Laser Doppler
Displacement Measurement

A Breakthrough In Submicrometer Positioning Technology

by Dr. Charles P. Wang

Existing precision displacement-measuring devices are primarily based on linear encoders (optical or magnetic) or laser interferometers. Most encoders use grating scales and frequency counters, while most interferometers use stabilized lasers and fringe counters. In general, interferometers are more expensive and more accurate than linear encoders. However, there are large gaps in price and performance between these two technologies.

Figure 1. The Laser Doppler Displacement Meter.

Based on current developments in laser radar technology, a new device, a Laser Doppler Displacement Meter (LDDM™) has been developed.[1] This device is an electro-optical assembly, which uses the Doppler shift of a laser frequency caused by the movement of a target to measure displacement accurately over a range of a few meters. As shown in Figure 1, the LDDM consists of a laser head, a retro-reflector, a processor (not shown) and a notebook. Using the latest in microelectronic, electro-optic and optical heterodyning technologies, an LDDM provides a high precision and low-cost alternative to submicrometer positioning. The key feature of the LDDM is that its performance compares with that of a laser interferometer, while its price compares with that of a linear encoder.

Encoders And Interferometers

A typical linear encoder is an incremental device. It has a series of lines ruled on a scale, either optically or magnetically, and has some type of pickup device that measures the position by counting the number of lines that pass the location of the pickup device. The encoder also typically extrapolates to produce measurement points between the resolution units of the lines.

The basic output of the device is usually a signal corresponding to the output of the detector. To determine which direction the system is running, it is usually necessary to use two or more detectors spaced at some increment apart. An electronic circuit then converts the direct output of the scale into a digital number that corresponds to motion along the axis. Typical accuracy is 10 to l00 parts per million.

As early as 1881, A.A. Michelson employed an interferometer, which now bears his name, to investigate the theory concerning the existence of the "ether." The use of interferometers in length measurement gained significance with the invention of the laser.[2] Basically, as shown in Figure 2, a laser beam is split into two parts of equal intensity by a beamsplitter. One portion is subsequently reflected onto a photodetector via the stationary mirror and the beamsplitter. The second portion of the beam is reflected at the movable mirror, propagates back onto the beamsplitter and is superimposed there over the first portion. These two laser beams generate fringe patterns on the detector. A zero-crossing

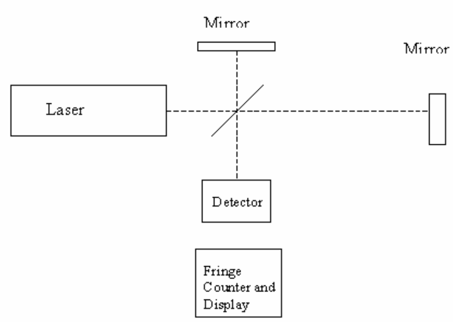

Figure 2. Schematic of a Michelson Interferometer

circuit counts the change in the number of wavelengths of light in the path between the laser and the mirror. It then gives a measurement of the distance the mirror has moved in terms of the number of wavelengths and fractional wavelengths that are counted.

The laser interferometer is an order of magnitude more accurate than the best linear encoders, but its cost is also an order of magnitude higher.

Time-Of-Flight And Chirp Radar Measurements

The time-of-flight technique for distance measurement is very simple. As shown in Figure 3, a laser pulse is launched at time t, and the pulse reflected by a target at a distance D, will reach the detector at time t + T. D then equals cT/2, where c is the speed of light. For high accuracy, the pulse-width should be small and the repetition rate should be high. However, the repetition rate is limited by the range of the two-way transit time T, so the repetition rate is less than 1/T. Otherwise, it is difficult to keep track of which return pulse corresponds to which output pulse.

To break this barrier, it is conceivable to mark the output pulse by different frequencies. That is, use a pulse train of different frequencies, so that the corresponding output pulses and return pulses can be tracked. Hence, the repetition rate can be increased M times, where M is the number of different frequencies of the output pulses.

Since the output pulse and return pulse can be identified by their frequencies, a continuous wave-train with variable frequency can be used to determine the distance. Furthermore, heterodyne techniques can be used to determine the frequency difference that corresponds to the two-way transit time, as shown in Figure 4. Here, the distance can be expressed as:

$$D = CT/2$$

$$\ldots = (c\Delta f/2)/(df/dt)$$

where Δf is the beat frequency and (df/dt) is the chirp rate. This technique is commonly known as a chirp radar.

