Practical Electro-Optic Deflection Measurements System

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Abstract

This paper describes an electro-optic displacement measurement system which measures both angular and lateral displacements simultaneously. The system consists of a CW laser, lenses, interference filters, beam splitter, and a position-sensing photodiode. The use of the described system has been checked and verified by use in an actual system. The system was used to measure flexure of a ship in a variety of different sea states and the results of these measurements are discussed along with the design criteria.

Introduction

Various applications in the past have led to the development of several optical alignment systems.[1-4] More recently an electro-optic alignment system which is insensitive to angular displacements has been built.[5] It consists of an intensity modulated laser, a lens and a Schottky barrier position-sensing photodiode. Another afocal lens system[6] with unit magnification has been developed to monitor displacement and tilt of an object moving in a straight line. However, it either measures displacement and is unaffected by tilt or measures tilt and is unaffected by displacement. Therefore, two assemblies need to be mounted side by side in a common block to measure tilt and displacement simultaneously.

This paper describes a system which has been developed to measure four degrees of freedom simultaneously. This system does not measure roll, the fifth degree of freedom. However, by using a polarizer or half wave plate and detecting polarization changes,[7] roll measurements can be incorporated.

This system consists of a highly collimated laser (beam divergence < 0.1 mrad full angle), lenses, a beam splitter, interference filters and a pin position sensing photodiode.

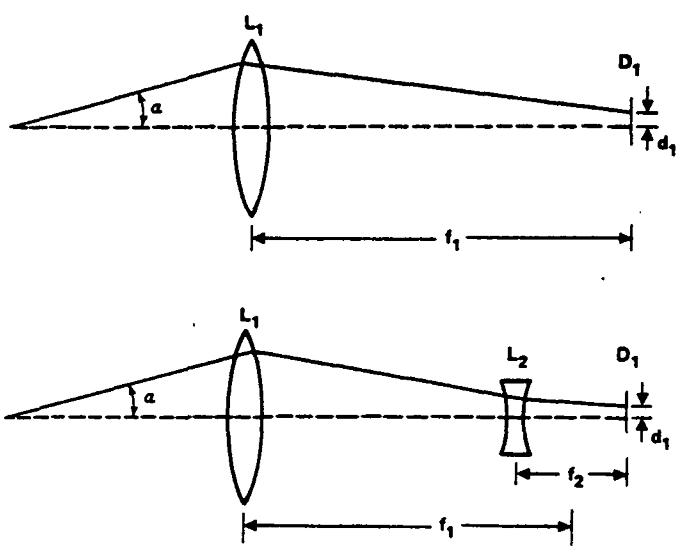

Fig. 1. a) Positive lens with detector at focal plane to measure angular displacements. b) Negative lens used to increase effective focal length.

System Design

Consider a simple lens/detector arrangement shown in Fig. 1(a) where the detector is in the focal plane of the lens. In this configuration the detector is insensitive to lateral displacement and sees only an angular displacement α, which is, for small angles

$$\alpha = \frac{d_1}{f_1} \tag{1}$$

where d_1 is the displacement on the detector and f_1 is the focal length of the lens. Under many circumstances the total angular deviation might be extremely small which indicates that only a small portion of the detector is used. To utilize a larger portion of the detector the focal length needs to be increased, however, it should be increased without significantly increasing the physical size of the system. This can be accomplished as shown in Fig. 1(b) with a divergent lens of focal length f_2. Now the angular displacement is given by

$$\alpha = \frac{d_1}{f_1}\left(1 - \frac{f_1 - \ell}{f_2}\right) \tag{2}$$

where ℓ is the distance between L_1 and L_2. This system is still invariant to any lateral displacement. In most applications an interference filter is needed so that the background light does not reach the detector. The interference filter has a thickness, t, and an index of refraction, n, which increases the effective focal length by a factor of

$$\Delta f = t\left(\frac{n-1}{n}\right) \tag{3}$$

For most cases this factor increases the focal length by one percent or less and is neglected.

