Using the Laser Doppler Displacement Meter For Precision Positioning And Motion Control

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Precision positioning and motion control are important for high accuracy linear or XY-stages. To achieve submicron tolerances and high speed motion on a linear or XY-stage is in increasing demand, particularly in IC manufacturing, video inspection, coordinate measuring machines and machine tools. A constant concern is maintaining the structural integrity of a complex stage or machine.[1] Lead screw nonuniformity and thermal expansion can be minimized by using a linear encoder. However, the effects of thermal gradients and their changes cause twisting and bending of structures, which can lead to angular motions and large Abbe offset errors.[2]

Also, because of the high pulse rates associated with high resolution positioning, the maximum speed of motion has to be reduced. For example, at 0.1 microinch resolution and 96 ips, the pulse rate is 960 MHz, which is beyond the capability of most servo controls.

However, a new type of position sensor, the laser doppler displacement meter (LDDM)[3], can provide both linear and angular measurement simultaneously, and both high resolution and low resolution positioning information simultaneously. By using the LDDM, Abbe error can be minimized and both high resolution and high speed motion of a linear or XY-stage can be achieved.

Laser Doppler Displacement Meter

The LDDM is based on the principles of radar, the Doppler effect and optical heterodyne. Basically, a target or retroreflector is illuminated by a laser beam. The laser beam reflected by the retroreflector is frequency shifted by the motion of the retroreflector, and the phase of the reflected laser beam is proportional to the position of the retroreflector. That is,

$$x = \frac{c}{2f}\left(N + \frac{phi}{2\pi}\right) \qquad (1)$$

where x is the position of the retroreflector, c is the speed of light, f is the laser frequency, N is the number of 2πs, and phi is the phase angle. For a typical output, N is expressed as the quadrature square waves and phi is expressed as the analog signal shown in figure 1. The maximum speed for the phase detection is 8 MHz, which corresponds to 96 ips (2.5 m/s), and the maximum resolution using an 8-bit ADC is 0.05 microinch (1.2 nm).

For motion control there are three types of laser heads: dual-aperture, dual-beam and dual-beam flat-mirror. As shown in table 1, for the dual-aperture laser head, there is an exit aperture for the output laser beam, a receiving aperture for the return laser beam, and a corner-cube used as a retroreflector. For the dual-beam laser head, there are two exit laser beams, two return laser beams, and two corner-cubes. The separation for the two corner-cubes or laser beams is D. Using a two-axis processor module, the outputs are the displacement x and the angular angle theta, which can be expressed as (X-Y)/D. For the dual-beam flat-mirror laser head, the first exit, return laser beam, and the corner-cube are the same as in the dual-aperture laser head. However, the second laser beam shares the same aperture for exit beam and return beam, and the retroreflector is a flat mirror. The output of the laser head is the difference of the displacement between the corner-cube and the flat-mirror. This eliminates any error caused by the mechanical motion and air current between the corner-cube and the laser head. Hence, higher accuracy can be achieved.

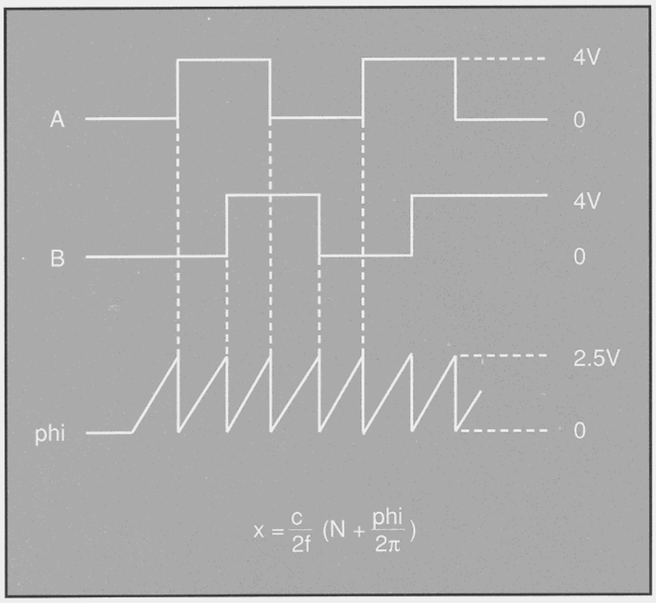


Figure 1, time chart of LDDM outputs — A quad B square waves and analog phase signal.