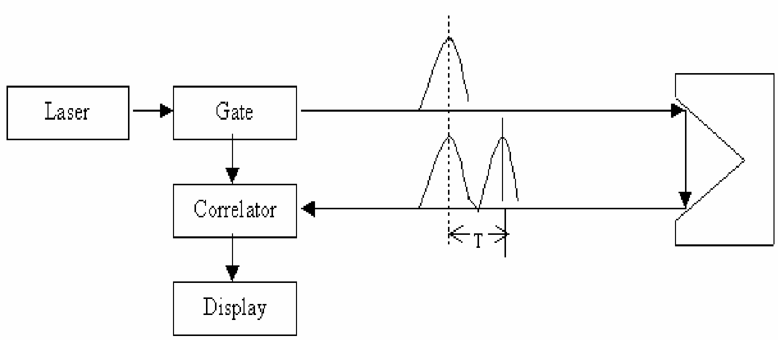

Figure 3 Schematic of time-of-flight detection.

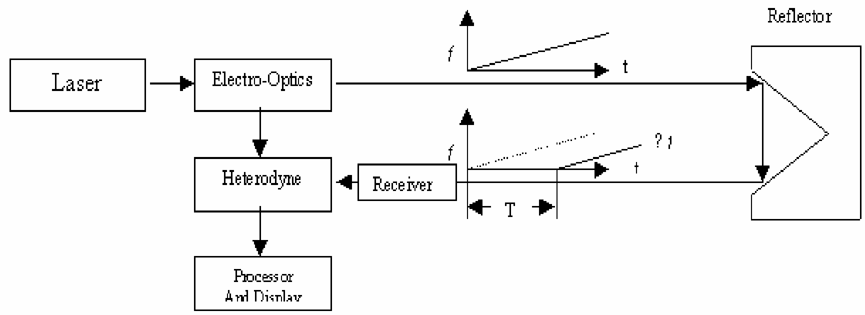

Figure 4. Schematic of frequency chirp detection.

Displacement Measurement By Doppler Effect

The LDDM is based on the principles of radar, the Doppler effect and optical heterodyning. Similar to a Doppler radar, a target (here, a retroreflector) is illuminated by a laser beam as shown in Figure 5. The light reflected by the retroreflector is frequency-shifted by the motion of the retroreflector. The Doppler frequency shift can be expressed[3] as:

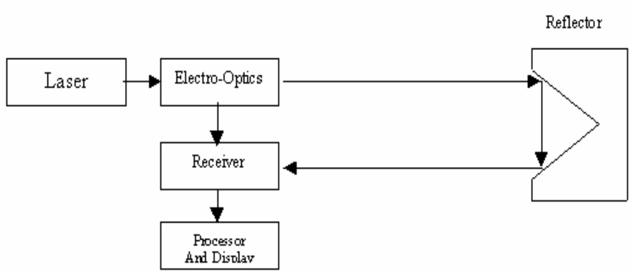

Figure 5. Schematic of Laser Doppler Displacement Meter

$$f = \frac{2f_0}{c}v \qquad (2)$$

or

$$\frac{\Delta\Phi}{2\pi} = \frac{2f_0}{c}\Delta z \qquad (3)$$

where f and $\Delta\Phi$ are the frequency and phase shift, respectively; v and Δz are the velocity and displacement of the retroreflector, respectively; f_0 is the frequency of the laser; and C is the speed of light.

A phase detector measures the phase variation, which corresponds to the displacement of the retroreflector. When the displacement is larger than the half-wave-length, X/2, a counter records the total phase changes. That is,

$$\Delta\Phi total = 2\pi N + \Phi \qquad (4)$$

where N is the number of half-wavelengths and Φ is the phase angle less than 2π. The total displacement, Δz, can be expressed as:

$$\Delta z = \frac{c}{2 f_0}(N + \Phi / 2\pi) \qquad (5)$$

A microprocessor is used to read the counter and the phase angle; convert them to inches or centimeters of travel; control the ten-digit display; compensate for the change in light speed caused by temperature, pressure and humidity variations; and communicate with an external computer or controller.

The resolution of the device is the minimum detectable phase Φ, which is limited by the electronic signal-to-noise ratio and the root-mean-square phase noise. The maximum velocity, or slew rate, is determined by the bandwidth of the phase detector and the counter. For a typical LDDM, the bandwidth is 3 mega-hertz, which corresponds to a maximum velocity of 36 inches per second (or 50 meters per minute).