Figure 2 shows a lens and detector arrangement which measures both lateral and angular displacement and the lateral displacement S is dependent upon α and is given by

$$S = \frac{f_1}{f_3} d_2 - \alpha R \tag{4}$$

where f_1 and f_3 are the focal lengths of lenses L_1 and L_3 respectively, d_2 is the displacement on the detector and R is the separation distance between L_1 and the laser source. As Eq. (4) indicates there exists an ambiguity since the reading of d_2 is dependent upon both S and α. Therefore, combining the two systems as shown in Fig. 3 with a beam splitter

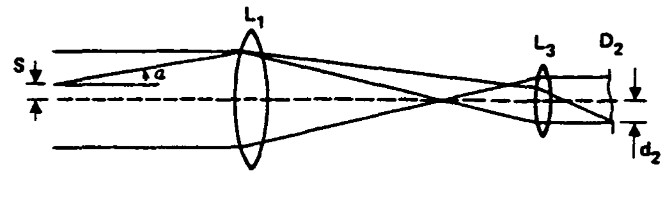

Fig. 2. Simple lens system to measure lateral displacements.

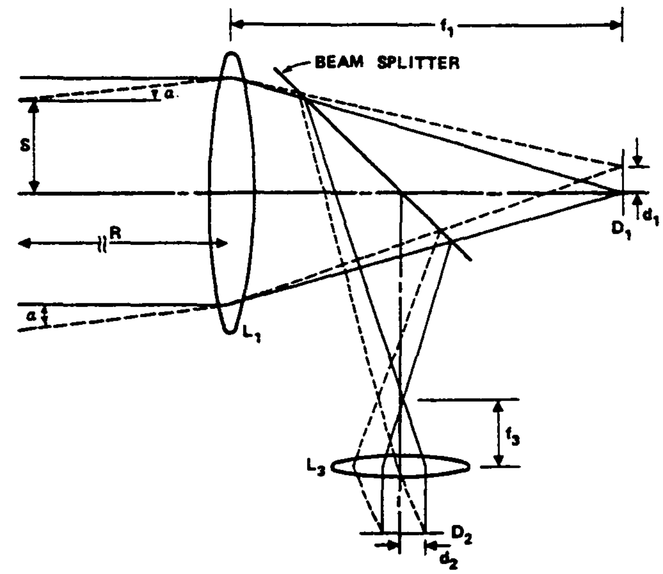

Fig. 3. Lens system to measure both angular and lateral displacement. Beam splitter is used to split 50% of the incoming light.

the lateral displacement becomes (for simplicity we will not use the negative lens)

$$S = \frac{f_1}{f_3} d_2 - \frac{d_1 R}{f_1} . \tag{5}$$

The beam splitter is of the pellicle type (thickness of 8 microns) so that no unwanted displacement is given due to the thickness of the beam splitter.

The photodiode is of the pin structure whose output is proportional to the position of the light impinging on the photodiode. A block diagram[8] of the position displacement electronics is shown in Fig. 4. The displacement monitor has three separate settings for displacement range on the photodiode. The monitor will read full scale for a displacement range of ± .005 inches, ± .05 inches, or ± .5 inches. For given focal lengths and maximum angles the system was tested and calibrated for ± .05 inches full scale. The photodiode has five connections, the center wire is a bias to the photodiode and each of the other four wires are equally spaced around the center connection. Two of the wires are spaced along the ± vertical axis and the other two are placed on the ± horizontal axis. The photodiode material has a linear resistivity such that the light striking the photodiode creates electron-hole pairs which causes current to flow in each of the wires which is inversely proportional to the distance from the light. Consequently, the photodiode tracks the position of the centroid of the light. It is very difficult to obtain a piece of silicon which is linear throughout the entire material. Figure 5 displays a linearity curve of the photodiode used in these experiments. The photodiode has a .3 inch radius with a linearity of 15% over the .3 inch radius, however, if only about 30% of the surface area is used the linearity is 2%. The position measuring instrument used in these tests has a unique normalization capability. In most other instruments of this kind the output of the photodiode is also sensitive to changes in light intensity. This instrument was designed to have a constant output with a change of an order of magnitude of light intensity, therefore, the system can be used in extreme circumstances where light transmission is a problem.

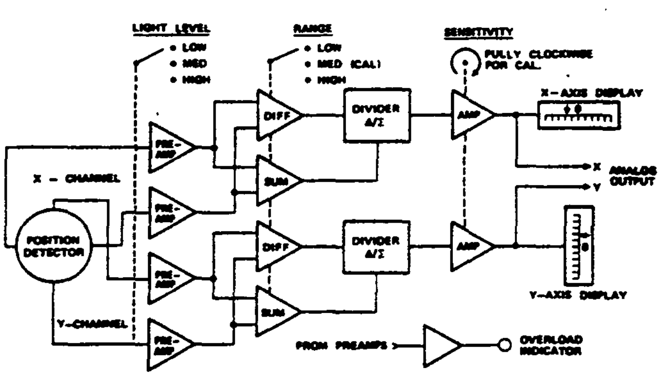

Fig. 4. Block diagram of displacement monitor electronics showing the sum, difference and dividing networks.

