A Long Stroke Fast Tool Servo with Integral Balance Mass

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Abstract

This paper briefly describes the configuration and control system of a linear long stroke fast tool servo (FTS) with integral balance mass for the production of asymmetric optics. The FTS is implemented on a T-base diamond turning machine (DTM). The in-feed axis of the DTM is used as an integral balance mass to attenuate base reaction forces. The FTS position controller consists of a conventional lead-lag inner loop, an adaptive feedforward cancellation (AFC) outer loop, and a feedforward filter. The balance mass position controller consists of a conventional lead-lag inner loop, a feedforward filter, and an AFC machine base acceleration feedback loop. Experimental results are presented comparing both the FTS performance and the measured base acceleration with and without AFC compensation.

1. Introduction

We have designed and built a linear long stoke fast tool servo (FTS) with an integral balance mass for the production of asymmetric optics. The FTS is intended to produce parts with an asymmetry of up to 2.5 cm with a form accuracy of 0.1 μm. A typical part is produced at 600 rpm and has an asymmetry greater than 1cm, which results in a tool tip acceleration of nearly 100 m/s^2. The challenge of the linear topology is that FTS actuation forces result in a significant disturbance to the DTM. In our design, the FTS has a mass of 3 kg and the DTM has a mass of 300 kg, thus without reaction force management the DTM may experience up to 0.1 g's of acceleration. In previous designs, long stroke FTS reaction forces have been reduced using both passive and active means[1,2]. We have proposed and built a semi-active topology in which an actively controlled balance mass is allowed to freely move in response to FTS actuation forces.

2. Mechanical Topology

Figure 2 shows a schematic drawing of the FTS/machine base system. A photograph of the system is shown in Figure 3. The FTS consist of a 2"x2" air bearing stage driven by a unique three phase oil cooled linear motor[3]. The FTS has 25 mm of travel and is capable accelerations of 100 m/s^2. The FTS is mounted on the in-feed axis of a T-base DTM with hydrostatic bearings from Moore Nanotechnologies [4]. The workpiece is attached to a Professional Instruments air bearing spindle mounted to the cross-feed stage. Position feedback is provided by Sony BS75A glass-scale encoders on both DTM axes, a rotary encoder on the spindle, and a MicroE M3500Si glass-scale serial interface encoder on the FTS. The DTM base acceleration is measured using a single axis PCB ceramic shear accelerometer. The in-feed stage is allowed to move freely in response to the FTS actuation forces and thus acts as an integral balance mass.

3. Control Topology

There are a number of challenges in the control of the FTS/reaction mass system. First, in order to produce optical quality parts the FTS following error must be very small, on the order of 0.001%. This requires that the FTS controller gain must be very high, preferably infinite, over a broad range of frequencies. The second challenge is to control the position of the in-feed stage such that we minimize the acceleration in the machine base while maintaining the desired FTS tool tip position (since the FTS is mounted on the reaction mass the tool tip position is a function of both the FTS position and in-feed stage position).

Figure 1 shows a block diagram of the overall FTS/balance mass control system. The control system consists of an FTS controller and an in-feed stage controller coupled through the trajectory generator, FTS actuation forces, and absolute FTS position. The FTS controller includes a conventional lead-lag inner loop ($P_{fts}(z)$), a command pre-shifting feedforward filter, and an adaptive feedforward cancellation (AFC) repetitive controller ($C(z)$) in the forward path.

Figure 4 shows the discrete time AFC structure used to form the AFC controller. It can be shown that this structure has a LTI equivalent of

$$C_n(z) = g_n \frac{z^{-1}[\cos(\omega_n T - \phi_n) - z^{-1}\cos(\phi_n)}{1 - 2\cos(\omega_n T) z^{-1} + z^{2}}{}_{5} \tag{1}$$

and

$$C(z) = \sum_{1}^{N} C_n(z). \tag{2}$$

Here ω_n are harmonics of the spindle frequency (Note: the FTS trajectory is composed of the DC component and harmonics of the spindle frequency only.) The conventional FTS inner loop is tuned to a bandwidth of 500 Hz. Figure 5 shows the FTS closed loop frequency response with 6 AFC resonators with a fundamental frequency of 23 Hz. The gain, g_n, and phase, ϕ_n, of each resonator is selected as described in Byl[6] for 20 dB of gain margin.

