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Measuring roll angle displacement based on ellipticity with high resolution and large range

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ABSTRACT

A novel and compact roll angle displacement measurement based on the principle of the light's polarization is presented. The ellipticity of the light has been chosen as the final output, which shows a good linear relationship with, and a high sensitivity to, the roll angle displacement. In the experiments, a 2.16″ step roll angle displacement has been recognized by this novel system and the linear range can be extended to 15°. The major components of this system are just a half-wave plate, a quarter-wave plate, a commonly used semiconductor laser, and a detector. Therefore, it is very easy to construct such a system both in the laboratory environment and the actual measurement environment.

1. Introduction

The first step in correcting angle errors of a high-precision measuring machine is to measure the angular displacement of such machines in actual operation with a high accuracy. Among pitch displacement, yaw displacement and roll displacement, it is the third that is most difficult to accurately measure [1,2]. Previously, the most commonly used device utilized to perform this kind of measurement had been the electronic levels, but due to its large size, considerable mass and moderate accuracy, the electronic level is not suitable for use in many situations, such as a desired measurement involving a long distance or conditions that force such measurement to take place in a small space [3]. Compared to roll angle measurements based on electronic levels, systems based on optical principles are usually more compact and more stable. Also, it is easier to obtain an accurate output in a reasonable angle range with such optical methods. These optical methods can be roughly divided into three classes. The first kind of method is based on the principle of interference [4–7]. Another basis for such a measurement uses the polarization state of light [8–10]. Finally, there is a technique for measuring roll angle by using diffraction beams [11–13].

It has been demonstrated that a system with two laser diodes (LDs) whose polarization directions were orthogonal can be used to perform roll angle measurements [14]. However, in this system, high accuracy requires two identical LDs; that is, the output power of the two LDs must be as consistent as possible, which is always very difficult to guarantee in reality, so many systems using just one light source had been subsequently proposed. The Faraday cell had been used in such systems extensively because, by adjusting the magnetic field, we are able to change the polarization of the light [15]. However, there are several problems with temperature drift and Faraday rotation drift because the Faraday cell was driven by a nonsaturated magnetic field. When the temperature changed, the Verdet constant would change, and it will affect the sensor's accuracy [16]. One improved system with the same principle also had been presented [17]. This system has the advantages of being compact, flexible, and immune to many kinds of outside interference. However, the angular resolution of this system can only reach 36″ over a range of 30°. The system including components such as a transverse Zeeman laser, a quarter-wave plate (QWP), and an analyzer also can be used to measure roll angle displacement, and with this kind of system, a resolution of 0.3 or 0.6″ was obtained [18,19]. Unfortunately, that high precision is acquired at the expense of expensive an Zeeman laser as well as other devices; moreover, such high accuracy in a real experiment with a 0.3″ or 0.6″ step size measurement has not been demonstrated. Zhao et al. [20] and Khiat et al. [21] proposed another technique, which used fiber optic inclinometers and other fiber optic angular displacement sensors to measure small angles. The fiber optic sensor has a small size, which allows easy integration in miniature mechanical systems, but the resolution of this technique is limited. In this paper, a novel approach based on the characteristics of polarized light is presented. Constructing this system requires only one simple semiconductor laser, a few optical fibers, one half-wave plate (HWP), one quarter-wave plates, and one polarization

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analyzer. With these devices, a roll angle displacement step size of 2″ can be recognized by a detector in real experiments, and the output – that is, the ellipticity of the light in the experiments has a good linear relationship with the displacement of roll angle.

2. Theory

An optical schematic of the scheme used in this study is shown in Fig. 1. The original beam from the simple semiconductor laser (1) first passes through a converging lens (2) and then couples into the single-mode fiber (3). Then the single frequency laser passes through the collimating lens (4). After that, the beam passes through the polarizer (5) and becomes linearly polarized light. Then the light passes through a half-wave plane (6), which serves as a sensing component – the small roll angle displacement of the half-wave plate is expected to be measurable by the overall system. Finally, the beam passes through a quarter-wave plane (7) and then is analyzed by a detector where the beam's ellipticity is chosen as the detector's (8) final output.

In order to simplify the calculation, we assume a coordinate system, whose x- and y- axes correspond to the two orthogonal linear components of the beam illuminating the HWP. Another proper assumption is that the fast axis of the HWP has a roll angle displacement θ with respect to the x- axis and that the fast axis of the QWP is at a 45° angle relative to the x- axis. It is important to note that these assumptions have nothing to do with the real experiments since what is expected to be detected is the variation of the ellipticity rather than the absolute size, so those assumptions are made just to simplify the analysis.

