Vol 16 No 3, March 2007
1009-1963/2007/16(03)/0735-05

Chinese Physics

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and IOP Publishing Ltd

Phenomena of optic-bound effect on fibre optic gyro

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(Received 22 May 2006; revised manuscript received 18 September 2006)

The optic-bound effect on fibre optic gyro (FOG) precision is analysed theoretically, and formulas describing the change of FOG light power under the action of optic-bound effect are given. It is confirmed that optic-bound effect is a main instantaneous non-reciprocity effect of FOG in addition to the Sagnac effect and can lead to a dynamic error of FOG in practical environments. An approach to suppressing or eliminating the error due to the optic-bound effect is presented and verified experimentally. The result shows that the approach is valid and the precision of FOG is improved observably.

Keywords: fibre optics, gyro, optic-bound effect, acoustic noise
PACC: 4281P, 4385

1. Introduction

The fibre optic gyro (FOG) is a kind of optical gyroscope based on the Sagnac effect. Under ideal conditions, the difference in phase between two coherent light beams in a fibre coil is induced by rotation uniquely. The light power into detector fluctuates due to the phase difference, and rotation rate then is resolved by the signal circuit. Theoretically, the absence of movable and wear parts in FOG can be free from vibration and shock compared with a spin gyro. However, fibres used as the transmission and sensing media in FOG are sensitive to vibration, shape change and magnetic field. Therefore, many other effects such as magneto-optical Faraday effect and optic-bound effect can affect the dynamic performance of FOG.[1−3]

Jet noise, aerodynamic noise and combustion noise generated by jet engine,[4] when FOG is used in aviation or space flight, are instantaneous acoustic sources which belong to vibration source and have high pressure level and high frequency.[5] The sound waves cause stress on fibre surface and then phase difference is produced by strain effect and optic-bound effect. These effects must be suppressed or eliminated in FOG because these transient nonreciprocal effects can be amplified by the asymmetry of fibre winding. This paper is devoted to the study of optic-bound effect in FOG theoretically and experimentally.

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2. Theoretical analysis of optic-bound effect upon coil

The optic path in FOG is a reciprocal architecture for reciprocity of clockwise (CW) rotation light and counterclockwise (CCW) rotation light. However, the length and refraction index of fibre change due to external pressure, which causes phase change as follows:[6]

$$\varphi = \beta L, \tag{1}$$

$$\begin{aligned}\Delta\varphi &= \beta\Delta L + L\Delta\beta \\ &= \beta L\frac{\Delta L}{L} + L\frac{\delta\beta}{\delta n}\Delta n + L\frac{\delta\beta}{\delta D_{\rm f}}\Delta D_{\rm f},\end{aligned} \tag{2}$$

where β is the propagation constant in fibre; L is length of fibre; n is refraction index of material in fibre, and $\Delta D_{\rm f}$ is the difference in diameter between fibres.

On the right-hand side of formula (2), the first term is for the strain effect and the second term is for the optic-bound effect. The third term can be ignored because of its little contribution.

Isotropic stress under the press, which is assumed to be P here on the surface of fibre can cause deformation, ε:[6]

$$\varepsilon = \begin{bmatrix}\varepsilon_x \\ \varepsilon_y \\ \varepsilon_z\end{bmatrix} = \begin{bmatrix}-P(1-2\mu)/E \\ -P(1-2\mu)/E \\ -P(1-2\mu)/E\end{bmatrix}, \tag{3}$$

where μ is the Poisson ratio, E is the Young's modulus of elasticity. Refraction index's variation along the axis of fibre is[7]

$$\Delta n = -\frac{1}{2}n^3\Delta\left(\frac{1}{n^2}\right), \tag{4}$$

where

$$\Delta\left(\frac{1}{n^2}\right) = \frac{1}{\Delta L}P_{ij}\varepsilon\Delta L. \tag{5}$$

