Modelling and Simulation of the Fiber Optic Gyroscope (FOG) in Measurement-While-Drilling (MWD) Processes

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Abstract: Gyroscopes are sensors that are used to determine angular velocity and position. Normally, magnetometers are used in horizontal drilling processes in oil industry to determine the azimuth of bottom hole assembly (BHA). Using magnetometers has some shortcomings in measuring earth’s magnetic field due to downhole ore deposits; drill string-induced interference and geomagnetic influences. To overcome these problems, we propose using Fiber Optic Gyroscope (FOGs) as a better alternative in measurement-while-drilling (MWD) processes for determining the azimuth of the BHA. Computer modelling and simulation confirm that the FOG could result in a better accuracy and performance considering the severe downhole conditions.

Keywords: Fiber Optic Gyroscope - Measurement While Drilling – BHA - ARW.

1. Introduction

Conventional methods in horizontal drilling processes normally employed magnetic surveying techniques (using magnetometer) to determine the BHA azimuth. Considering the shortcomings of using magnetometers, it seems that some inertial navigation devices are better solution for monitoring azimuth and therefore such devices can be used for horizontal drilling processes [6]. The devices must perform fittingly in high temperature and vibration as well as shock forces resulting from harsh conditions in drilling. Considering the severe conditions, the devices must have high mean time between failure and accuracy, hence they must not require frequent calibration and maintenance [2].

In this paper, first we introduce the principles of operation of the FOG and its components. Then the FOG modelling and simulation is discussed. Using the MATLAB environment, we analysed the result of the FOG simulations under severe conditions e.g. noise, shock force and vibration in measurement-while-drilling. Also the effect of the length of the fiber optic coil and electronic gain are investigated in the system performance.

2. The principle of operation of fiber optic gyroscope

The principle of operation of the FOG is based on Sagnac effect. In 1913, Sagnac showed that two light beams propagated along two opposite directions in a rotational loop interferometer make an optical path difference (equation 1) appear and consequently make a phase difference with respect to each other (equation 2). Both the optical path and the phase differences are proportional to the rotation rate [1,5].

\[ \Delta L = \left( \frac{Ld}{C_0} \right) \Omega \]  
\[ \varphi_s = \frac{2\pi}{\lambda} \Delta L = \left( \frac{2\pi d}{\lambda C_0} \right) \Omega \]  

In these equations, \( L \) is the length of the fiber optic coil and \( d \) is the diameter of the fiber optic coil, \( \Omega \) is the applied rotation rate, \( C_0 \) is the speed of the light in free space, \( \lambda \) is the peak wave length of the optical beam, \( \varphi_s \) is the sagnac phase shift and \( \Delta L \) is the optical path difference.

3. Components of fiber optic gyroscopes

The schematic diagram of a closed-loop FOG is shown on Fig.1. Fiber optic coil is chosen
as a single mode fiber optic so that the length of the given coil determines an acceptable precision [1]. A Super Luminescent Diode (SLD) with a relatively narrow spectral width and high emitting power is applied as an optical source. An optical directional coupler and a multifunction integrated optics chip (MIOC) are employed to divide and inject the beams of the optical source into two opposite directions of the fiber optic coil as well as to collect the returned emitted beams, electro optically modulate the light. This chip also polarizes the unpolarized light source. As a detector, a pin diode analyses the resulting interference beam and detect a voltage signal proportional to the beam intensity. An AC-bias modulator activates the phase shifter in MIOC for phase modulation of the propagated light beams in opposite direction. The phase modulation improves the sensitivity of FOG and makes a directional and sensitive output [1,2]. Serrodyne phase modulator is used to filter sagacc phase shift and drive the voltage controlled optical phase shifter, which cancels out the sagnac phase shift. The rotation rate can be extracted via the input signal to the voltage controlled optical shifter [1].

\[ \tilde{V} = K\phi_s \]  
with K is: \[ K = \frac{S_0 J_1(A)}{\lambda C_0} \].