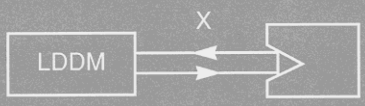
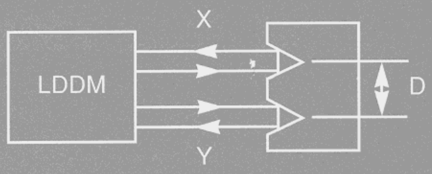
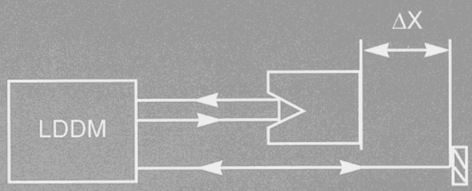
Types	Schematics	Functions
Dual-Aperture		Linear, x
Dual-Beam		Linear, x and angle $\theta = (X - Y)/D$
Dual-Beam Flat-Mirror		Linear, Δx

Table 1, types of LDDM laser heads.

The major features of the LDDM are that it provides both quadrature signal and analog signal, and measures both displacement and pitch angle (or yaw angle). As a result, high maximum velocity, high resolution and high positioning accuracy are simultaneously attainable. Other features are:

- no need for a complex interferometer,
- no need for expensive optical components,
- no serpentine error,
- no interpolation error, and
- compactness and simplicity.

Applications

A typical application in a linear measuring device is shown in figure 2. Here a dual-beam laser head is used. Both displacement and pitch angle can be measured. The true dimension L can be expressed as:

$$L = X - d \bullet \text{theta} \qquad (2)$$

where X is the measured displacement, d is the distance between the measuring axis and the anvils, and theta is the measured pitch angle. Hence, the true dimension L can be obtained even without extremely accurate guideways and a heavy and stable structure.

A typical application in a precision XY-stage is shown in figures 3a and 3b. Here two dual-beam flat-mirror laser heads are used to measure X and Y motions. Mount both the x-axis corner-cube and the y-axis corner-cube on the camera or lens holder as references, and both the x-axis flat-mirror and y-axis flat-mirror on the XY-stage. The position of the XY-stage with respect to the camera holder can be determined and both dead path error and Abbe error are minimized.

A typical application in a high speed and high resolution XY-stage is shown in figures 4a and 4b. For simplicity in illustration, only the x-stage is shown. Here a two-loop servo control is used. A DC motor is used for fast and coarse control and a piezoelectric translator (PZT) is used for fine control. The PZT has a unique ability to convert electric energy directly into mechanical movement with high resolution. The PZT effect is non-linear with hysteresis and slow creeping. However, the PZT is used here only as a driver, therefore the position accuracy is determined by the accuracy of the

