

ELECTROMAGNETICALLY DRIVEN FAST TOOL SERVO

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INTRODUCTION

Fast Tool Servo (FTS) technology can enable precisely manufacturing complicated surfaces with nanometer-scale resolution requirement. Such surfaces are used in a wide range of products, including films for brightness enhancement and controlled reflectivity, as well as in micro-optical devices such as Fresnel lenses and microlens arrays. The limits on stroke, bandwidth, acceleration, and position noise of the FTS impose limits on the types, quality, and rate at which the intended surfaces can be produced. The requirements for high throughput drive simultaneously the need for high bandwidth, high acceleration, and accuracy for the FTS.

Most of the high bandwidth short stroke FTS's are based on piezoelectric actuators [1][2][3]. Piezoelectric FTS's have the advantage that they can readily achieve bandwidths on the order of several kHz and high acceleration on the order of hundreds of G's, are capable of nanometer resolution of positioning, and can achieve high stiffness (usually greater than 50N/ μm in the typical sizes used). However, piezoelectrically actuated FTS's also have significant disadvantages. When the piezo materials undergo deformation, heat will be generated by the hysteresis loss, especially in high bandwidth and high acceleration applications. Another problem is that the structural resonance modes of the PZT stacks limit the working frequency range, because operation near internal resonances will cause local tensile failure of the PZT ceramics.

However, electromagnetic actuators do not have such problems and thus are a promising alternative. Electromagnetic force density can be as high as $9 \times 10^5 \text{ N/m}^2$ at 1.5 Tesla flux density, and this can possibly generate a 4000G acceleration on a 3mm thick iron disk. This research focuses on developing an electromagnetically driven FTS as a replacement for the widely used piezoelectrically actuated FTS's. The experimental results of the first prototype show that the electromagnetically driven FTS is very promising for high bandwidth application.

DESCRIPTION OF FTS DESIGN

Figure 1 shows the configuration of our electromagnetically driven fast tool servo. The backbone of the moving assembly is a carbon fiber tube. On its rear end is attached a disk-shaped armature and the cutting tool tip is installed on the front end. The whole moving assembly is suspended to the FTS frame by two flexures made from spring steel sheet. As shown in Figure 2, these flexures guide the tool tip moving along only one degree of freedom in the tube axial direction with the other five degrees of freedom constrained. The armature is push-pull driven by a pair of circular E-type solenoids in the rear and front sides. The air gaps between the armature and solenoid surfaces are set at 100 μm to ensure easy fabrication, though a smaller air gap will improve the energy efficiency. The coil windings are implanted into the slots of the solenoids and these slots are 2mm wide and 20mm deep to ensure enough Ampere-turns. The coils are made from 4 strands of gauge #30 self-bonding wires to reduce the skin-depth effect in the copper conductor at high frequency operation. A $\pm 100\text{V}$ 2A 100kHz bandwidth linear power amplifier is designed to drive the coils. A 100kHz bandwidth capacitance probe is installed in the rear side of the FTS to sense the motion of the armature. In this design, in order to reduce the mass of the moving assembly and thus reduce the reaction force, the size of armature is minimized and carbon fiber is

used as the backbone. To reduce the eddy current induced along the magnetic flux path, the materials for both the armature and the solenoids are sintered soft magnetic material made from iron particles of about 100 μm in diameter.

DESCRIPTION OF CONTROLLER DESIGN

The electromagnetically driven actuator is difficult to control in the sense that the actuating force is proportional to the current squared and inversely proportional to the air gap squared. Moreover, the force will decrease with frequency because the magnetic field cannot penetrate the magnetic material at high frequencies. In order to compensate these nonlinear and frequency dependent characteristics, a dynamic nonlinear compensation (DNC) method shown in Figure 3 is applied. Here $K(x)$ represents the relation between current and magnetic field, $D(s)$ the eddy current effect, and the "Square" block relates the magnetic flux to the actuating force. This DNC is used to partially compensate the nonlinearity of the actuator, but is not expected to linearize the actuator completely because it is a feed-forward model-based method and modeling errors always exist. The whole position control loop is compensated with a lead-lag controller and low-frequency