The in-feed stage controller consists of a conventional lead-lag high frequency pole inner loop ($P_{stage}(z)$) tuned for a bandwidth of 100 Hz , a base acceleration feedback outer loop, and a feedforward filter. Since we have modeled the in-feed stage and FTS as free masses, the feedforward filter simply inverts and scales the sinusoidal portion of the FTS trajectory. The base acceleration feedback outer loop consist of a high-pass filter to remove the low frequency drift of the accelerometer, an acceleration controller $G_a(z)$, and an AFC repetitive controller tuned to the same frequencies as the FTS AFC controller. Since the AFC resonators are in the feedback path relative to the stage position controller, they act as narrow band notch filters allowing the in-feed stage to move freely in response to the FTS disturbance forces. The acceleration controller $G_a(z)$ is simply a double integrator which is used to phase stabilize the loop. The techniques from Byl[6] are used to tune the AFC resonators for 20 dB of gain margin. Figure 6 shows the in-feed stage closed loop position response with an eight harmonic 13.5 Hz fundamental AFC controller.

4. Results

Figure 7 shows the measured FTS following error for a six harmonic 23 Hz fundamental, 4.8 mm pk-pk, 6.6 g sinusoid under conventional control, conventional control with command pre-shifting, AFC control, and AFC control with pre-shifting. The measured following error is 103 μm pk-pk and 31 μm rms under conventional control. The following error is reduced to 3.1 μm pk-pk and 0.28 μm rms with the addition of command pre-shifting and AFC control. Similarly, Figure 8 shows the measured base acceleration for an eight harmonic 13.5 Hz fundamental, 6 mm pk-pk, 2.85 g FTS trajectory with no acceleration feedback, feedforward filter only, and feedforward filter with an AFC outer loop. The overall measured base acceleration is 0.154 m/s^2 pk-pk with no acceleration feedback, 0.056 m/s^2 pk-pk with the feedforward filter, and 0.044 m/s^2 pk-pk with AFC. More importantly the component of the acceleration at each harmonic of the FTS trajectory has been reduced by a factor of 100. For example the component of the measured base acceleration at 13.5 Hz has been reduced from 0.063 m/s^2 with no acceleration feedback to 1.1×10^{-4} m/s^2 with AFC compensation.

5. Conclusion

The experimental results verify the performance of both the overall mechanical topology and the control topology. In the case of both the measured FTS following error and the measured base acceleration with AFC control, the residual following error and base acceleration are at the noise level of the associated sensors. We believe the use of lower noise sensors would result in reduced base acceleration and following error.

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[4] Moore Nanotechnoloty Systems, LLC, 426A Winchester St. PO Box 605, Keene NH 03431-0605 USA, 603-352-3030.

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[6] M. Byl, S. Ludwick, and D. Trumper. A loop shaping perspective for tuning controllers with adaptive feedforward cancellation. *Precision Engineering*, 29(1):27-40, 2005.

