Electro-optical systems are increasingly used in position sensing and in dynamic measurements that require noncontact sensors with wide frequency bandwidth.

Using Photodetectors for Position Sensing

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Applications are expanding rapidly in the use of electro-optical instruments to measure angle, distance, height, centering, surface uniformity, and other parameters related to position sensing. Applications also include dynamic measurements such as vibration and dynamic balancing, which require noncontact sensors with wide frequency bandwidth. This article discusses the relative merits of different types of position sensing photodiodes, with emphasis on lateral-effect units. It also describes how to readily determine accuracy and resolution for typical applications.

► **Electro-Optical Setups.** A typical system consists of a fixed-position laser or LED light source, a mirror or system of mirrors, some optics, and a photodiode receiver to collect the reflected light and provide an output signal proportional to position. Figure 1 illustrates a system for precisely locating the displacement of an object positioned, for example, on a test bed. This system can also measure angular rotation of a mirror. For the robotics and biophysics industries, motion studies can be made by multiplexing several systems. In the photocopier, OCR, and facsimile manufacturing industries, similar systems measure the overall alignment accuracy of the series of mirrors used in the reproduction processes. Simple setups without mirrors are used for the straight line alignment of laser beams.

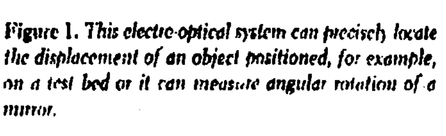

Figure 1. *This electro-optical system can precisely locate the displacement of an object positioned, for example, on a test bed or it can measure angular rotation of a mirror.*

$$\text{X Position} = \frac{(A+D) - (B+C)}{A+B + C+D}$$

$$\text{Y Position} = \frac{(A+B) - (D+C)}{A+B + C+D}$$

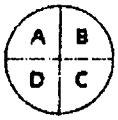

Figure 2. *The quadrant detector features four sensing elements on a single chip. Electronic instruments can automatically perform the algebraic operations and read directly in X and Y the position of the spot on the detector.*

► **Multi-Element Arrays.** The traditional concept of position sensing detectors is that there is an array of one- or two-dimensional photodiode elements. An image spot on the array induces photocurrents in the illuminated elements. All elements are then scanned to determine the position of the image spot.

Arrays have two major disadvantages: their ultimate resolution is defined by pixel size, and the light spot must be smaller than the pixel size. If the spot is larger, you must calculate the centroid location by measuring the output of several adjacent elements, a process which increases the cost and complexity of analyzing the data.

► **Bi-Cells and Quadrant Detectors.** A simplified array in the form of a bi-cell or quadrant detector overcomes the disadvantages of multi-element arrays for certain applications. Consider the quadrant detector shown in Figure 2.

The quadrant detector features four sensing elements on a single chip. For optimum resolution, the spot size should be

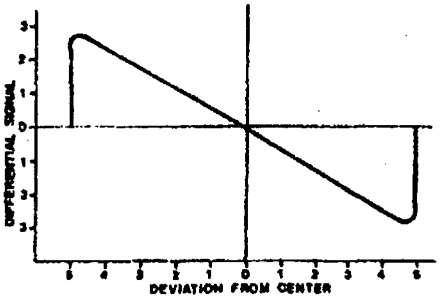

Figure 3. *With the linear transfer function, lateral-effect diodes ensure a wide dynamic range. In the real world, most units exhibit linearity within 0.5 percent over the central 25 percent of their active area, within 3 percent out to 75 percent of area, and within 25 percent out to the periphery.*

as small as possible without being smaller than the gap between the cells. The magnitudes of the outputs of the individual cells permit computation of the light spot's position with respect to the center of the detector. Electronic instruments are available that automatically perform the algebraic operations of Figure 2 and read directly in X and Y the position of the spot on the detector or the test object's position. Computer interfaces are also available that transfer the position information to personal computers.

With bi-cell and quadrant diodes, position resolution is excellent but is relatively dependent on the element size and spot diameter. Also, the dynamic range is limited by the diode transfer function, which is linear only around the center of movement. With resolutions of 0.1 micron or better, bi-cells ~~and quadrant cells are~~ ideally suited for precise centering and nulling, and for tracking position over narrow ranges.

► Lateral-Effect Diodes. Most applications require measurement over a wide range of positions, which is accomplished with high resolution and linearity by using lateral-effect diodes. Available in a variety of shapes and sizes, these devices differ from quadrant cells and arrays because they use only a single photodiode with continuous detection capability, eliminating "dead" regions that otherwise exist between cells.

