Construction of all digital closed-loop interferometric fiber optic gyroscope with erbium doped fiber amplifier

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This paper describes the design details and the characterization of an all digital closed-loop (ADCL) Interferometric Fiber Optic Gyroscope (IFOG) Prototype with sine wave biasing modulation and an erbium doped fibre amplifier (EDFA) pumped by DFB laser emitting at 1549.0 nm as a broadband source. The output of demodulation circuit in the prototype, proportional to the applied rotation rate, was sampled by AD7714YN analog to digital converter (ADC) and operated in 16 bit resolution. Error voltage, generated by microcomputer-controlled LTC 1667CG, 14 bit digital to analog converter (DAC), was sent to the phase modulator through a linear summing circuit, to make Sagnac Phase Shift zero, depending on the rotation direction. The averaged sensitivity of the ADCL-IFOG prototype in unit of error voltage applied to the phase modulator was calculated as 129.21 μV/(°/h) which equals to a scale factor of 7.739 (°/h)/(mV) with a standard deviation of 0.71% for a range of 1-15270 (°/h) rotation rate, corresponding to a range of Sagnac Phase Shifts varying from 0.00115 (°) to 17.57448 (°). The maximum peak to peak noise and the bias stability of the prototype were determined as 3.88 (°/h) and 1.38 (°/h) at 23.0°C, respectively.

Keywords: All digital closed-loop IFOG, Open-loop IFOG, Sagnac Phase, EDFA, Scale factor, Bias modulation

1 Introduction

Optical gyroscopes, which are absolute measurement sensors for measuring the rotation rate, are composed of ring laser and fiber optic gyroscopes. These are widely used in navigation applications and their physical principle to sense rotation rate is based on the Sagnac phase shift, which was discerned in 1913 by G Sagnac. Although the first ring interferometer experiment to demonstrate Sagnac phase shift propagating in a rotating media was performed by F Harress with many problems encountered¹, the first successful attempt to measure the rotation rate belonged to A A Michelson and H G Gale in 1925 with a gigantic Michelson interferometer configuration. With development of optical fiber manufacturing technology, a fiber ring interferometer with multiple optical paths was first constructed by V Vali and R W Shorthill in 1976 to show Sagnac phase shift and this interferometer configuration is known as a pioneering step in the applications of optical fiber gyroscope¹.

Sagnac phase shift $\phi_R$, which is to measure the rotation rate with an interferometer configuration with respect to an inertial frame, is induced by rotation taking place in an interferometer with N turn optical path is:

$$\phi_R = \frac{8\pi N A \Omega}{\lambda_0 c_0} \ldots(1)$$

where $A$ is the area of the enclosed optical path, $\Omega$ the rotation rate of the two beam interferometer, $\lambda_0$ and $c_0$ are wavelength and light velocity in vacuum, respectively. Sagnac effect in matter is more delicate to explain, but it is completely independent of the indices of refraction or of the guidance condition, and keeps the same value as that in the vacuum². For a monochromatic wave divided into two beams by a beam splitter placing in a two-beam-interferometer, the typical response is;

$$I_D = K (1 + \cos \phi) \ldots(2)$$

where $K$, peak photocurrent, is the function of both spectral responsivity of photodiode and the amplitude of interfering monochromatic beams, $\phi$ is the phase difference between two monochromatic beams. The generated photocurrent $I_D(t)$ in an interferometer to which reciprocal phase modulation is applied:

$$I_D(t) = I_0[1 + \cos(\phi_R + \phi_m \sin \omega_m t)] \ldots(3)$$
where \( \phi_{m0} \sin \omega_m t \) is the periodic phase bias created by the sine wave biasing modulation applied to phase modulator such as piezoelectric transducer (PZT) or electro-optic modulator \(^3\) (such as LiNbO\(_3\)). The sine wave modulation/demodulation technique is sufficient to defeat zero response problem of the interferometer resulting from \( N \pi \) Sagnac phase shift \((N \text{ is an odd integer})\) and to clarify the direction of the rotation rate.