Here, $P_{ij} = \begin{bmatrix} P_{11} & P_{12} & P_{12} \\ P_{12} & P_{11} & P_{12} \\ P_{12} & P_{12} & P_{11} \end{bmatrix}$ is the elastic coefficient of fibre, so

$$\Delta n = \frac{1}{2}n^3(P/E)(1-2\mu)(P_{11}+2P_{12})\Delta L. \tag{6}$$

The pressure on the surface of fibre can be caused by the propagation of acoustic noise through air. An acoustic wave equation may be described as

$$A = A_0\sin(\omega_{\rm a}t), \tag{7}$$

where A_0 is the maximum amplitude of acoustic wave, $\omega_{\rm a}$ is the angular frequency of acoustic wave, A is the amplitude of acoustic wave. The phase difference between the CW rotation light and CCW rotation light due to optic-bound effect is[8,9]

$$\Delta\varphi_1(t) = \delta\varphi_1\cos\left[\omega_{\rm a}\left(t-\frac{L}{2c}n\right)\right], \tag{8}$$

$$\delta\varphi_1 = \delta\beta P\frac{2c}{n\omega_{\rm a}}\left(\cos\frac{Ln}{2c}-\cos\frac{\omega_{\rm a}n}{2c}\Delta L\right), \tag{9}$$

where c is speed of light in vacuum, $\delta\varphi_1$ is the maximum amplitude of phase difference $\Delta\varphi_1(t)$.

When the light passes through an interferometer, the light intensity received by detector is described as[10]

$$P_{\rm d}(t) = P_{0\rm d}\{1+\cos[\varphi_{\rm s}(t)+\varphi_{\rm F}(t)+\Delta\varphi_1(t)]\}, \tag{10}$$

where $\varphi_{\rm s}(t)$ is the Sagnac phase shift, $\varphi_{\rm F}(t)$ is the compensation phase shift in closed-loop, $P_{\rm d}(t)$ is the optical power intensity in detector, and $P_{0\rm d}$ is the maximum amplitude of $P_{\rm d}(t)$.

In a closed-loop scheme, which includes preamplifying, A/D converter, digital demodulation, digital filter, and D/A converter,[4] the measured output of FOG, $D_{\rm out}(t)$, is

$$D_{\rm out}(t) = -\frac{2\pi LD}{\lambda c}\frac{2^N}{K_{\rm fp}V_{\rm pp}}\Omega(t), \tag{11}$$

where $K_{\rm fp}$ is the modulation coefficient of phase modulator, $V_{\rm pp}$ is the peak-to-peak amplitude of step wave, D is the diameter of fibre coil, N is resolution of D/A converter, and $\Omega(t)$ is the input rotation rate.

Under ideal conditions, the output is not related to the light source power. That is to say, when the closed-loop gain is large enough, the light source power will not influence the output, otherwise it is another story. The reason is that the feedback error signal of closed-loop FOG can be described as[10,11]

$$\Delta(t) = GP_{\rm d}(t)\sin\varphi_m\sin[\varphi_{\rm S}(t)+\varphi_{\rm F}(t)], \tag{12}$$

where G is the gain of the detection circuit, and $\varphi_{\rm m}$ is the amplitude of modulation signal. Under ideal conditions, the loop will work at null position

$$\Delta(t) = 0. \tag{13}$$

In practice, the nonsymmetrical existence of electrical device can lead to $\Delta(t)\neq 0$, with a small error Δ existing. When the loop is stable, we can obtain[11]

$$\varphi_{\rm F}(t) = \frac{\Delta}{GP_{\rm d}(t)\sin\varphi_m} - \varphi_{\rm S}(t). \tag{14}$$

The feedback signal has a certain relationship with $P_{\rm d}(t)$ and G.

From the derivation above, it is obvious that the length and the refraction index of fibre can vary with external pressure acting on the surface of fibre, which causes nonreciprocal phase difference $\Delta\varphi_1(t)$ and fluctuation of light intensity $P_{\rm d}(t)$, consequentially leading to the variation in the bias and drift.

