High-precision and non-contact Fiber Optic Gyroscope
dynamic calibration system with dual Laser Doppler
Vibrometers

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Abstract. Since the advantages of high precision, large dynamic range in angular velocity measurement, Fiber Optic Gyroscopes (FOGs) are recently proposed to be used as angle measuring instrument. However, in dynamic testing condition like sway, the outputs of FOGs contain inevitable angular velocity measurement error, harming angle measuring accuracy. Therefore, FOGs must be calibrated before using. In this paper, we first propose a high-precision and non-contact angle measurement method with dual-Laser Doppler Vibrometers (d-LDVs) to calibrate the angle measurement error of FOGs in sway condition. Firstly, we verify the accuracy and dynamic range of this proposed angle measurement method by using a high-precision rotary table as an angle benchmark. Experimental results indicate that this method can reach the dynamic angle measurement with the range of \(\pm 10^\circ\), and the maximum angle measurement error is less than 0.0088\(^\circ\). Secondly, in order to calibrate the angle measuring error of FOGs, we establish an angle calibration system for FOGs based on d-LDVs under sway condition. Experimental result shows that the dynamic angle measurement error of the FOG caused by dynamic environment is less than 0.015\(^\circ\). Because of the zero drift of angular velocity, integral angle of the FOG shows angle drift, and the maximum angle drift is 0.06\(^\circ\) (during 30s).

1. Introduction
Fiber optic gyroscope (FOG) is a kind of fiber-optic sensor measuring angular velocity based on Sagnac Effect [1, 2]. Since the advantages of high precision, large dynamic range in angular velocity measurement, FOGs are recently proposed to be used as angle measuring instrument [3, 4]. Most application environment of FOG contains violent and fast movement, such as shock caused by tidal or air convection [4, 5, 6]. Research found that FOGs contain inevitable angular velocity error in violent and fast movement, which harms angle measuring accuracy and restricts the application of FOG in dynamic environment [7, 8].

Sway is a typical dynamic movement for FOGs, which can be conducted by rotary table when performing ground test stage. When a close-loop FOG is tested under condition of sway, the angular acceleration of system is not zero and changes with time, the feedback phase shift of the FOG thus contains an additional phase shift error [8]. This error is the key factor that influences the accuracy of angle and angular velocity of FOG, and it is complex and immeasurable for a FOG system. Therefore, it is necessary to calibrate the angle measurement error of FOG under dynamic condition of sway.
In this paper, we first propose a high-precision and non-contact angle measurement method with dual-Laser Doppler Vibrometers (d-LDVs) to calibrate the angle measurement error of FOGs in sway condition. Firstly, we verify the accuracy and dynamic range of this proposed angle measurement method by using a high-precision rotary table as a benchmark. Specific geometry structure of d-LDVs is designed to measure the rotating angle using the velocity measured by dual laser Doppler vibrometers. Experimental results indicate that this method can reach the dynamic angle measurement with the range of $\pm 10^\circ$, and the maximum angle measurement error is less than 0.0088°.

Secondly, in order to calibrate the angle measuring error of FOGs, we establish an angle calibration system for FOGs based on d-LDVs under sway condition. Experimental result shows that the dynamic angle measurement error of FOG caused by dynamic environment is less than 0.01°. Because of the zero drift of angular velocity, integral angle of FOG shows angle drift, and the maximum angle drift is 0.06° (during 30s).

2. Design of a high-precision and non-contact angle measurement method with d-LDVs
In this part, we will introduce the theory of the proposed angle measurement system and experiment we have done to verify the accuracy and dynamic range of this method.

Section 2.1 introduces the basics of Laser Doppler Vibrometer. Section 2.2 explains principle and geometry structure of the proposed angle measurement method with d-LDVs. In section 2.3, an experimental setup was established to verify the accuracy and dynamic range of the proposed angle measurement method with d-LDVs by using a high precision rotary table as an angle benchmark under dynamic condition of sway. Section 2.4 discusses the experimental setup and calibration of FOG based on our proposed method.