Position is derived by dividing photogenerated electrons within the substrate (N-region) rather than by profiling intensity distribution on the surface. Therefore, a two-axis lateral-effect photodiode acts as a pair of light-controlled variable resistors for measuring the position of a light spot on its X and Y coordinate axes.

The current, I_s, appearing at each contact may be calculated as:

$$I_s = I_0 \frac{\sinh[\alpha(L\text{-}S)]}{\sinh(\alpha L)} \qquad (1)$$

where:

I_0 = photo-induced current
α = a falloff parameter characteristic of the diode's N-region
L = active length of the diode
S = distance of the light spot from the center

A characteristic of high-quality lateral-effect diodes that ensures good linearity is that when α approaches zero then:

$$I_s = I_0(1\text{-}S/L) \qquad (2)$$

With the linear transfer function, lateral-effect diodes ensure a wide dynamic range (see Figure 3). In the real world, most units exhibit linearity within 0.5 percent over the central 25 percent of their active area, within 3 percent out to 75 percent of area and within 25 percent out to the periphery.

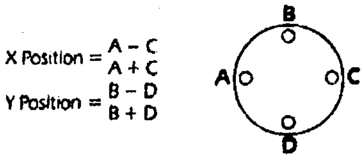

Figure 4. *Positional resolution of the lateral-effect detector is not quite so good as it is for bi-cells and quadrant cells because these cells exhibit a higher S/N ratio than a lateral-effect detector.*

Spot position is calculated as shown in Figure 4. Positional resolution is given by:

$$\delta P \approx \frac{L}{2\ S/N} \qquad (3)$$

where:

L = active length of the diode
S/N = signal-to-noise ratio

Resolution is not quite so good as it is for bi-cells and quadrant cells because of a higher S/N ratio resulting from linearity requirements for a small impedance between lateral contacts. Nevertheless, substitution of typical values in the equation proves resolution is excellent—far superior, in fact, to the CCD devices employed in video cameras.

Confusion often exists between the application of video cameras and photodiodes, perhaps because both use a camera lens. Video cameras are good devices for pattern recognition, but their field of view is so large that even with 1000 or greater pixel resolution, their positional resolution is very poor. In actuality, the two devices complement each other: use a video camera to recognize an object, and use a lateral-effect photodiode independently to measure its position.

► Calculating Position Resolution. Consider a single-axis, lateral-effect position sensor that produces current x_1 and x_2. Position is given by:

$$P = \left(\frac{x_1 - x_2}{x_1 + x_2}\right) \cdot \frac{L}{2} \qquad (4)$$

There is uncertainty, however, in the values of x_1 and x_2 because of noise currents n_1 and n_2. Therefore, the measured position is:

$$\text{Pmeas} = \frac{[(x_1 \pm n_1) - (x_2 \pm n_2)]}{[(x_1 \pm n_1) + (x_2 \pm n_2)]} \cdot \frac{L}{2} \qquad (5)$$

Maximum error occurs when both noise signals are negative and approximately equal in value. The maximum measured position is:

$$\text{Pmeas (max)} = \left(\frac{x_1 - x_2}{x_1 + x_2 - 2n}\right) \cdot \frac{L}{2} \qquad (6)$$

Since the S/N ratio is:

$$S/N = \frac{x_1 + x_2}{2n} \qquad (7)$$

we can solve for n and substitute into Equation 6 to obtain a maximum error value in terms of the S/N ratio, which we can readily estimate and control. Thus:

$$\text{Pmeas (max)} = \frac{x_1 - x_2}{x_1 + x_2 - \left(\frac{x_1 + x_2}{S/N}\right)} \cdot \frac{L}{2} \qquad (8)$$

$$\frac{S/N}{S/N\text{-}1} \cdot \left(\frac{x_1 - x_2}{x_1 + x_2}\right) \cdot \frac{L}{2} \qquad (9)$$

is the worst-case erroneous measurement.