3. Experimental verification of optic-bound effect on FOG performance

The derivation above argued that the effect of acoustic noise is a representative form of optic-bound effect in FOG. The experimental verification can be conducted through monitoring the change of gyro output within the acoustic environments. The test environments include free sound field and diffusible sound field. Free sound field is referred to the field where the sound waves transmit subject to the absence of reflection, while the diffusible sound field is opposite to the free sound field, namely the reflection is present. The free sound field is produced in an anechoic chamber and a stationary wave tube, while the diffusible sound

field test is carried out in a reverberation chamber.[4] The drift of FOG in experiment is 0.1°/h.

1) Anechoic chamber: The frequency of sound source is 250 Hz –8 kHz and the sound pressure level is 100 db. The FOG output indicates that the stronger noise appears in experiment and the peak-to-peak of bias variation is about 4°/h (Fig.1).

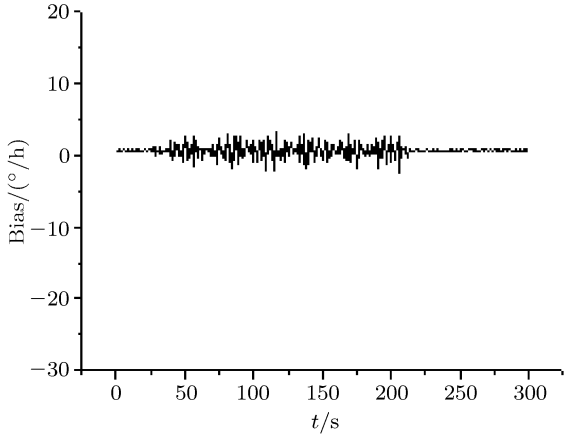


Fig.1. FOG output curve.

2) Stationary-wave tube: It can provide two types of sound sources. One is a broad-spectrum white noise with frequencies in the 50–100 kHz range and a sound pressure level of 160 db, the other is continuous swept signal with frequencies in the of 50 Hz–20 kHz range and a sound pressure level of 160 db. The FOG outputs are shown in Fig.2 and Fig.3.

From the figures above, it is obvious that the FOG output noise becomes high as sound pressure level and frequency increase, and bias changes at some frequencies.

3) Reverberation chamber: The maximal sound pressure level is 146 dB ± 1.5 dB in a frequency range of 50 Hz–20 kHz. Three FOGs are assembled on a holder of inertial measurement unit with a shield outside in three directions as shown in Fig.4.

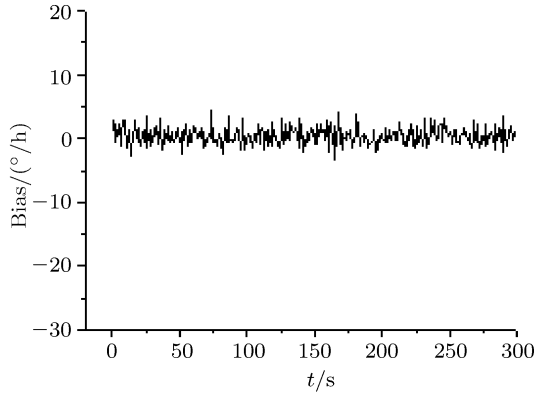


Fig.2. FOG output curve with a broad spectrum white noise.

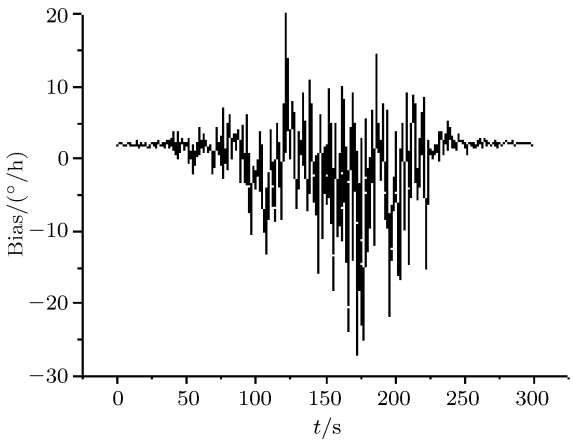


Fig.3. FOG output curve with sweep frequencies.

