Modeling and analysis of fiber optic gyroscope dynamic north-finding algorithm based on Simulink

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Abstract: In view of the problems such as the low automation degree and low precision in the traditional fiber optic gyroscope(FOG) static north-finding method, the in-depth analysis of the FOG dynamic north-finding principle and algorithm was focused on. The simulation model of FOG dynamic north-finding algorithm with least square method by points was established based on Simulink toolbox in MATLAB, and then the turntable rotation speed and sampling frequency which affected obviously the FOG dynamic north-finding precision, were simulatedly calculated and optimally analyzed as the key consideration. The simulation and calculation results show that, in the case of adopting the proposed parameters, when the turntable rotation speed is 4.5–8.5 (°)/s and the sampling frequency is about 50 Hz, the FOG dynamic north-finding system can reach higher precision. The simulation model and the research conclusions can provide theoretical reference for the design of FOG dynamic north-finding system. Meanwhile, it also provides reference for the theoretical research and concrete realization of the FOG dynamic north-finding system.

Key words: optical fiber gyroscope; dynamic north-finding; Simulink; algorithm modeling
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基于 Simulink 的光纤陀螺动态寻北算法建模及分析

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摘　要: 针对传统光纤陀螺静态寻北方案中存在的自动化程度较低、精度不高等不足,对光纤陀螺动态寻北的原理及算法进行了深入分析,利用 MATLAB 软件中的 Simulink 仿真工具箱建立了光纤陀螺逐点最小二乘拟合动态寻北算法的仿真模型,并重点针对影响光纤陀螺动态寻北精度的平台转速和采样频率进行了仿真计算和优化分析。仿真及计算结果表明,在采用文中提出参数的情况下,当旋转平台的转速约位于 4.5~8.5 (°)/s 之间,采样频率为 50 Hz 左右时,光纤陀螺动态寻北系统可以得到较高的寻北精度。论文所建立的模型结构及研究结论可以为光纤陀螺动态寻北系统的设计提供理论参考,同时对于光纤陀螺动态寻北技术的理论研究及具体实现也具有借鉴意义。

关键词: 光纤陀螺; 动态寻北; Simulink; 算法建模

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0 Introduction

With the in-depth development of equipment information, modern warfare has gradually changed to all-weather, all-direction, rapid maneuverability and precision strikes. Therefore, it requires the weapon system to have the abilities of rapid and precise positioning and direction [1-2]. For the inertial north-finding technology is independent on the outside world, which has become one of the important guarantees for the weapon system to realize rapid autonomy maneuverability and precision strikes. Fiber optic gyroscope (FOG) north-finding system is one of the new inertial north-finding technologies, which has been used increasingly in defense and civil applications[3-4]. It not only provides ideal directional information for weapon system and equipment, but also provides precise direction and attitude control reference for oil drilling, robots and other civilian areas[5-6].

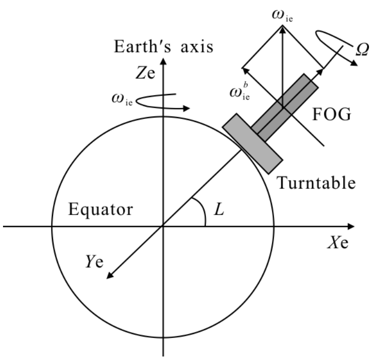
The principle of FOG north-finding system mainly relies on its sensitivity of the horizontal component of the Earth angular rate. For this value is very small, the north-finding resolution mainly depends on the precision of FOG. However, it will pay a higher cost for improving the level of hardware resources on the basis of manufacturing processes and technology at present. On the other hand, the north-finding algorithm affects the FOG north-finding precision and rapidity obviously, so the north-finding algorithm can be considered to be improved in order to better meet the practical requirements for the FOG north-finding system. Among the FOG north-finding algorithm, static north-finding method is a traditional method and has been used widely, but the operation is complex, and north-finding precision is limited [7-8]. The FOG dynamic north-finding method is a new inertial positioning method, which is being explored and focused on by the researchers at home and abroad. It refers to a new method that the FOG rotates with the turntable around its central axis in continuous constant-speed in the process, and calculates the initial direction according to the FOG output signal [9-10]. Compared with the FOG static north-finding method, the FOG output signal can be modulated periodically by continuous constant-speed mechanical rotation. Using the appropriate solution, it can suppress the constant drift and random drift of FOG effectively, shortening the north-finding time and improving the north-finding solution accuracy. However, for the limitation of structure and process level, there is few example of FOG dynamic north-finding system used in engineering[11].