If Eq. (3) is expanded series of \( n \)th order Bessel functions, even and odd frequency harmonics are obtained and it can be seen that the odd frequency harmonics of \( \omega_m \) carries the Sagnac phase shift information with sine function, which is the odd function, making IFOG the direction sensitive-absolute angular rate sensor \(^4\). The resultant photocurrent:

\[
I_D'(t) = 2KJ_1 \left( 2\phi_{m0} \sin \frac{\omega_m \tau}{2} \right) \sin \omega_m t \sin \phi_R \quad \text{...}(4)
\]

where \( 2\phi_{m0} \sin \frac{\omega_m \tau}{2} \) is the non-reciprocal phase difference, \( \tau \) is the loop transit time of the sensing coil, and \( J_1 \) is the first order of Bessel function and takes the maximum value at;

\[
2\phi_{m0} \sin \frac{\omega_m \tau}{2} = 1.8 \text{ rad} \quad \text{...}(5)
\]

When the non-reciprocal phase difference goes to zero, the interference signal begins to disappear. Therefore, the intensity of the photocurrent resulting from the odd frequency harmonics, carrying Sagnac phase, can be maximized \(^6\) by adjusting \( \omega_m = 2\pi f_m = 2\pi (1/2\tau) \). After the completion of band-pass filtering and demodulation steps for the signal coming from the open-loop IFOG in turn, Sagnac phase shift carried by the odd frequency components is obtained as a function of sine. Although sine function exhibits a solution to determine the rotation direction of an open-loop IFOG the linearity of the dynamic range of the open-loop IFOG is wholly restricted the periodic behaviour of the sine function \(^4\) \( \sin \phi_R \) and the linearity of the scale factor of the open-loop IFOG is significantly disturbed by large Sagnac phase shifts, induced by relatively high rotation rates.

Both the accuracy and the linearity of Scale Factor are those of the most critical performance parameters of an IFOG together with Random Walk induced by thermal \(^7\), photon-shot \(^8\) and excess noise \(^9\) in unit of \(^\circ/h/\text{Hz}^{1/2} \) or \( ^\circ/h^{1/2} \), and bias stability (long term drift) induced by magneto-optic Faraday effect, non-linear Kerr effect and Shupe effect, which create lack of reciprocity \(^4\) \( ^6\) \( ^10\) in unit of \( ^\circ/h \).

After demodulation of the photocurrent coming from IFOG the voltage contain optical and electrical scale factors together with optical and electrical offsets:

\[
V_{\text{de mod}}(\Omega) = A_4 \sin(A_2 \Omega + A_3) + A_4 \quad \text{(V)} \quad \text{...}(6)
\]

where \( A_1, A_2, A_3 \) and \( A_4 \) are the electrical scale factor, the optical scale factor, the optical bias (or offset), and the electrical bias, respectively \(^11\). Sine function in Eq. (6) causes an inherent non-linearity in scale factor of an open-loop IFOG and the non-linearity of scale factor not only directly affects to determine the rotation rate information but also the total angular displacement, calculated through the electronic integration (including digital signal processing methods) of the demodulation circuit output with precise clock generation. Every past error resulting from this non-linearity on the dynamic range of an open-loop IFOG causes the errors in the determination of the total angular displacement because of time and voltage integration \(^6\).

The constraint related to the non-linearity of the dynamic range of an open-loop IFOG is overcome by closed-loop IFOG approach.

2 Description of ADCL-IFOG Prototype with EDFA

In the proposed ADCL-IFOG prototype, an EDFA pumped by 1549.0 nm DFB laser was used as a broadband source, the output spectrum of which is demonstrated in Fig. 1. The peak value of the EDFA emission was at 1593.18 nm, the spectral width of

![Fig. 1 — EDFA output spectra, source in the proposed ADCL- IFOG.](image-url)
which was about 45.0 nm and corresponding temporal coherence length was 56 μm. The optical pump power for EDFA, the length of which was about 70 m, was 33 mW and the resultant broadband ASE (Amplified Spontaneous Emission) of 32 μW was obtained.

Variations on the output characteristics of Er³⁺ doped fiber depending on its length, pump wavelength and pump power and the effects of these parameters (especially, mean wavelength and broadband emission of ASE) to the gyroscope implementations were studied in detail. PZT is engaged as phase modulator to form sine wave biasing modulation on IFOG prototypes. Several turn of sensing coil optical fiber is wrapped on PZT to attain adequate modulation depth in interference pattern. Resonant frequencies of PZT in three modes are determined by its dimensions. Before using PZT as a phase modulator, the resonant frequencies were examined by a RLC-meter (impedance-meter) instrument. With this examination, the radial resonant frequency of the PZT was found around 66 kHz. To avoid non-reciprocity and obtain an identical bar/cross passing of CW and CCW light waves two 3 dB-splitters were included in IFOG.

