AIAA-98-4401

FIBER OPTIC RATE GYROS AS REPLACEMENTS FOR MECHANICAL GYROS

by

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Abstract

Fiber optic gyroscopes are beginning to replace mechanical gyroscopes in both new design and existing applications. The high reliability, absence of "g" sensitivity, and high tolerance for shock and vibration make optical gyroscopes ideal for mobile and military tactical applications. Based on the Sagnac interferometer effect, as is the Ring Laser Gyroscope, the Fiber Optic Gyroscope (FOG) concept is almost 20 years old. Both closed loop and open loop configurations exist, but due to high cost of the former, only open loop configurations are currently being used to replace mechanical rate gyros. We have developed a series of inexpensive FOGs, based on an all-fiber concept using elliptical-core polarization maintaining fiber, directional coupler(s) and polarizer.

Open-loop FOGs are constructed in accordance with the "minimum configuration" concept, such that the laser light traverses the fiber sensing coil in opposite directions, and in a reciprocal manner. Early versions of such gyros utilized a directional coupler to isolate the laser source and photodetector, a polarizer to ensure single mode propagation, and a second coupler to interface with the coil. A piezoelectric phase modulator at one end of the coil imposes an optical modulation permitting synchronous detection of the interferometer output. The source-detector coupler is not part of the minimum configuration, and can be eliminated by employing a photodetector at the back facet of the laser. Many lasers incorporate such a detector to monitor the power output, but since the gyro rotation signal is modulated it can be separated easily from the steady state laser signal. We have termed this gyro the "Reduced Minimum Configuration (RMC)". Comparisons between the two open-loop configurations suggest that there is little discernable difference between the two approaches. However, qualitatively, the laser in the RMC configuration is operated slightly closer to threshold, resulting in a somewhat narrower optical spectrum. A broad optical spectrum is desirable to avoid a type of bias instability caused by polarization wander in the coil, and so there are likely to be limits on the use of RMC optical circuits in much higher performance gyros

The performance of a fiber optic gyro can be optimized for individual applications by choice of fiber length, coil diameter and laser power within wide limits, without significant change in other construction aspects. The fiber optic gyro is intrinsically broadband, and the output spectral characteristics can be controlled by simple analog filters, extending the dynamics of servo loops. This broadband characteristic extends to very low frequencies, resulting in improved pointing accuracy when compared to similarly specified mechanical gyros.

We have produced over 1000 units of the two configurations, and present data in this paper on Allan variance, bias versus temperature, scale factor versus temperature, and scale factor linearity. Typical performance characteristics are:

Input Rotation Rate	± 100 deg/sec
Scale Factor Stability	± 2 or ± 1 percent, full temp range
Scale Factor Linearity	0.5 or 0.1% (rms)
Bias Stability	0.005 or 0.001°/s, constant temp
Bias Repeatability	0.02°/s, constant temp
Bias Offset	0.2 or 0.03 °/s (peak-to peak), full temp
Angle Random Walk	5 or 20 (°/h)/ √Hz (equivalent rotation rate in a 1 Hz bandwidth)
Operating Temperature	-40 °C to + 75 °C

Perhaps the most significant limitation of the FOG is form factor, since the sensitivity of the Sagnac interferometer depends on the length of fiber times the diameter, and both the physical size, and the orientation of the sensitive axis perpendicular to the plane of the coil make certain retrofit applications difficult to satisfy. Within broad limits, the FOG is a gyro technology that is finding its place in a wide variety of systems.

Introduction

It is no surprise that the newer technologies have advantages over the existing mechanical gyros, but each technology has its attributes. This paper describes a class of fiber optic gyroscopes termed "open-loop all fiber", which are currently in production and use for many stabilization applications in both new design and as form, fit and function replacements for mechanical gyros. Closed loop designs, which we will not discuss, are also in production, primarily for higher performance applications such as inertial navigation systems. They are considerably more expensive, and are not now economic for stabilization or low cost land navigation systems.

Traditional mechanical gyroscopes based on angular momentum have served as the means of measuring angular rotation for almost 100 years. In the last quarter of a century, two differing developmental paths have been followed in the quest for cheaper and more reliable gyroscopes based on the Sagnac effect (ring laser and fiber optic gyroscopes) and the Coriolis effect (micromachined vibrating structures). Each shows the promise of achieving high reliability, and performance comparable with mechanical gyros in all performance ranges, suitable for strategic through automotive dynamic stabilization applications. Traditional mechanical gyros are being replaced in new designs, and in some cases in existing designs, as reliability and other economic factors dictate. The perceived advantages range from vastly increased reliability and higher shock and vibration tolerance, to smaller size and lower cost. Not all of these are realized in each situation, and in some cases the development programs have not yet met all of their objectives.

