APPENDIX M. REPRINTS OF PAPERS

HIGH SPEED AND HIGH ACCURACY MACHINE TOOLS USING LASER ENCODER FEEDBACK

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I. Introduction

A revolutionary concept in the design of machine tools eliminated the lead screw to increase the speed of the machine tool, as well as accuracy and rigidity. The lead screw, as a machine's main source of inertia limits speed, so it has been replaced with a linear motor and motion control servo that uses a laser as feedback. The result is a machine tool that is very fast when performing operations, such as moving between cuts, tool retraction and tool changes. The machine tool's path accuracy and settling time is improved, because of the benefits the laser provides for the machine's servo control system. The speed, power, and rigidity of the system makes both high metal removal rate and high part accuracy possible at the same time. In addition, the high acceleration and deceleration rates provided by this drive system make improved tool life at high feed rate possible because a constant chip load on the cutting tool is maintained at all times.

II. High Velocity Manufacturing

Starting in 1985, Ingersoll Milling 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 rate which are 10 - 15 times higher than conventional machining centers (1-1.5 g).
- Rapid traverse and feed rates that are 3 - 4 times higher than conventional machining centers (3,000 IPM, 76 m/min).
- A 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 rethought. 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. A photo of the Ingersoll high Velocity Machining Center is shown in Fig. 1. Ingersoll experimented with three different kinds of axis feedback systems and concluded that only one had all the capabilities needed for this demanding application - laser encoder feedback.

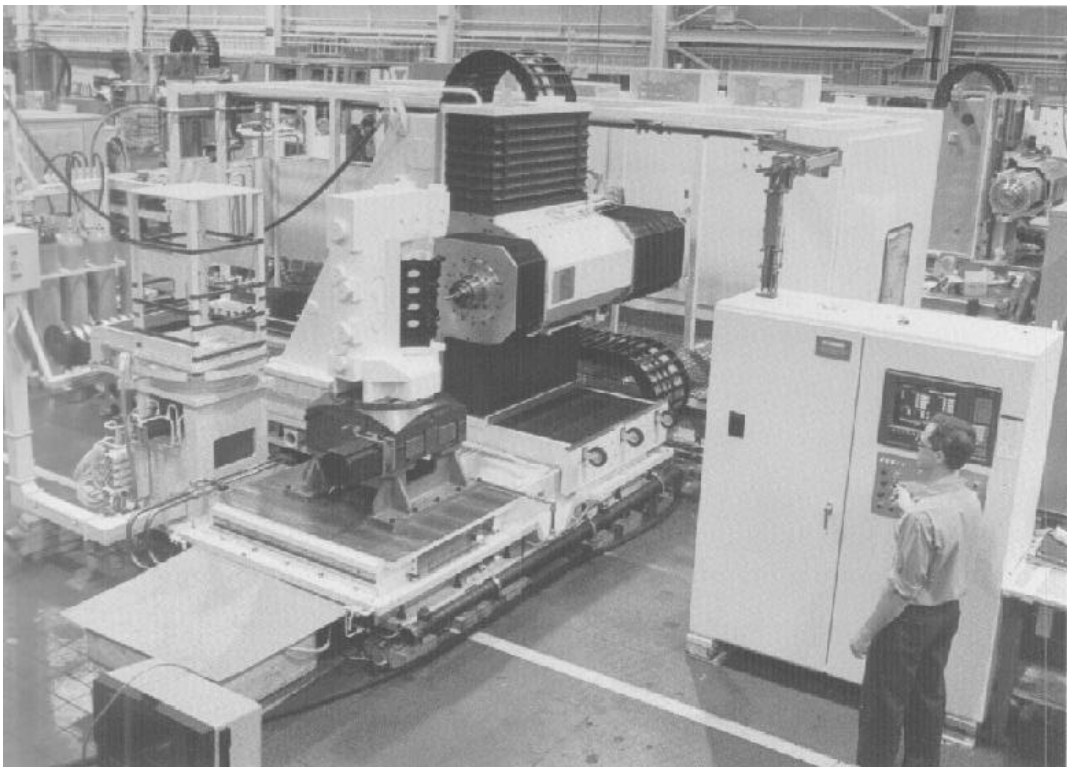

Fig. 1 Ingersoll High Speed Milling Center

III. Laser Doppler Displacement Technology

As described in Ref. 1, 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

$$x = \frac{c}{2\mathrm{f}} \cdot (\mathrm{N} + \frac{f}{2 \cdot p}) \qquad (1)$$

Where x is the position of the retroreflector, c is the speed of light, f is the laser frequency, N is the number of $2p$'s and f 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 2.5 m/s (96 ips) and the resolution per pulse is 0.63 micrometer (0.000012 inch). An LDDM™ laser encoder is shown in Fig. 2.