Sensing coil consists of 1711 meter long single mode optical fiber wrapped on a mandrel the diameter of which is 15 cm. Even though the laboratory, where IFOG prototype is constructed, is a temperature controlled-environment, the sensing coil is of symmetrical dipolar winding, to impede the thermal induced phase shifts in sensing coil and to compensate the temperature transient effects together with acoustic parasitic effects.

In the configuration shown in Fig. 2, to assure ideal number of cross/bar passing of counter propagating waves, two 3-dB couplers are used and a fiber optic

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Fig. 2 — ADCL-IFOG prototype with EDFA. Dashed border line shows the feedback circuit, controlled by 89C51 microcontroller.
polarizer is placed between them so as to remove/minimize circular polarized components which create strong polarization influence on the bias stability and the scale factor accuracy.

The minimum response time of the sensing coil against the applied rotation rate is 8.5 μs, the loop transit time. 3-dB frequency of the low pass filter, used for suppressing the high frequency component \( \sin^2 \omega_m \) and minimizing the fluctuations at the output of the demodulation circuit with AD630, is set to 10 krad/s, which corresponds to 1.592 kHz. The frequency of sine wave bias modulation applied to PZT is \( f_m = 65.411 \text{ kHz} \) for 1711 meter long sensing coil therefore, this low pass filter suppresses \( f_m \) components with an attenuation of -32.3 dB.

In order to reduce Kerr effect, two 2×2 couplers used in IFOG were so selected that the optical power difference between two arms of 2×2 coupler is the smallest at the end of a series of optical power measurement at 1593.18 nm. Therefore, the reciprocity arising from refractive index change, Kerr effect-based, was minimized.

Regarding Magneto-optic Faraday effect, the single mode sensing coil was covered by a μ-metal (Cu) and it was settled in a Faraday cage. Therefore, the effect of earth magnetic field change on the portion of the circular polarization fields propagating in the single mode sensing coil was minimized.

To relieve Shupe effect (variation longitudinally and cross-section ally and refractive index change in the sensing coil, depending on temperature and acoustic effects), the sensing coil was wrapped in a manner of symmetric dipolar winding so the sensing coil was symmetrically subjected to temperature and acoustic variations for CW and CCW waves. Moreover, low coherence length of optical source inherently reduces the backscattering and spurious reflections at the air/glass interfaces and spurious standing waves. In order to minimize noise causing random walk, it is necessary to make successive and suitable operations in optical side and electronic side.

The optical scale factor in a FOG, relating the induced phase shift to the rotation rate, is inversely proportional to the mean wavelength \( \lambda_{\text{mean}} \) of the source. The long term scale factor stability required for a navigation grade gyro thus requires that the SFS mean wavelength is stable to 1 ppm as well. The mean wavelength of a rare-earth doped source varies intrinsically with the fiber temperature, as well as with temperature-dependent changes in pump power and pump wavelength. It was demonstrated that the mean wavelength dependence on pump power is highly length sensitive, and can be reduced to zero for a chosen pump power by tailoring the fiber length. This makes it possible to nearly eliminate \( \lambda_{\text{mean}} \) variations with pump power and wavelength for a wide range of pump powers and reduce the temperature coefficient of the EDFA wavelength stability to the intrinsic \( \lambda_{\text{mean}} \) variation with fiber temperature\(^{12} \). Considering this information about dependence of mean wavelength on the length of EDFA, in the proposed ADCL-IFOG prototype 70 m long EDFA, pumped by a highly stable 1549.0 nm DFB laser diode with a pump power of 33 mW, was used.

Excess noise is inversely proportional to the spectral bandwidth of the optical source and it decreases with the increasing spectral bandwidth. Considering that increasing the spectral bandwidth of low coherent source restricts IFOG dynamic range (°/h-mV), and thermal noise (Detector thermal noise-Johnson noise) is dominant over excess noise for the optical power levels under 5 μW, for the proposed ADCL-IFOG an optimization was made by means of a series of bias stability measurements. As a result, for a spectral bandwidth of 45.0 nm, an optimized ASE optical power of 32 μW on pigtailed InGaAs of ADCL-IFOG was applied to the proposed ADCL-IFOG.