The Modulus of Error is:

$$\delta P = \frac{1}{(S/N + 1)} \cdot \frac{L}{2} \qquad (10)$$

If S/N >> 1 then:

$$\delta P = \frac{L}{2\ S/N} \qquad (11)$$

Consider maximum S/N. For an SC/10D, one can expect a noise equivalent current of about 10 nA and a maximum signal current of about 100 μA without saturating the detector (under laboratory conditions). This gives a S/N ratio of 10,000:1. Since the SC/10D has an active length of 1 cm, Equation 11 gives

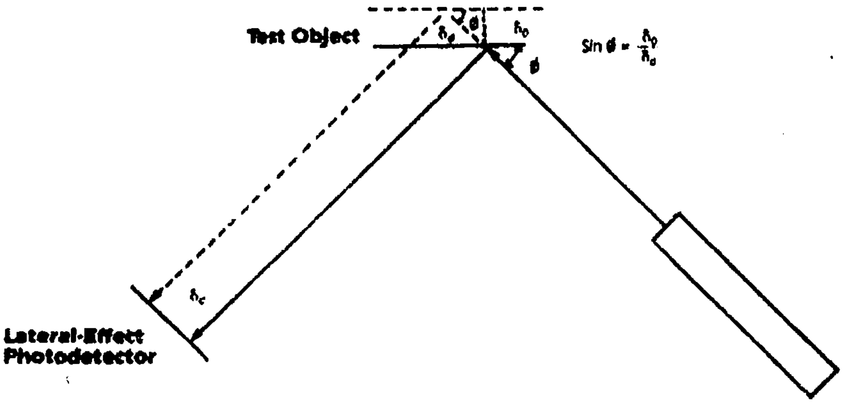

Figure 5. *Shown is a representative application for measuring linear displacement of a test object with the laser beam incident at angle ϕ.*

a resolution of 0.5 micron, or typically 1 micron.

▶ Measuring Position. Up to this point we have discussed only the positional resolution of a spot of light on a detector. Now let us define the parameters related to positional resolution of a test object and see how the two interrelate.

Figure 5 illustrates an application for measuring linear displacement of a test object; the laser beam is incident at angle ϕ. The relationship between movement of the light spot, δ_d, and object movement, δ_o, is:

$$\delta d = \frac{\delta_O}{\sin\Phi} \qquad (12)$$

For the required position resolution of the test object and the predicted resolution of the detector:

$$\delta d = \frac{\delta_O\,(\min)}{\sin\Phi} \qquad (13)$$

Therefore,

$$\Phi = \frac{\sin^{-1}[\delta_O(\min)]}{\delta d(\min)} \qquad (14)$$

For example, with a detector resolution of 15 microns and an object resolution of 1 micron, $\Phi = 41$ degrees.

Similarly, the angle of incidence and the maximum movement of the test object determine the minimum active length of the detector:

$$\delta d(\max) \geqslant \frac{\delta_O(\max)}{\cos\Phi} \qquad (15)$$

For movement of 100 microns by the object and an angle of 49 degrees, the detector must have a length of at least 152 microns.

Figure 6 shows a setup for measuring the rotation of a test object about a fixed point.

$$\tan(\delta\Phi) = \frac{\delta d}{L} \qquad (16)$$

$$L = \frac{\delta d}{\tan\delta\Phi} \qquad (17)$$

For the predicted resolution of the detector and the minimum angular resolution of the object:

$$L \leqslant \frac{\delta d(\min)}{\tan[\delta\Phi(\min)]} \qquad (18)$$

Similarly, the photodetector must have an active length of

$$\delta d(\max) \geqslant L\,\tan[\delta\Phi(\max)] \qquad (19)$$

As can be seen from Figures 5 and 6, error can occur if there is any linear displacement when a test object is rotated or if there is any rotation when it is positioned linearly. Many applications require that this error be corrected in the measurement. Other applications require that an object be positioned individually for both linear displacement and angular rotation or tilt.

Figure 7 shows an example of combined linear displacement and rotation. Had either movement occurred in the opposite direction, the individual effects on the light spot would have been in opposite directions. Photodetectors cannot distinguish between an object's linear and its angular movement. Users can solve this measurement problem, however, by using a photodetector to measure the combined effect and an autocollimator to measure the rotation effect. Linear displacement and angular rotation can then be determined algebraically.

A classical autocollimator (see Figure 8) projects the image of a reticle at infinity so that a viewer can observe angular displacement of a remote reflective surface by measuring the relative position of the projected reticle to the eyepiece reticle. The advantage of an autocollimator is that it is insensitive to linear displacement of the observed surface.

