Gated phase-modulation feedback approach to fiber-optic gyroscopes

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Received January 26, 1984; accepted March 20, 1984

A new approach to closed-loop operation of an all-fiber-optic gyroscope using phase modulation and signal gating is described. This approach provides simplicity of implementation and the capability of wide dynamic range with an approximately linear scale factor. Experimental results are compared with theoretical calculations.

The dynamic range of open-loop optical-fiber gyroscopes is limited by the periodic response of the output optical signal to the rotation rate.\(^1\)\(^4\) One approach to overcoming this limitation is to null out the rotation-produced differential phase shift by feeding from the electrical output of the detector to a suitable electronically controllable element within the sensing coil that can produce a nonreciprocal optical effect. The feedback signal then reflects the rotation rate. Nonreciprocal magneto-optic effect\(^6\) and reciprocal frequency shifters located asymmetrically within the coil\(^6,7\) have been utilized to produce the nonreciprocal effect. However, suitable devices of these kinds have not yet been reported in all fiber forms.

It was recently shown\(^8\) that a simple all-fiber reciprocal phase shifter located asymmetrically within the loop, and driven at twice the modulation frequency \(f_1\) of the phase shifter used for bias modulation and heterodyne detection, can be used to null out rotation-produced detector output at frequency \(f_1\). In this Letter we show that the same type of phase shifter can be used in a different, simpler arrangement, operating at a frequency \(f_2\) much lower than \(f_1\).

A reciprocal phase modulator located asymmetrically in the sensing loop can produce a differential shift \(\Delta \phi_C\) between the phases of the two counterpropagating waves in the loop. This \(\Delta \phi_C\) is time varying at the modulation frequency \(f_C\) and contains no dc term because the phase shift produced by the modulator in one half of its modulation cycle is canceled by that produced in the next half cycle. Thus \(\Delta \phi_C\) cannot be used directly to null out the differential shift \(\Delta \phi_R\) that is due to rotation because, for a fixed rotation rate, \(\Delta \phi_R\) is a dc quantity. However, if we gate the gyro off during every other half cycle of the modulation waveform, the average \(\Delta \phi_C\) produced in the remaining operational half cycles can be used directly to null out the average \(\Delta \phi_R\) produced in those same half cycles. The time gating can be easily done after detection.

For dynamically biased gyroscopes,\(^9\)\(^-\)\(^11\) the rotation-induced nonreciprocal phase shift \(\Delta \phi_{R}\) is measured by modulating the phase difference of the counterpropagating waves, followed by demodulation of the output from the photodetector at the modulation frequency. The detector output amplitude \(I_1\) at the modulation frequency \(f_1\) is

\[
I_1 = CP_0 J_1(\Delta \phi_1) \sin \Delta \phi. \tag{1}
\]

Here \(C\) is a constant, \(P_0\) is the optical power incident upon the detector, \(J_1(\Delta \phi_1)\) is the amplitude of the phase-difference modulation between the counterpropagating waves, \(J_1\) is the first-order Bessel function of the first kind, and \(\Delta \phi\) is the phase difference between the counterpropagating waves in the sensing coil. When an additional sinusoidal phase-difference modulation is applied, at a frequency \(f_2\) much lower than the bias modulation frequency \(f_1\), the waveform of the phase-difference modulation in the presence of rotation-induced nonreciprocal phase shift, \(\Delta \phi_{R}\), is shown in Fig. 1(a). When we switch off the signal from the photodetector during 50\% of each cycle of phase modulation at frequency \(f_2\) as in Fig. 1(a), the demodulated output power at bias modulation frequency \(f_1\) is shown in Fig. 1(b). Under the condition that the demodulator integrates the signal over many cycles of phase modulation at frequency \(f_2\), the demodulated output power can be made zero by adjusting the amplitude of phase-difference modulation \(\Delta \phi_{R}\). This means that the rotation-induced nonreciprocal phase shift can be canceled on the time average by the phase modulation with gating. The demodulated output power in the case of Fig. 1(b) becomes

\[
I_1 = (C/T)P_0 J_1(\Delta \phi_1) \times \int_{-T/4}^{T/4} \sin(\Delta \phi_R + \Delta \phi_2 \cos \omega_2 t) dt, \tag{2}
\]

where \(T = 1/f_2, \omega_2 = 2\pi f_2\), and \(\Delta \phi_2\) is the amplitude of the phase-difference modulation at frequency \(f_2\).

The condition for nulling this demodulated power to zero can be obtained from the relation

\[
\tan \Delta \phi_R = -\frac{4}{\pi} \frac{1}{J_0(\Delta \phi_2)} \sum_{n=1}^{\infty} \frac{1}{J_n(\Delta \phi_2)}, \tag{3}
\]

where \(J_n\) is the \(n\)th order Bessel function. Figure 2 shows the calculated relationship between \(\Delta \phi_R\) and \(\Delta \phi_2\) in Eq. (3). This curve represents the response of the gyroscope to rotation when operated in an electronically
Fig. 1. (a) Waveform of phase-difference modulation. The photodetector output for the dashed part of the phase-difference modulation will be switched off. (b) Demodulated output [Eq. (1)] at the bias modulation frequency $f_1$ after a half of the signal from the photodetector (dashed part) is turned off.

