INTERFEROMETRIC CLOSED-LOOP FIBER OPTIC GYROSCOPES WITH LINEAR OUTPUT

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Abstract

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The Optolink's single-axis and three-axis fiber optic gyroscopes are described. The results illustrate the versatility of the technology, showing its potential to meet both the low-cost, compact sized needs of tactical guidance, as well as the very high performance needs of inertial navigation and precision applications. The optical and electronic blocks of closed-loop gyroscopes with integrated optic components are considered.

Introduction

The interferometric fiber optic gyroscopes (FOGs) are well known as sensors of rotation, which are based on Sagnac effect [1], and have been under development for a number of years to meet a wide range of performance requirements. As with ring laser gyroscope (RLG), FOG can be used in higher reliability and longer lifetime, as well as in more severe environment due to its having no revolving component. Relative advantages of the FOG over the RLG are the lack of a high-voltage power supply requirement, the elimination of mechanical dither and its associated reaction torques, and the ability to more easily obtain small angle quantization.

The development of FOGs for both the high performance inertial navigation market and the lower performance interceptor grade market has shown the FOG to be a rotation sensor with unique capabilities [2]. Optolink Ltd. developed, designed and started the industrial fabrication of the family of closed-loop fiber optic gyroscopes for sensor of rotation rate. Single-axis and three-axis FOGs of three different performance classes (of high precision navigation grade in the 0.01-0.1 °/hr range, tactical grade 0.1-1 °/hr and intermediate grade 1-10 °/hr) have been developed. Their null-centered operation and digital output promise greater scale factor accuracy and dynamic range than its open-loop counterpart, making them ideal for many applications.

1. Single axis gyros

1.1. Configuration

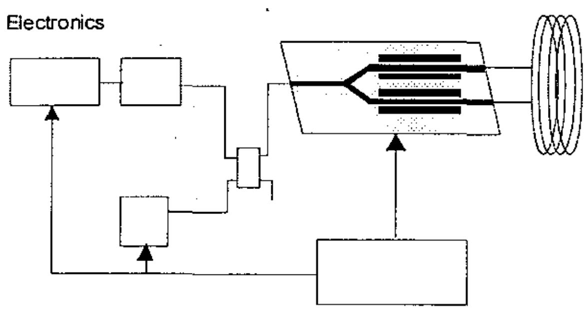

Fig.1. Minimum configuration of single-axis gyroscope SLD– superluminescent diode, DP – depolarizer, FS – fiber splitter, PD– photodetector, MIOC – multifunction integrated optic chip

Our single-axis FOGs have so-called minimum configuration (Fig.1) that provides reciprocal optical paths for two beams counter-propagating in a fiber loop. The FOG consists of the one Light Source, one Photodetector, one 1:1 Fiber Splitter (Coupler) to divide the light into two parts, one ring interferometer to sense angular rate, and printed circuit boards installed signal processing circuits.

The ring interferometer consists of a multifunction integrated optic chip (MIOC) and polarization maintaining (PM) fiber coil. The MIOC is a three-port optical gyrochip providing three functions. First, it polarizes the propagating light to reduce bias instability due to polarization non-reciprocity. Second, it splits the light into clockwise and counterclockwise waves, each with equal optical power and

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recombines them with a Y-junction waveguide. Third, with electro-optical phase modulator, it applies a biasing phase shift between the counter-propagating beams. PM fiber is used in order to reduce both the drift caused by the polarization cross coupling and the drift caused by earth's and outside magnetic field via the Faraday effect.

In single-axis FOGs developed by Optolink, the wideband integrated optic phase modulators placed at both arms of MIOC are employed to introduce phase ramp modulation, thus enabling close-loop operation. The output of the photodetector, in this case, is converted to a discrete signal and then demodulated. The output of demodulator then serves as an error signal which is effectively integrated and used to generate a phase ramp signal of slope proportional to the rotation rate. One loop closure scheme developed by Optolink uses a digitally synthesized sawtooth (serrodyne modulation) of 2π amplitude in optical phase shift. In this case the Sagnac phase is compensated by saw-tooth modulation of light with calibrated amplitude 2π and frequency f, determined from well-known equation [1]:

$$f = \frac{D}{n\lambda}\Omega, \tag{1.1}$$

where Ω is a rotation rate, D – diameter of fiber coil, n- effective refractive index of waveguiding mode, λ - wavelength.