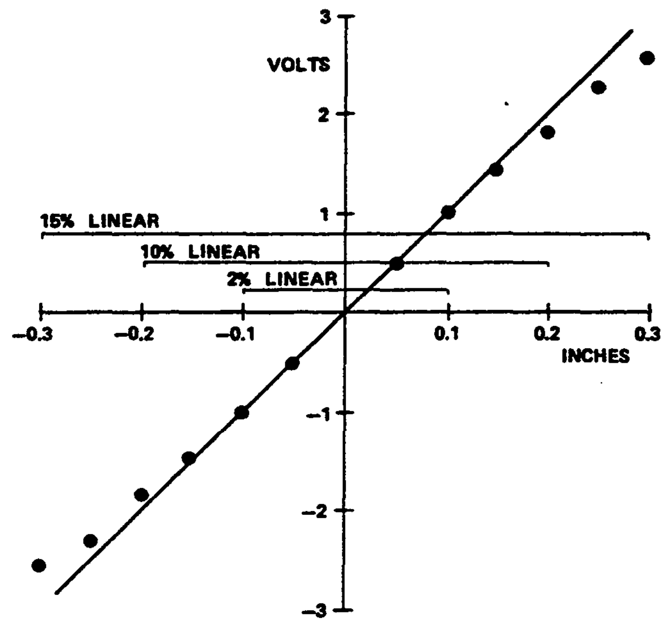

Fig. 5. Linearity measurement of the silicon pin photodiode used in the displacement measurements.

Measurements

Typical experimental and theoretical curves are shown in Figs. 6 and 7. Figure 6 shows the angular data and Fig. 7 shows the lateral displacement data where the straight lines are the theoretical curves. Similar data were taken under a variety of circumstances. The system was given no angular displacement and in this case detector 1 gave no output and detector 2 measured the lateral displacement. The system was given a fixed angular displacement and the lateral displacement was varied yielding a change in output only from detector 2. The system was given a fixed lateral displacement and the angular displacement was varied. In this case both detectors varied and were in good agreement. In all cases the detectors were in excellent agreement with the known angular and lateral displacement changes. The frequency response of the system is 3 kHz so that there is no problem if the system is to measure rapid displacement changes. The BNC outputs of the instrument provide an analog output of ± 5 volts with an output impedance of 1 kΩ.

Once the system was calibrated in the laboratory it was mounted to measure flexure of a ship. Several flexure mea-

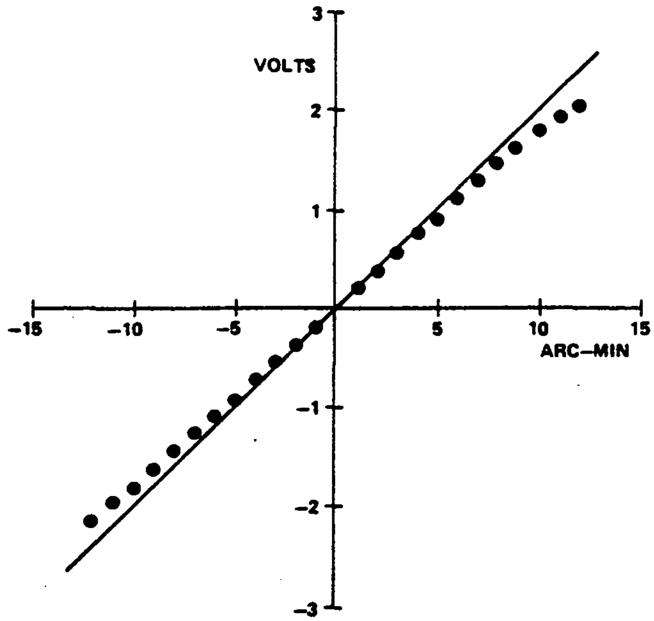

Fig. 6. Angular displacement calibration measurements where the fall-off of the larger angles is due to both the non-linearity of the photodiode and the lens.