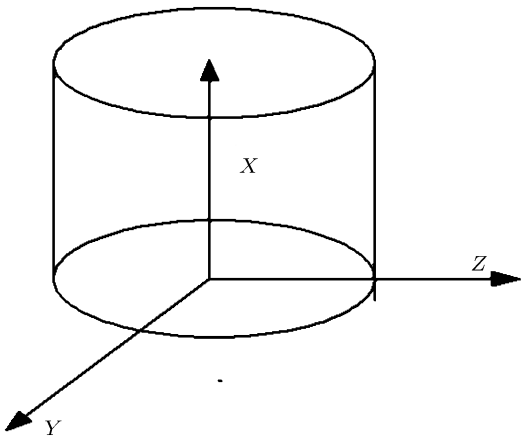


Fig.4. Input sensing axes directions of three FOGs.

The test results are presented in Table 1 and Fig.5, which show that the drift during test is almost 100 times as great as that before test, and the bias variation is approximately 4°/h.

Table 1. Numerical results of biases.

Test Process \ Bias(°/h)	x-axis	y-axis	z-axis
pre-test	2.12	2.59	1.27
undergoing-test	−1.76	−1.42	−1.85
post-test	2.23	2.63	1.23

The test results in the free and diffusible sound fields are as follows:

1) The bias and drift of gyro can change under the influence of acoustic noise.

2) The variation ranges of bias and drift are directly proportional to the press level of sound source.

The test results validate the derivation of formulas (10)–(14).

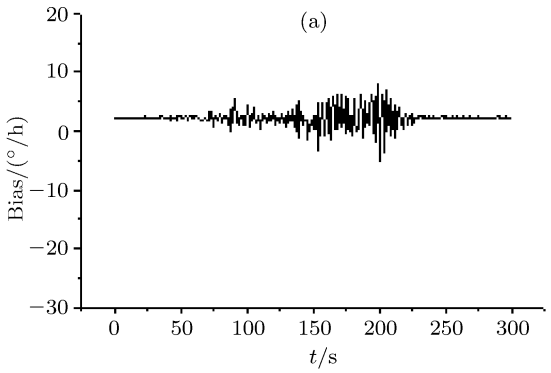


Fig.5(a). Bias in the x-axis direction.

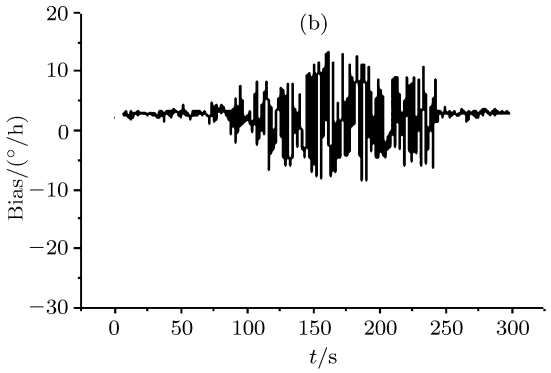


Fig.5(b). Bias in the y-axis direction.

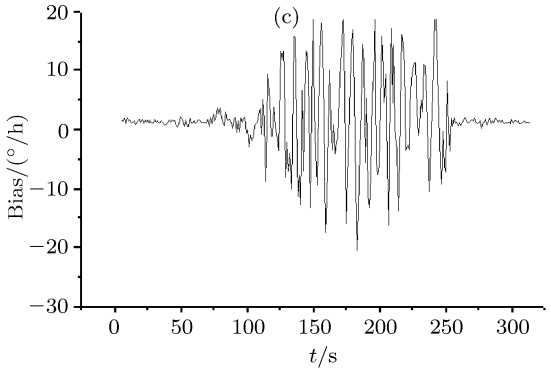


Fig.5(c). Bias in the z-axis direction.

To distinguish the influence due to the optic-bound effect on the surface of fibre coils from the influence due to other effect, the shell of y-axis and the housing of its coil were taken off, that is, the fibre coil was directly exposed to the diffusible sound field entirely. The bias variation is more than 20 °/h that is its big offset (Fig.6). Comparing with Fig.5(b), a conclusion assertion could be made that the above error is caused mainly by the strain induced by sound pressure and optic-bound effect on the exposing surface of the fibre coil. This conclusion can be verified in the following improved experiment.