A modern electronic autocollimator op-

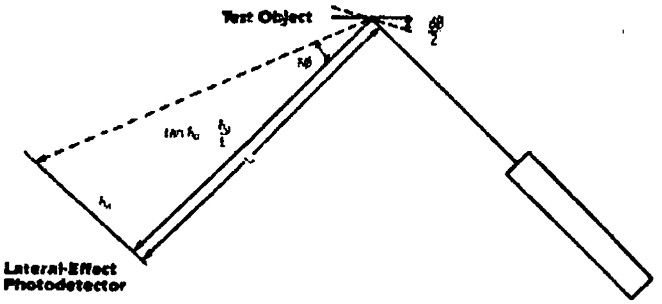

Figure 6. *This shows a setup for measuring the rotation of a test object about a fixed point. It can be seen from Figure 5 and Figure 6 that error can occur if there is any linear displacement when the object is rotated or if there is any rotation when it is positioned linearly.*

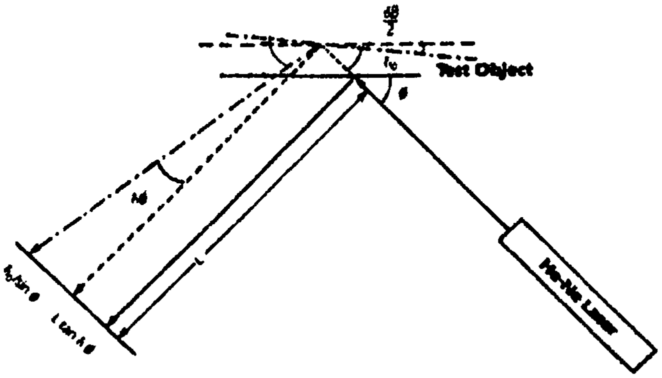

Figure 7. *This example of combined linear displacement and rotation serves to illustrate the fact that had either movement occurred in the opposite direction, the effects on the light spot would have been in opposite directions.*

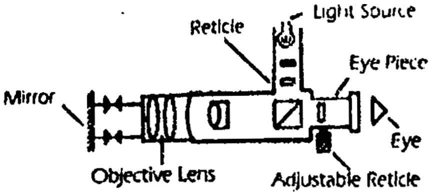

Figure 8. *A classical autocollimator projects the image of a reticle at infinity so that a viewer can observe angular displacement of a remote reflective surface by measuring the relative position of the projected reticle to the eyepiece reticle. The device is insensitive to linear displacement of the observed surface.*

erates on the same principle as the classical version, with the exception that it projects the image of an infinitely small point source of light at infinity, back onto a photodiode instead of the viewer's eye. This provides greater angular resolution, and permits electronic readout and fully automated measurement systems.

The UDT Models 1010 and 1020 electronic collimators (see Figure 9) use a high-power IR LED generating a beam of light that is emitted through a beamsplitter (B) and then collimated by a lens. The resulting parallel beam of light reflects off a reference mirror (M) or other reflective surface on the test object and then travels back through the lens and beamsplitter to a photodetector (D), which converts the position of the beam into an electrical measure of changes in angular position of the reference surface. The focal length of the lens determines the angle of coverage. A filter (F) prevents ambient light from interfering with the measurement.

The Model 1010 uses a two-axis lateral-effect photodiode for continuous detection of angular position. At 0.025 radians, it has perhaps the widest coverage of any autocollimator. Yet it features an extremely high resolution of 5 μradians. The Model 1020, using a quadrant detector for centering or nulling applications, has a resolution of better than 1 μradian.

Figure 10 shows an instrumentation system for combining the measurements of linear and angular displacement. The Model 1233 lateral-effect photodetector measures the combined displacements, while the 1010 or 1020 measures angular displacement only. The Op-Eye VI optical position indicator performs the computations given in Figure 4 and interfaces the system to a computer, which calculates linear and angular displacement. Op-Eye's dual-channel capability enables it to serve two setups simultaneously.

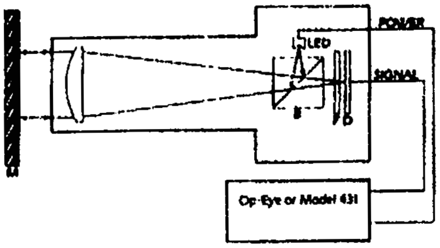

Figure 9. *The UDT Model 1010 or 1020 uses a high-power IR LED generating a beam of light which is emitted through a beamsplitter and then collimated by a lens.*

► **Dynamic Measurements.** Photodiodes are noncontact sensors capable of sensing extremely small motions over frequencies from DC to 30 kHz. With their high-speed electronics, they are ideally suited to vibration measurement, resonance testing, dynamic balancing, and other cyclical or impulsive changes in position. Output signals can be delivered to conventional oscilloscopes, spectrum analyzers, and storage devices.

