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DESIGN NOTE

A comparative study of two types of feedback loop for stabilization of the scale factor in open-loop fibre-optic gyroscopes

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Abstract. An open-loop fibre-optic gyroscope with stabilized scale factor has been constructed with a spectrum-broadened laser diode as the light source. A comparative study of two types of servo loop for scale factor stabilization showed that the automatic gain control (AGC) loop is superior to the automatic power control (APC) loop.

The instability of the scale factor is one of the most serious problems encountered in open-loop fibre-optic gyroscopes (FOG). Kersey *et al* (1984), Kim and Shaw (1984), Moeller *et al* (1989), Oh and Kim (1988) and Ono *et al* (1990) have reported several techniques to solve this problem. Recently, we demonstrated a novel method which simultaneously reduced the phase noise of the FOG and stabilized its scale factor (Chien and Pan 1991). A spectrum-broadened laser diode was used as the light source. The scale factor was stabilized by employing an automatic gain control (AGC) loop. In this note, we report a comparative study of our method and the methods used by Moeller *et al* (1989) and Ono *et al* (1990). These workers stabilized the scale factor by controlling the output power of the laser diode. Our results show that the AGC loop is superior to the APC loop in scale factor stability for an FOG employing a spectrum-broadened laser diode as the light source.

Our method is based on the following. A phase modulation signal $\phi_m \sin \omega_m t$ is applied to a phase modulator in the fibre loop. The intensity of the laser diode output is also modulated by a sinusoidal waveform $1+K \sin \omega_s t$, where K is the intensity modulation depth. The output signal of the FOG at the detector, $I(t)$, can be expressed as

$$I(t)=P_0(t)\gamma(t)(1+K \sin \omega_s t) \times [1+\cos(\Delta\phi_m \sin \omega_m t-\Delta\phi_R)] \quad (1)$$

where $P_0(t)$ is the laser output power, $\gamma(t)$ is the instability of the polarization state of the FOG, $\Delta\phi_m=2\phi_m \sin(\phi_m \tau/2)$ and τ is the time delay of the fibre loop. We can extract two harmonic terms from equation (1) which are of interest to us. These are

$$I_{d1}(\omega_s, \omega_m=0)=P_0(t)\gamma(t)(1+K \sin \omega_s t) \times [1+J_0(\Delta\phi_m) \cos \Delta\phi_R] \quad (2)$$

and

$$I_{d2}(\omega_s, \omega_m)=2P_0(t)\gamma(t)(1+K \sin \omega_s t) \times J_1(\Delta\phi_m) \sin \Delta\phi_R \sin \omega_m t. \quad (3)$$

If $J_0(\Delta\phi_m)$ in equation (2) is set to zero by applying the phase-sensitive detection (PSD) technique to $I_{d1}(t)$ at ω_s, the demodulated voltage signal at the output of the PSD at ω_s is given by

$$V_{out1}(t)=G_1 K P_0(t)\gamma(t) \quad (4)$$

where G_1 is the conversion gain of the electronic circuit at ω_s. Similarly, the term $K \sin \omega_s t$ in equation (3) can be removed by using low-pass filtering with the PSD at ω_m. The PSD output signal at ω_m for $I_{d2}(t)$ is then

$$V_{out2}(t)=2G_2 P_0(t) J_1(\Delta\phi_m) \sin \Delta\phi_R \quad (5)$$

where G_2 is the conversion gain of the electronic circuit at ω_m. The scale factor of the FOG, S, in the limit of small $\Delta\phi_R$, is then

$$S=\frac{V_{out2}\ (\mathrm{mV})}{\Omega\ (\mathrm{deg\ h^{-1}})}=2G_2 P_0(t)\gamma(t) J_1(\Delta\phi_m) R \quad (6)$$

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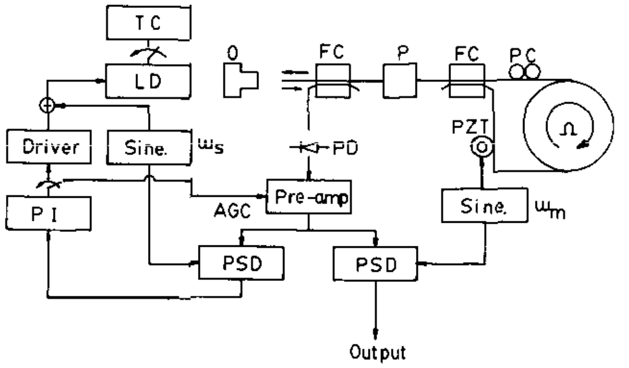

Figure 1. Experimental set-up of the FOG for scale factor stabilization. LD, laser diode; TC, temperature controller; O, objective lens; FC, fiber coupler; P, polarizer; PC, polarization controller; PZT, piezoelectric transducer; PD, photodetector; PI, proportional and integrating circuit; PSD, phase-sensitive detector; Sine.; sinusoidal waveform generator.

where $\Delta\phi_R = R\Omega$ and Ω is the rotation rate. The term $J_1(\Delta\phi_m)$ can be stabilized by controlling the amplitude of the phase modulation signal. The factor R depends on the wavelength of laser diode, which can be stabilized by a properly designed temperature controller. The product $P_0(t)\gamma(t)$ can be determined from equation (4) and is not influenced by the rotation rate of the gyroscope if the condition $J_0(\Delta\phi_m)=0$ is satisfied. $P_0(t)\gamma(t)$ can be stabilized by controlling either the output power, $P_0(t)$, of the laser diode, i.e. an APC loop, or the gain, G_1 and G_2 of the optical receiver, namely the AGC loop.