Table 1 summarizes the situation in the regime that we are addressing: rate gyros for stabilization and land navigation.

Characteristic	**Mechanical Gyro**	**Fiber Optic Gyro**	**Coriolis Vibratory Gyro**
Reliability	Low	High	Potentially very high
Size	Small	Difficult to make in same form factor as mechanical gyros. Typically larger.	Very small
Temperature variation of performance	Good	Good to very good	Still under investigation
Environmental Sensitivity	g and g^2 sensitivity	Single axis rate sensor	g and g^2 sensitivity, but can withstand large shocks
Cost	Moderate, but trending higher as it becomes obsolescent	Low and trending lower	Potentially very low in large quantities

Table 1, Comparison of Gyro Technologies for Angular Rate Sensors

Sagnac Effect

Discovered in 1913, the Sagnac effect[1] found its first practical application several decades ago in the ring laser gyroscope (RLG), now used extensively in commercial inertial navigation systems for aircraft. But, since this implementation requires high vacuum and precision mirror technology, cost has been a factor limiting its application.

The physical principal is analogous to the Doppler effect, but in this instance it involves determination of the phase shift between two counter-propagating light beams. For an RLG this occurs in an evacuated mirrored cavity, but in the interferometric fiber optic gyro (IFOG) the same effect can be obtained in a fiber coil[2], eliminating the high voltage and high vacuum, making low-cost inertial rotation sensors practical.

The performance of a fiber optic gyro is mainly characterized by bias offset, scale factor linearity and stability, bias stability, and a random noise component termed angle random walk (ARW). Within the scope of IFOG technology are bias stabilities ranging from 1 °/s to 0.001 °/h; scale factor linearities of 10,000 parts per million (ppm) to 1 ppm: and ARW from 200 (°/h)/√Hz to .001 (°/h)/√Hz . The costs, as one might imagine, also vary accordingly. For the performance range likely to useful for rate sensors, however, suitable IFOGs are being built and sold for less than $2,000.

Fiber Optic Gyro Concept

Figure 1 illustrates the open-loop configuration of an (interferometric) fiber optic gyro, consisting of a fiber coil, two directional couplers, a polarizer, solid state optical source (laser) and detector. A piezoelectric (PZT) disk or cylinder wound with a small length of one end of the fiber coil applies a non-reciprocal phase modulation. This is termed the "minimum (optical) configuration" all-fiber gyro.

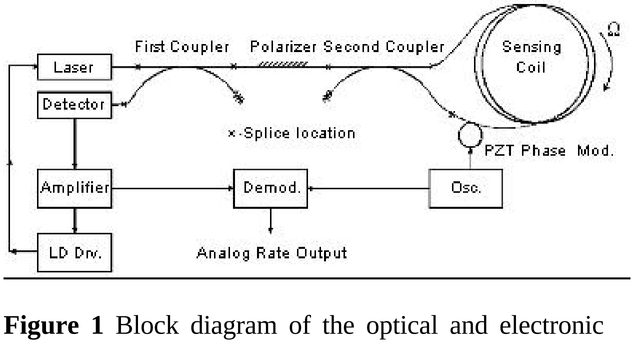

Figure 1 Block diagram of the optical and electronic circuits of an open loop fiber-optic gyroscope

Light from the laser traverses the first directional coupler, polarizer and second directional coupler where it is split into two signals of equal intensity that travel around the coil in opposite directions. At the directional coupler attached to the coil, the two waves, having traversed the coil in opposite directions are combined in an optical interferometer, returning though the polarizer, and half of the light is directed by the first coupler into a photodetector.

The light intensity returning from the coil to the polarizer is a raised cosine function of the Sagnac phase shift (Figure 2), having a maximum value when there is no rotation and a minimum when the optical phase difference is ±π (half an optical wavelength). This effect can be shown to be independent of the shape of the optical path, and of the propagation medium[3], and we produce some gyros with elliptical shaped coils.

