Basic Investigations on an Angle Measurement System Using a Laser

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A novel precise angle gauge is proposed. Incoming laser light is fed to the system through two separate condensing lenses. The phase difference between two rays are compensated by a phase modulator to hold a constant interference condition. The angle of the incoming light is measured by the modulation voltage. In comparison with conventional angle gauges, its advantages are: 1) high measurement accuracy, 2) simple structure, and 3) compatibility to feed-back control systems. Owing to these advantages, the angle gauge is suitable for navigation using angular information.

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I. INTRODUCTION

Lasers inherently have strong coherency and hence strong focusing capability. Also, the modulation techniques of laser light have been greatly advanced in the field of telecommunication. Utilizing these features of the laser, a novel precise angle gauge is proposed [1].

There have been conventional angle gauges such as an auto-collimator [2], a laser spot detecting gauge [3], or a laser-Doppler-shift [4] gauge. The measurement accuracy of an auto-collimator is worse than 1 arcsecond at present. Because the adjustment is made by looking into a telescope, it is difficult to automatically control a system by feeding back the angle error.

In a laser spot detecting gauge, the spot deviation is detected by spot detectors arrayed in four quadrants. The best measurement accuracy has not exceeded 16 arcsecond. A laser-Doppler-shift gauge integrates the Doppler shift of a moving target to give a displacement or an angle. Though the measurement accuracy reaches up to 0.1 arcsecond, the constitution cannot be simplified due to heterodyne detection.

In comparison with these conventional angle gauges, the proposed angle gauge has the following advantages: 1) high measurement accuracy, 2) simple structure, and 3) compatibility with feed-back control systems.

Recently, navigation using angular informations has attracted attention [5]. The proposed angle gauge is suitable for that purpose owing to the above-mentioned advantages.

The concept of the angle gauge is explained first. Subsequently, experimental system constitution and experimental results are clarified. Finally possible applications are referred.

II. PRINCIPLE OF ANGLE GAUGE

Fundamental configuration of the angle gauge is shown in Fig. 1. An incident wave is fed into a pair of condensing lenses 1 and 2 with a large diameter and is collimated to narrower beams by a pair of collimation lenses 3 and 4 with a smaller diameter. Two rays are adjusted by mirrors and a translucent mirror to form nearly the same wavefronts and to interfere with each other. The interference pattern is enlarged to an appropriate size by lens 5 onto the pupil. A light detector and a power meter are used to measure the interfered power level.

The phase modulator 1 is used to compensate phase changes due to mechanical or thermal variation of the optical system. The angle of the incident wave is measured by the modulation voltage of the phase modulator 2 which is adjusted to hold the same interference condition.

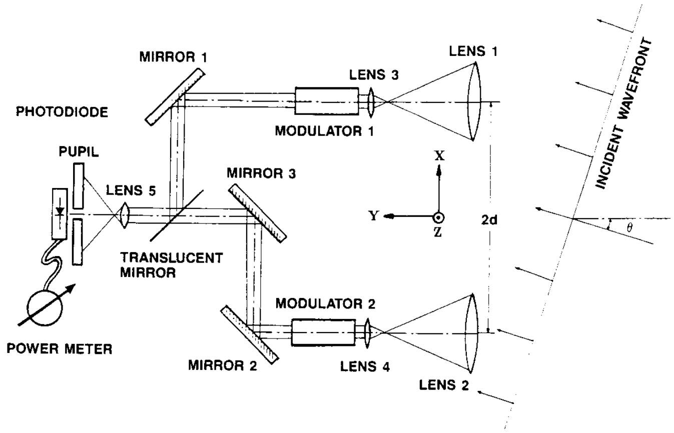

Fig. 1. Basic configuration of angle gauge.