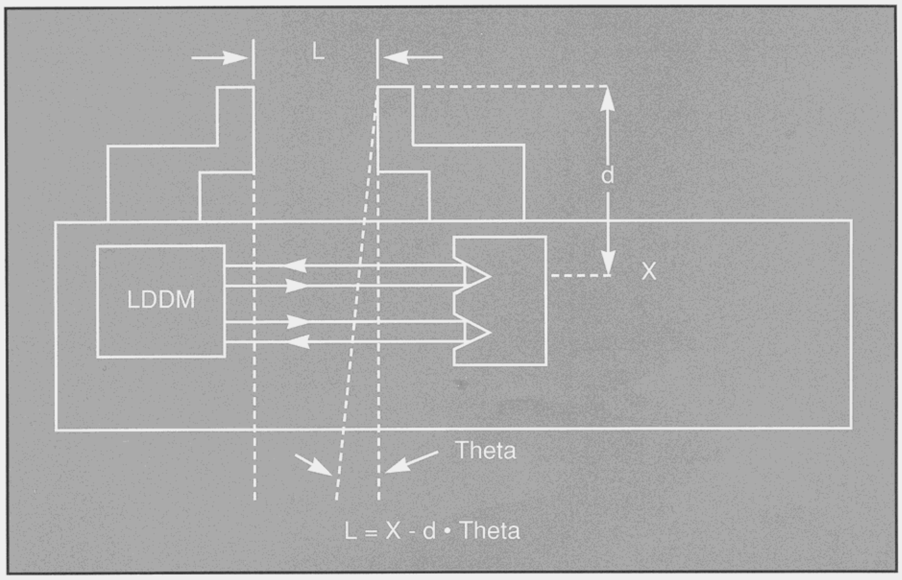


Figure 2, a schematic of a linear measuring device. Here the true dimension L is determined by the measured X and theta. Hence, the straightness of the guideway and rigidity of the structure become less important.

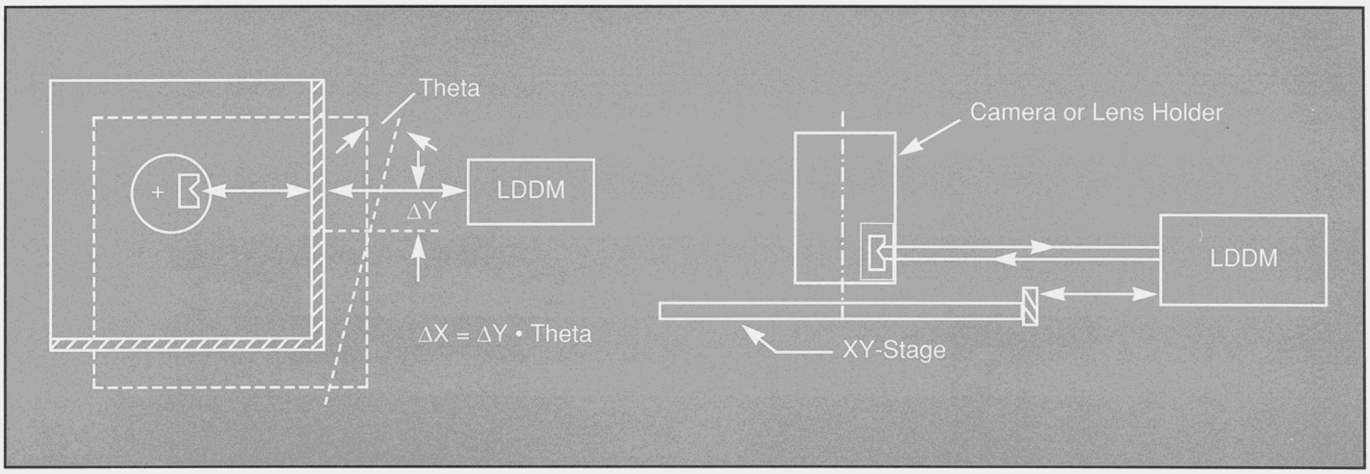


Figure 3, schematics of an XY-stage using two dual-beam flat-mirror laser heads (only one is shown). This arrangement minimizes the dead path and Abbe error. Figure 3a (left) shows how Abbe error due to yaw motion is minimized and figure 3b (right) shows how the dead path error is minimized.