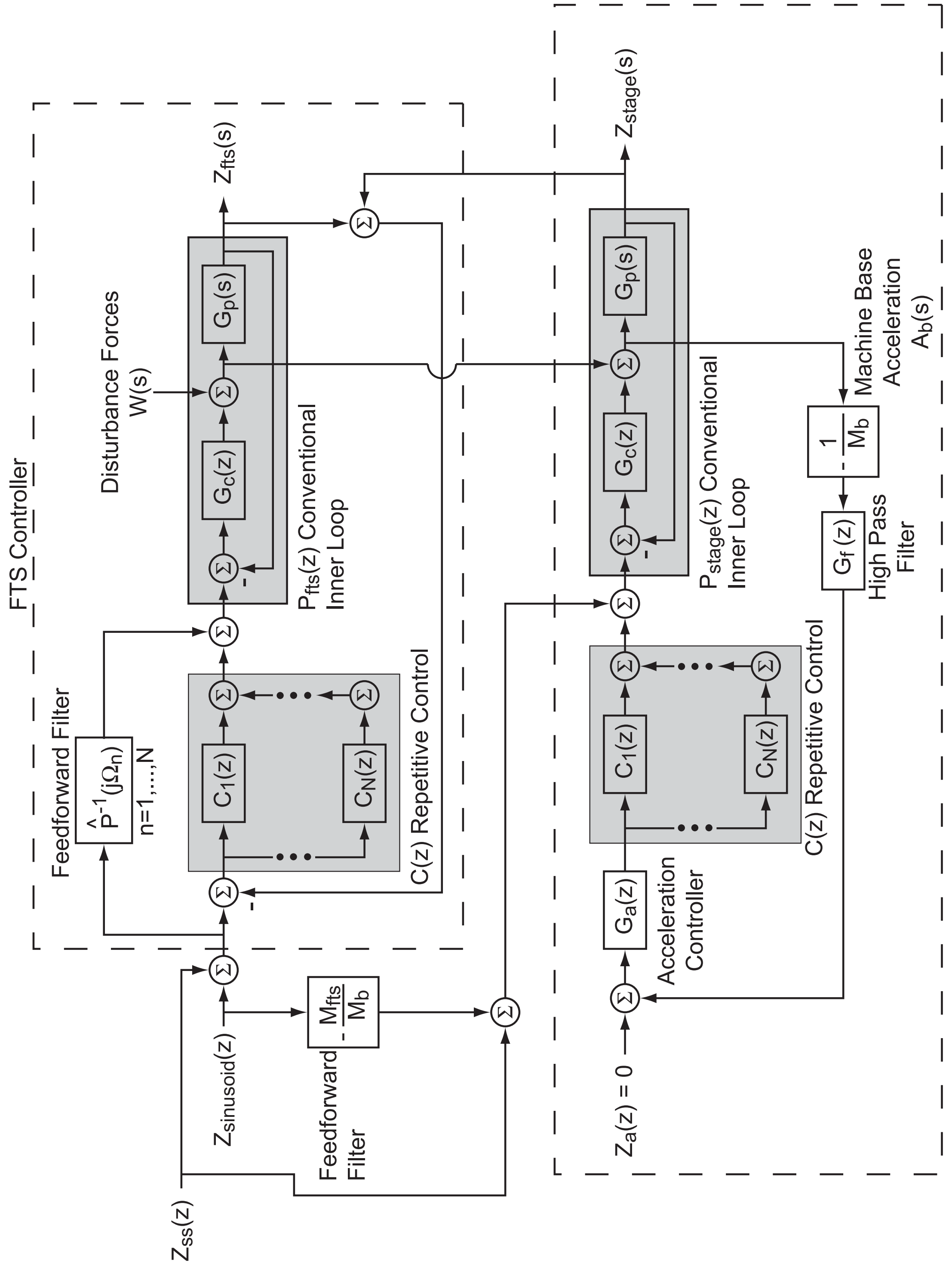

Figure 1 – Block diagram of the overall control structure for our prototype fast tool servo with integral balance mass.

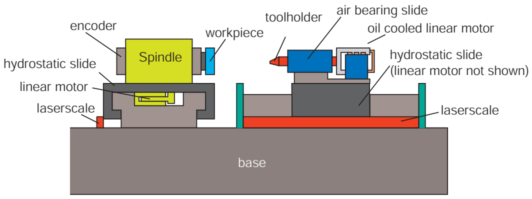

Figure 2 – Schematic drawing of the linear long stroke fast tool servo.

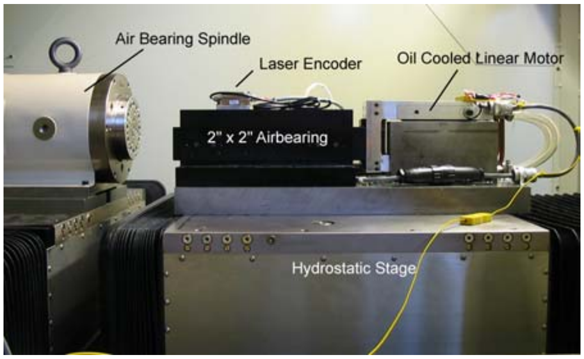

Figure 3 – Photo of the prototype FTS mounted to the Moore Nanotechnologies machine base

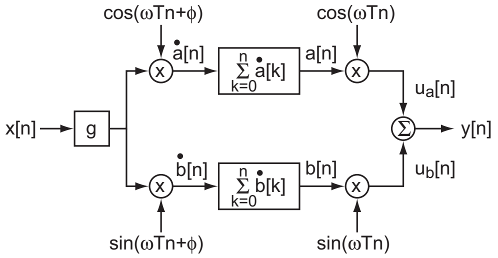

Figure 4 – Discrete Time AFC structure.