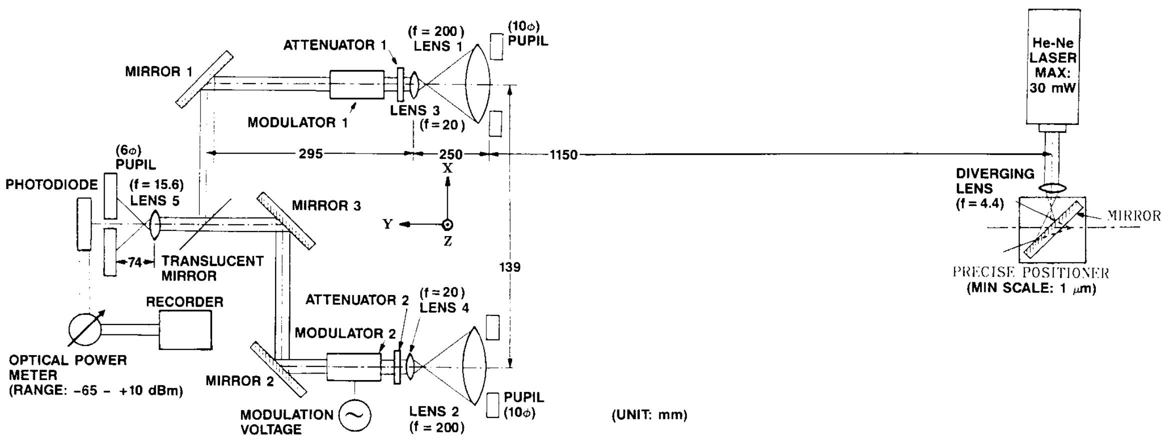

Fig. 2. Experimental system configuration.

The receiving pattern of the gauge in the plane of the paper of Fig. 1 is analyzed using a two-dimensional model of the optical system for simplicity. The change of the incident angle causes the following two effects: 1) the optical path lengths through lens 1 and lens 2 to lens 5 change each other, and 2) the beam spot moves on the pupil at the back of lens 5. Effect 2) is verified to be negligible for practical use.

Taking account of effect 1), the fields guided to lens 5, $F_1(k_x)$ and $F_2(k_x)$, are expressed by (1) and (2), respectively.

$$F_1(k_x) = 2a(\sin k_x a/k_x a)\exp j(k_x d + \phi_1) \tag{1}$$

$$F_2(k_x) = 2a(\sin k_x a/k_x a)\exp j(-k_x d + \phi_2 + \phi_m) \tag{2}$$

where a is the radius of the lenses 1 and 2, $2d$ is the distance between the lens centers, $k_x = k\sin\theta$ is the wave number in the x-direction, k is the wave number in free space, ϕ_1 and ϕ_2 are the phase shift correspondent to the path length of each ray, and ϕ_m is the phase modulation depth.

The combined $F_t(k_x)$ field on lens 5 is expressed by the following equation.

$$F_t(k_x) = F_1(k_x) + F_2(k_x). \tag{3}$$

From modulation theory [6],

$$\phi_m = \pi(V_{\mathrm{mod}}/V\pi) \tag{4}$$

where V_{mod} is the modulation voltage, and $V\pi$ is the half-wavelength modulation voltage.
The power function $|F_t(k_x)|^2$ is described using $\Delta\phi = \phi_2 - \phi_1$ as,

$$|F_t(k_x)|^2 = 8a^2(\sin k_x a/k_x a)^2 \times (1 + \cos(2k_x d - \Delta\phi - \phi_m)). \tag{5}$$

III. EXPERIMENTAL SYSTEM

A. General Configuration

The experimental system of the angle gauge is shown in Fig. 2. An He-Ne laser was used as a light