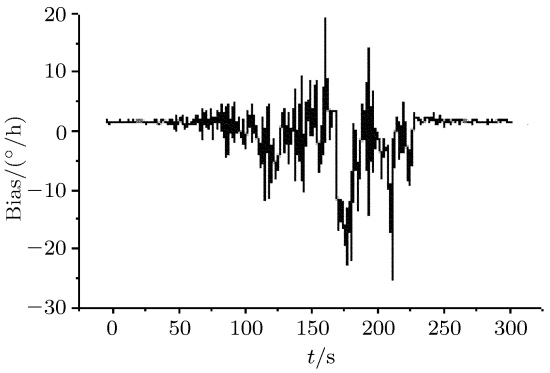


Fig.6. Bias without the shell and housing of coil.

4. Improving measures and experiment verification

The theoretical analysis and experimental verification above can confirm that the nonreciprocal phase difference is produced due to the optic-bound effect caused by air vibration and propagation when FOG is in strong noise environments. Therefore, the measures in two respects can be taken as follows:

1) Some measures introduced to solve pure vibration problems are proven to be effective, such as solidification of pig-tail of fibre coil and photo-electronics device, avoidance of resonance point by appropriately designing structures, and broadening the band width of system, fast response ability and compensation of output signal.

2) Optic-bound effect acting on the surface of fibre produces mechanical deformation of fibre and causes variation of optics parameters. To reduce and eliminate the effect of optic-bound on FOG, the fibre coil can be sealed or coated with an absorptive material on the surface, in addition to the symmetry and uniformity of fibre winding that must be guaranteed in craft. The experimental verification of this measure is shown in Fig.7.

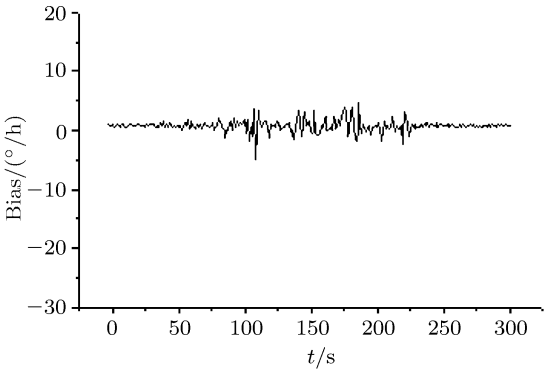


Fig.7. FOG output curve with absorptive material filled.

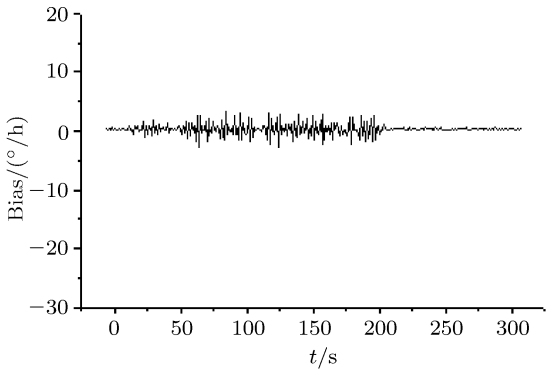


Fig.8. Improved FOG output curve.

Experimental results demonstrate that the optic-bound non-reciprocity effect can be suppressed in FOG, and the bias caused by it is less than 0.5°/h that can meet the requirement for a static accuracy of 0.1°/h (Fig.8).

5. Conclusions

The optic-bound effect is a non-reciprocal parasitic effect in FOG. The pressure caused by acoustic noise on the surface of fibre produces a phase difference. Therefore, some measures should be taken to suppress or eliminate the noise in practice. Experimental results verify that many methods, such as optimizing design and craft, strengthening the structure rigidity, sealing the fibre coil or coating some sound-absorbing material on the surface, are effective under acoustic environments.

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