Note that in Equation 5, the N and Φ are two different terms; hence, high resolution and high maximum velocity could be obtained at the same time. In a typical interferometer, however, higher resolution is obtained by dividing the wavelength or doubling the number of counts. Hence, higher interferometric resolution can only be achieved at lower maximum velocity.

Accuracy And Resolution

The accuracy of the LIDDM can be expressed[4] as:

$$\frac{\Delta z}{z} = \pm\frac{\Delta n}{n} \pm \frac{\Delta\lambda}{\lambda} \pm \frac{\left(<\Phi\frac{2}{n}>\right)^{1/2}\lambda}{4\pi\quad z} \pm \Theta^2 \qquad (6)$$

where Δz/z is the accuracy expressed as the ratio of maximum error and the total displacement; n is the refractive index of

air; λ is the laser wavelength; $(<\Phi\frac{2}{n}>)^{1/2}$ is the rms electronic noise; and Θ is the misalignment angle.

The refractive index of air varies with temperature, pressure and relative humidity.

At visible wavelengths,

$$n-1 = 1O^{-6}\,(79/T)\,(P + 4800\,e/T), \qquad (7)$$

where T is the temperature (Kelvin), P is the pressure (millibars) and e is the vapor pressure (millibars).

As a rule of thumb, a one-degree-Kelvin increase in temperature corresponds to an increase of the laser wavelength of 1 part per million. A one-degree-Kelvin increase in temperature is equivalent to a 3.3-inbar decrease in pressure or a 25-percent decrease in relative humidity. Thus, for accurate displacement measurements, temperature, pressure and relative humidity should be measured and their effect compensated by using Eq. 7.

The laser wavelength may be changed by thermal expansion and mechanical vibration of the resonator. In general, the gain bandwidth of a helium-neon laser is approximately 1 gigahertz. The output frequency of the laser is determined by the separation of the resonator mirrors. Laser frequency can be stabilized by adjusting the resonator length, either by controlling the tube temperature or by using a piezoelectric-controlled resonator mirror.

Laser frequency stabilities of better than 10^{-11} have been achieved. Frequency-stabilized HeNe lasers based on the transverse or longitudinal Zeeman effect, the intensity ratio of two longitudinal modes, an absorption cell, a temperature sensor, and a reference quartz cell are commercially available. Their frequency stabilities range from 10^{-7} to $l0^{-9}$.

For a free-running HeNe laser, the frequency stability is roughly 10^{-6}. Because of this property, the National Bureau of Standards has concluded that physical principles of laser action preclude a HeNe laser from producing light of a wavelength that differs from the accepted value by more than I ppm. Hence for all technical purposes, a HeNe laser that produces a beam realizes the international and U.S. standard of length to an accuracy sufficient to the needs. NBS also considers all such devices traceable to national standards in all the usual contexts.

The dominant electronic noise is the phase noise induced by photodetector shot noise. The mean squared phase noise is:

$$
\begin{aligned}
<\Phi\frac{2}{n}> &= <i\frac{2}{n}>/<i\frac{2}{h}> \\
&= 2B\left(id>/<i\frac{2}{h}>\right) \qquad (8)
\end{aligned}
$$

where $<i\frac{2}{n}>$ is the mean squared detector noise current, e is the electron charge, *i*d is the detector cathode current, *B* is the filter bandwidth, and *i*h is the optical heterodyne current.

For a typical LDDM using a 0.5-milliwatt HeNe laser and a 4MHz bandwidth, the ims phase noise is less than $l0^{-3}$, which corresponds to a resolution of 0.3 nm.

The fourth term of Eq. 6 is the error due to misalignment, commonly known as cosine error. For an accuracy of 1 ppm, the misalignment angle must be limited to less than 1 milliradian. Other error sources are laser mode hopping; the position change of the laser beam, detector and optical components due to mechanical vibration and thermal stability; and radio frequency interference and noise pickup. All of these could be minimized by proper design and proper installation of the instrument.

Conclusion

A laser Doppler displacement meter offers a number of attractive benefits to submicrometer positioning. First, it can use any continuous wave laser with a reasonable frequency stability. Second, the electro-optical device acts as an optical isolator, preventing stray light from the target from entering the laser resonator and disturbing the laser's frequency stability. Third, the entire system is compact and easy to align. The interior of the laser head box is kept at a constant temperature to reduce thermal distortion of the optical components. Fourth, high maximum velocity (slew rate) and high resolution are simultaneously attainable.

Applications for such a device include x-y stages, pattern generators, steppers and aligners, magnetic and optical disk drives, diamond-point turning machines, precision machine tools, computer-numerical-control machines and coordinate-measuring machines.

References

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