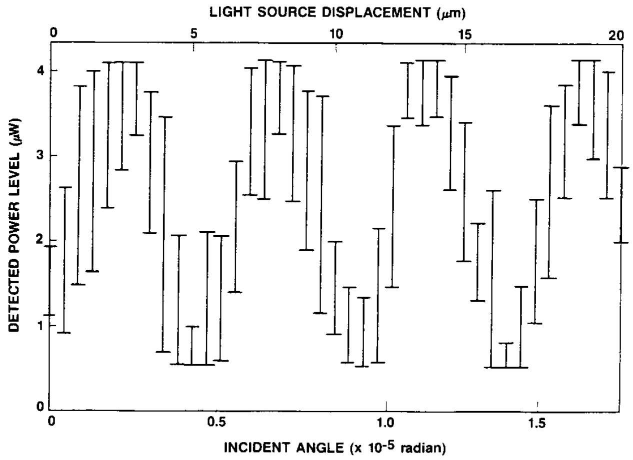

Fig. 3. Interference characteristics versus incident angle (narrow angle range).

source because of specially strong coherency and excellent operability.

A plane wave of sufficiently wide extent is difficult to form at sufficient power level. Even though it is achieved, the precise adjustment of an incident angle needs a big implement. The experiment is, therefore, performed using a spherical wave.

The light beam out of the laser is expanded by the diverging lens of 4.4 mm focal length. The angle of $1/e^2$ power is 14.2 deg. in full width which is sufficient value to illuminate the two condensing lenses. The source of the spherical light wave is moved equivalently by changing the location of the movable mirror instead of the laser itself. The read-out precision of the scale reaches 0.1 mm. The quantitative investigation of the system with a spherical wave will be given in the next section.

The wavefront of two rays from both condensing lenses should be identical on the light detector. But the aberration of lenses or scattering at the lens surface or the modulator side walls may degrade the quality of interference pattern and hence extinction ratio [7].

To suppress such unfavorable effects, the following schemes were adopted: 1) pupil are placed before the condensing lenses, 2) spatial filters are placed at the focusing point of the condensing lenses, 3) the rays are carefully guided not to touch the modulator side walls, 4) the light detector is placed behind the focus of the outputs lens, and 5) a pupil is placed before the light detector.

B. Phase Modulator

The crystal of $LiNbO_3$ in bulk shape is used for phase modulation. In Fig. 2 the orientation of the crystal is so that $n_x = n_y = n_0$ and $n_z = n_e$. The modulation field is applied along the z axis, and the light ray propagates along the x axis [6].

The polarization of the light is fixed along the z axis to minimize the half-wavelength modulation voltage $V\pi$. Accounting the length and thickness of the crystal, the $V\pi$ is nominally 130 V. For further study, integrated thin film modulators can be applied to reduce the modulation voltage.

IV. EXPERIMENTAL RESULTS

A. Characteristics of Interferometer

The interference characteristics of the angle gauge were measured in the configuration of Fig. 2 without the modulators. The result is shown in Fig. 3. The abscissa is the displacement of the light source or its translated incident angle.

The detected power level varies along each bar for measuring time of 10 s. The instability was verified to be the result of mechanical vibrations, air flow, and thermal fluctuation. We can see that the average curve is a sinusoid with the period of 6 μm. Later we got more stable data under improved experimental circumstances.

When the incident angle is changed in a wide range, the maximal detected power level decreases at both extremes as shown in Fig. 4. It is because the rays shift and go out of the pupil of 6 mm diameter which is placed in front of the light detector. The period of interference fringes is the same as in Fig. 3.

When the incident angle is changed, the focused points behind the condensing lenses and behind the output lens shift from the optical axes correspondingly. As the light detector is placed behind the focal plane of the output lens, the amount of ray shift becomes larger than that at the focal plane.

The measured result is shown in Fig. 5. The angle change of 8×10^{-5} rad causes the ray shift of about 2 mm in this experimental system.

