Optical Angle Sensor Based on Laser Autocollimation with a Photodiode Array and a Multi-Longitudinal-Mode Laser

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An optical angle sensor based on laser autocollimation using a photodiode (PD) as a photodetector can detect angular displacement with high resolution. By narrowing the focused laser beam diameter on the PD, the angle detection resolution can be improved but the measurement range is sacrificed. To expand the measurement range while maintaining high resolution, a new optical angle sensor based on laser autocollimation employing a multimode longitudinal laser as the light source and a photodiode array as the photodetector is attempted in this paper. To evaluate the basic characteristics of the proposed method through experiments, a prototype optical system is constructed.

1. Introduction

In the production of precision instruments, angle, along with length, is an important physical quantity that is better to evaluate, and its importance is increasing, especially in the field of precision engineering [1]. Angle sensors based on laser autocollimation [2] can be used for applications where the axis rotation is not fixed and detect angular displacement with high sensitivity by converting the angular displacement of the measurement target into the displacement of a focused light spot on a photodetector. With the employment of a photodiode (PD) as the photodetector, a resolution of 0.001 arc-second has been realized so far [3, 4]. However, the angle measurement range in this method depends on the diameter of the focused laser beam on the PD, and there is a trade-off between the sensitivity and measurement range.

In response to the background described above, this paper attempts to expand the measurement range of an angle sensor based on laser autocollimation while maintaining high resolution by introducing a multi-longitudinal mode laser as a laser source. By projecting the laser beam onto a reflective-type diffraction grating, a group of the first-order diffracted laser beams can be obtained. With the employment of the photodiode array having multiple photosensitive elements, the focused spot array can be observed. By adjusting the spacing of the focused spot array appropriately, it is possible to expand the measurement range compared to a conventional laser autocollimator employing a PD and a single-mode laser source.

2. Principle

Laser autocollimation enables high-resolution angular measurement. An example of the optical setup of an angle sensor based on laser autocollimation is shown in Figure 1(a). When the

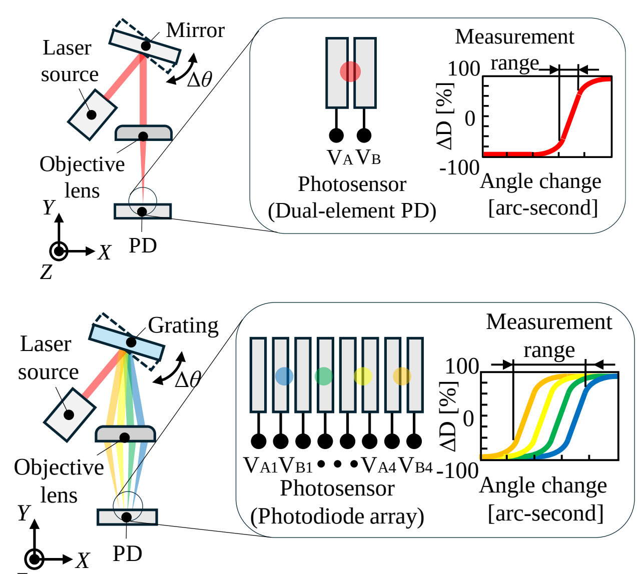

Fig. 1 A schematic diagram of the optical angle sensor: (a) An angle sensor based on laser autocollimation; (b) The optical angle sensor proposed in this study with a multi-longitudinal mode laser

measurement target rotates by $\Delta\theta$ about the Z-axis, the displacement of the focused laser beam on the photodetector Δx can be expressed by the following equation.

$$\Delta x = 2f \tan \Delta\theta$$

The displacement of the focused laser beam is detected by the changes in the voltage signals obtained from PD elements. By normalizing the voltage outputs, the influence of noise components and disturbances in the voltage signals can be canceled. The arithmetic operation for the normalization is expressed by the following equation [5]:

$$\Delta D[\%] = \frac{V_A - V_B}{V_A + V_B} \times 100[\%] \quad (1)$$

where ΔD represents the relative position of the focused laser beam between PD elements A (PD-A) and B (PD-B), V_A represents the voltage output obtained from PD-A, and V_B represents the voltage value obtained from PD-B.

In the proposed method, the angular displacement of a grating is detected by projecting a multi-longitudinal mode laser beam onto the grating and focusing each of the generated diffracted beams onto a PD array with a collimator objective. The schematic diagram of the proposed optical angle sensor is shown in Figure 1(b). The angle sensor output can be continuously obtained by setting the focused laser beam spacing appropriately regarding the element spacing of the PD array. The spacing Δd_i of each of the adjacent focused laser beams on the PD array can be expressed by the following equation:

$$\Delta d_i = f \tan \Delta\alpha \quad (2)$$

where $\Delta\alpha$ represents the difference between the angle of diffraction of adjacent modes.

3. Experiments

A prototype of the experimental setup shown in Fig. 2(a) was designed and constructed to confirm the feasibility of the proposed method. Figure 2(b) shows a photograph of the prototype optical system constructed in this study.

Figure 3 shows the changes in the normalized output of the PD element when a small angular displacement was applied to the grating. From the linear part of the sensor output, the sensitivities of each diffracted beam were evaluated to be 1.3~1.6%/arc-second. From the obtained sensitivity, the resolutions of each diffracted beam were evaluated to be 0.011~0.015 arc-second. Angular displacement was detected continuously over a range of 70 arc-seconds from each diffraction beam, for a total of 170 arc-seconds.

4. Conclusions

In this study, a multi-longitudinal mode laser and a photodiode array have been employed as the laser source and the photodetector, respectively, for a precision optical angle sensor based on laser autocollimation to expand its measurement range. To confirm the feasibility of the proposed method, a prototype optical angle sensor has been designed and fabricated. As a result of basic characterization experiments, the measurement range has been expanded to 2.5 times

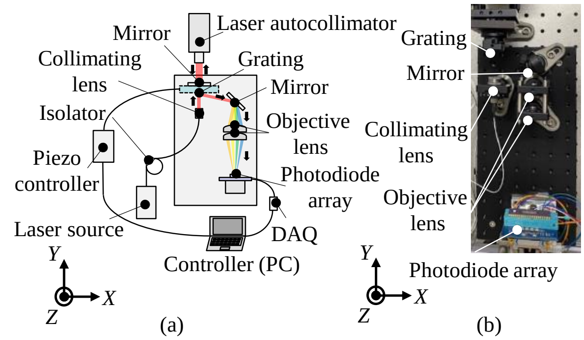

Fig. 2 (a) A schematic of system diagram; (b) A photograph of the developed optical setup

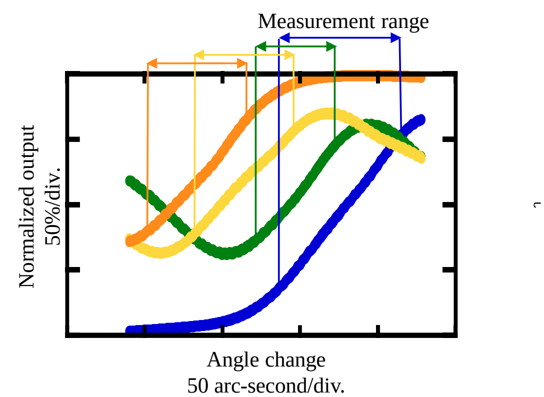

Fig. 3 The changes in the normalized outputs of PD elements in the PD array

that achieved by a single focused laser beam while maintaining a resolution of 0.01 arc-second over the measuring range.

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