Unfortunately, when the input rotation rate is increased, Sagacc phase shift also increases and the equation 4 will be no longer valid for this open-loop system. So, the system will be faced with sinusoidal nonlinearity. Serrodyne modulator is suggested to solve this problem [1]. This modulator produces a saw tooth signal of which frequency and slope are controlled by output signal \( \tilde{V} \). The modulator cancels out the Sagnac phase shift (\( \phi_s \)) caused by the rotation rate. The output signal of open loop configuration (\( \tilde{V} \)) also feedbacks to the Serrodyne modulator and fed to the voltage control oscillator (VCO) (figure1). Since Serrodyne modulator creates a phase shift between the propagated beams in very low value, AC-bias phase shifter is modelled as a gain block in forward path of the system. The Serrodyne modulator is modelled as an integrator block, which integrates the output of the AC-bias phase shifter and delivers the output of the FOG system. This output is fed back through a gain block to deliver an estimate of the sagnac phase shift (\( \phi_s \)) produced by the input rotation rate so that the loop is kept locked (figure2).

Thus if FOG is installed in BHA (Bottom Hole Assembly), it is able to measure azimuth angle of drill bit. To calculate the azimuth angle, one must integrate the output signal (rotation rate) of FOG.

4. FOG Modelling

In this paper, the FOG was modelled as a closed loop system in MATLAB environment. The block diagram of the system is shown in figure 2. According to sagnac equation, gain block \( \frac{2 \pi Ld}{\lambda C_0} \), converts the input rotation rate into Sagnac phase shift. AC-bias modulator also transforms the phase shift into an output signal (\( \tilde{V} \))[1],

\[ \tilde{V} = S_0 J_1(A) \sin \phi_s \]  
where \( S_0 \) is the power of the main optical beam, \( A \) is the amplitude of the sinusoidal signal produced by the AC-bias modulator activating the phase shifter, and \( J_1(A) \) is a 1st order polynomial of the Bessel function of 1st kind. For low values of the rotation rate and respectively low values of the sagnac phase shift, \( \sin \phi_s \) can be replaced by \( \phi_s \).

5. Disturbance inputs in a closed-loop control system

5.1. Disturbance due to Angle Random Walk (ARW)

ARW effect is modelled as white noise created in the photodetector and considered as disturbance input to the system through the same model of that (figure2). This suggests that AC-bias demodulation and electronic gain affect the output of the detector before it is delivered to the output of FOG [3, 5,7].
5.2. Disturbance due to shock forces

At the time of the penetration of drill bit, the effect of the shock force is applied on that due to the load of hard rocks. Shock forces are considered as pulses with high amplitude $F_s$ and short time duration $\Delta t$ and have an instantaneous effect on the output of FOG. The rotation rate corresponding to this shock force is obtained as the following equation [8]:

$$\Omega_s = \frac{F_s \Delta t}{m_c r_0}$$

(5)

where $m_c$ is the mass of the drill collar and $r_0$ is the outer radius of that.

These shock forces are applied as a disturbance input to the closed-loop model of FOG (figure 3).

5.3. Disturbance due to mud pump noise

Circulation of drill mud within drill string can create this vibration effect. In fact, this vibration mainly originates in mud pump noise. The pressure signal of the mud pump noise is taken as sinusoidal signal with frequency $f$ and maximum amplitude $A_{\text{max}}$ as follows:

$$p(t) = A_{\text{max}} \sin(2\pi ft)$$

(6)

Also the corresponding angular velocity resulting from mud pump noise in FOG is expressed as follows [4]:

$$\Omega_m = \frac{A_{\text{max}} r_i \cos(2\pi ft)}{2m_c}$$

(7)

where $m_c$ is the mass of the drill collar and $r_i$ is the internal radius of it.

The pressure signal of the mud pump noise is also applied as a disturbance input in the closed-loop model of FOG (figure 4).

5.4. Disturbance due to bending moment

When the center of gravity of the drill collar is not exactly aligned with the hole center, the centrifugal force makes the drill collar get bent and produce this vibration effect. The bending vibration makes the most effect on FOG output. The angular velocity corresponding with the occurred bending moment is expressed as follow [9]:

$$\Omega_B = \frac{B \Delta t}{m_c r_0^2}$$

(8)

where $B$ is the bending moment.

Bending moment is also applied as a disturbance input in the closed-loop model of FOG (figure 5).
As shown in figures 3, 4, and 5, the rotation rates $\Omega_s$, $\Omega_m$ and $\Omega_v$ are considered as disturbances to the original system and are incorporated into the FOG model in the same manner as the angle random walk, except that the gain in the numerator of the these systems with parallel configurations includes the gain block $\frac{2ndLd}{\lambda C_0}$, which describes the linear relationship between the Sagnac phase shift and the applied rotation rate [2].