In addition, free arms of the two 2×2 couplers were tightly wrapped in order to impede Fresnel reflections at the air/glass interfaces and spurious standing waves. Moreover, low coherence length of optical source inherently reduces the backscattering inside the sensing coil, guided to the InGaAs photodiode.

In electronic side, the demodulation circuit, which provides narrow noise bandwidth by means of the band pass filter inherently, was well-grounded and powered by highly stabilized and filtered ± 15 V dc source. The operational amplifiers (opamps) used in demodulation circuit are OPA111s and OP27s, which have low bias currents and offset voltages. All the passive circuit elements are precision elements and so exhibits low temperature dependence.

Photodetector, pigtailed InGaAs, was not supplied with a reversed dc bias so that shot noise constituting a dark current, is not induced. Therefore, detector noise figure is only limited with \( kT \) based-Johnson noise. Noise Equivalent Power (NEP) of the pigtailed InGaAs is an order of \( 10^{14} \) W/Hz\(^{1/2} \) (small active area). The temperature stability of the location, where the measurements, were carried out is \((23.0 ± 1.0)°\text{C}\).
2.1 Principle of ADCL-IFOG prototype operation

The principle of closed-loop approach is to make rotation induced-Sagnac phase shift zero by manipulating the phase modulator with a feedback voltage. Rotation rate $\Omega$ affects Sagnac phase shift $\phi_R$ and of course the interference pattern, which is caused by sine wave modulation, as a linear change together with an optical offset, Eqs (1 and 6). The linear relationship between Sagnac phase shift and rotation rate enables to manipulate Sagnac phase shift linearly by a suitable feedback operation and it is, therefore, possible to defeat inherent non-linearity of scale factor of an open-loop IFOG, with the help of a closed-loop approach.

Even though this approach is necessary for obtaining more linear scale factor, it is not individually sufficient to get more accurate scale factor results. Taking into account the components of Eq. (6), besides electrical drifts in the demodulation circuit, the optical source-based effects like wavelength and intensity stability, and the opto-geometrical variations on the sensing coil caused by the non-linear Faraday, Kerr and Shupe effects result in the changes on both accuracy and linearity of scale factor of an IFOG regardless of closed-loop or open-loop.

The output of the demodulation circuit is adjusted to $\pm 1.25000 \text{ V}$ by adjustable gain amplifier. To hold the output of the demodulation circuit at positive when IFOG is subjected to CW and CCW rotations, this output is fed into a linear summing circuit with a reference voltage of +1.25000 V. Therefore, the null rotation rate voltage of the IFOG is +1.25000 V and the full range is 0.0000 V to 2.50000 V.

The voltage output is sampled by AD7714YN 24-bit sigma-delta analog to digital converter (ADC), which is operated at 16-bit mode, and it can easily be achieved by writing Filter High Register of AD7714YN, which has a series of on-chip serial registers. As compared with the other type ADCs (flash, multistage, successive-approximation register) the sigma-delta ADCs, which have higher resolution through their digital filtering, have relatively lower sampling speeds. In this application the reference voltage is 2.50000 V and 2.4576 MHz crystal is used for the clock generation. For a full scale of 2.50000 V, the step size of AD7714YN equals to 38 $\mu$V. In order to run AD7714YN, the necessary pins to be connected to microcontroller (or bus/port of a PC) were introduced in Fig. 1 RESET, CS (Chip Select), DRDY (Data Ready) inputs are active LOW signals. DIN (Data In) and DOUT (Data Out) pins run fully synchronously with rising edge of SCLK signal. When DIN pin is used to write the configuring data into the on-chip registers of AD7714YN the data bits proportional to input voltage are read from DOUT pin after DRDY pin goes to LOW state. The LOW state of DRDY output of AD7714YN demonstrates that the data bits are ready for reading. For this application 2.50000 V at the input of AD7714 corresponds to (1111111111111111)2 = (FFFFh) = 2.50000 V. The null rotation voltage is 1.25000 V and the binary data which corresponds to the null rotation voltage is (1000000000000000)2 = (8000h) = 1.25000 V. The duration of DRDY high state14 is 500 $\times$ $t_{\text{clk}}$ = 205 $\mu$s. In this application, a write operation to AD7714YN and a read operation from it take a 120 $\mu$s and 30 $\mu$s, respectively. Total time duration consumed by AD7714 is about 360 $\mu$s for one sampling.