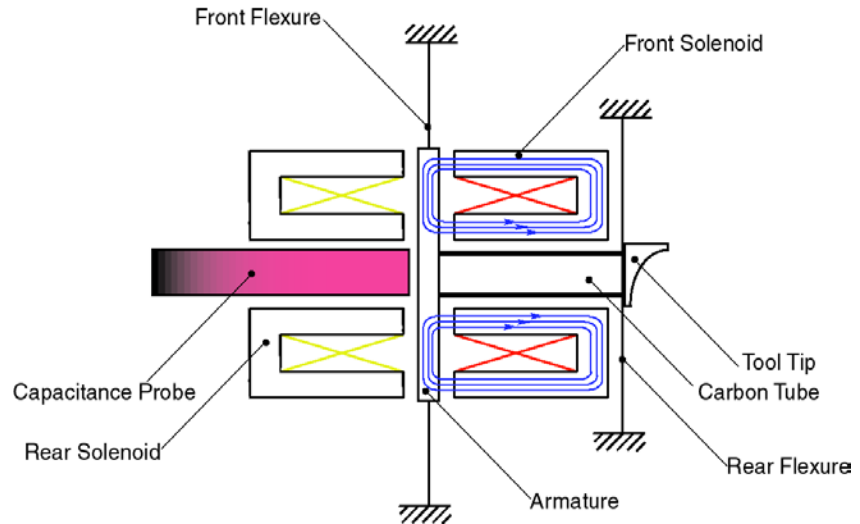


Figure 1: Configuration for the electromagnetically driven FTS

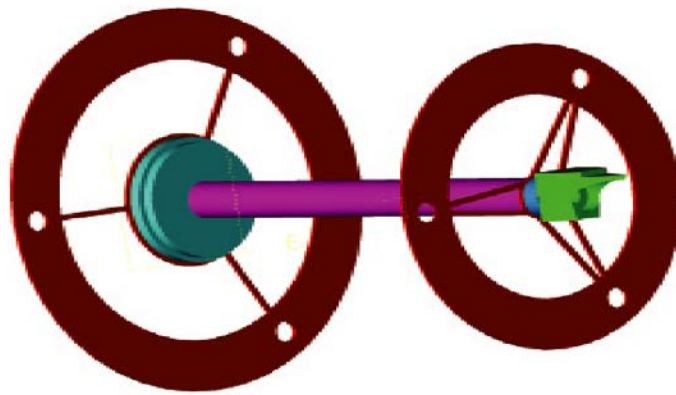


Figure 2: Flexures for the moving assembly

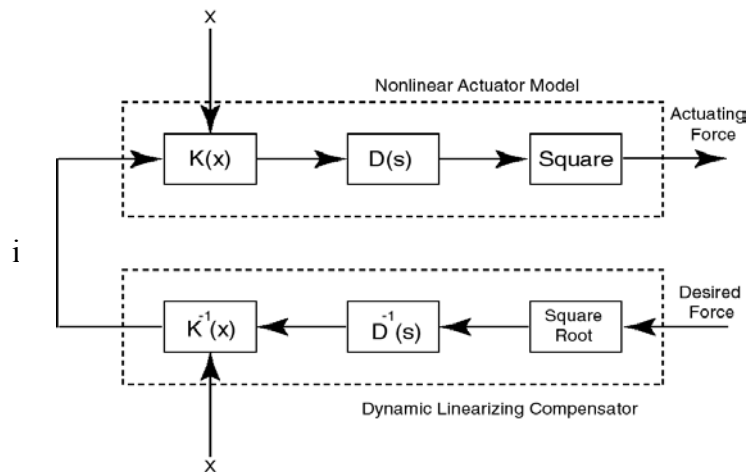


Figure 3: Dynamic Nonlinear Compensation

integrator. At the spindle rotational frequency and its higher harmonics, a plug-in type adaptive-feedforward-compensation (AFC) controller is used to improve the rejection of spindle-generated disturbance and to improve the spindle-synchronized trajectory tracking performance. The whole controller is shown in Figure 4.