The frequency of resulting ramp is then a digital measure of the rotation rate, with each ramp reset proportional to the angular turned, i.e. one ramp is equal to $\frac{n\lambda}{D}$.

1.2. Optical block of single-axis FOGs

The accuracy of FOG depends strongly on parameters of optical block. The device noise is smaller the larger is output power of SLD and smaller optical losses at all optical components, including PM fiber. The minimal measured rotation rate depends on polarization crosstalk h and beat length L_p of PM fiber as following [4]:

$$\Omega_{min} \sim \frac{\sqrt{hL_p}}{DL}. \tag{1.2}$$

So, the main our activity was directed to reduce optical loss, polarization crosstalk and beat length in PANDA fibers. Table 1 shows the present parameters of our PM fibers.

Table 1

Parameters of Optolinks PM fibers

Operating wavelength	0.83 μm	1.55 μm
Mode Field Diameter	4.5 μm	6.5 μm
Cladding Diameter	80 μm	80 μm
Coating Diameter	120÷160 μm	120÷160 μm
Numerical Aperture	0.15	0.13
Polarization crosstalk (h-Parameter)	$<10^{-5}$ /m	$<10^{-5}$ /m
Attenuation	< 3 dB/km	< 2 dB/km
Cutoff Wavelength	680m-780 nm	1250nm-1450nm
Beat Length	<3mm	<3mm
Stress Type	PANDA	PANDA

The four families of single-axis FOGs having fiber coils with lengths 200 m (SRS-200), 500 m (SRS-500), 1000 m (SRS-1000) and 2000 m (SRS-2000) are developed. Quadrupole winding technique implies winding a coil from a single length of fiber, starting at the center of the fiber length, winding outward toward the ends, alternately from one or another of two supply spools, in a geometrically structured way. Indeed, optical fiber is elastic but very delicate. Elasticity implies a need to keep fiber always under constant tension during winding. Delicacy implies a need to control not only in-process fiber tension, but also fiber flexure or curvature, and a surface contacts. The coil is placed at temperature isolated plate with diameter from 80 to 230 mm depending on type of FOG (see Tables 2 and 3 below). Our fiber coil winding machine was specially developed basing on standard wire winding machine.

The isotropic fiber splitters are fabricated by fusion elongation method and have following parameters:
- power splitting ratio, % .... 50±1
- insertion power loss, dB 0.1

Well-known Lyot fiber depolarizer was taken as a basis of depolarizer design. The technology of manufacturing of this element provides achievement of the following parameters:
- optical power loss, dB .... < 0.5;
- residual light polarization at the width of a spectral line 15 nm, %........... < 0.1.

MIOCs are fabricated on $LiNbO_3$ crystals by high-temperature proton exchange method [3]. This technique enables one to achieve following parameters of MIOC:

- half wave modulation voltage .... < 2 V (λ=0.83 μm) and <3 V (λ=1.55 μm)
- polarization extinction ratio .... < -50dB
- intensity modulation: .... < 0.2%
- insertion loss (for depolarized light) .... < 7 dB

As a light source is used Superluminescent diode (SLD) ILPN-330-4, which is produced by the enterprise "Inject", Saratov. The SLD contains the following components:

1. Superluminescent diode based of double heterostructure GaAs/GaAlAs, which have an absorbe layer in the active area. Such design of SLD provides practically smooth spectrum with halfwidth around 30 nm and up to 2 mW of optical power launched into the single-mode fiber pigtail.
2. Microcooler on the base of Peltier elements for maintaining SLD crystal temperature in the given range at joint operation with the thermal control device.
3. Thermoresistor for error signal formation in the thermal control device.
4. Silicon p-i-n photodiode in the feed-back circuit of light power stabilization.

All components in the ILPN -330-4 SLD are placed in the standard hermetic case, with electric and optic pressure seals.