A schematic diagram of the experimental setup is shown in Fig. 3. An all-fiber gyro\(^1\) with 580 m of fiber wound around a 7-cm-radius spool was used. The light source was a laser diode with wavelength of $\sim 830$ nm. Phase-difference modulations for bias ($f_1$) and feedback ($f_2$) were achieved by using a single piezoelectric hollow cylinder with several turns of fiber wrapped around it. The dynamic range of this phase modulator is sufficient to meet the operating criteria of navigational gyroscopes. The optimum frequency and amplitude\(^1\) for the bias modulation were used ($f_1 = 172$ kHz, $\Delta \phi_1 = 1.8$ rad). A separate signal generator was used for the feedback phase modulation at frequency $f_2 = 15$ kHz. The optical output signal was detected by a silicon photodetector followed by an amplifier, a gate, a bandpass filter at 172 kHz, and a phase-sensitive demodulator (PSD). The gate was triggered by the synchronizing signal from the $f_2$ signal generator, and the phase of the gating was adjusted by pulse delay.

Feedback was implemented manually, and no electronic circuits were used to close the loop between the output terminal and the $f_2$ signal source. While the gyroscope was rotated, the amplitude of the phase-difference modulation $\Delta \phi_2$ was adjusted until the rotation signal from the PSD was nulled. Figure 4 shows good agreement between experimental data and theoretical calculation. The Sagnac phase shift $\Delta \phi_R$ in Fig. 4 is evaluated by measuring the rotation rate that corresponds to $\Delta \phi_R = \pi$. Output from the PSD is zero at this rotation rate in the absence of phase-difference modulation at the frequency $f_2$. The amplitudes of the phase-difference modulation, $\Delta \phi_2$, are determined from the amplitude of the electric signal applied to the phase modulator. The conversion factor is determined by measuring the amplitude of the electric signal that produces $\Delta \phi_2 = 4.33$ rad. Output from the PSD is zero for this value of $\Delta \phi_2$ when the gyrooscope is not rotating. This result is obtained by using Eq. (2). A linear response of the phase modulator to amplitude of driving signal is assumed.

One of the attractive features of this approach is its simplicity. No optical modifications to the dynamically biased, all-fiber, open-loop gyroscope are necessary. The scale factor shown in Fig. 2 has no dependence on the amplitude and phase of the bias phase-difference modulation. Only the sensitivity to rotation depends on the amplitude of the bias modulation.

Fig. 2. Relationship between Sagnac phase shift $\Delta \phi_R$ and the amplitude of the phase-difference modulation at frequency $f_2$, $\Delta \phi_2$, required to null the demodulated power [Eq. (3)].

Fig. 3. Schematic of the experimental setup.
An analogy can be made between this gated phase-modulation approach and frequency-shifting approaches described elsewhere. The present case is equivalent to a frequency-shifted gyroscope in which the frequency difference between counterpropagating waves is modulated sinusoidally and the signal is gated off during half of the period of the sinusoidal modulation. Therefore the phase-difference modulation at frequency $f_2$ in Fig. 1(b) is equivalent to a sinusoidally modulated frequency shift. The gating process introduces a loss of half of the optical power and a loss of rotation information during half of the time. This information loss can result in an error in the measured rotation angle $\theta$ when a sudden change in angle occurs within a gated-out time interval. Take as an example the case of a full cycle of square-wave angular acceleration. For a gating frequency $f_2 = 15$ kHz, an acceleration $|d^2\theta/dt^2| = 1000^\circ$/sec$^2$ within the first half of a gated-out time interval, followed by a deceleration of the same magnitude within the second half of the interval, leads to an error in $\theta$ of about $2.8 \times 10^{-7}$ deg. This is equivalent to a phase offset of multiple $\pi$ rad.

The stability of the scale factor depends on that of the phase modulator and of the electronic components in Fig. 3. The linearity of the scale factor can be improved by sampling smaller portions of the signal centered at the peak of the phase-difference modulation in Fig. 1(b). But more optical power and rotation information are lost in this case. Another way of getting a linear scale factor is to use a phase modulator that provides a dc phase difference during the sampling period (e.g., a triangle or a saw-tooth wave-phase modulator). If the scale factor in Fig. 2 is strictly linear and we measure the voltage applied to the phase modulator as a rotation signal of a closed-loop gyroscope, the source wavelength dependence of the scale factor will be completely suppressed. This results from the fact that the amplitude of the phase modulation has the same wavelength dependence as the rotation-induced phase shift. The frequency of the feedback phase modulation and gate ($f_2$) should be adjusted so that its harmonic frequencies do not coincide with bias modulation frequency in order to avoid possible offset or noise.

A new simple approach to closed-loop operation of an all-fiber gyroscope using phase modulation and gating is demonstrated. The dynamic range of this system is limited only by that of the phase modulator, the electronic components, and the ac voltage measurement. All the devices required are readily available.

We want to thank R. A. Bergh and L. F. Stokes for helpful discussions and W. Hipkiss and M. Galt for technical assistance. This work was supported by Litton Systems, Inc.

References