The Sagnac phase shift, ΔS, is given by

$$\Delta S = 2\pi L D \Omega / c\lambda \qquad (1)$$

where

L = length of fiber in coil
D = effective coil diameter
λ = mean optical wavelength
c = velocity of light in vacuum
Ω = angular velocity about sensitive axis

Due to the cosine response shape, the change in interferometer output amplitude is small for small input rotation rates, and it would not be possible to determine the sense of rotation as the decrement in amplitude is equal for both directions of rotation, making it necessary to apply a dynamic phase bias to the light path. Not only does this overcome these problems, but it also moves the demodulation to a frequency well removed from DC, minimizing bias drifts associated with offsets in the low level amplifiers.

The demodulation technique shown in Figure 1 is a simple one consisting of a synchronous detector at the modulation frequency. The output of the photodetector is converted from current to voltage in a transimpedance amplifier, and further amplified prior to a synchronous detector. The other input to the synchronous detector is the PZT modulation signal, which is phase shifted to correspond to that of the gyro output. The detector output is a voltage that represents the magnitude and sense of the coil rotation. Since the optical circuit is intrinsically broadband, the output is low-pass filtered to establish the temporal response desired. Often this is intended to match the mechanical gyro that it replaces. But higher frequency response is not precluded, and may well find application in new design.

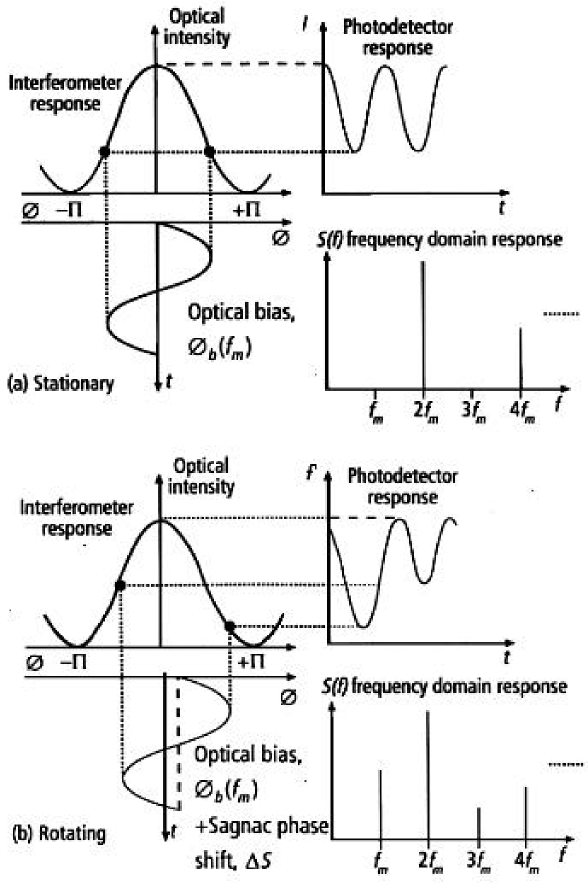

Figure 2 Sagnac interferometer response for open loop configuration

Modulating the PZT with a sinusoidal voltage impresses a differential optical phase shift between the two light beams at the modulating frequency. The photodetector output for no coil rotation exhibits the periodic behavior of Figure 2a, whose frequency spectrum comprises Bessel harmonics of the modulation frequency. Since the phase modulation is symmetrical, only even harmonics are present; the ratio of the harmonic amplitudes depends on the phase modulation amplitude. When the coil is rotated, the modulation occurs about the shifted position of the interferometer response. The phase modulation results in an unbalanced response, and the fundamental and odd harmonics will also be present (Figure 2b). The amplitudes of the fundamental and odd harmonics are proportional to the sine of the angular rotation rate, while the even harmonics have a cosine relationship.

The open-loop IFOG is sometimes criticized for the sinusoidal relationship between the input and output characteristics. However since this is a well known analytic function, it can be dealt with by subsequent signal processing, or by demodulation schemes which take advantage of information in the higher order harmonics to accomplish the same end.

Remarkably this optical configuration permits measuring the difference in phase between the two signals to one part in 10^{16}. This is possible due to the principal of reciprocity[4]. Light passing from the laser through the polarizer is restricted to a single state of polarization, and the directional couplers and coil are made of polarization-maintaining fiber to ensure a single mode path. Both directions of light travel are through the same path, and almost all environmental effects, such as temperature and vibration have the same effect on light passing in either direction and are canceled.