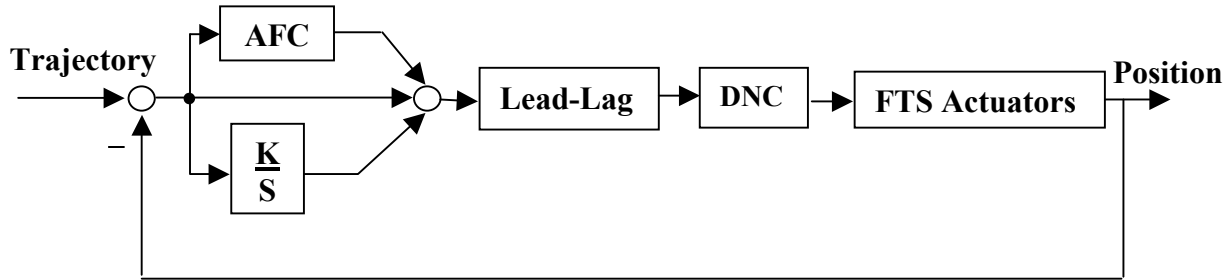


Figure 4: Controller Structure

EXPERIMENT AND RESULTS

The controller is implemented with a DSPACE 1103 board, and all the digital controllers are in the discrete domain. The full stroke of 50 μm can be achieved up to 1kHz operation. The maximum acceleration is 160 G's when tracking a 9 μm peak-to-valley 3kHz sine wave. For a sampling frequency of 100kHz, the closed-loop frequency response is shown in Figure 5 and the small signal bandwidth can be as high as 10kHz. For a sampling frequency of 83kHz, the closed loop bandwidth is 8kHz. The 100nm closed-loop step response is shown in Figure 6.

The position error is 1.2nm RMS when the spindle is turned off. After the spindle is turned on, the error degrades to 3.5nm RMS because of the PWM noise from the spindle amplifier. To evaluate the tracking performance, a 10- μm peak-to-valley 1 kHz sine wave trajectory is applied to drive the fast tool servo. When the AFC is not plugged into the control loop, the tracking error is 1.048 μm RMS. When the first harmonic AFC is applied, the error is 0.0214 μm RMS. The tracking error reduces to 0.0148 μm RMS when the second harmonic AFC is further applied and to 0.0073 μm RMS when the third harmonic is also added. This shows that the nonlinearity of the actuator and the power amplifier will introduce disturbance