A photodiode FP1-850 K ("Inject", Saratov) on the basis of silicon p-i-n structure is used as a photodetector. Photodiode has electric current sensitivity to the light at wavelength λ = 0,835 μm not less than 0,3 A/W with delay time of a pulse signal front no more than 2 ns. The photodiode is pigtailed with multimode fiber and is placed in the hermetic case.

The integration of MIOC to optical block is produced by direct coupling two output channel waveguides with ends of PM fiber coil and by coupling of input channel waveguide with isotropic fiber splitter. Note, the used length of fiber splitter is enough for spatial filtration of radiation.

The decision to operate the present FOGs in the 830 nm wavelength region is based on the fact that the cheapest light sources with the highest reliability of a mass production are available in this wavelength region.

There are two main sources of scale factor errors: (i) the finite flyback time and (ii) the nonstability of phase amplitude [4]. To avoid influence of first factor we used the special transformation in the circuit, which creates a control voltage signal for MIOC. In our scheme the flyback time excludes from transmission characteristics of electro-optical modulator. The nonstability of phase amplitude is minimized by creating the astatic follow-up system. The response of device on periodic signal with calibrated constant period is considered as an error signal. Special circuit, independently on FOG moving, generates this periodic signal securing the zero error of stabilization of phase saw-tooth at 2 π value at stationary rate and negligibly small error of this value at dynamic rate.

1.3. Single-axis FOG performance

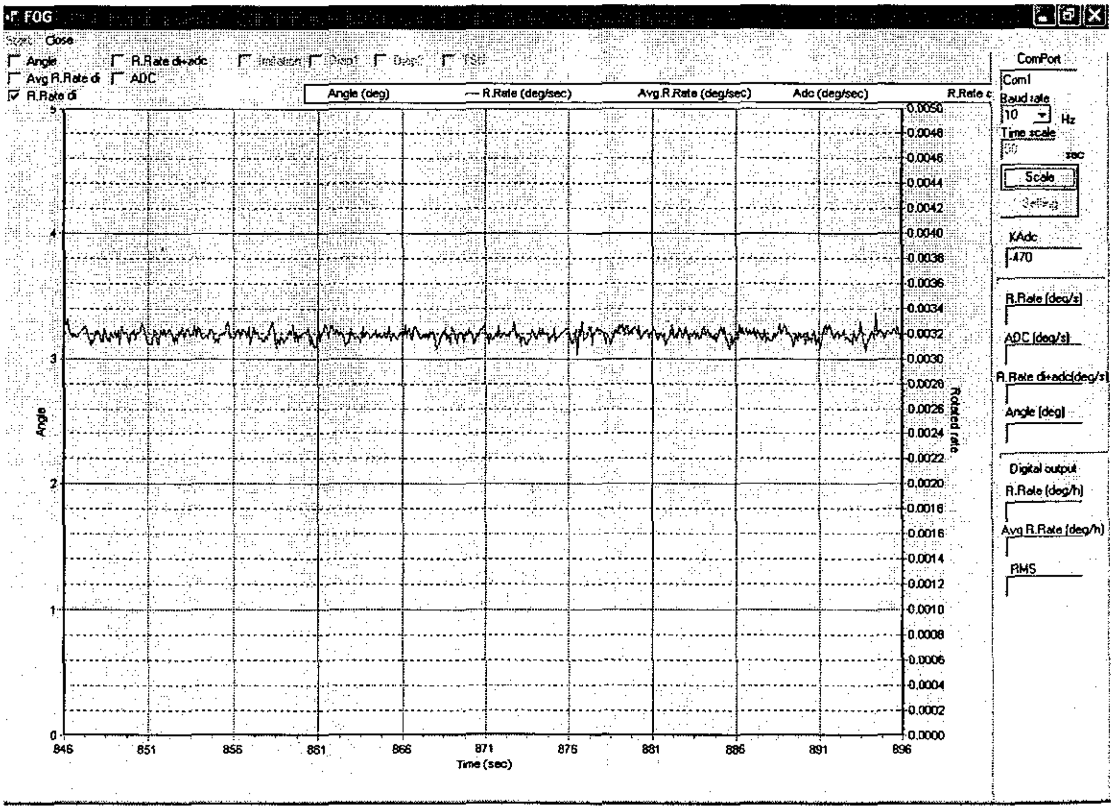

Fig.2. Uncompensated room temperature data for SRS-1000 device

Fig.2. illustrates the performance of our SRS-1000 FOG. Here the uncompensated output is plotted as a function of time. The Bias drift is less than 0.1 deg/h.