2.1. Basics of Laser Doppler vibrometer
Laser Doppler vibrometer (LDV) is a technology for accurate and non-contact measurement of velocity and displacement in industrial and metrological application [9, 10]. It is an instrument combines the Doppler Effect and heterodyne interferometer [10]. The Doppler Effect is a phenomenon that light back-scattered from a moving target contains information about its velocity and displacement [11]. The phase of the light wave is modulated by the surface displacement while the light frequency is shifted by instantaneous velocity. Therefore the intensity of the interference signal is modulated by velocity and displacement of the moving target.

The interference signal detected by photodetector is given by

$$i(t) = I_{DC} + i \cdot \cos(2\pi f_0 t + \phi_0)$$

(1)

where $I_{DC}$ is DC component, $i$ is AC amplitude, $f_0$ is Bragg cell drive frequency, and $\phi_0$ is offset phase angle, which is defined by the initial object position.

The second term of eq.(1) can carry both direction-sensitive frequency and phase modulation information resulting from target motion. In case of a moving target, $\phi_0$ becomes superimposed by a time-dependent portion $\varphi_m(t)$:

$$\varphi_m(t) = \frac{4\pi s(t)}{\lambda}$$

(2)

where $\lambda$ is laser wavelength, and $s(t)$ represents displacement of moving target.

The phase modulation can also be expressed as frequency modulation. Time derivation of the modulated phase angle $\varphi_m(t)$ is the modulated frequency shift $\Delta f(t)$. According to the basic relationships $\frac{d\varphi}{dt} = 2\pi f$ and $\frac{ds}{dt} = v$, object velocity $v(t)$ results in a frequency shift $\Delta f(t)$ with respect to the carrier frequency $f_0$, commonly known as the Doppler frequency shift:

$$\Delta f(t) = \frac{2v(t)}{\lambda}$$

(3)
2.2. Principle and geometry structure of the proposed angle measurement method with d-LDVs

Based on d-LDVs, we designed a dynamic angle measurement system according to the Trigonometric relation when a target is rotating. Figure 1 shows the schematic diagram of d-LDVs angle measurement system.

\[
\theta = \tan^{-1}\left(\frac{\int_0^T v_1 dt - \int_0^T v_2 dt}{L}\right)
\]  

Figure 1. The schematic diagram of dual laser Doppler vibrometers angle measurement system.

The moving status of the detected target is shown as follows: the target surface turns a small angle \( \theta \) from state 1 to state 2 around the point o in clockwise. Suppose \( v_1 \) and \( v_2 \) represents the instantaneous measurement velocity of laser Doppler vibrometer A and B respectively, \( t \) represents the time difference from state 1 to state 2, and \( L \) is the distance between two laser Doppler vibrometers. The displacement difference of the moving target along the direction of laser is \( \int_0^T v_1 dt \), \( \int_0^T v_2 dt \) respectively. Hence, the rotation angle can be obtained as follows:

2.3. Experiment setup to verify the accuracy and dynamic range of the angle measurement method

To verify the accuracy and dynamic range of this angle measurement method, we use a high-precision rotary table as an angle benchmark. The hardware structure of experiment setup is shown in figure 2. The experiment system consists of two laser Doppler vibrometers, a rotary table, a test surface, a device with data acquisition and synchronization module function and a PC. The test surface is fixed on the rotation surface of the rotary table. Under the control of PC, rotary table sways in a certain amplitude and frequency, the test surface thus move with the rotary table at the same time. Laser Doppler vibrometers A and B measure the velocity of test surface during sway. Data acquisition and synchronization module collects the data of d-LDVs and the rotary table synchronously, and transfers the collected data to the PC. In the end, the PC will process the collected data and compare the calculated angles from d-LDVs and rotary table. We set the rotary table as an angle benchmark, the accuracy of d-LDVs angle measurement system can be obtained.