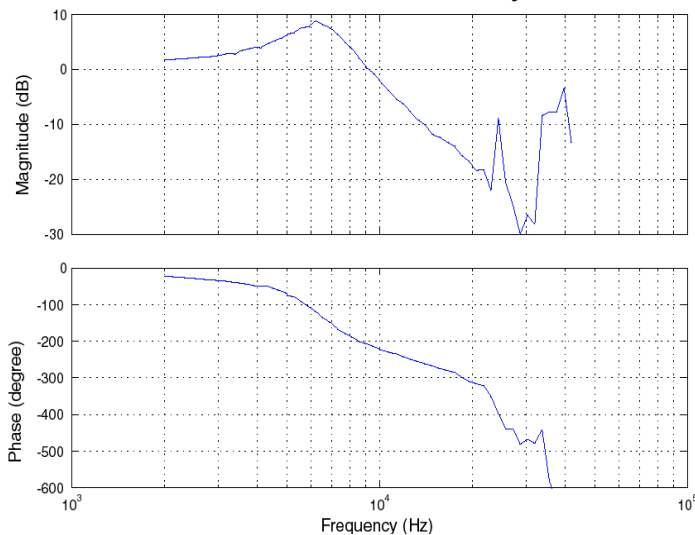


Figure 5: Closed loop Frequency Response

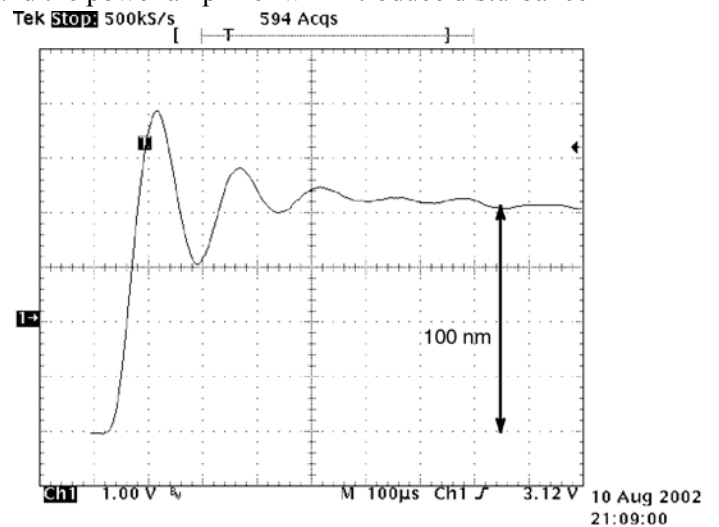


Figure 6: Small signal step response

forces of second and higher order harmonics, and the AFC of poles at multiple harmonic frequencies can significantly improve the tracking error.

A cutting experiment is conducted on a Moore diamond turning machine. The same DSPACE 1103 board controls both the X-Z slides of the machine and the FTS. A multiple sampling rate system is implemented. The sampling rate for the FTS controller is 83kHz and the sampling rate for the spindle and X-Z slides controller is 4kHz to ensure that the slides controls achieve 100Hz bandwidth. As shown in Figure 7, the sinusoidal surface of 30 harmonics per revolution is faced on a piece of aluminum material.

In conclusion, the electromagnetically driven fast tool servo is promising to achieve high bandwidth and high acceleration performance for complicated surface manufacturing.

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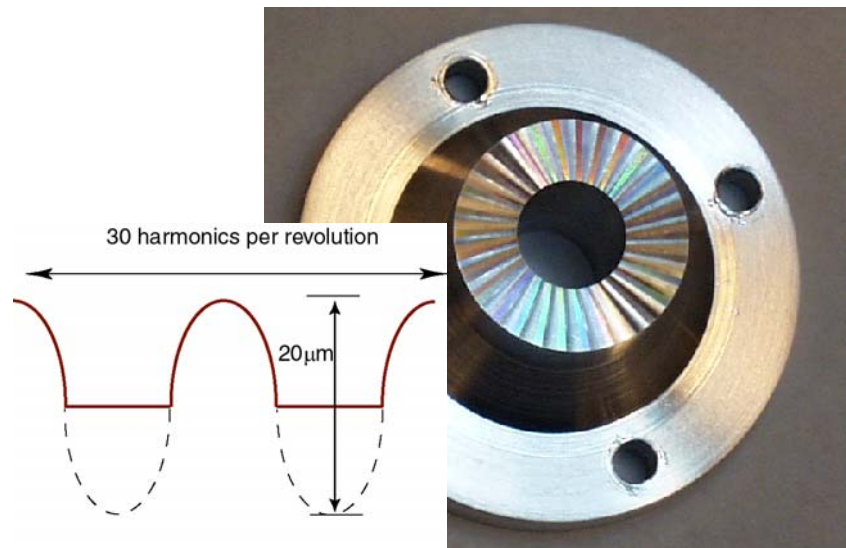


Figure 7: Diamond turned part by the electromagnetically driven prototype FTS. The surface is machined by face turning. The spindle speed is 1800rpm. The profile expanded in the circumference is half sinusoidal wave, as illustrated in the bottom left curve. There are 30 harmonics for each spindle revolution, and the peak to valley amplitude of the sine wave is 20 μm . The flat surface was machined first and then the sinusoidal surface was cut.

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