Laser Doppler Sensor Brings New Performance to Machining

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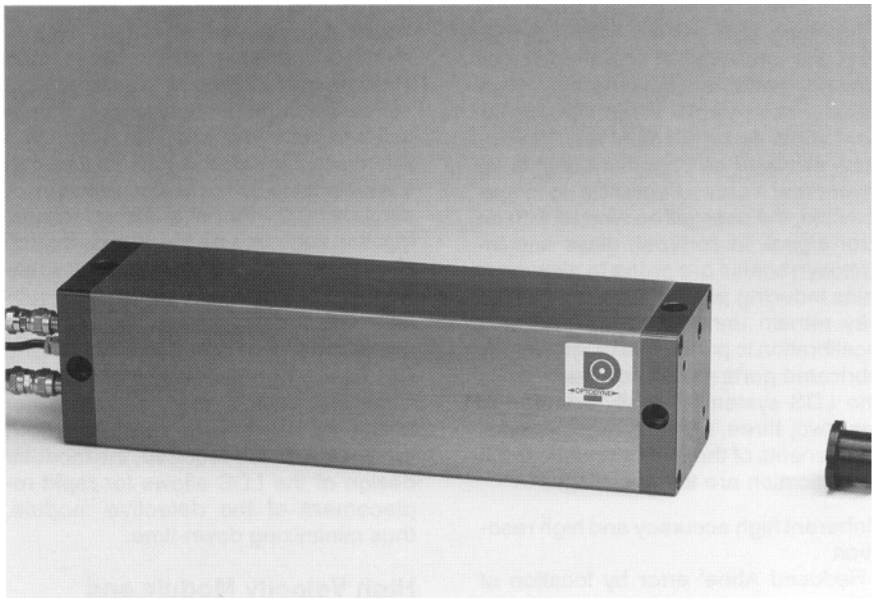

Figure 1 - LDS Laser Head

Introduction

Competition in the worldwide market place demands high quality parts with increasing productivity and accuracy. A new generation of Laser Doppler Scale™ (LDS™) addresses these needs making it possible to build machines that are both accurate and fast while keeping the cost down.

The new way of thinking is to boost accuracy and speed through high-tech or electro-optic devices such as the LDS. In other words, precision can come from sophisticated feedback and control systems rather than through extraordinary mechanical rigidity and precision manufacturing and assembly.

Conventional machine tools are either built for high precision or for high speed. To achieve both high precision and high speed in machine tools higher spindle speed, better cutting tools, higher stiffness, faster and tighter servo control, low inertia drives, accurate and fast position sensors are needed. Recent emerging technologies such as fluid spindle bearings have pushed the limits of spindle speed up to 50,000 RPM and with higher accuracy. Current hardened cutting tools have improved the cutting tool life at high speed and high feed rate. New chatter suppression through the active damping of the turning process has been developed. New tool holder and tool changer designs have improved the tool changing speed and accuracy of the cutting tools. Low inertial linear drives can replace the lead screw and the ball bearing leading to low friction, stiff drives. High feedback rate, high speed data processors and servo algorithms lead to faster and stiff servo control.

Recent developments in high resolution, high accuracy and high speed LDS lead to more accurate positioning, tighter servo loop, less vibration and higher speed, which vastly improve the next generation of machine tools. For example, Ingersoll has developed its Octahedral-Hexapod machine, a revolutionary design due to its combination of stiffness, speed, accuracy and portability. Another example is Ingersoll's High Velocity Module (HVM) which utilizes a high speed spindle, linear motors and the LDS to achieve both high volume production and flexibility.

Position Feedback Technology

There are several methods of measuring position such as with inductive scales, magnetic scales, glass scales and laser interferometers. Inductive scales are known for ruggedness. Made of metal, they can withstand greater vibration and speed, and are perceived to be more reliable. Magnetic scales have the reputation for being less sensitive to contamination. Glass scales with higher resolution are more sensitive to hostile environmental conditions. Laser interferometers have the highest accuracy and resolution.

In general, encoder makers often process output signals through a special kind of circuitry known as interpolation electronics. This circuitry takes the two output sinusoidal signals from encoder and produces output signals of a higher frequency. These output signals can be used to measure distance traveled with more resolution than available from a non- interpolated encoder output.

However, imperfections in the scanning signals produce measuring errors on the order of 1 % to a fraction of 1 %, hence, the smaller the distance between encoder gratings or pitches, the smaller the interpolation error. Typical pitches, P for inductive scales is P=2 mm; for magnetic scales, P=200 µm, for glass scales, P=20 µm, and for laser interferometers a pitch of 0.6 µm is typical. Interferometers are the most expensive and difficult to use. As a result, the precision positioning industry has been locked behind a price/precision barrier.

A new Laser Doppler Displacement Meter (LDDM™) technology has broken through the technological barrier of bulky, cumbersome interferometer laser heads, time-consuming installation and alignment, and costly measurement methods. The LDS is a durable, compact, simple, and economical precise laser-based linear scale.

The LDS is based on the LDDM™ technology. The LIDS measures displacement by monitoring the phase shift of a laser beam reflected from a target. Recent progress in microelectronics, electro-optics, and computer and communication technologies, makes it possible to produce the surprisingly compact LDS with stunning performance at a very low cost.