2.4. Primary experimental result

Based on the setup introduced above, argumentative experiment has been done to verify the accuracy of dual laser Doppler vibrometers angle measurement system. A high angular position measurement accuracy rotary table TD-300 is used to verify the accuracy of d-LDVs angle measurement system. The angular position measurement accuracy of the rotary table is 10'' (0.0028°), the angular position positioning repeatability of the rotary table is 3'' (0.00083°), the rotary table satisfies requirement for an angle reference. Center wavelength of the laser Doppler vibrometer is 632.8nm, velocity measurement range is 50mm/s. Dual laser Doppler vibrometers are fixed on a tripod by which the lights emitted from the vibrometers are guaranteed parallel from each other. The distance between
dual laser Doppler vibrometers is 70mm. Sampling frequency of the data acquisition and synchronization module is 2000Hz.

![Figure 2. The hardware structure experiment setup.](image)

Rotary table sway at the frequency of 1Hz and the angle amplitude of 10°, Figure 3 (a) and (b) shows the angle measurement result by d-LDVs and rotary table. It is shown that both of them have the same angle response under the given movement. The angle measurement error of d-LDVs is obtained by doing subtraction between d-LDVs and the rotary table. Figure 3 (c) presents the angle measurement error of d-LDVs, and the maximum error |e| is less than 0.0088°.

![Figure 3. Angle measurement result by the d-LDVs and the rotary table.](image)

3. **Calibration for FOG**

As is shown above, the proposed angle measurement system based on d-LDVs shows high measurement accuracy and good repeatability. So, we consider using this method to calibrate the angle measurement error of FOGs under dynamic condition of sway. The FOG we use in experimental is made by our laboratory. The calibration system is depicted in figure 4. In this system, a rotary table controlled by a PC, is used to conduct dynamic environment of sway for the FOG and d-LDVs. The
amplitude of sway is 10°, and the frequency is 1Hz. Data acquisition and synchronization module collects the data of d-LDVs and FOG synchronously. The PC processes the collected data and compares the calculated angles from d-LDVs and the FOG. Figure 5 (a) represents angle measured by d-LDVs and the FOG. The measurement error of the FOG is obtained by taking subtraction between the angles measured by the FOG and d-LDVs.

Figure 4. Schematic of calibration system to FOG.

The results of the angle measurement error of the FOG contain two parts. The first one is the random angle drift. In the data processing, we firstly get angular velocity of the FOG, and then integral the angular velocity to get the angle measured by the FOG. The angular velocity of the FOG with random zero drift, will be added to the random angle drift during the integral processing. The maximum angle drift shown in figure 5 (b) is 0.06° (during 30s). The other is the angle measurement error caused by dynamic condition, in range of ±0.015°. The mechanism is explained in section 1 and our experiments verify the existence of angle measurement error caused by dynamic condition of sway.

Figure 5. Calibration result to FOG by d-LDVs.
4. Conclusions
A high-precision and non-contact angle measurement method with d-LDVs to calibrate the angle measurement error of FOGs in sway condition has been proposed. Specific geometry structure of d-LDVs is designed to measure the rotating angle using the velocity measured by d-LDVs. Experimental results indicate that this method can reach the dynamic angle measurement with the range of ±10°, and the maximum angle measurement error is less than 0.0088°, and it satisfies the demand of high accuracy and large dynamic angle calibration.

Secondly, we establish an angle calibration system for FOGs based on d-LDVs under sway condition in order to calibrate the angle measuring error of FOGs. Experimental result shows that the dynamic angle measurement error of FOG caused by dynamic environment is less than 0.015°. Because of the zero drift of angular velocity, integral angle of FOG shows angle drift, and the maximum angle drift is 0.06° (during 30s).

LDV shows great potential in high accuracy and dynamic angle measurement. Works need to be done to analyze the nonlinear influence of environment to LDV and try to improve the angle measurement accuracy of system. Besides, FOG contains measurement error in other environment such as temperature, magnetic field and vibration. Calibration of FOG under sway condition in this paper based on d-LDVs has a certain degree of practicality and scalability, which means we can apply this method into the calibration of FOG in other environment. Study on the calibration of FOG in these dynamic condition needs to be done.

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