6. Simulation Results

In this section, the main affecting factors on the function of FOG are studied. To do so, first the effects of the length of the fiber optic coil and the electronic gain on FOG sensitivity and bias drift are simulated. Then the simulation is carried out to find the effect of ARW and severe drilling conditions (like shock forces and vibrations) on the FOG output.

In each simulation, an abrupt change in the input rotation rate was modelled as a unity step input and the resulting step response was analysed. Simulations were made by means of simulink toolbox of MATLAB software.

6.1. Simulation of FOG sensitivity and bias drift.

Fig.7 shows the FOG step response for different values of the fiber optic coil length while keeping $G=50000$

Fig.8 shows the FOG step response for different values of the electronic gain while keeping $L=500$

Results: more increase in G or L, more increase the FOG sensitivity but reduce the rise time and the bias drift.

6.2. Simulation of the effect of ARW

The FOG step responses to the noise actions (ARW effect) as a disturbance input of FOG closed-loop system for two different gains are shown in figures 7 and 8.

Result: reducing the electronic gain reduces the noise level at the FOG output but increases the rise time and the bias drift.
6.3. Simulation of the effect of shock forces

In this section, a drill collar with an outer diameter: 5", length: 30 ft and weight: 722 kg is considered and a shock force is applied with an amplitude of 1000g[N] at the time $t=20s$ with a time duration of 0.01 second. This force is considered as disturbing input into the operating system ($g=9.81m/s^2$). According to the previous studies, such force can be considered as the maximum shock force in drilling.

![Fig.11. FOG output signal (containing ARW) with the 1000g shock force at t=20 s for a duration of 0.01 s.](image)

Result: clearly, the FOG can perform properly with a reasonable accuracy under the effect of short-duration shock forces up to 1000g[N] (figure 11).

6.4. Simulation of the effect of vibration due to the mud pump noise.

In this section, a drill collar with an inner diameter of 2.25", length: 30 ft, and weight: 722 kg is considered. The mud pump noise is simulated as a sinusoidal signal with a frequency of 1.7 Hz and a maximum amplitude of 200 psi and applied as a disturbing input into the system.

![Fig.12.FOG output signal (containing no ARW) with the effect of the mud pump noise at the $G=90000$](image)

![Fig.13.FOG output signal (containing no ARW) with the effect of the mud pump noise at the $G=45000$](image)

Result: It is clear that the most electronic gain, the more increase in FOG sensitivity to this vibration effect. In both curves (figures 12 & 13), it can be seen that the FOG signal demonstrates itself as an envelope to the mud pump noise.

6.5. Simulation of the effect of bending vibration

In this section, a drill collar with an outer diameter of 5" is considered and a rotational bending moment with approximate amplitude of $\pm 10000$ ft-lb is applied as a disturbing input into the system. According to the studies made, this moment can be considered as the maximum bending moment in drilling.

![Fig.14.FOG output signal (containing no ARW) with the effect of bending vibration at $G=90000$](image)

![Fig.15. FOG output signal (containing no ARW) with the effect of bending vibration at $G=45000$](image)

Result: It is clear that an increase in electronic gain increases the FOG sensitivity to this vibration effect.
7. Conclusion remarks

In this paper, the application of microelectronic fiber optic gyroscopes in horizontal drilling was studied. In order to study on the effects of hostile downhole conditions and various parameters on the function of FOG, a quantitative model was introduced and examined. The results of this study showed that desired accuracy could be achieved by increasing the length of fiber optic coil and electronic gain. This clearly improves FOG sensitivity and decreases bias drift.

As it was observed, the considerably high value of electronic gain increases the noise (ARW effect) and makes FOG more sensitive to the vibrations and shock forces. In hostile downhole environment, FOG can operate with an acceptable precision under the effect of shock forces of approximately 1000g[N] in limited duration. Although vibrations due to mud pump noise creates many errors in FOG output, some of signal processing techniques can be applied to extract FOG signal and to decrease the effects of vibrations. On the other hand, bending vibrations are natural in severe drilling environment and never omitted completely from FOG output. Its effect increases when electronic gain increases. However, if vibrations and shock forces are controlled via shock absorbers and stabilizers, remarkable improvement in FOG function will be achieved. Thus one can come to conclusion that FOG can be a reliable and inexpensive replacement of magnetometers in MWD borehole surveying.

References