89C51 microcontroller which has a special software designed to control both 16 bit AD7714 ADC and LTC1667CG 14-bit DAC synchronously. The microcomputer holds (8000h) =1.250000 V, corresponding to the null rotation rate and loads 14-bits (10000000000000)2 = (8000h) = 2.0000 V to directly the input pins of LTC1667, which generates an output current proportional to its input data bits, and supplies with a $dc$ bias voltage for PZT with current to voltage converter15. During operation of IFOG the microcomputer compares continuously the voltage data carrying Sagnac Phase Shift, sampled by AD7714, with the 16-bit null rotation binary data (8000h) =1.250000 V in real time. With this comparison, the microcomputer determines which direction the IFOG rotates and in order to null the rotation induced-Sagnac phase shift, a counting which creates the opposite phase shift on PZT, and which is to be loaded on the input pins of LTC1667, is started by the microcomputer, beginning from (2000h) [Fig. 3(a and b)]. This counting is downward from (2000h) = 2.0000 V to (0000h) = 0.0000 V for zeroing the Sagnac phase in CW direction and is upward (2000h) = 2.0000 V to (3FFFh) = 4.0000 V for zeroing the Sagnac phase shift in CCW direction.

The total phase in IFOG $\phi_T$;

$$\phi_T = \phi_R + \phi_{FB} \; (^\circ) \quad \cdots(7)$$

Where $\phi_{FB}$ is the feedback phase, created by LTC1667CG output6. Therefore, $\phi_T$ is written in place of $\phi_R$ in Eq. (3) and the total phase $\phi_T$ is induced to zero or an offset by the feedback phase, resulting in
Sagnac Phase Shift $\phi_R$ to zero, for closed-loop approach.

$$\phi_T = \phi_R + \alpha (2.0000 + V_{DAC}) \text{ (°)} \quad \ldots (8)$$

where $(2.0000 + V_{DAC})$ is $V_{FB}$ in Fig. 2 and the total phase shift on phase modulator can be written as in Eq. (8) in terms of voltage. Where $\alpha$ is a constant which relates the voltage to the phase and so, LTC1667CG adds $\alpha V_{DAC}$ to the total phase through PZT. When the IFOG is stationary, the AD630 demodulation circuit output is 1.25000 V and the Sagnac Phase $\phi_R$ is zero. Due to no counting, $V_{DAC}$ is zero: In this case, there is a constant phase of $\alpha 2.0000$ (°) in the IFOG as an offset phase for counter-propagating waves only.

$$\phi_T = \alpha 2.0000 \text{ (°)} \quad \ldots (9)$$

when ADCL-IFOG rotates in CW direction, AD7714YN sends the binary data higher than (8000h) = 1.250000 V, yielded by demodulation circuit, to microcontroller. The microcontroller decides the direction of rotation by comparing the new data stream with the data previously loaded (8000 h) and then counts down by beginning from (2000 h),

Fig. 3 — The Sagnac Phase Nulling voltage applied to the phase modulator of the ADCL-IFOG prototype rotating on (a) CW direction, (b) CCW direction
corresponding to 2.0000 V, and send the each count to LTC1667CG by synchronizing with CLK signal to compensate the rotation induced-Sagnac Phase Shift. The microcontroller checks the output of AD7714YN whether or not 1.250000 V. If not, the counting down is maintained. In this case the spontaneous phase change in phase modulator is written as follows:

$$\phi_T = \phi_{RC}^{CW} - \alpha V_{DAC} + \alpha 2.0000 \text{ (°)} \quad \ldots (10)$$

As soon as the output of AD7714YN is 1.250000 V = (8000h) the counting down is completed by microcontroller, the error voltage bits are sent to serial buffer register of microcontroller, and the total phase remains constant $\alpha 2.0000$ (°). When the IFOG is kept stationary, microcontroller output and so, LTC1667CG input go back (2000h), resulting in 2.0000 V at the output of current to voltage converter in the feedback circuit, default value.