The laser must exhibit low optical coherence, to minimize interaction of parasitic light beams cross-coupled at discontinuities such as splices, and a compact disk-type laser operated below threshold has proven to be satisfactory for rate gyros.

Reduced Minimum Configuration IFOG

In the minimum configuration, the first coupler is not part of the optically reciprocal Sagnac interferometer. Its sole purpose is to direct some of the returning light into a detector, while minimizing the amplitude of the laser signal that has not traversed the interferometer. A “reduced minimum configuration” (RMC) has been proposed[5], in order to reduce the optical configuration complexity and cost, and yet maintain the principal of reciprocity (Figure 3).

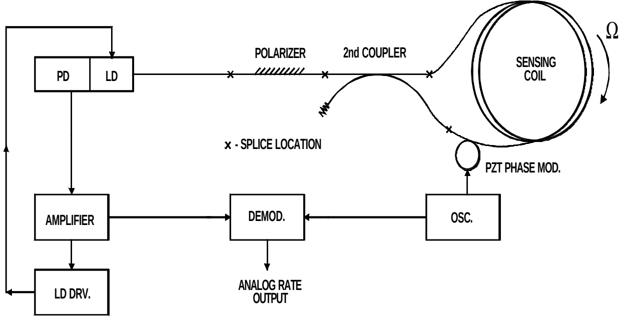

Figure 3. Reduced Minimum Configuration IFOG.

The first coupler is eliminated and the interferometer modulated light output is measured through a photodetector positioned at the back facet of the laser diode. The light passes through the laser cavity before being received by the photodetector. The gyro signal is considerably weaker than that emitted by the laser directly from the back facet, however the light which has passed through the Sagnac interferometer has been modulated by the PZT and can be separated from the static laser signal in the demodulator.

Many low cost laser diode packages contain a back facet photodetector, which is aligned to the back facet of the laser by the manufacturer. The cost of purchasing a separate detector, as well as the hardware and labor needed to align the first coupler output fiber to a separate detector, is eliminated in the RMC gyro design. When the fiber pigtail is aligned to the optical source, the output is automatically aligned to the detector in the same operation. The new configuration also eliminates two of the six fiber-to-fiber fusion splices of the minimum configuration design. Our present construction pigtails the polarizer directly to the laser, resulting in a gyro with only three fiber splices.

Performance

KVH Industries is now producing IFOGs based on these techniques. A typical gyro product (Figure 4) operates at an optical wavelength of 820 nanometers, with a 75 meter coil of elliptical-core polarization maintaining fiber.

Figure 4. Fiber Optic Gyro

The short coil length results in operation in the linear portion of the sine response curve. The sensitivity of the gyroscope depends on the optoelectronic noise, which is broadband and inversely proportional to the optical power, and the Sagnac scale factor, which is the proportionality between angular rate and optical phase shift. From equation 1, this is seen to be proportional to the length of the fiber coil and its effective diameter. In addition, the performance of the gyro depends on the demodulation approach chosen. We present data from a low noise rate gyro series with two different maximum rate specifications. Since many applications are exposed to the environment, performance as a function of temperature is a significant factor. More important that the variation of parameters with temperature is the repeatability, as many system applications employ individually modeled corrections as a function of temperature and rate.

The gyroscopes have maximum rate specifications of ± 30 and ± 100 °/s. Figures 5a and 5b illustrate the variation of bias versus temperature.