The bias stability is achieved by using PM optical fiber as well as MIOC with parameters mentioned above and also, by reducing losses of fiber fusion splicing. To reduce bias drift, appeared due to drift at electrical circuits, the data processing at all cascades, except integrator of main follow-up system, is carried out at alternating signals. The integrator is fabricated at precision integrated circuit with small thermal noise which secures the bias repeatability of output signal less then 0.002 deg/h at working temperature interval.

Fig. 3 shows the bias stability of SRS-500 FOG with six running.

The single-axis gyros can be applied to the gyrocompass system. Indeed, FOGs are able to identify the direction of the earth's rotation axis (i.e. north-finding). In the gyrocompass system, the FOG is rotated so that its sensing axis may scan the horizontal projection of the earth's rotation rate. The fiber sensing loop of the FOG is placed perpendicular to the horizon and rotated around its vertical axis to allow the earth's rotation rate to be measured in each direction. This measurement produces a sinusoidal signal in which values of zero correspond to the west and the east, and maximum and minimum values - to the north and the south, correspondingly (Fig.4). Amplitude of this signal is the projection of the earth's rotation rate at the local horizon, and its phase reflects the initial direction which is to be found.

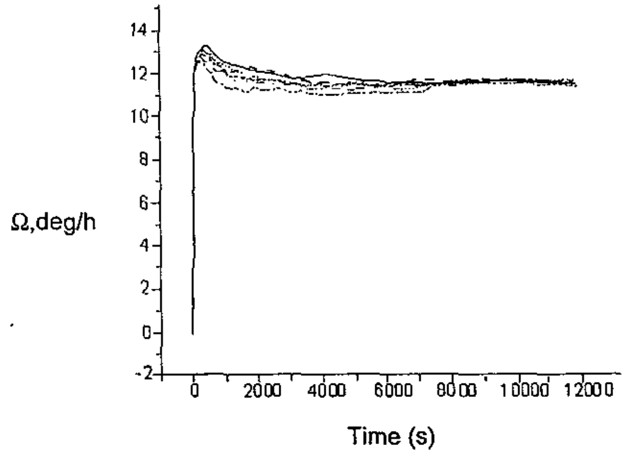

Fig.3. Bias stability of SRS-500 FOG with six running

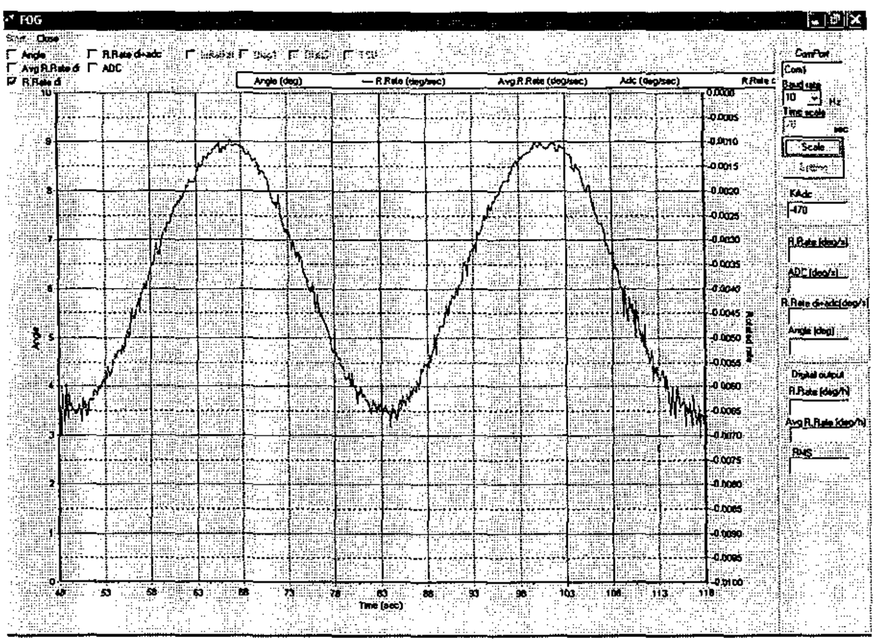

Fig.4. Output of SRS-1000 FOG with rotation in gyrocompass regime, so that its sensing axis scans the horizontal projection of the earth's rotation rate