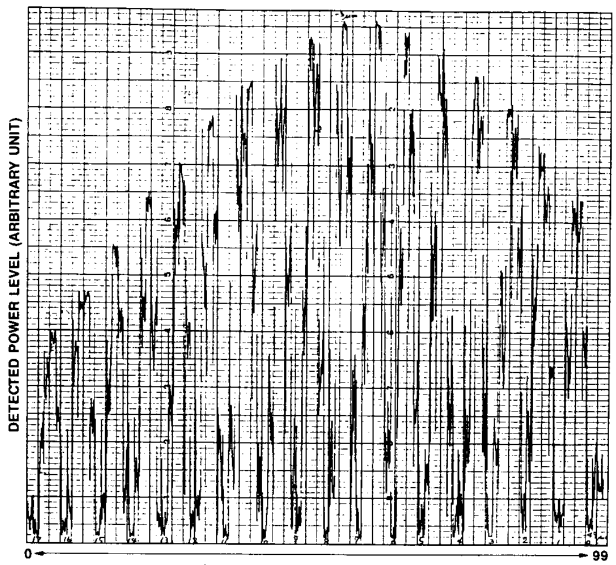

Fig. 4. Interference characteristics versus incident angle (wide angle range).

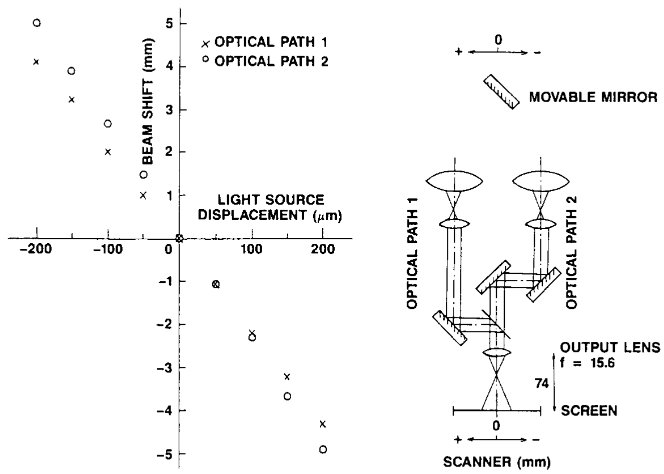

Fig. 5. Output ray shift due to the change of incident angle.

B. Phase Modulation Effects

The modulation charactistics were measured using the experimental system of Fig. 2. The modulated ray interferes with the other ray which keeps the reference phase.

The half-wavelength modulation voltages are 140 V for both modulators.

C. Angle Measurement

The modulation voltage used to hold the same interference condition was measured changing the incident angle. It is convenient to maximize the detected power, and the condition is derived from (5) as

$$2k_x d - \Delta\phi - \phi_m = 0. \tag{6}$$

Equation (6) is transformed to give the following equation, using (4) and the relation $k_x = k\sin\theta$:

$$\pi(V_{\mathrm{mod}}/V\pi) = 2kd\sin\theta - \Delta\phi. \tag{7}$$

The straight lines in Fig. 6 are drawn by the method of least squares for each set of data. The lines have slight variations due to imperfections of the experimental system. But the slopes of the lines show tolerable coincidence with that of the theoretical curve expressed by a dotted line.

The modulation voltage ambiguity of about 260 V corresponds to higher order interferences. The light

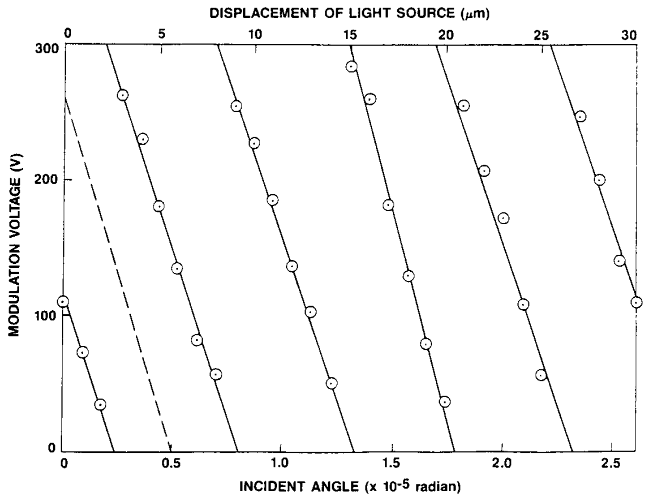

Fig. 6. Angle measurement by modulation voltage. Slope of dotted line represents theoretical value.

extinction ratio is about 71. The angle resolution less than 1×10^{-7} rad can be expected from this figure.

