loss of

gain.

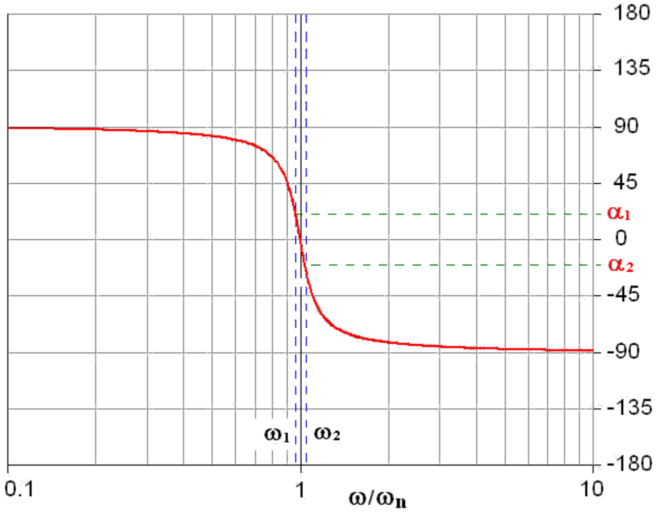

Fig. 16. Gyro resonance phase response. A resonant system has a definite phase consequence to being driven off of its natural frequency.

Each drive axis can be stimulated to run the system at the central frequency by off-setting the phase of the drive voltage. The two specific phases that are required for this effect are derived from the natural resonances of their respective axes, ω_1 and ω_2. The phase shifts required from figure 16 are α_1 and α_2.

Historically, this has been done using torquing electrodes, which are separate from the drive electrodes. Since the four drive electrodes are now available for driving and torquing, it is a similar step to use these electrodes for adjusting out small tuning errors.

The answer to this problem is to drive each axis at an appropriate phase to compensate for the tuning error in its axis. This can be done as a preset signal or as a closed loop active correction system. Either case depends on mixing signals trigonometrically.

$$Drive_1 = V_{D1} SIN(\omega t - \alpha)$$
$$Drive_2 = V_{D2} SIN(\omega t + \alpha) \qquad (10)$$

Where:

$$SIN(\varpi t \pm \alpha) = COS(\alpha) SIN(\omega t) \pm SIN(\alpha) COS(\omega t) \qquad (11)$$

For small phase adjustment this is equivalent to:

$$SIN(\varpi t \pm \alpha) = SIN(\omega t) \pm \alpha COS(\omega t) \qquad (12)$$

Therefore:

$$Drive_1 = (T + AGC) SIN(\omega t) + \alpha COS(\omega t)$$
$$Drive_2 = (T - AGC) SIN(\omega t) + \alpha COS(\omega t) \qquad (13)$$

This is implemented as a system as shown below in Figure 17 as a complete and final driver design.

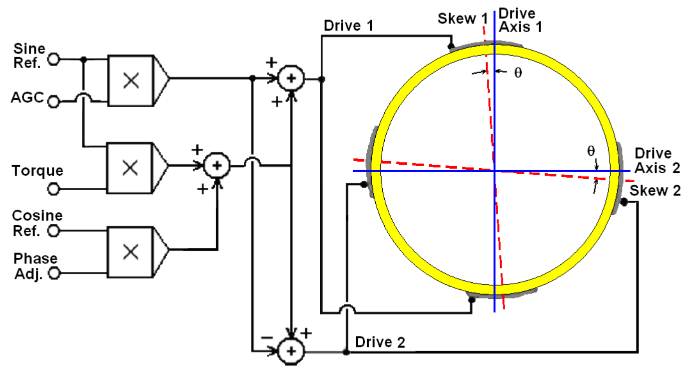

Fig. 17. Complete skew driver system. All three functions make full use of all four drive axis electrodes.

The traditional gyro system diagram is shown below in Figure 18.

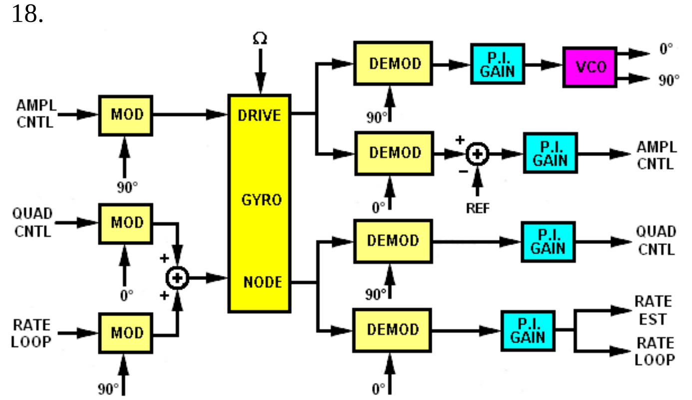

Fig. 18. Complete traditional Coriolis rate gyro system. This form favors symmetry and isolation of functions[6].

This implementation of the skewed drive and sense systems results in subtle, but definable changes to the traditional gyro system. There are now two drive outputs into or near the drive axes and two sensing inputs at or near the node axes as shown in Figure 19 below. The change is the inclusion of "mixing" functions to sum and difference the signals passing through. This brings the function of adding energy to the vibration for the gyro to the drive axes only and the detecting of vibration patterns to the node axes only. In this way the flow of signals for both the drive loop and rate loop pass through the same path, using the same electrodes, from the drive axes to the node axes. Effects from temperature and warm-up should then be better compensated.