A typical application in the computer industry is in the testing of hard disk drives. Disk drive systems must be precisely balanced to prevent any out-of-balance motion that could cause head crashes. Figure 11 illustrates a light beam being reflected off a shiny surface on the head onto a lateral-effect photodetector in order to measure and effectively damp any troublesome vibration before the disk assembly is shipped.

In structural engineering, photodiode systems can measure the natural oscillation of structures ranging from walls and floors to bridge supports. Using conventional methods of structural excitation and electro-optical measurement, the output of a photodetector system can be fed directly to an FFT analyzer for modal analysis. Unlimited structural applications also exist in the aerospace industry.

The electronic autocollimator enables engineers to extend dynamic applications to the measurement of angular vibration. For example, spinning polygon mirrors used in IR missile guidance systems must be balanced to prevent any vertical rocking motion of the mirrors. With the

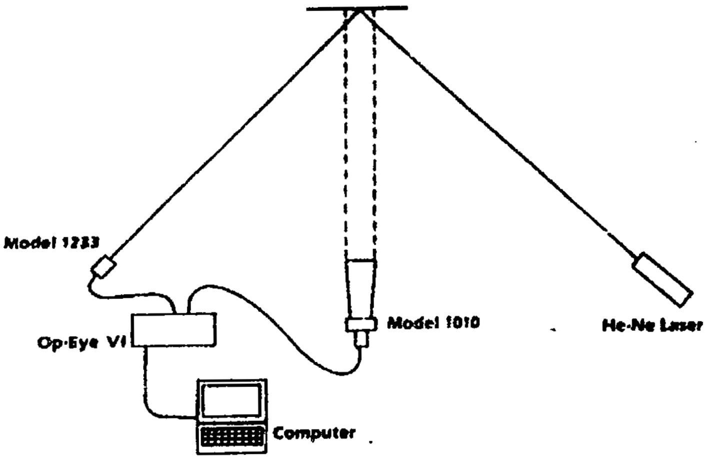

Figure 10. *An instrumentation system has been developed to combine the measurements of linear and angular displacement.*

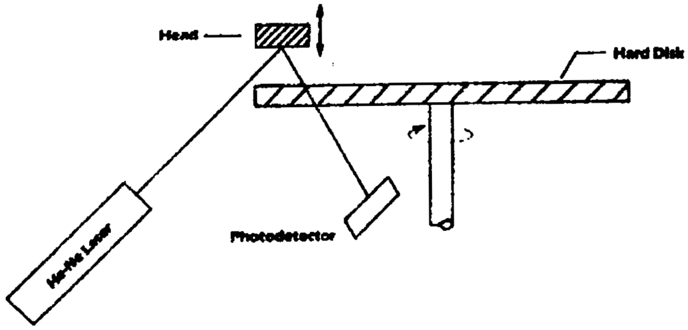

Figure 11. *To measure head vibration in a hard disk drive assembly, a light beam is reflected off a shiny surface on the head onto a lateral-effect photodetector.*

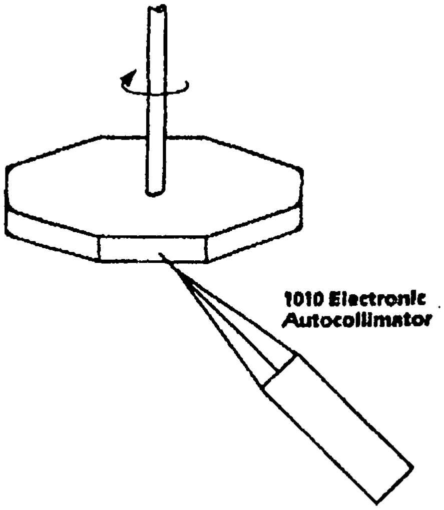

Figure 12. *Engineers can use an electronic autocollimator to test spinning polygon mirrors for any vertical rocking motion that would inhibit proper operation. The mirrors, used in IR missile guidance systems, can be tested in a fixed position or during spinning.*

measurement system shown in Figure 12, engineers can test mirrors, in a fixed position or during spinning, for any vertical rocking motion that would interfere with proper operation.

► **Conclusions.** Electro-optical systems provide the high resolution necessary for precision positioning and alignment applications. Because of their wide frequency response, they can also measure structural vibration modes and angular vibration. They readily interface to conventional recording, analysis, and storage devices.