V. APPLICATION EXAMPLES

As examples, applications to spacecraft tracking and attitude determination are illustrated in Fig. 7, which are key technologies to rendezvous and docking missions. Two sets of the angle gauges #1 and #2 are necessary to measure angles in two orthogonal directions.

In the configuration (a), spacecraft "A" is equipped with two sets of the angle gauge #1 and #2 in two orthogonal directions. Spacecraft "B" carries a laser radiating light to A. The angle gauge #1 and #2 measure the angles of incoming light relative to the boresight direction of A. Therefore, spacecraft A can determine the location of spacecraft B relative to the boresight of A, or A measures the attitude of A relative to the direction of B.

In the configuration (b), the laser is carried by the spacecraft A only, and B carries a corner cube. The laser light emitted from A is reflected by the corner cube back to A. Therefore, the system functions in the same way as to configuration (a) except for the considerate reduction of received power.

In the configuration (c), each spacecraft is equipped with the function of (a) or (b), though the laser is borne only by the spacecraft A. Therefore, A and B can measure the relative position and attitude of each spacecraft.

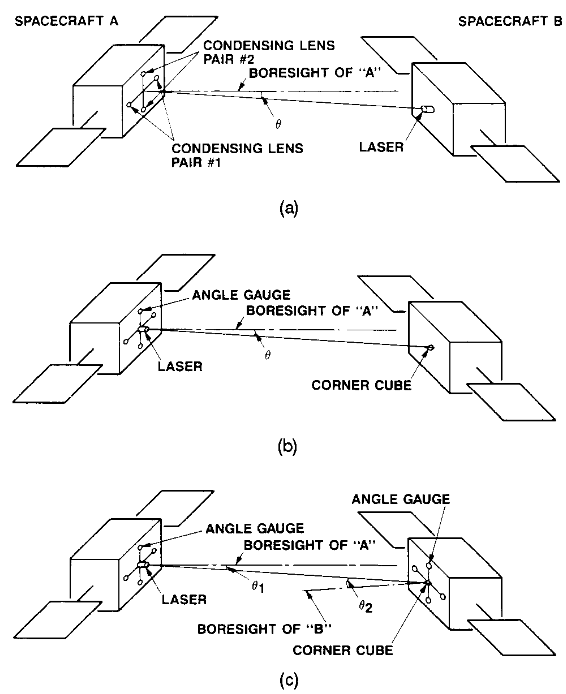

Fig. 7. Application to spacecraft tracking and attitude control. (a) Angle gauge on A, laser on B. (b) Angle gauge and laser on A, corner cube on B. (c) Angle gauge and laser on A, angle gauge and corner cube on B.

VI. CONCLUSION

A novel precise angle gauge was proposed and its basic performances were analyzed. The experimental system was formed to be compatible with practical conditions and its performances were verified experimentally. It is shown that an angle resolution less than 1×10^{-7} rad can be expected.

This angle gauge can be used for very precise angle measurement in machinery, space navigation, etc. And it is also effective in precisely track an object because the feedback loop can be easily attached to it. The incident wave may come from a laser borne on a target, or may come scattered back from a target which is illuminated by a laser installed on the same body as the gauge.

Achieving better performances and resolving the angle ambiguity still remain to be pursued in the future.

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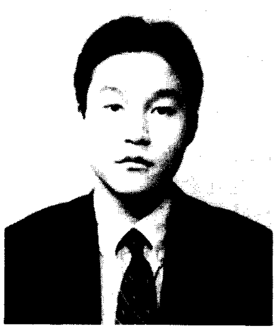

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