Table 2

Parameters of Optolink's single-axis fiber optical gyroscopes

Parameter	SRS-2000	SRS-1000	SRS-500	SRS-200
Range of measured angular rate, °/sec	±10	± 30	±100	±200
Bias drift at fixed temperature, ° /h	<0.01	<0.1	<1.0	<10.0
Scale factor repeatability, %	≤ 0.01	≤ 0.02	≤ 0.02	≤ 0.05
Bandwidth, Hz	10	10-30	100	100
Random walk, ° /√h	≤0,001	≤0,003	≤0,005	≤0,01
Length of fiber coil, m	2000	1000	500	200
Weight (net), kg	1.2	0.8	0.8	0.8
Dimensions, mm	Ø 250×40	Ø150×40	Ø 150×40	Ø 150×40
Output	RS232	RS232	RS232	Analog

2. Three-axis gyros

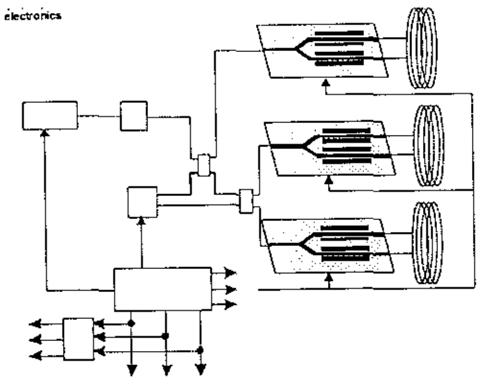

Fig. 5. Configuration of three-axis FOG.

Our 3-Axis FOG adopts just one light source for three fiber coils.

Our 3-axis FOGs have also minimum configuration (Fig.5) that provides reciprocal optical paths for two beams counter-propagating in a fiber loop. The FOG consists of the one Light Source, one Photodetector, two Fiber Splitters to divide the light into three parts, three ring interferometer to sense three orthogonal angular rates, and printed circuit boards installed signal processing circuits.

Block of electronics produced three voltages U_1, U_2 and U_3 for saw-tooth phase modulation for compensation of the Sagnac phase as well as for making constant phase difference between two waves.

In this case the measured rotation rate is determined as following:

$$\Omega = \frac{\lambda n}{\pi D}\varphi_{rs} f \tag{2.1}$$

where φ_{rs} and f are amplitude and frequency of saw-tooth, respectively.

In our three-axis FOG a frequency is stabilized by quartz resonator so, f = const. Therefore, rotation rate can be determined by measuring amplitude of saw-tooth $\varphi_{rs} = \frac{\pi D}{\lambda n f}\Omega$. This value is determined by measuring voltage U, which create this amplitude of saw-tooth. In this case

$$\varphi_{rs} = K_{PM}\, U, \tag{2.2}$$

where $K_{PM} = \frac{\pi}{V_\pi}$ – efficiency of phase modulation, V_π – half-wave voltage. Therefore

$$U = \frac{V_\pi D}{\lambda n f}\Omega \tag{2.3}$$

So as V_π is proportional to wavelength λ, the scale factor of FOG does not depend on λ. This is worth because temperature stability of FOG is increasing.

In our three-axis gyro the modulation switching with frequency 1 KHz is realized. This uses the fact that the each of three channels provides rate output only when an electrical modulation signal is applied to the phase modulator in the light path of interferometer. Therefore, simple switching of an electrical signal is used to activate only one axis at a time $\approx$333 μs. In a consistent design the same electrical functions are used for all axes in a time sequence, which on the other hand avoids any crosstalk between the axes as only the functions for one axis are active at the same time. With the exception of the electrical switches, which are readily available, and a small overhead of digital logic to control the switching, the same optical configuration and the same signal processing scheme are used as in the single-axis FOGs. Analog to digital processor (ADP) transfers analog outputs A1, A2 and A3 to digital output D1, D2 and D3 with RS485 interface.