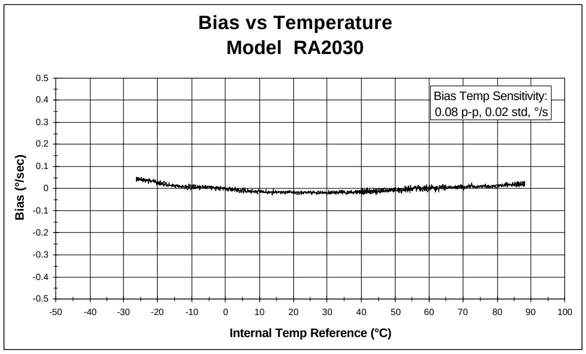

Figure 5a. Bias Variation Over Full Temperature Range for RA2030

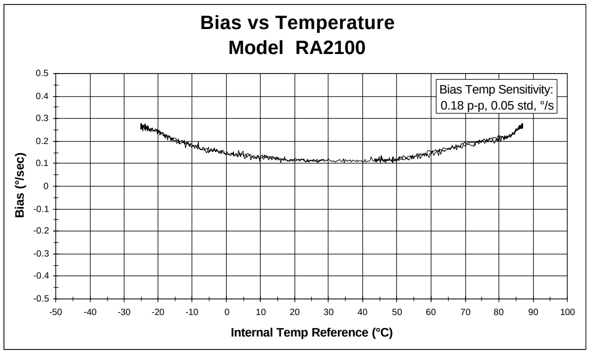

Figure 5b. Bias Variation Over Full Temperature Range for RA2100

The data were obtained by ramping a thermal chamber at a rate of 1° C/min, with a dwell at the maximum and minimum temperatures. The indicated temperature is measured by a thermal sensor incorporated in the product, whose output is available to the user for possible thermal modeling. The bias is observed to be slowly varying and repeatable. It is known that the best optical circuit bias performance is obtained when the modulation frequency is equal to half the transit time of the light through the coil, and any second harmonic effects are suppressed. Since the modulation frequency we use is less than one tenth the “proper frequency” we have investigated the source of this bias offset and determined that it is predominantly due to the DC offsets in the operational amplifiers that are used to amplify the signal after the demodulator. This is evident in the comparison between the performance of the two gyros, as the difference in maximum range is achieved by varying the DC gain. The larger rate range has greater amplification, and is thus more susceptible to the offsets.

The input-output rate relationship is shown in Figure 6a and b, illustrating the excellent linearity that can be achieved by a simple demodulation technique. The product is available with either analog or digital output formats. The data shown are for the analog output and the left-hand scale represents the output voltage as a function of input rotation rate.

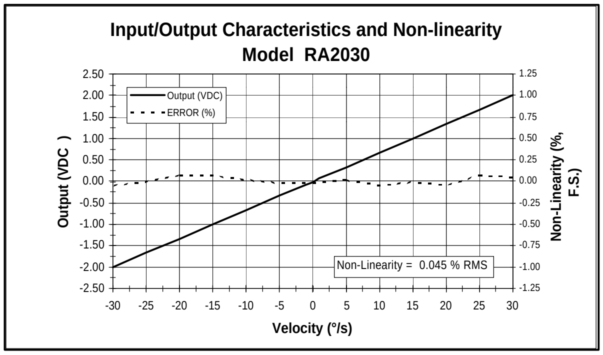

Figure 6a. Input-Output Characteristics and Non-Linearity for RA2030

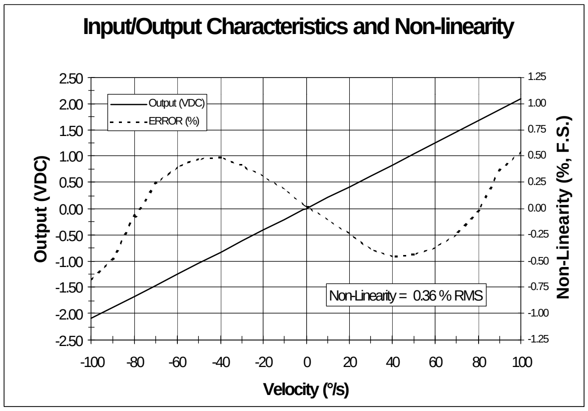

Figure 6a. Input-Output Characteristics and Non-Linearity for RA2100

The underlying cause of non-linearity is the sinusoidal response of the Sagnac interferometer. The gyro can therefore be expected to exhibit an increasing non-linearity as the rate increases. For low rates, the deviation from linearity is minimal. For higher rates ranges, a systematic deviation from linearity occurs. This is clearly seen in Figure 6b, although the overall characteristic has been modified by a compensating function to minimize the excursion at the higher rates. The non-linearity is shown in percent of full scale on the right-hand axis.

The overall relationship of the input rate to output voltage is the scale factor, which is proportional to the Sagnac phase shift. However, the constancy of scale factor depends on the modulation depth and optical power being constant over temperature and time. We have electronic control loops to minimize the variations of these parameters, and the resultant scale factor versus temperature is shown in Figures 7a and 7b.

Overall stability of the gyro is best characterized by the Allan variance statistics[6], which are shown in Figures 8 a and 8b.

