Adaptive Feedforward Cancellation Viewed from an Oscillator Amplitude Control Perspective

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Abstract

This paper summarizes the design and implementation of Adaptive Feedforward Cancellation (AFC) on a fast tool servo (FTS) for use in high-precision diamond turning applications. Experimental results are presented and compared to those of a conventional integral controller. A method of viewing AFC from an Oscillator Amplitude Control (OAC) perspective is also discussed, which provides additional use of classical control techniques to determine the convergence and error properties of AFC resonator systems.

Keywords: Adaptive Feedforward Cancellation, Fast Tool Servo, Oscillator Amplitude Control.

Introduction

In diamond turning applications, fast tool servos commonly follow near-periodic trajectories, since the tool motion is keyed to the fundamental spindle rotation frequency. The FTS axis can develop significant following errors, since conventional feedback loops (*i.e.*, PID and lead-lag) only provide a finite controller gain at non-zero frequencies, even when command pre-shifting feedforward is included [1]. The error signal primarily consists of a summation of sinusoids of known frequencies and unknown Fourier coefficients. In the literature, a number of methods exist for the rejection of this periodic error. In this paper, we focus primarily on the applicability of AFC for reducing/eliminating the steady-state tracking errors of fast tool servos in high-precision diamond turning applications.

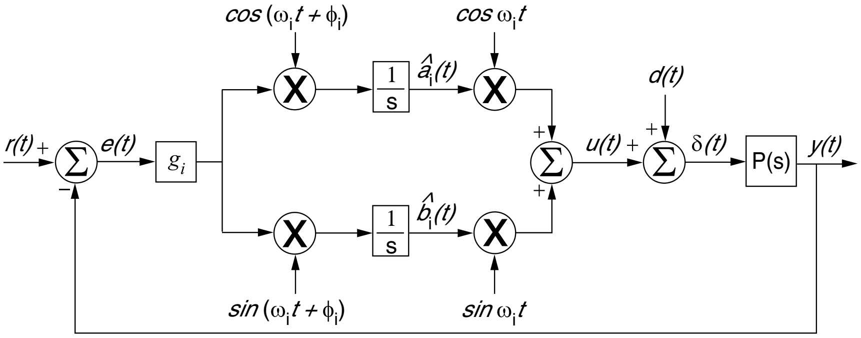

Figure 1: Single resonator AFC closed-loop block diagram.

Figure 1 illustrates the loop configuration for a single resonator AFC controller, where P(s) is the transfer function of the plant being controlled. This system is designed to provide zero steady-state error at frequency ω_i. The internal dynamics of the AFC algorithm are linear time-varying (LTV) but in the literature it is shown that the input-output relationship from e(t) to u(t) is equivalent to a linear time-invariant (LTI) system [1]. The equivalent continuous-time transfer function is given by

$$C_i(s) = g_i \left[\frac{s \cos\phi_i + \omega_i \sin\phi_i}{s^2 + \omega_i^2} \right], \tag{1}$$

where g_i is a proportional gain and ϕ_i is a phase advance parameter that can be chosen to improve the closed-loop system's robustness.

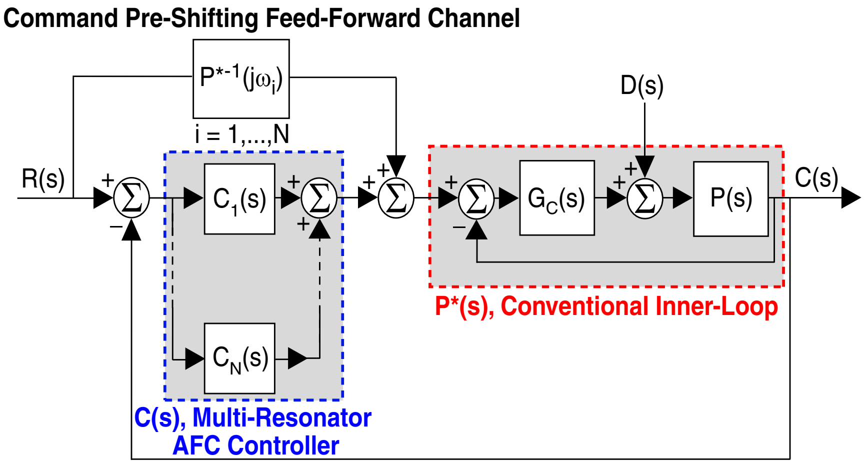

Figure 2: AFC feedback loop configuration used with the Variform FTS.