Fig.6 illustrates the stability of our TRS-500 FOG. Here the uncompensated output is plotted as a function of time. The Bias drift is less than 5 deg/h.

Our three-axis gyros sense earth rotation rate and also can be applied to the gyrocompass system. Fig. 7 shows the output from two axis (X and Y) while gyro is rotating around its vertical axis Z. This measurement produces a two sinusoidal signals with phase shift π/2 in which values of zero correspond to the west and the east (Fig.7).

Table 3

Parameters of Optolink's three-axis fiber optical gyroscope TRS-500

Parameter	Three axes TRS-500
Range of measured angular rate, ° /sec	±500
Bias drift at fixed temperature (3σ), ° /h	<10.0
Scale factor repeatability, %	≤ 0.5
Bandwidth, Hz	From 100 to 500
Random walk, ° /√h	≤0,05
Length of fiber coil, m	500
Weight (net), kg	1.1
Dimensions, mm	110×110×90
Power consumption	<6W
Output	Analog and Digital RS485

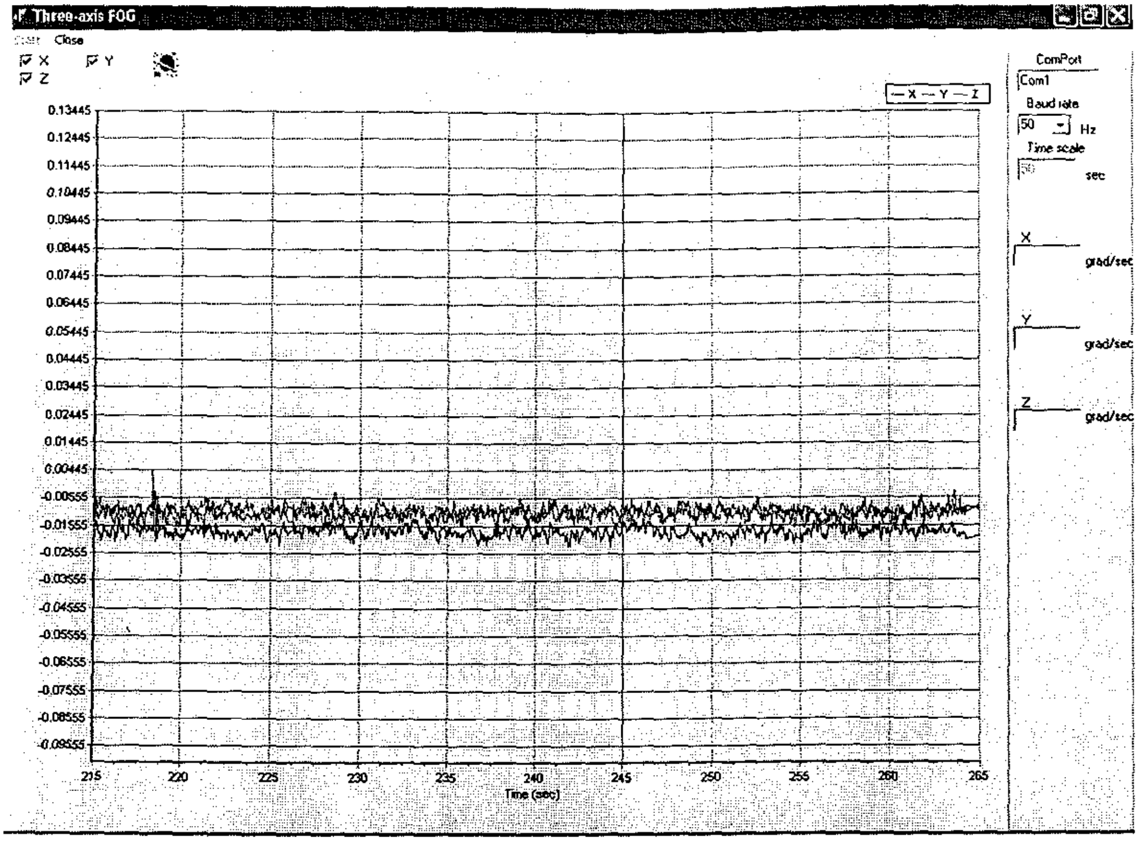

Fig.6. Uncompensated room temperature data for TRS-500 device

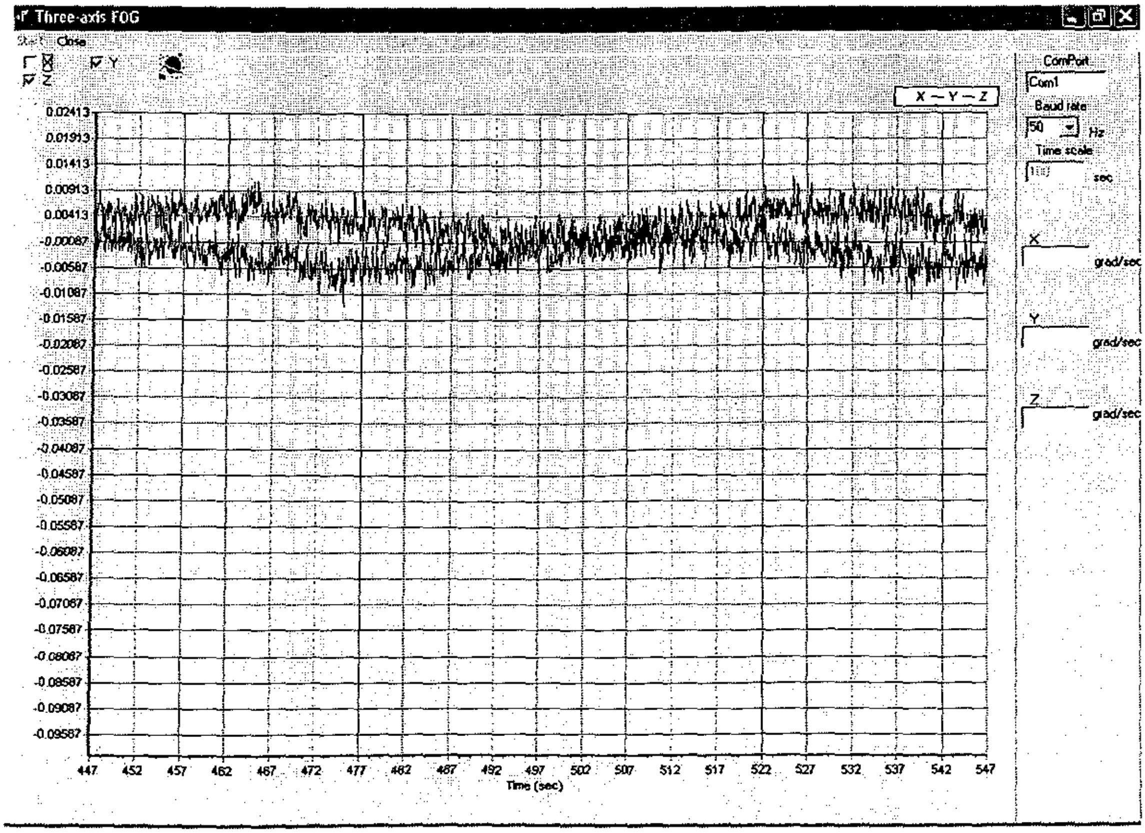

Fig.7. Output of TRS-500 FOG with rotation in gyrocompass regime, so that its sensing axes scan the horizontal projection of the earth's rotation rate

Fig.8 shows results of testing TRS-500 FOG at Acutronic three-axis rate table in the range from +100 to -100 deg/h.