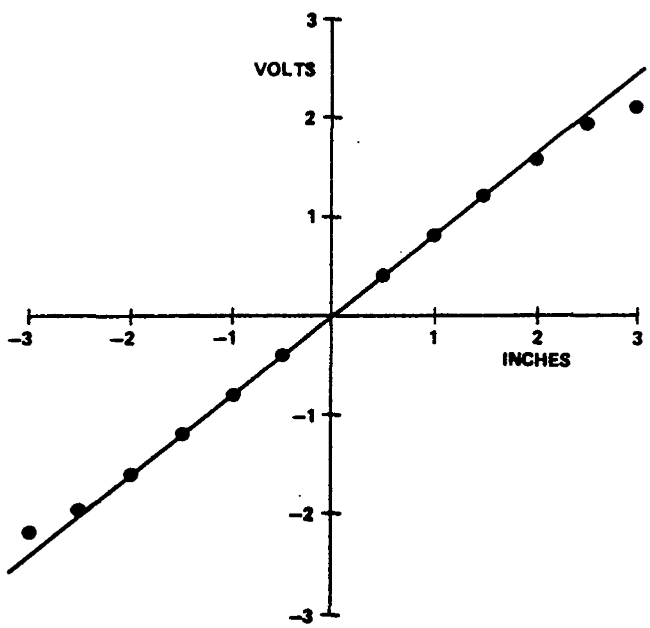

Fig. 7. Lateral displacement measurements where the fall-off at larger displacements is due to both the nonlinearity of the photodiode and the lens.

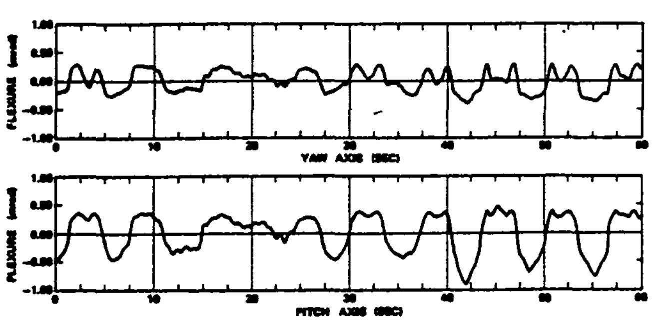

Fig. 8. Angular ship flexure measurements, the top figure is the yaw measurement and the lower figure is the pitch measurement, both are plotted as a function of time.

surements were made with various sea conditions and Fig. 8 shows a typical angular displacement measurement. Both yaw and pitch are plotted over a one-minute time interval for wave heights of about 4 feet. The figure shows that maximum angular flexure was about 0.9 mrad peak and 1.3 mrad peak to peak. The above data were obtained by recording the outputs of the displacement measuring units on an analog tape recorder and digitizing the data and plotting the data with a digital computer. For comparison purposes the data were recorded on an oscillograph simultaneously as it was recorded on the analog tape recorder. Figure 8 and the oscillograph record compare exactly. It appears from Fig. 8 that the yaw and pitch follow each other somewhat which implies that the ship flexure occurs along some plane and all variations are about this plane. Figure 9 shows the angle of this plane as a function of time, with respect to vertical. The average angle measured from vertical about which the ship flexes is 29.8°.

The lens system described here has a problem in that it is extremely sensitive to the placement of the detectors with respect to the lenses. Detector 1 has to be exactly at the focal plane of the lens and if interference filters are used as they were in this system detector 1 has to be shifted even though the increase in focal length is only about 1%. Otherwise, once the detectors, lenses, and interference filters are situated in their proper position the system is extremely sensitive and can measure changes on the detector of ± .001 inch. The system is easy to handle and use after the initial alignment is accomplished.

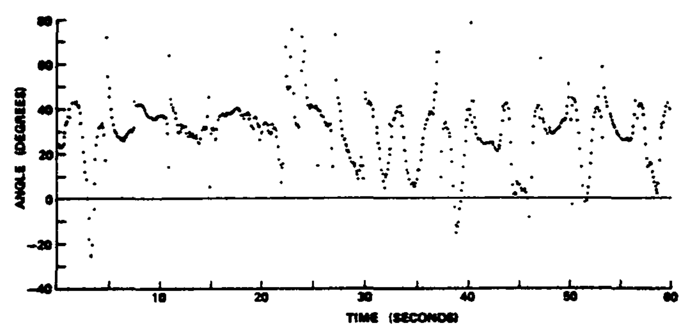

Fig. 9. Plotted as a function of time, this shows the angle of the plane with respect to the vertical at which the ship flexure occurs. The average angle about which the ship flexes is 29.8°.

Acknowledgments

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