According to the above background, this paper mainly researches on the FOG dynamic north-finding principle and algorithm, using Simulink simulation toolbox of MATLAB, and focuses on the simulation model building and analysis of least square method by points of FOG dynamic north-finding algorithm, which is in order to realize the parameters optimization design of the rotation speed and sampling frequency for FOG north-finding system, and provide reference for practical engineering of FOG dynamic north-finding system.

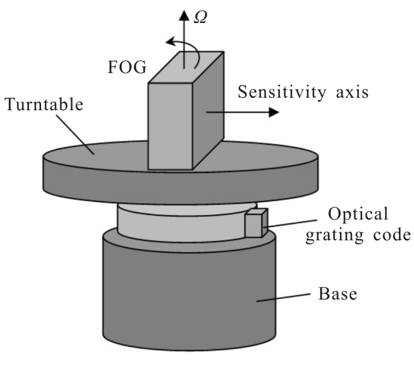
1 FOG dynamic north-finding principle

FOG is a new solid-state angular rate sensor based on Sagnac effect, compared with conventional electro-mechanical gyroscope, it not only has the advantages of quick start speed, wide dynamic range, withstand overload, but also has better zero deviation repeat ability, is insensitive to the movement and noise of the intersecting axes[12-13]. In engineering application, although the north finding methods are different, its basic principle is through sensitive Earth rotation angle rate ω_{ie} in the geographic coordinate system of level component ω_{ie}^{b}, and calculate the included angle between the carrier ordinate axis direction and geographic north direction, and then realize independent direction, its principle is shown in Fig.1(a).

FOG dynamic north finding method refers to FOG and turntable beginning with initial location and continuous rotation around vertical axis together with the constant speed Ω during the north finding process, and sampling the FOG output data in real-time, then calculating the north component of the Earth rotation angle rate directly according to different algorithm, or the initial angle between the FOG sensitivity axis and geographic north. The schematic is shown in Fig.1(b).



(a) FOG north-finding principle



(b) Principle of dynamic FOG north-finding system

Fig.1 FOG and its dynamic north-finding principle

Ideally, when the FOG and turntable turn around together with a constant rate ω, the projection that horizontal component of the Earth angular velocity of rotation on the vertical axis is[14]:

$$\omega_{ie}^{b}=\omega_{ie}\cos L\cos\theta\cos(2\pi ft_i+\Psi_0)+\omega_{ie}\sin\theta\sin L \tag{1}$$

where ω_{ie}=15.041 08 (°)/h is the Earth angular velocity of rotation; L is the geographic latitude value of the system; Ψ_0 is the initial angle between the carrier FOG sensitivity axis and geographical north; θ is the angle of pitch; f is the rotation frequency of the turntable, and there is $\Omega=2\pi f$.

In theory, when the FOG is in the condition of constant input, its output is also a constant which is proportional to ω_{ie}^{b}. However, because of the existence of many factors such as FOG drift itself, thermal noise of data acquisition circuit, turntable rotation speed changes, surrounding low frequency interference (such as ground shaking, people walking and wind etc.) and so on, the FOG actual output data contains a number of random errors. Therefore, the practical FOG dynamic output model can be expressed as[15]:

$$\omega_{outi}(t)=K\omega_{ie}\left[\cos L\cos\theta\sin\left(\frac{\pi}{2}-(2\pi ft_i+\Psi_0)\right)+\sin\theta\sin L\right]+\varepsilon_0+\varepsilon_i \tag{2}$$

where K is the scale factor of FOG; ε_0 is the constant bias (drift) of FOG; ε_i is the FOG random drift term which includes white noise.

In ideal experiment conditions, FOG can be fixed on the turntable which has been leveled, that is, θ=0. When the turntable rotates with a constant angular rate Ω, the output model of FOG can be simplified to:

$$\omega_{outi}(t_i)=K\omega_{ie}\cos L\cos(\Omega t_i+\Psi_0)+\varepsilon_0+\varepsilon_i \tag{3}$$

It just needs to calculates the value of Ψ_0 according to Eq.(3), and the true north direction can be known, then the north-finding and directional task have been completed. In general, the system overall performance requirement is higher for the dynamic north-finding method, its outstanding advantages are high north-finding precision and shortening north-finding working time, which is in line with the FOG north-finding system towards the development directions of integration, automation, high-precision and rapid north-finding.