In case of rotation of ADCL-IFOG on CCW direction AD7714YN sends the binary data lower than (8000h) = 1.250000 V, yielded by demodulation circuit, to microcontroller. The microcontroller decides the direction of rotation by comparing the new data stream with the data previously loaded (8000 h) and then counts up by beginning from (2000h), corresponding to 2.0000 V and send the each count to LTC1667CG by synchronizing with CLK signal, to compensate the rotation induced-Sagnac phase shift. In this case, the spontaneous phase change in phase modulator is written as follows:

$$\phi_T = \phi_{RC}^{CCW} + \alpha V_{DAC} + \alpha 2.0000 \text{ (°)} \quad \ldots (11)$$

As soon as the output of AD7714YN is 1.250000 V = (8000h) the counting up is completed by microcontroller, the error voltage bits are sent to serial buffer register of microcontroller, and the total phase remains constant $\alpha 2.0000$ (°) again. When IFOG is kept stationary, microcontroller output and so, LTC1667CG input go back (2000h), resulting in 2.0000 V at the output of current to voltage converter in the feedback circuit, default value.

The scale factor (SF) of the ADCL-IFOG prototype is defined as the ratio of the applied rotation rate to the error voltage produced by LTC1667CG;

$$SF = \Omega / V_{DAC} \quad (°/h)/mV) \quad \ldots (15)$$

The time constant (RC) of the low-pass filter, is within 100 μs. This value is important to determine whether or not the dc output of the demodulation circuit reaches to the sufficient level at the output of the low pass filter. To achieve it, the microcontroller is held at NOP (no operation) for 610 μs just after the phase step is applied to PZT so as to the dc output of demodulation circuit attains to the required voltage level due to the time constant of the low pass filter. Taking into account that the total duration of write/read operation and sampling cycles of AD7714YN is 360 μs, it is vital to synchronize LTC1667CG with the sensing coil, demodulation circuit and AD7714YN. It is achieved by adjusting 1 machine cycle of 89C51 microcontroller to 1 μs (more realistic value is 1.0850694 μs) by using Special Function Registers (TMOD, TCON, TH0 and TL0 registers) of 89C51 with 11.0592 MHz clock (Fig. 4).

3 Results

3.1 Bias Stability Measurement Result of ADCL-IFOG

Before bias stability measurement of ADCL-IFOG is shown in Fig. 1, it is so positioned that the scalar product of $\hat{A}$ and $\hat{\Omega}_{\text{earth}}$ in Eq. (1) equals to zero. The latitude, where the measurements are carried out, is 40.8° for Gebze / KOCAELI.

The ADCL-IFOG prototype was tilted at angle of $\alpha = 40.8^\circ$ from the northwards before bias stability and scale factor measurements, are shown in Fig. 5. In this setting of the sensing coil, the insensitive (lateral) surface vector of the sensing coil was parallel with the earth axis and the sensitive surface vector of the
Fig. 5 — Settling of the ADCL-IFOG before measuring the bias stability and determining the scale factor to avoid earth rotation rate induced contribution

sensing coil was perpendicular to the earth axis. Bias stability and scale factor measurements were carried out in this position of the ADCL-IFOG, which was less sensitive to the rotation rate of the earth. The errors arising from angular displacement of optical fiber wraps on the fiber mandrel was disregarded. Moreover, it should be known that the curvature of the sensing coil prevents the insensitive surface from being completely parallel with the earth axis for each point on the insensitive surface.

After completion of 3 hours conditioning of ADCL-IFOG, the bias stability measurements are carried out. In the measurements, the error voltage \( V_{DAC} \) is sampled and collected by 8½ digit voltmeter for a period of 6 hours as shown in Fig. 6.

Fig. 6 — Bias stability of the ADCL-IFOG at 23.0 °C

100 samplings, each of which is within a bandwidth of 1 Hz, constitute every voltage data, corresponding to bias rotation. The bias stability of the prototype is calculated with Allan Variance method;

\[
\text{AVAR}^2(t) = \frac{1}{2(n-1)} \sum_{i} \left[ V_{i+1}(t) - V_{i}(t) \right]^2 \quad \ldots(16)
\]

where \( \text{AVAR}^2 \) is Allan Variance as a function of time \( t \), \( V_{i} \) is the \( i^{th} \) average value of the error voltage \( V_{DAC} \) and \( n \) is the total number of data collected. The bias stability of the ADCL-IFOG was calculated as 1.38 (°/h) by using the data which form the bias stability graphic as shown in Fig. 6.