A schema of our experimental set-up is shown in figure 1. The laser diode used in this work was a single-mode device (Hitachi HLP-1400, $\lambda = 0.83$ µm). Its operating temperature and driving current were both stabilized. A deep current modulation signal at 1 MHz was injected into the laser diode to increase its spectral width. Optical feedback from the fibre end further broadened the laser spectrum. With the bias current in the range 105–114 mA, the spectral width of the laser was ≈20 GHz. The magnitude of the current modulation signal was adjusted such that a modulation index K of 70% was observed from the detector output. In order to simulate fluctuations in the polarization state, we employed single-mode fibre in the sensing loop fibre and a polarization controller (PC). The fibre length was selected such that the optical phase shift $\Delta\phi_R$ (deg) = $2.0\,\Omega$ (deg s^{-1}). A 40 kHz sinusoidal signal was applied to the PZT as the phase modulation signal. The amplitude of the modulation signal was adjusted such that the condition $J_0(\Delta\phi_m)=0$ was satisfied. This can be checked from one of the output signals, $V_{\mathrm{out}1}(t)$ by changing the rotation rate. The condition $J_0(\Delta\phi_m)=0$ was maintained by adding a servo loop to detect the change in either $J_1(\Delta\phi_m)/J_3(\Delta\phi_m)$ or $J_2(\Delta\phi_m)/J_4(\Delta\phi_m)$ and using the error signal to control the amplitude of the phase modulation signal. The drift due to the PZT (piezoelectric transducer) can be eliminated in this manner. The PSD output signal, $V_{\mathrm{out}1}(t)$, was then compared with a stable reference voltage, processed by a proportional and integrating (PI) circuit, and used to control either the driving current of the laser diode or the gain of the preamplifier of the photodetector. The PSD output signal $V_{\mathrm{out}2}(t)$ was used to monitor the system performance.

In the experiments examining the effectiveness of the two types of servo loop for scale factor stabilization, one of the two servo loops, i.e. the AGC loop or the APC loop, was closed. The drift of the laser power, $\Delta P_0(t)$, was simulated by turning off the temperature controller and allowing the temperature of the laser diode to vary. The fluctuations in the polarization state of the system, $\Delta\gamma(t)$, were generated by changing the axis of the polarization controller (PC). Figures 2(*a*)–(*d*) are the experimental results for different test conditions. In our experiment, $V_{\mathrm{out}1}(t)$ was stabilized such that $\Delta V_{\mathrm{out}1}/V_{\mathrm{out}1} \leqslant 1.0\times10^{-4}$. A rotation rate of $\Omega = 360°\,\mathrm{h}^{-1}$ was employed to generate an output bias voltage of 200 mV at PSD (ω_m). By monitoring $V_{\mathrm{out}1}(t)$, we observed good scale-factor stabilities, $\Delta S/S \leqslant 1\%$, for all cases. Nonetheless, the performance of the FOG with the AGC loop appears superior.

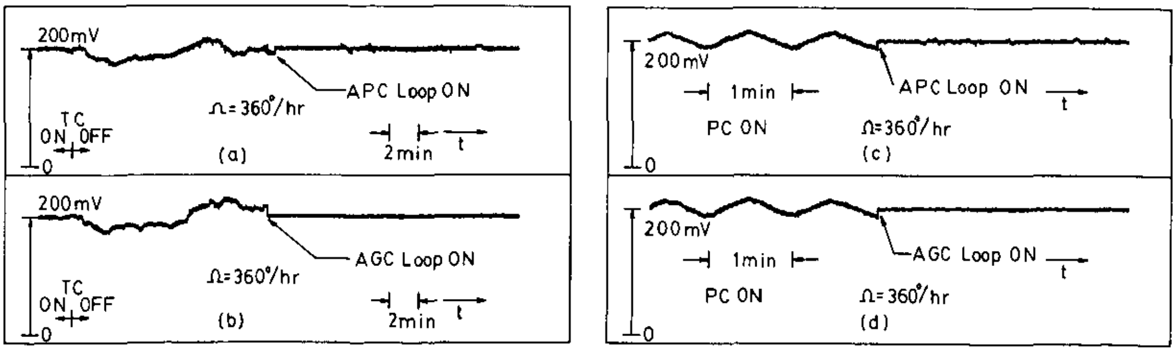

Figure 2. Recorder trace of the output signal of the gyroscope when the APC and the AGC loops were free-running or closed. The test conditions were: (i) a constant rotation rate of 360° h^{-1} was employed; (ii) the bias output signal of $V_{\mathrm{out}2}$ was adjusted to 200 mV. (*a*) Test condition: the temperature controller (TC) was OFF; the APC loop was ON. (*b*) Test condition: the temperature controller (TC) was OFF; the AGC loop was ON. (*c*) Test condition: the axis of the polarization controller (PC) was varied; the APC loop was ON. (*d*) Test condition: the axis of the polarization controller (PC) was varied; the AGC loop was ON.

This is probably due to the method we used to broaden the spectrum of the laser diode. The broadening factor depends on the bias current of the laser diode. With the APC loop, the bias current might be shifted to a region that is not optimal for spectrum broadening. As a result, the phase noise of the FOG would increase. On the other hand, the output power of the laser diode will decrease as it ages. If the APC loop is employed, the bias current must be increased to compensate for the drop in laser power. As a result, the wavelength of the laser will shift and the scale factor of the FOG will vary.

In summary, we have conducted a comparative study of the performance of two types of servo loop for stabilization of scale factor of an FOG employing a spectrum-broadened laser diode as the light source. We conclude that the AGC loop is superior to the APC loop in our method.

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