The Jones vector of the beam is given as:

$$\vec{E} = QH(\theta)\overrightarrow{E_0} \tag{1}$$

where H is the Jones matrix of the HWP, Q is the Jones matrix of the QWP, and $\overrightarrow{E_0}$ is the Jones vector of the original polarized light, which are written as follows:

$$\left\{ \begin{array}{c} Q = \begin{pmatrix} 1 & 0 \\ 0 & i \end{pmatrix} \\ H = \begin{pmatrix} \cos 2\theta & \sin 2\theta \\ \sin 2\theta & -\cos 2\theta \end{pmatrix} \\ \overrightarrow{E_0} = \begin{pmatrix} E_x \\ E_y \end{pmatrix} \end{array} \right\} \tag{2}$$

Substituting all the values above into Eq. (1) gives:

$$\vec{E} = \begin{pmatrix} E_x \cos 2\theta + E_y \sin 2\theta \\ i(E_x \sin 2\theta - E_y \cos 2\theta) \end{pmatrix} \tag{3}$$

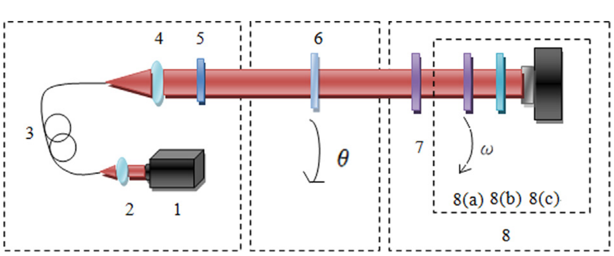

Fig. 1. Optical schematic of the new system for roll angle measurement, consisting of the following: 1. Semiconductor laser. 2. Convergent lens. 3. Optical fiber. 4. Collimating lens. 5. Polarizer. 6. Half-wave plane (HWP). 7. Quarter-wave plane (QWP). 8. Detector, which consists of: 8(a). Rotary QWP. 8(b). Polarizer. 8(c). Power meter.

So the final beam is elliptically polarized light, and the ellipticity of the light can be represented by:

$$Y = \tan \eta = \frac{E_x \cos 2\theta + E_y \sin 2\theta}{E_x \sin 2\theta - E_y \cos 2\theta} = \frac{E_{ox}}{E_{oy}} \tag{4}$$

It can be seen clearly from Fig. 2 that on limiting θ in a 40″ range, Y has a good linear relationship with θ and the scale factor between θ and Y is related to the ratio of E_x to E_y.

Fig. 2 indicates that when $E_x = E_y$, the variation of the ellipticity is most sensitive to the roll angle displacement, which changed by about 0.0008 when the θ valve changes from 0 to 40″, but when $E_x \neq E_y$, it is possible for the slope of the Y–θ line to decrease. However, even in the worst case, when $E_y \gg E_x$ (in Fig. 2 that is $E_y = 100E_x$), the slope of the Y–θ line changes little compared to the condition $E_y = E_x$; that is, when θ changes from 0 to 40″, the variations of the ellipticity are both near 0.0004. What should be noted is that θ the roll angle of the sensing component (here, the HWP) starts from zero. When increasing the original angle, the variation of the ellipticity can become more sensitive to the roll angle displacement, as can be seen in Fig. 3.

Fig. 3 demonstrates that if the original angle between the HWP's fast axis and the x-axis is chosen properly, more accurate results can be obtained. From another perspective, it is obvious that when the starting angle is approximately 22.5°, the most accurate result can be obtained. As shown in Eq. (4), in that case, Y tends to be infinite when $E_x = E_y$. However, a real detector can never produce an output that is infinite, so in the experiments, a proper starting angle is supposed to be chosen to ensure that an accurate measurement can be obtained and that the detector is able to give us the correct output.

From another perspective, the ellipticity can be represented by means of an angle –: the phase difference between E_x and E_y. From this point in the paper, the term ellipticity represents this angle and thus a kind of relationship between one angle (the roll angle) and another angle (the ellipticity) has been established. The relationship between these two angles is shown in Fig. 4. Moreover, when changing the original ratio of E_x to E_y, the relationship between the two angles does not change substantially and just remains a change of initial ellipticity, which is also shown in Fig. 5. As we continue to increase the range of θ, a kind of cyclical repetition appears with a period of 90°, as shown in Fig. 6.

In Figs. 4 and 5, a perfect linear relationship between the roll angle and ellipticity over a large scale is shown, and when the roll angle changes by one degree, the ellipticity changes by two degrees, indicating a two-fold magnification relationship between these two angles. So if there is an appropriate detector that is able to distinguish a 2″ variation of ellipticity, a 1″ roll angle displacement can be recognized. Furthermore, because nearly all optical detectors are only able to detect the light intensity, the ellipticity which can be read directly from the detectors actually is determined from the ratio E_{ox}/E_{oy}, which is found by separately measuring E_{ox} and E_{oy}. On the one hand, in what case E_{ox}/E_{oy} is most sensitive to the roll angle θ has been discussed in above content. On the other hand, since what is expected to be measured is a minute angle displacement, the changes to E_{ox} and E_{oy} are still very small. In order to measure such minute changes, a rotating QWP should be positioned to serve as a filter and achieve a phase-locking function. After the QWP, a polarizer and a power meter are positioned as shown in Fig. 1. Up until now, how to make a detector sensitive enough to distinguish a minute change of the ratio of E_{ox} to E_{oy} has been discussed, but under the actual measurement, the only thing that needs to be done is to choose a detector that can determine the ellipticity of the light directly so that the roll angle displacement can be detected.