In order to be able to provide zero steady-state tracking error to multiple harmonics, several AFC resonators can be placed in parallel to form a multiple resonator AFC system. Byl *et al* [1] have developed a loop-shaping approach to designing these multi-resonator AFC systems. Their complete design, as shown in Figure 2, includes a conventional inner-loop controller $G_c(s)$, command pre-shifting feedforward channel $P^{*-1}(j\omega_i)$, and multiple resonator AFC controller C(s).

Experimental Hardware

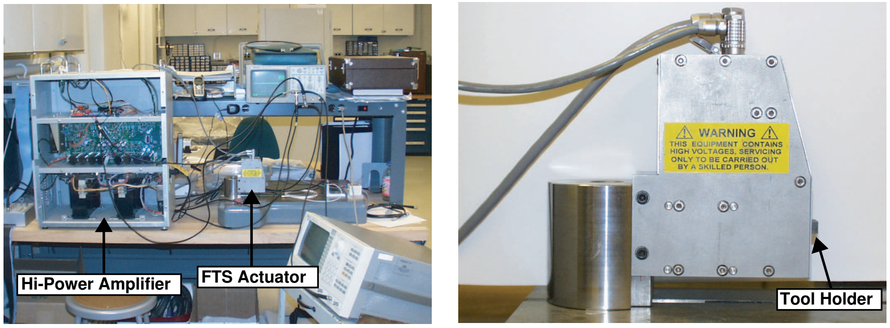

Figure 3: (left): Variform FTS and experimental hardware. (right): Close-up of the Variform FTS actuator.

We used the previously mentioned loop-shaping approach and the controller configuration in Figure 2 to implement a ten resonator AFC system on a commercially available FTS. This system, the Variform FTS, was designed and manufactured by Kinetic Ceramics [2] and is shown in Figure 3. This particular FTS actuator consists of a tee-lever mechanism actuated by a double piezoelectric (PZ) stack arrangement coupled to two H-plate flexures. A high-power amplifier, with an on-board digital feedback controller, drives the PZ stacks differentially to a maximum of ±400 V, which provides about a 200 Hz 0 dB crossover frequency with a total displacement of up to ±250 μm (±0.010”).

The Variform FTS on-board controller takes advantage of an inner charge loop to minimize the PZ hysteresis curve along with an outer position feedback loop. During our FTS experiments, we utilized a PC-based digital control system to apply our AFC algorithms. Thus, we bypassed the on-board controller, while keeping the inner charge loop enabled, and used the PC-based digital controller to perform all of our closed-loop experiments.

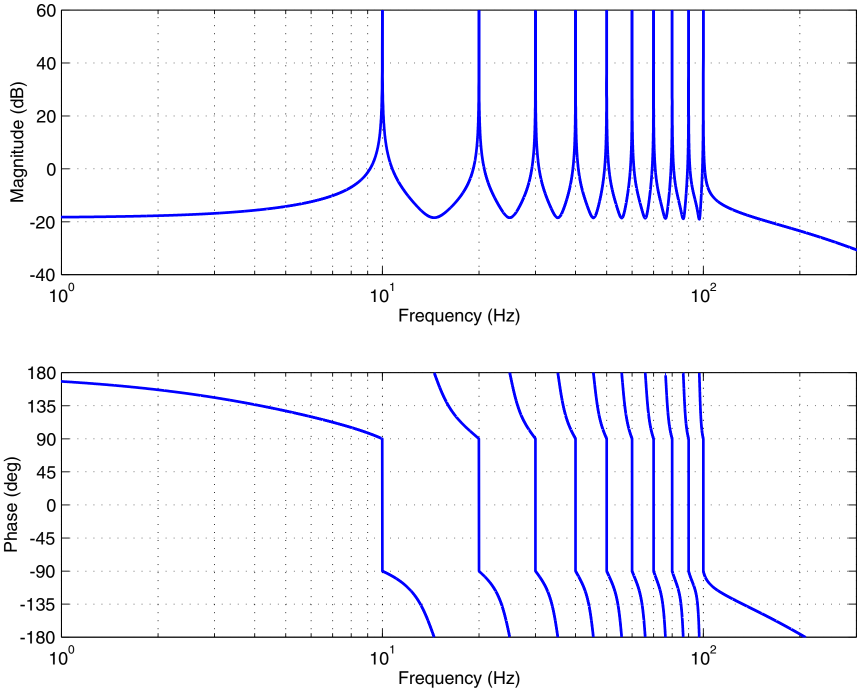

Figure 4: Calculated Variform FTS negative of the loop transmission frequency response with a ten resonator AFC and conventional inner-loop integral controller.