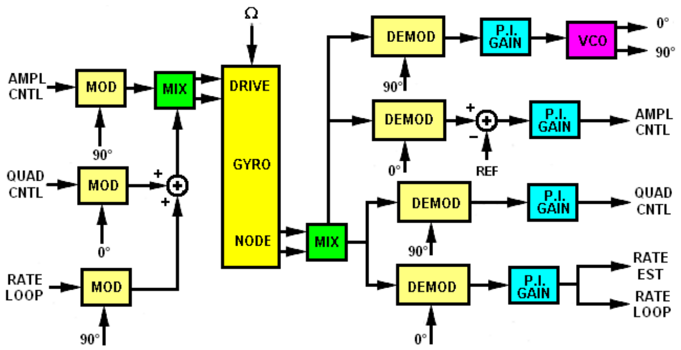

Fig. 19. Complete "Skew" rate gyro system. All functions make full use of all four drive axis electrodes and all four node axis electrodes.

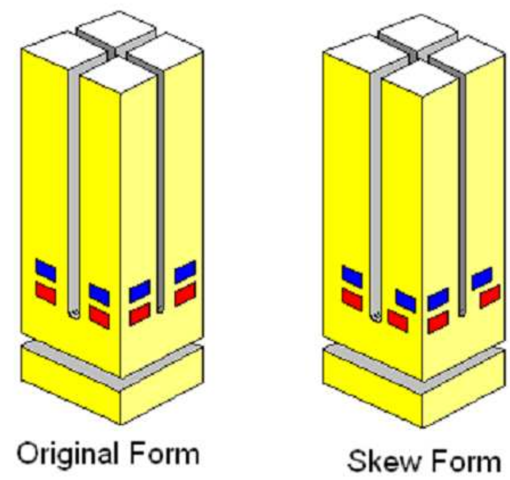

Fig. 21. An example of a tuning fork gyro. Simple realignment of the sense and drive patches is all that is needed.

APPLICATION TO OTHER GYROS

These principles can be applied to other gyro configurations such as the silicon ring type and others. One silicon ring configuration is shown in Figure 20 below. To use this concept, the driving and sensing elements (using capacitive and/or magnetic means for driving and/or sensing) would be skewed from the ideal orientation by small angles producing the same functions and advantages as shown above. Also, the capacitive interface leaves no asymmetry in the vibrating element since only the stationary electrodes need be skewed.

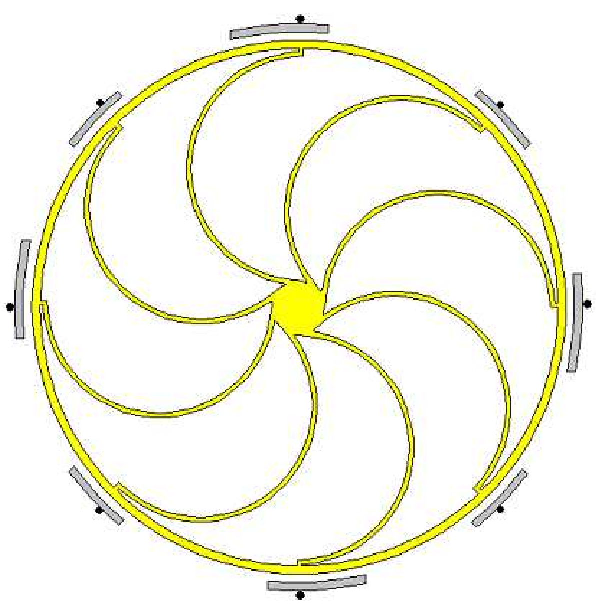

Fig. 20. An example of ring gyro. Such a gyro would benefit fully from skewed sensing and driving mechanisms.

These skew principles can also be applied to tuning fork gyros 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. See Figure 21. As before, the pickoff signals are separately processed for mixing.

There are also ways to apply these principles to the many planar MEMS structures that exist.

CONCLUSIONS

Moving away from total orthogonality 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 these improvements is that the same material and structure used to detect drive motion is used to detect rate response. If the material has variations from temperature, 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 used for the drive loop is used for the torque loop. If the material has variations from temperature, age, or any other effect, the AGC correcting the drive amplitude will exactly correct the torque drive as well.

CONTINUING WORK

The research depicted above is continuing with improved designs to verify performance and influences of various physical parameters such as Q, resonance frequency and tuning errors. Figure 22 shows a hybrid gyro cup made of metal with a piezoceramic ring at the base for the electrical interface.

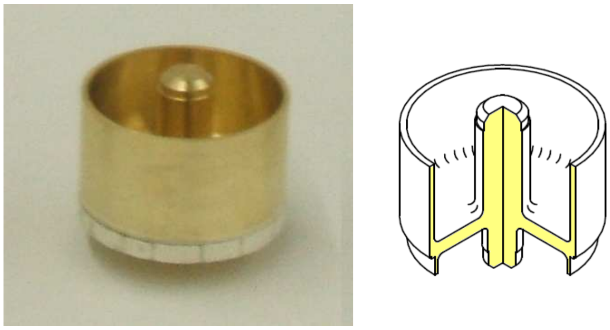

Fig. 22. A cup gyro with a hybrid structure. The electrode interface utilizes a piezoceramic ring bonded to the bottom of a metal cup.

This structure allows better uniformity and temperature performance and will improve identification of the sources of gyro errors.

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