2 Modeling and simulating analysis

2.1 Least squares parameter estimation algorithm principle

When the FOG rotates together with the turntable at a constant speed, particular frequency sampling is used on the FOG dynamic output data in real time. According to the total sampling points of a full period or more than one full period, the initial angle Ψ_0 between the FOG sensitivity axis and the geographical north direction is calculated using least squares parameter estimation. According to the FOG dynamic output model in Eq.(3), it can be decomposed into:

$$\omega_{\mathrm{out}i}(t_i)=K\omega_{\mathrm{ie}}\cos L\cos\Omega t_i\cos\Psi_0-K\omega_{\mathrm{ie}}\cos L\sin\Omega t_i\sin\Psi_0+\varepsilon_0+\varepsilon_i \tag{4}$$

Making $A=K\omega_{\mathrm{ie}}\cos L\cos\Psi_0$, $B=-K\omega_{\mathrm{ie}}\cos L\sin\Psi_0$, $\alpha_i=\Omega t_i$, and not considering the effects of error term temporarily, there is:

$$\omega_{\mathrm{out}i}(t_i)=A\cos\alpha_i+B\sin\alpha_i \tag{5}$$

Using least squares parameter estimates in Eq.(5), the values of A and B can be determined as follows:

$$\begin{cases}\hat{A}=\dfrac{\sum\limits_{i=1}^{n}\sin^2\alpha_i\sum\limits_{i=1}^{n}\omega_{\mathrm{out}i}\cos\alpha_i-\sum\limits_{i=1}^{n}\omega_{\mathrm{out}i}\sin\alpha_i\sum\limits_{i=1}^{n}\sin\alpha_i\cos\alpha_i}{\sum\limits_{i=1}^{n}\sin^2\alpha_i\sum\limits_{i=1}^{n}\cos^2\alpha_i-\left(\sum\limits_{i=1}^{n}\sin\alpha_i\cos\alpha_i\right)}\\ \hat{B}=\dfrac{\sum\limits_{i=1}^{n}\cos^2\alpha_i\sum\limits_{i=1}^{n}\omega_{\mathrm{out}i}\sin\alpha_i-\sum\limits_{i=1}^{n}\omega_{\mathrm{out}i}\cos\alpha_i\sum\limits_{i=1}^{n}\sin\alpha_i\cos\alpha_i}{\sum\limits_{i=1}^{n}\sin^2\alpha_i\sum\limits_{i=1}^{n}\cos^2\alpha_i-\left(\sum\limits_{i=1}^{n}\sin\alpha_i\cos\alpha_i\right)}\end{cases} \tag{6}$$

At this point, the estimated value of initial angle is:

$$\Psi_0=ac\tan(-\hat{B}/\hat{A}) \tag{7}$$

When using this method to realize north-finding dynamically, it can adjust parameters flexibly according to the precision and real-time requirements. It has advantages of simple operation and well system stability.

2.2 Modeling and analysis of algorithm

Depending on the least squares estimation algorithm principle of dynamic north-finding based on FOG, the algorithm using Simulink simulation toolbox in MATLAB is modeled. The specific parameters in the model is: FOG scale factor K_s=0.81; latitude L is 34° 16′; the Earth′s rotation angular velocity ω_{ie} is 15.041 08 (°)/h; and the initial angle between FOG sensitivity axis and the geographical north is 10°. Because the specific algorithm model is complex, due to the space limitations of this paper, we mainly analyze and discuss the simulation results. In the dynamic north-finding system based on FOG, when the hardware resources have been determined, the turntable rotation speed and frequency are two important parameters which affect the north-finding precision. It uses the above algorithm model as follows, and focuses on simulation analysis of the north-finding precision effect by changing the just two parameters.

Firstly, under the conditions that the sampling frequency and other parameters have no changes, when the turntable rotation speed is respectively 1, 2, 5, 10 (°)/s, the output results of dynamic north-finding system are calculated based on FOG, the specific results are shown in Fig.2.

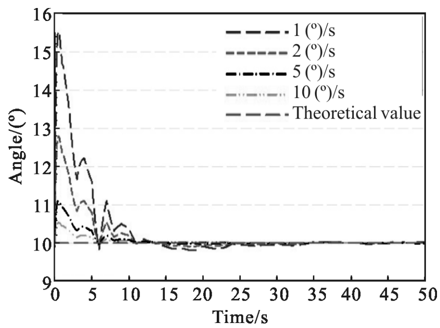


Fig.2 Simulation results under different rotation speeds of turntable

It can be seen from Fig.2 that, in the initial stage of the north-finding system working, the system output value has deviation from the theoretical geography north value (10°) further away. However, after about 20 seconds, the system output value of north direction gradually comes close to the theoretical geography north value. In addition, according to the simulation results, it can be seen that when the turntable rotates at different speeds, the steady-state error between the final output value of north-finding system and theoretical geography north value is different. The steady-state error when the turntable rotation speed changes from 1 (°)/s to 10 (°)/s is calculated respectively, and the results are shown in Fig.3.