The LDS laser head measures 2" x 2" x 8.5". The resolution is 0.000025", the accuracy is 1.5 ppm or 0.000060" over 40" of travel, the maximum speed is 160 ips and the maximum range is 2000". The LDS can be used in hostile environments with dust particles and mechanical vibrations up to 8 g. Because of the new technology breakthrough, the LDS provides laser interferometer performance, glass scale price and linear transducer size.

Compared to other position transducers such as glass or Inductosyn scales and single frequency laser interferometers, the LDS requires less setup time and is less complicated. Also, the total system accuracy is significantly better and considerably more stable. For example, in the LIDS, alignment shifts do not usually result in position errors. If an alignment shift is so severe that a measurement is no longer possible, the user will be alerted with an error signal. In contrast, glass and Inductosyn scales are prone to alignment shifts inducing positioning errors which may remain undetected until either a recalibration is performed or improperly fabricated parts are discovered.

The LDS system is easily adapted to one, two, three, or multi-axis systems. The benefits of the LDS for major areas of application are the following:

- Inherent high accuracy and high resolution
- Reduced Abbe' error by location of LDS near axis center line
- No thermal expansion or mounting stress on scale
- Optimal hermetic seals for hostile environment
- Higher loop gain possible for closed loop servo control
- Easy installation and alignment reduces installation cost
- Electronics flexibility with variable increment and automatic temperature compensation

Laser Doppler Technology

The LDS 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:

$$X = C/2f\ (N+\theta/2n)$$

Where: x is the position of the retroreflector, c is the speed of light, f is the laser frequency, N is the number of 2 π's and θ is the phase angle. For a typical output, N is expressed as quadrature square waves and f is expressed as analog signal. The maximum speed for the phase detection is 8 MHz which corresponds to 5 m/s (200 ips) and the resolution per pulse is 0.63 micrometer (0.000025 inch). An LDS laser encoder is shown in Figure 1.

Briefly, a laser beam is directed to a retroreflector. The retroreflector will reflect the laser beam back parallel to the output beam, and its position will be determined by the Doppler Shift. There are a number of advantages to working with a laser beam for precise positioning. The inherent accuracy of using a laser beam from a stabilized laser as the measurement ruler is achieved with no periodic re-calibration. The measurement is non- contact eliminating mechanical linkages with the stage. One important advantage is the freedom to locate the point of measurement close to the measured object. The retroreflector can be mounted closely in line with the location to be measured reducing or eliminating the Abbe' offset or increasing the tightness of the servo control. The LIDS requires very little maintenance. There are no moving parts subject to wear. All machine mounted parts are of rugged design that insures long life. The laser tube is small and rugged it can withstand 8 g of force and its laser beam never needs re-calibration. When repairs are required, the modular design of the LDS allows for rapid replacement of the defective module, thus minimizing down-time.

High Velocity Module and Octahedral Hexapod Machine

Starting in 1985, Ingersoll Machine Company, in conjunction with Ford Motor Company, began the development of a radically new machine tool technology which utilized high thrust linear motors to drive the machine's linear axis. These linear motors replace the ball screws, ball nuts, gear boxes, servo motors, encoders and end bearings traditionally used in a machine tool axis drive system. Magnetic force alone is used to drive the machine axis and hold them in position. The objective of this development was to produce a machine which would be several times more productive than conventional machining centers with superior accuracy and reliability. Ultimately, flexible systems of these machines would be used to replace transfer lines for mid-to-high volume production applications.

The result of this effort was the development of machines with the following characteristics:

- Acceleration and deceleration rates which are 10 to 15 times higher than conventional machining centers (1 -1.5 9)
- Rapid traverse and feed rates that are 3-4 times higher than conventional machining centers (3,000 ipm, 76 m/min)
- Very stiff, stable machine platform capable of supporting new spindle technology also developed by Ingersoll high speed, high power, hydrodynamic bearing motorized spindles

In order to achieve these results, every area of machine design needed to be re-evaluated. A rigid machine structure with a first order resonant frequency three times higher than a conventional structure was required, but the structure had to weigh less than half that of a conventional steel or iron structure. Very high position and velocity loop gains were required for the machine's control system in order to maintain high path accuracy at high acceleration and feed rates. Ingersoll experimented with three different kinds of axis feedback systems and concluded that only one had all the capabilities needed for this demanding application--the LDS.

The Octahedral-hexapod machine was jointly developed by Ingersoll and the National Institute of Standards and Technology (NIST). This machine, compared with conventional base and tower machines combines parallel, kinematic-link manipulators with an octahedral machine frame to provide six-axis machine capability and a structure that is extremely rigid and self contained. With an octahedron based structure, any force or load into the corners would result in all members being either in tension or compression. Thus, no bending forces would occur. Also, a tubular structure of a hexapod could be made to transmit all loads only to those corners. Hence, the combination of these would bring a machine toward ultimate stiffness. Because of the symmetric structure, the thermal distortion will be minimum and easily be compensated by the machine software. The stiffness of the machine means that it will handle ultra-high speeds and traverse rate with ease. Six LDS are used for the position feedback of the six-axes to achieve high speed and high accuracy.

Summary

The LIDS has been successfully applied to the HVM and the Octahedral-hexapod machine with extremely high performance. The major considerations in using the LDS for position feedback are to:

1) achieve higher accuracy and stiffness
2) minimize Abbe' offset error
3) survive the hostile and vibration environment
4) automatically compensate for temperature changes

Other considerations are long range, easy installation, maintenance and service, and total system cost.