3.2 Scale Factor Measurement Result of ADCL-IFOG Prototype

In order to derive the scale factor of the ADCL-IFOG in terms of Sagnac phase nulling voltage \( V_{DAC} \) (error voltage) applied by LTC1667CG connected to
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89C51, it is subjected to the stable rotation with varying from 1 (°/h) to 15270 (°/h) by keeping the position which eliminate the earth rotation rate contribution. During the stage of the scale factor measurements of the ADCL-IFOG, the rotation rate applied by servo motor plate having an accuracy of 0.02 (°/h) is maintained stable until the binary data, which made Sagnac phase zero, is generated by microcontroller. The voltage outputs of the feedback circuit versus the stable rotation rate applied are shown in Fig. 7.

Considering 1000 μs phase step of LTC1667CG, 16383 steps of 14 bit resolution takes 16.4 s approximately. That is, the full voltage range to be applied to PZT is 0.0000 to 4.0000 V and this range is completed in 16.4 s. The rotation rate of 15270 (°/h) equals to ~ 4.2 (°/s) and therefore an angular displacement larger than (4.2 (°/s)×(16.4 s) = 68.9°) is allowed to nullify Sagnac phase shift for the ADCL-IFOG during the count up/down of microcontroller. Averaged scale factor of ADCL-IFOG is derived as 7.739 (°/h)/mV versus the applied rotation rate with a relative standard deviation of 0.71% [Fig. 8(a and b)].
4 Discussion

In this paper, the details belonging to an ADCL-IFOG are presented together with bias stability (long term stability) measurement and the determination of scale factor of the ADCL-IFOG prototype.

In order to avoid inherently non-linear behaviour of a conventional open-loop IFOG, which especially take places in larger Sagnac phase shifts induced by higher rotation rates, an ADCL-IFOG with a digital feedback circuit, composed of AD7714YN (operated in 16-bit resolution) and LTC1667CG (14 bit DAC) synchronously controlled by 89C51 microcontroller, was designed for use in the metrological purposes such as angle measurements together with precise frequency generator. For a Sagnac Phase Shift range of $0.00115^\circ$ to $17.57448^\circ$ in CW and CCW rotation directions, instead of an increasing trend of scale factor expected in a conventional open-loop IFOG which results from the demodulation of interferometer signal, to obtain ADCL-IFOG scale factor having a relative standard deviation of 0.71% showed that it had high linearity in dynamic range with a Sagnac Phase Shift of $35.41^\circ$. With relative standard deviation of 0.71%, the averaged sensitivity of the ADCL-IFOG in unit of voltage (error voltage) was calculated as $129.21 \mu \text{V}/(^\circ/\text{h})$, which equals to a scale factor (SF) of $7.739 (^\circ/\text{h})/\text{mV}$.

For the ADCL-IFOG, minimum rotation rate of $1.90 \ (^\circ/\text{h})$ was nullified by applying the feedback voltage, which corresponds to the opposite phase shift to the rotation induced Sagnac phase shift, to PZT through the digital feedback circuit with LTC1667CG and a bias stability of $1.38 \ (^\circ/\text{h})$ was reached with a maximum peak to peak noise of $3.88 \ (^\circ/\text{h})$ at $23.0^\circ\text{C}$. In order to evaluate the temperature dependent-performance of the ADCL-IFOG in terms of bias stability and peak to peak noise, the temperature of the location, where the ADCL-IFOG was settled, was varied among $23.0^\circ\text{C}$-$40.0^\circ\text{C}$. Even though relative increase became in noise of ADCL-IFOG, peak to peak noise and bias stability didn’t exceed $4.60 \ (^\circ/\text{h})$ and $1.65 \(^\circ/\text{h})$.

Considering the earth rotation rate of $15.041 \ (^\circ/\text{h})$ according to WGS84 (World Geodesic System 1984), the bias stability value, scale factor linearity, minimum rotation rate and the temperature dependence, the ADCL-IFOG prototype can be proposed for an absolute angular displacement sensor in metrology and other related fields.

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