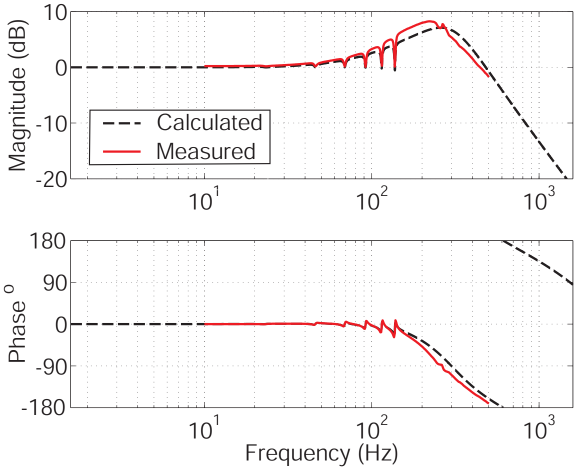

Figure 5 – FTS closed loop position frequency response.

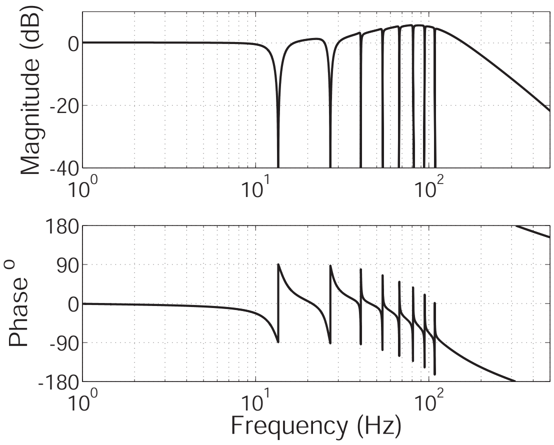

Figure 6 – Calculated closed loop in-feed stage position response.

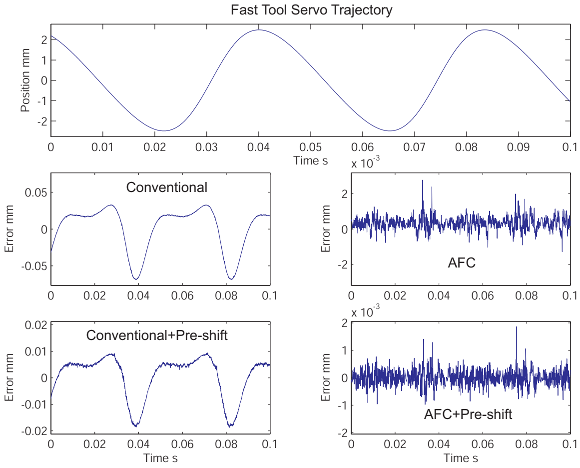

Figure 7 – Measured FTS following error to a six harmonic 23 Hz fundamental sinusoid.

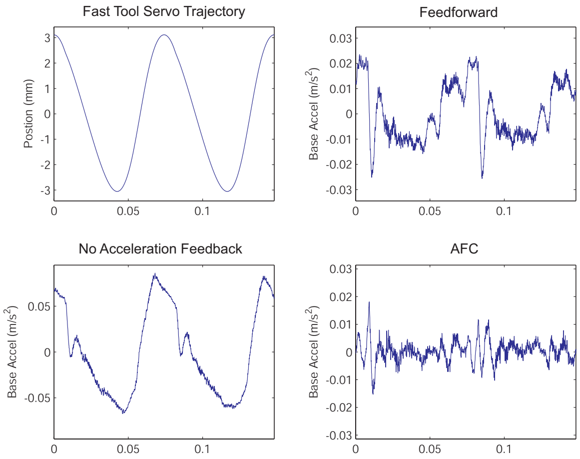

Figure 8 – Measured base acceleration for an eight harmonic 13.5 Hz fundamental FTS trajectory.