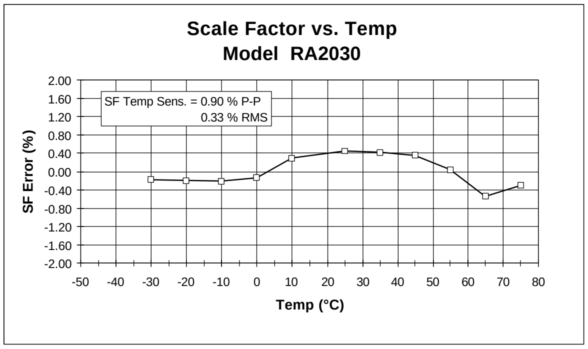

Figure 7a. Scale Factor vs. Temperature for RA2030

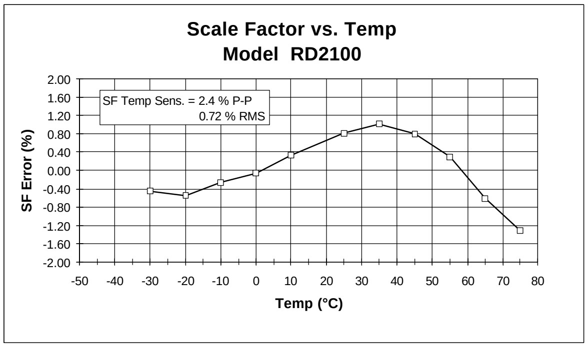

Figure 7b. Scale Factor vs Temperature for RA2100

This measurement is performed at a fixed temperature and can be interpreted to determine the Angle Random Walk (ARW) and bias instability. Typically the square root of the Allan variance is plotted, as in Figures 8a and 8b, and the region at short time differences, τ, is characterized by a slope of -½. The intercept of the slope with the one hour time yields the angle random walk in °√h, which can also be expressed as a noise power spectral density, obtained by multiplying this value by a factor of 60, transforming the units to (°/h)/√Hz. Since both gyros have the same coil length and optical source, the ARW is also the same. The horizontal portion of the Allan variance plot is the bias instability, and is equal to 1.51 times the measured value in °/h . This corresponds to a bias instability of 0.3°/h and 1.35 °/h for the RA2030 and RA2100 gyros respectively. As the bias instability represents the best performance of the gyro after the angle random walk is eliminated by averaging, this parameter is a measure of how well one can measure the bias offset of the gyro for purposes of modeling.

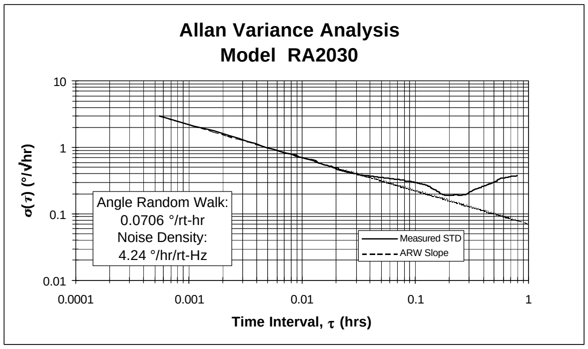

Fig 8a Allan Variance for RA2030

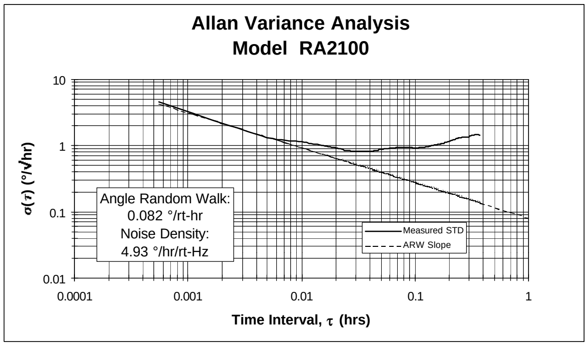

Figure 8b. Allan Variance for RA2100

Summary

One of the more recent uses of fiber optic gyros has been as a replacement for mechanical rate gyros. This is a departure from the development path of prior years in which the emphasis has been placed on high-performance applications. Now that the optical circuits can be produced a low cost, it is possible to address less demanding applications. In this, the high reliability, broadband frequency response and single-axis dynamic response are considerable advantages.

The performance of the optical circuit is better than the overall gyro. This arises from the simple nature of the demodulation approach taken. Use of the higher harmonics of the modulation frequency would result in better performance in the areas of scale factor versus temperature and scale factor linearity. Digitizing the gyro signal at an earlier point in the processing would improve the bias versus temperature performance.

The gyros described in this paper are in production and have been used in projects throughout the world.

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