Fig. 2   LDS Laser Head

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 he 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 Abbé offset, (Ref. 2) or increasing the tightness of the servo control. LDDM™ 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 LDDM™ allows for rapid replacement of the defective module, thus minimizing down-time.

IV. Application of Laser Feedback to the High Velocity Module

A. Primary Drivers

1. Capable of high resolution feedback at high data rates. The ability of system to provide 0.000012" positional resolution at velocities of 50"/second was a benefit of this design.

2. Rejection of vibration in two of three planes reduced the effect of structural resonances. A linear motor (Ref. 3) machine must close the velocity feedback loop through the position feedback system since no rotating encoder or tachometer is available. This introduces the machine structure into the velocity loop. In order to achieve high servo stiffness and high acceleration and deceleration rates, high velocity loop gains are required. The laser systems rejection of resonance in two planes makes it possible to have high velocity loop gains without exciting the machine structure. A block diagram of the servo control is shown in Fig. 3.

3. Immune to electric noise or interference. Linear servo motors do not contain electrical noise or interference as well as rotary motors. The immunity of the laser feedback system to the electrical noise created by a linear motor drive system contributed to a clean feedback signal and stable machine control system.

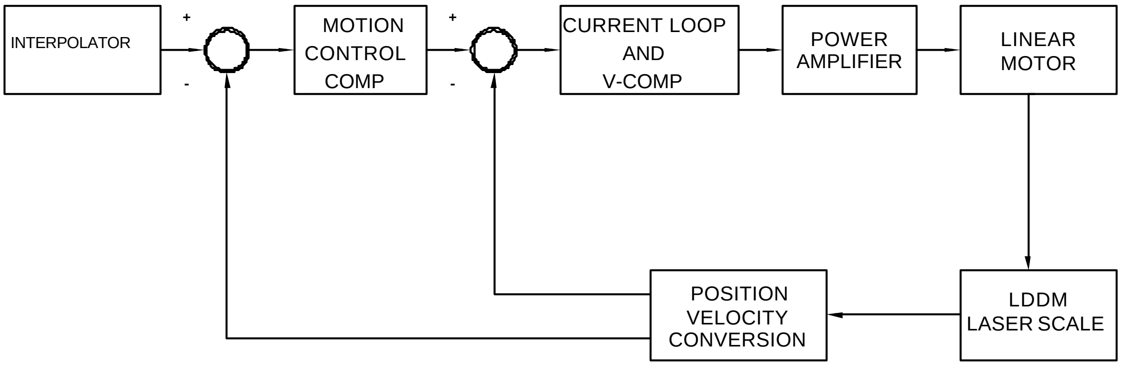

FIG. 3 BLOCK DIAGRAM OF A DIRECT DRIVE AND LASER FEEDBACK SYSTEM

B. Secondary Benefits

1. Compensation for temperature related growth in the machine structure. When properly applied, a laser feedback system can provide compensation for thermal growth in a machine structure because of its low coefficient of expansion compared with other scale designs (Ref. 4). The laser coefficient of expansion of 0.56 parts/million is approximately one-eight the coefficient for glass scales and one-eleventh the coefficient of steel scales. As a result, the laser system is capable of maintaining axis position despite growth of the machine structure.

2. Ease of installation and calibration. No precision machined surfaces are required to mount the laser scale system. No time-consuming alignment and calibration process is required. Wiring is required only for the laser head itself. The laser retroreflector is a passive device. If the laser head is mounted to an adjustment mechanism, the alignment procedure consists of reading a beam strength signal off a test point on the laser controller card and adjusting the laser position to maximize the beam strength signal. No additional calibration or alignment is required.

V. Conclusion

While it would have been possible for High Velocity Machines to achieve their productivity and quality objectives using more conventional linear scales, our testing shows that the use of a laser feedback system materially improved machine stiffness and accuracy due to the benefits this system offers the machine's servo control system. The High Velocity Machines' combination of direct axis drive system and high control gains for the position and velocity loops results in improved dynamic stiffness, acceleration/deceleration, and path accuracy. The use of laser feedback systems improved the servo system performance and thus the overall level of machine performance and accuracy.

References:

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2. Wang, "Abbé Error and Its Effect on Position Accuracy of an XY-Table", Motion, 5, (No. 6) pp. 19-22, Nov/Dec 1989.

3. Chris Koepher, "Linear Motor Drive--- A Fast Track for Machine Tools", Modern Machine Shop, 67 (No. 2), pp. 64-7(), July 1994.

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Figure Captions:

1. Photo of the Ingersoll High Velocity Machining Center
2. Photo of the LDDM™ laser encoder
3. Block diagram of the servo control loop

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