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INTERFACING THE LINEAR MOTOR SLIDE DRIVE
TO A PRECISION MACHINE TOOL

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April 1979

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OAK RIDGE Y-12 PLANT
OAK RIDGE, TENNESSEE

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INTERFACING THE LINEAR MOTOR SLIDE DRIVE TO A PRECISION MACHINE TOOL

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ABSTRACT

A linear-motor slide-drive system has been used to replace the mechanical lead-screw drive train on a large-component diamond-turning machine. Test results have demonstrated improved surface texture quality, and machining operations are continuing on a variety of workpieces.

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SUMMARY

A linear-motor slide-drive system has been used to replace the mechanical gear train on a large-component diamond-turning lathe. Inaccuracies in the previous lead-screw drive system resulted in cyclic errors of 0.25 to 2.5 μm (10 to 100 μin), which corresponded to the pitch of the screw. These cyclic errors have been eliminated, and the machine is presently being used to successfully fabricate reflective metal optics.

INTRODUCTION

Special-purpose diamond-turning machine tools are used in the Oak Ridge Y-12 Plant^(a) for the fabrication of extremely high-quality optical components.¹ These machines utilize precision slides and spindles as well as pneumatic isolation mounts to provide a very smooth motion of the diamond tool across the surface of a workpiece. These machines rely on ball nut/lead screw slide drives as shown in Figure 1. Inherent system positioning errors that arise from the mechanical gearing degrade the quality of the slide motion. Accurate slide location is difficult because of vibration, backlash, bearing problems, lead errors, lead-screw run out, etc, that result in unwanted roll, pitch, yaw and translation slide motions. In addition, any Abbe offset present in the axes position-transducer system magnifies the effects of these extraneous motions.

The linear-motor slide drive² shown in Figure 2 does not have mechanical drive components; hence, gearing-related problems are avoided. Nevertheless, the use of this drive system does present some unusual challenges. This report gives a brief description of a diamond-turning machine system that utilizes a linear-motor drive. General performance characteristics are discussed, and the quality of surface finish and contour obtained on an aluminum test part are presented.

Figure 1. TYPICAL BALL NUT/LEAD SCREW SLIDE DRIVE.

Figure 2. LINEAR-MOTOR TEST BED.

(a) Operated by the Union Carbide Corporation's Nuclear Division for the Department of Energy.

MOTOR-MACHINE INTERFACE

Figure 3 shows a precision machine tool used to fabricate high-quality optical components using diamond-turning techniques.³ This machine has an air-bearing spindle, a structural vibration-isolation system, and air-bearing slides. The configuration of the machine's metal base and the exposed slideways is shown in Figure 4. The machine slides are metal, and the riser blocks used to elevate the spindle and tool post are granite. Machine motion is controlled by a hard-wired numerical control (NC) system incorporating a laser interferometer for position feedback information. The slides were previously driven by DC torque motors through the lead screw shown in Figure 5; however, inaccuracies in this drive system resulted in cyclic errors of 0.25 to 2.5 μm (10 to 100 μin), with a period that corresponded to the 6.4-mm (0.250-in) pitch of the lead screw.

The linear-motor drive system was chosen to replace the lead-screw drive because it does not require any mechanical gearing and thereby offers the potential for a much smoother slide motion. In addition, the linear motor had been used successfully on a test bed to drive a small air-bearing slide at speeds between 0 and 0.1 m/min (4 in/min) with an associated positioning uncertainty of $<76\text{ nm}$ (3 μin).⁴ However, in spite of the advantages of the linear-motor drive, there are also features that require careful

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Figure 3. LARGE-COMPONENT MACHINE TOOL PRIOR TO SLIDE-DRIVE UPGRADE.

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Figure 4. SLIDEWAYS OF LARGE-COMPONENT TURNING MACHINE.

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Figure 5. LEAD SCREW OF TURNING MACHINE.

consideration during the design of the motor-machine interface. Since the motor does not utilize any mechanical coupling between the slide and the machine base, there is nothing to restrain the slide when the motor power is off. This can allow an air bearing slide to drift freely until it is stopped by some object. To avoid this, positive mechanical caliper brakes were installed on the production machine shown in Figure 6. The brakes also provide a positive stopping feature for use in an emergency-stop situation such as what might arise due to loss of feedback, excess following error, programming error, etc. Also, shock absorbers were mounted at each end of the slide travel to provide an additional means of controlled deceleration.