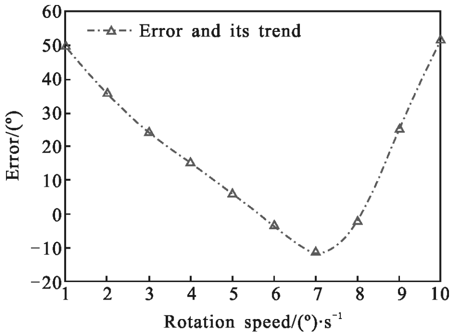


Fig.3 Steady-state error when the turntable has different rotation speed

The results in Fig.3 show that the turntable rotation speed will have significant impact on north-finding precision when other parameters of FOG have no change; the turntable rotation speed is too big or too small which results in a large error. For the parameters used in FOG, when the turntable rotation speed is approximately between 4.5 (°)/s and 8.5 (°)/s, the FOG north-finding precision can be located within a range of ±10″ in theory. Therefore, it needs an appropriate turntable rotation speed of FOG dynamic north-finding system working in practice.

In addition, the sampling frequency for FOG output data can also have a certain impact on north-finding precision. When all other parameters are constant, selecting the sampling frequency of the model respectively at 10, 20, 50, 100 Hz for simulation, and calculating the steady-state errors in different sampling frequency, the results are shown in Fig.4.

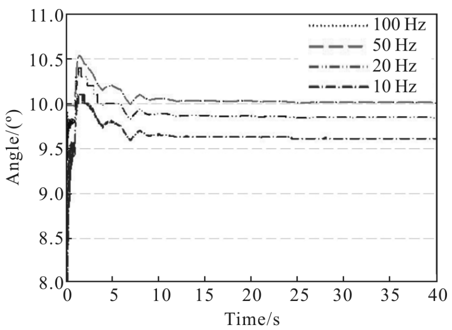


Fig.4 Steady-state error simulation results in different sampling frequency

According to the simulation results in Fig.4, when the sampling frequency is lower, the output true north direction error of north-finding system is larger. When the sampling frequency increased step by step, the steady-state error decreases gradually to a steady state. The error change trends between the FOG north-finding system output value and theoretical value with the sampling frequency have been given in Fig.5.

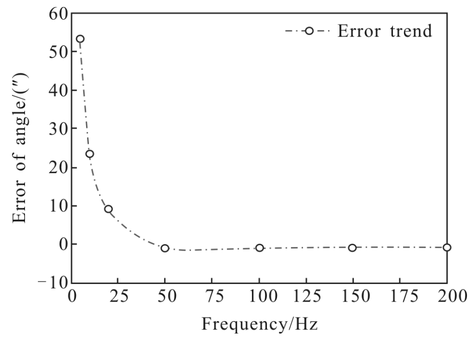


Fig.5 North-finding errors change trends with sampling frequency

According to the above calculation results in Fig.5, when the sampling frequency is lower than 50 Hz, the north-finding steady-state error is larger. When the sampling frequency is higher than 50 Hz, the steady-state error of FOG north-finding system output value is stabilized at about −1′. It is thus clear that, too higher sampling frequency does not improve the precision of FOG north-finding system any more, but it may actually increase the system costs. Therefore, the sampling frequency of FOG north-finding system can be determined generally by the maximum output sampling frequency of FOG.

To sum up, during dynamic north-finding in the use of FOG, in order to obtain higher true north calculation precision and system response time, the best turntable rotation speed and output data sampling frequency should be determined based on the precision and performance parameters of FOG. For the proposed FOG parameters, the turntable rotation speed should be approximately between 4.5(°)/s and 8.5(°)/s, and the sampling frequency is about 50 Hz, it can achieve higher north-finding precision.

3 Conclusion

As a new type of solid-state angular rate sensor, FOG is very suitable as the main inertial measurement unit in north-finding and directional system. Compared with the traditional static north-finding method, the dynamic north-finding method can suppress the constant drift and random drift of FOG, shorten north-finding working time significantly, and improve the north-finding precision, so it is a very promising north-finding method. Based on the analysis of north-finding principle of dynamic continuous rotation FOG, this paper focuses on the realization principle analysis of least squares parameter estimation algorithm, and the dynamic north-finding system model based on FOG has been established by using the Simulink simulation toolbox, and then the turntable rotation speed and sampling frequency that affects FOG dynamic north-finding precision, have been stimulatedly calculated and optimally analysed as key consideration. The simulation results show that, there has a suitable turntable rotation speed range for high precision measurement, and the north-finding precision will be affected when the turntable rotation speed is too low or too high. Along with the sampling frequency increasing step by step, the steady-state error decreases to a steady state gradually. It is thus clear that, too higher sampling frequency does not improve the precision of FOG north-finding system any more, but it may actually increase the system costs. Therefore, the conclusions of this paper can provide theoretical reference and simulated verification for the engineering and practicality of FOG dynamic north-finding system.

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