Experimental Controller

Figure 4 illustrates the calculated negative of the loop transmission frequency response for the Variform FTS with a multi-resonator AFC controller and conventional inner-loop integral compensator. The design of these loops is described in detail in [4]. This particular system is designed to provide zero steady-state error to a signal with up to ten harmonics at frequencies of

$$\omega_i = 10 \text{ Hz}, 20 \text{ Hz}, \ldots, \text{and } 100 \text{ Hz}. \tag{2}$$

Results

Figure 5 shows the experimental closed-loop error signal during an air-cutting experiment, which includes the previously mentioned ten harmonics. Without AFC, the peak-to-peak system error amounts to approximately 15% of the reference signal, while the peak-to-peak system error with AFC control reduces to about 0.5%. Note that the error signal with AFC control is dominated by the noise of the feedback sensor and there appears to be no apparent signal left that is correlated to the input reference signal.

Oscillator Amplitude Control

Roberge [3] showed that the amplitude of a sinusoidal oscillator can be stabilized by using an auxiliary feedback loop. He refers to this approach as an oscillator amplitude control system and states that if the bandwidth of this loop is much lower than the frequency of oscillation, then we can analyze the amplitude dynamics alone and ignore the sinusoidal portion of the loop. A detailed discussion of Roberge's oscillator amplitude control system is located in [4], which also develops a method of viewing AFC from an OAC perspective.

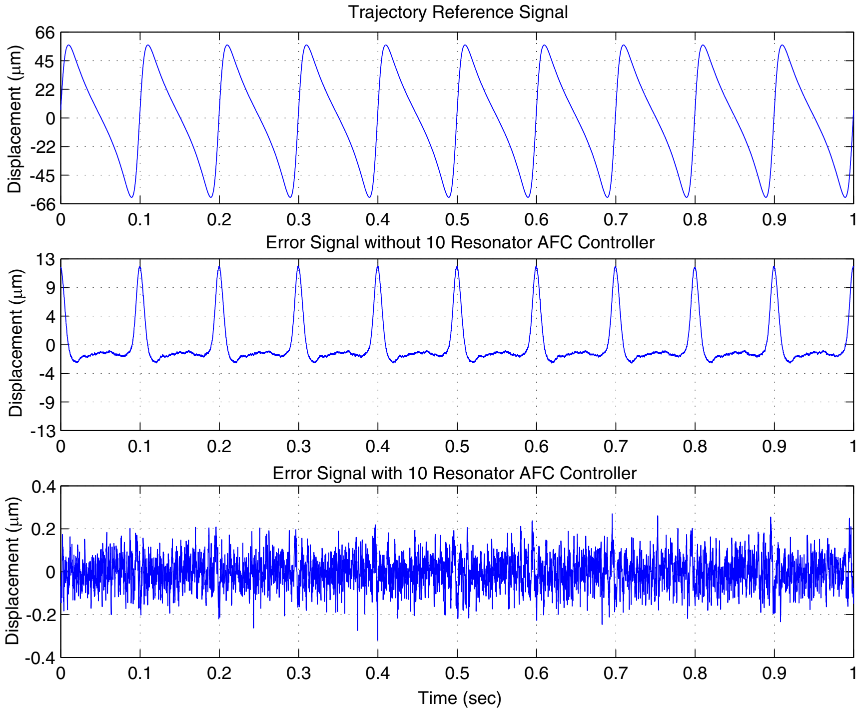

Figure 5: Comparison of the experimental closed-loop error signal with and without AFC Control.

Viewing AFC from an OAC perspective provides an approximate measure of the amplitude dynamics of an AFC closed-loop system. This perspective also allows the additional use of classical control techniques to determine an AFC loop's stability, convergence, and error properties. In [4], Cattell uses an averaging analysis to simplify a properly tuned single resonator AFC system into two single-input single-output amplitude control loops. With these loops de-coupled, the performance of any combination of AFC resonators can be approximated by the superposition of N OAC loops.

Conclusions

The results of these AFC experiments illustrate a dramatic improvement in the Variform FTS's steady-state tracking performance to constant amplitude periodic signals. However, determination of the AFC closed-loop convergence and error properties to changes in the reference/disturbance amplitude is not an obvious output of these analyses. Thus, we can simplify any AFC resonator system into the sum of N OAC loops and approximate the performance from the amplitude dynamics alone, independent of the detailed time variation of the AFC output signal.

References

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