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Figure 6. DIAMOND-TURNING MACHINE WITH LINEAR-MOTOR SLIDE DRIVE.

In addition, the location of the motor on the machine base was carefully considered. The open end of the motor has a strong magnetic field, and it may be necessary to shield the

motor from cutting fluids, chips, etc. Also, a motor-mounting arrangement in which the motor is driving the center of the slide is more desirable than the arrangement shown in Figures 6 and 7. At the time this interface was initiated, however, it was necessary to leave

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Figure 7. CLOSE-UP OF CROSS-SLIDE LINEAR-MOTOR MOUNTING SUPPORTS.

the lead-screw drive system intact, thereby requiring the motor to be mounted on the side of the slide. Finally, careful consideration was given to the motor-mounting brackets to ensure that no unwanted motion occurs between the motor and the machine base due to dynamic structural flexures.

SERVO SYSTEM

The servo system that is used with the linear-motor drive is similar to the systems associated with conventional machine-tool slide drives. However, the use of air-bearing slides does present a problem because there is very little inherent damping to assist in obtaining system stability, and unless reliable modeling capabilities exist, it may be necessary to compensate each servo system on an individual cut-and-try basis. In addition, since there are no rotating members associated with the drive system, it is not practical to use a tachometer to generate a slide velocity signal. Instead, the displacement pulses from the laser interferometer can be coupled to frequency-to-voltage (F/V) converters that generate the required analog rate signal.²

The 25.4-nm (1- μ in) system used with the 454-kg (1000-lb) slide shown earlier in Figure 2 exhibits a high DC gain with lag compensation and filtered velocity feedback. Performance tests conducted on this system show an excellent step response and dynamic positioning uncertainty when operating in a reasonably quiet environment (where dynamic positioning uncertainty is defined as the "time-varying" or AC component of the position error signal, as opposed to the steady-state position lag inherent in closed-loop control systems). Unfortunately, the servo system used with the machine tool shown in Figure 6 was required to operate with an 1820-kg (4000-lb) tool slide and a 4080-kg (9000-lb) work slide. Potential disturbances from an unbalanced spindle and "interrupted cuts" also had to be considered. Due to these differences in operating conditions and the lack of a completely reliable system model that includes system nonlinearities, it was necessary to obtain a suitable form of servo compensation using a combination of analytical techniques and trial-and-error tuning.

Figure 8 shows a block diagram of the servo system. The laser-interferometer position transducer utilizes a 10X resolution extender to provide feedback information with a resolution of 15 nm (0.6 μ in). The NC utilizes the feedback data and the internally interpolated position-command data to generate the following-error signal that drives the servo system. The F/V-generated rate signal is used to improve system stability.

Figure 8. BLOCK DIAGRAM OF SERVO SYSTEM.

MACHINING RESULTS

Machining tests were conducted using a solid aluminum test part that incorporated a flat face, a central spherical section, and tapered sections of 3 and 45 degrees. Table 1

Table 1
TYPICAL PEAK-TO-VALLEY SURFACE FINISH
FOR ALUMINUM TEST PART

	Spherical Section, nm (μ in)		Flat Section, nm (μ in)		3-degree Taper From X Axis, nm (μ in)		45-degree Taper; nm (μ in)	
Maximum	48	(1.9)	81	(3.2)	89	(3.5)	58	(2.3)
Minimum	25	(1.0)	58	(2.3)	38	(1.5)	25	(1.0)
Mean	36	(1.4)	66	(2.6)	71	(2.8)	43	(1.7)
Standard Deviation	5	(0.2)	5	(0.2)	15	(0.6)	10	(0.4)

summarizes the finish inspection results obtained on this part. Other parts machined using the linear-motor drives include plastic test samples for an aircraft windscreen and an octagonal diagnostic mirror mask which measured ~ 1.3 m (50 in) across the diagonal.

FUTURE WORK

Based on the results shown above, the decision has been made to continue development efforts to utilize the linear-motor drive on the diamond-turning machine. Additional work will be performed to accurately model the system and simplify servo system design as well as make the motor less susceptible to external disturbances. Also, an advanced-design linear motor is being investigated that features a square cross section which occupies less area than the present motors. This design offers the potential to locate the motor below the machine slide and make it more of an integral part of the machine.

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