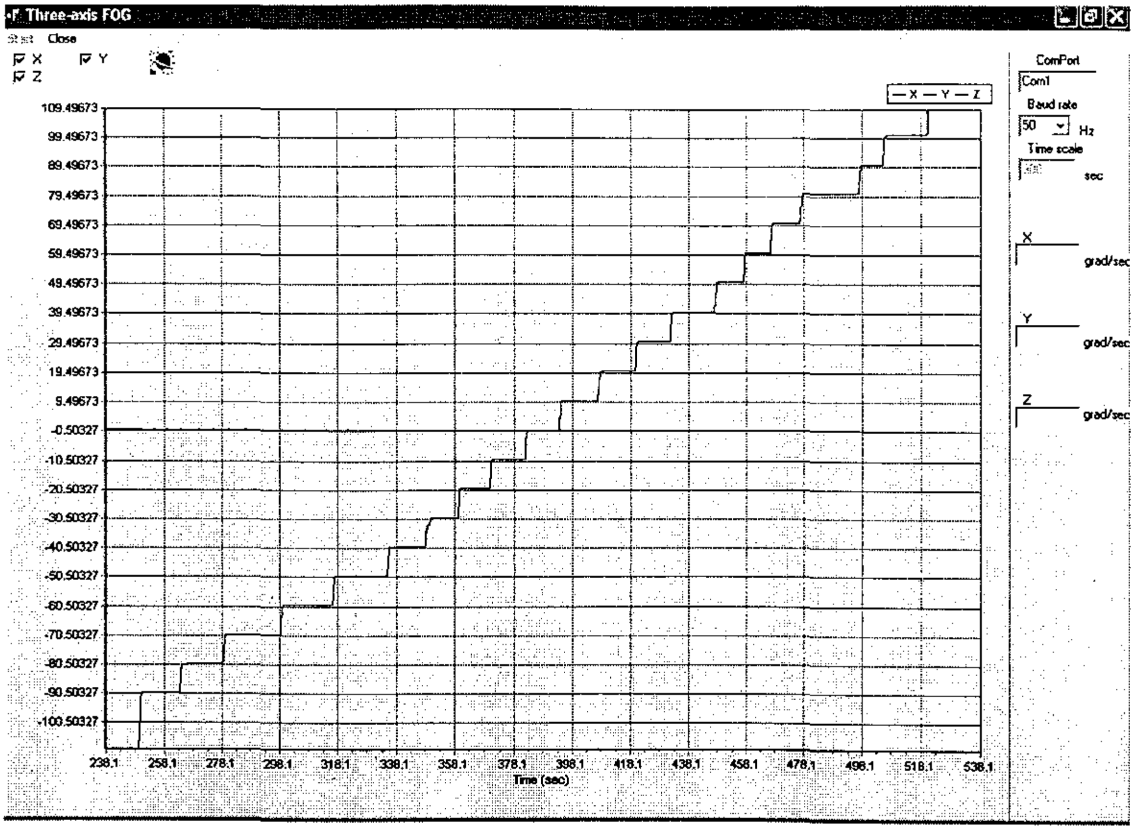

Fig.8. Outputs of TRS-500 FOG with changing rotation rate around only one axis

3. Influence of magnetic field

The drift of FOGs induced by the magnetic field through the Faraday effect has been estimated at company "Electropribor", St.Petersburg. Each measurement consists on six intervals with constant magnetic field strength 5 Oersted. One interval differs from another one by changing the sign of magnetic field. The maximum magnetic field induced drift around 0.1 deg/h/Oe has been obtained when magnetic field is orientated along sensitive axis of gyro. In other directions the influence of magnetic field is smaller.

Conclusion

Progress in fiber optic gyroscopes' development and manufacturing at Optolink is presented. Closed-loop gyroscopes of three different performance classes have been developed. Among them there is a relatively small 3-axis 1-10 deg/h FOG. Its null-centered operation and both analog and digital output provide greater scale factor accuracy and dynamic range than its open-loop counterpart, making it ideal for vehicles requiring high maneuverability, such as tactical missiles. The other two classes of closed-loop FOGs perform at 0.1 deg/h range and beyond. The first is a 1.0 to 0.1 deg/h gyro. A precision FOGs having bias performance better than 0.1 deg/h and even better than 0.01 deg/h are also developed. These two high performance devices can be used at military and commercial ship, aircraft and satellite inertial navigation systems as well as at north-found systems. A prototype of satellite system is scheduled to fly at different spacecrafts at 2004 and beginning 2005. The on-going development and engineering effort are concentrated on singe-axis and multiple-axis solutions with reduced size and optimized manufacturing cost.

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