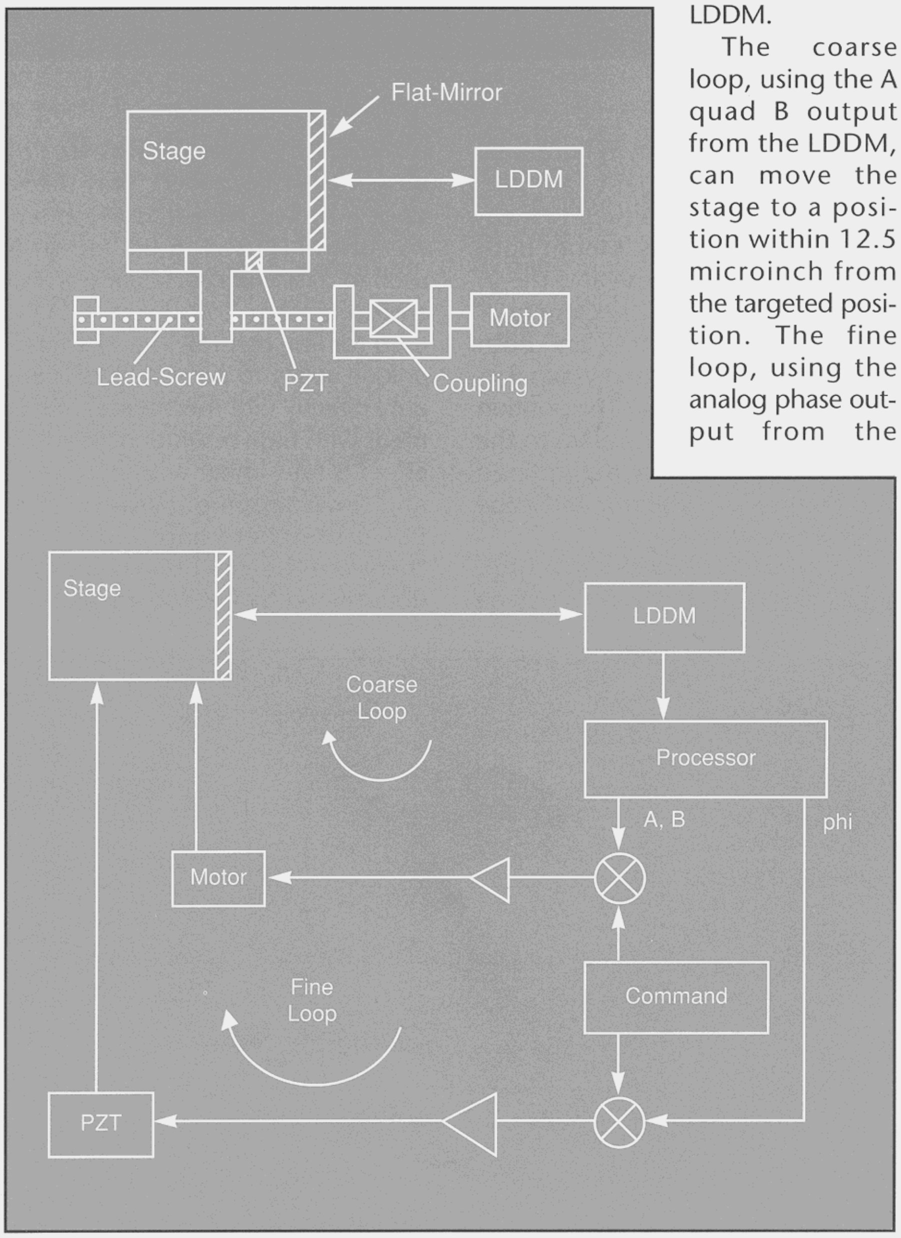


Figure 4, schematics of a two-loop servo control using a DC motor and a piezoelectric translator. Figure 4a (top) is a physical layout and figure 4b (bottom) is a functional block diagram.

LDDM.

The coarse loop, using the A quad B output from the LDDM, can move the stage to a position within 12.5 microinch from the targeted position. The fine loop, using the analog phase output from the same LDDM, can further move the stage to a resolution of 0.1 microinch. This configuration allows both high speed, up to 96 ips, and high resolution, up to 0.1 microinch, to be achieved.

Conclusion

Through using the LDDM both linear and angular motion, and both high speed and high resolution motion control can be achieved. Usually, to achieve high speed and high precision positioning, very difficult and expensive mechanical solutions are required. However, because of the recent developments in microelectronics, digital electronics and electro-optics, the electro-optical solutions are relatively easy and low cost.

References

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