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Design and testing of a long-range, precision fast tool servo system for diamond turning

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ABSTRACT

A long-range, precision fast tool servo (FTS) system was developed that is capable of accurately translating the cutting tool on a diamond turning machine (DTM) with maximum accelerations of 260 m s^{-2} and bandwidths of up to 140 Hz. The maximum displacement range of the cutting tool is 2 mm. The FTS utilizes a flexure mechanism driven by a voice coil actuator, a custom linear current amplifier and a laser interferometer feedback system. This paper describes the design of the electromechanical system, controller configuration and cutting tests to evaluate the system. Initially, low disturbance rejection and poor command following degraded the surface finish of machined test parts. Several techniques to add damping to the dynamic system were investigated to improve the generated surface finishes. Electromotive damping was applied inside the voice coil actuator, and two different viscoelastic damping materials were applied to the flexure mechanism. A control strategy consisting of linear and non-linear feedforward controllers and a proportional, integral and derivative (PID) feedback controller was implemented to accommodate the changed system dynamics. The workpieces were analyzed using form and surface inspection instruments to evaluate the overall system performance. A cylindrical part with five lobes cut across the face had a surface finish value between 20 and 30 nm R_a.

1. Introduction

Fast tool servos (FTSs) are intended to compensate slide error motions of diamond turning machines (DTM) [1] or help produce various kinds of non-axisymmetric optics by modulating the cutting tool position towards and away from the workpiece several times per revolution [2–4]. It is possible to generate such parts without an FTS by translating the tool using the machine carriages and axes controls only [5]. Due to the large moving mass, bandwidths at which the carriages can be moved are generally low. FTS's provide higher bandwidths and allow higher spindle speeds and productivity. The FTS system described in this paper was used to produce non-rotationally symmetric metrology artifacts on a DTM by translating the cutting tool in and out of the workpiece several times per one revolution during a facing operation as conceptually shown in Fig. 1. The FTS was tested on a Precitech Nanoform 350 DTM and on a Moore 3 jig bore base that was converted to a DTM using a motorized 4R Professional Instruments air-bearing spindle and servo controlled axes. To cancel out inertia forces, a mass damper opposing the motion of the cutting tool was installed. The motions of the FTS were synchronized with the spindle and the x- and y-axis encoder outputs of the machine. The amplitude was largest while cutting near the outer diameter of the workpiece and linearly decreased to zero while the cutting tool moved towards the part center. This process generated a lobed surface across the face of the workpiece.

One of the applications of this FTS system was the fabrication of non-axisymmetric molds for silica lenses [6]. Another application was the generation of non-rotationally symmetric metrology artifacts at the Center for Precision Metrology at the University of North Carolina at Charlotte. The artifacts with known deviations from roundness, circular flatness or cylindricity were designed for the dynamic calibration of stylus-based roundness instruments and scanning coordinate measuring machines (CMM). Test parts were machined from 6061-T6 aluminum blanks with peak lobe amplitudes of up to ±1 mm near the outer diameter. The part shown in

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Fig. 2 has three continuous lobes across the face with 250 μm peak amplitude near the outer diameter of 40 mm.

2. FTS electromechanical design

2.1. Flexure

The FTS consists of four principal components: flexure mechanism, voice coil actuator, current amplifier and control system. The flexure mechanism acts as a linear bearing for the cutting tool. The main design advantage of flexures for this application was the lack of backlash and stiction in the direction of motion [7]. This provided very smooth, high precision operating characteristics without wear due to high speeds or continuous operation [8,9]. The monolithic FTS flexure mechanism shown in Fig. 3 is 154-mm wide (6 in.) and 25-mm tall (1 in.). It consists of a moving tool shuttle that carries the diamond tool, four curved leaf flexures and two mounting flanges. A finite element analysis (FEA) was performed to optimize axial travel of the tool shuttle and minimize lateral compliance. The curved leaf flexures maximize the displacement range and accommodate the over constraint that would exist with straight leaf flexures [10]. Elastic averaging and symmetry of the design reduces error motions of the flexure mechanism. Heat-treated 17Cr–4Ni stainless steel was selected as material with an ultimate tensile strength σ_{ut} of 1360 MPa. The endurance limit σ_{end} under cyclic load was calculated by [11]:

$$\sigma_{\mathrm{end}} = 0.504\sigma_{\mathrm{ut}}. \qquad (1)$$

Stress calculations were carried out under static plane strain conditions using the Mises failure criterion. The flexure mechanism was designed such that the system dynamics could be approximated by a second-order differential equation with a resonance frequency of approximately 40 Hz and negligible higher order modes, allowing for a less complex controller design.

2.2. Actuator

A BEI Kimco voice coil actuator was used to drive the tool shuttle. This actuator provided maximum continuous stall forces of 89 N (20 lbs) and short-term peak forces of 267 N (60 lbs). The tool tip accelerations that could be achieved with this actuator were approximately 270 m s^{-2}. The frequencies of the cutting tool at a maximum amplitude of 1.0 mm were 70–80 Hz. At 140 Hz system bandwidth the maximum amplitude decreased to about 280 μm. Voice coil actuators have certain design characteristics that made them suitable for the FTS design. Permanent magnet voice coil actuators are generally free of hysteresis with a nearly linear current versus force relationship for smaller strokes. The voice coil actuator selected was built for a total travel of 25 mm, but only 2 mm were used to operate in a nearly linear range. This is an advantage over the commonly used piezoelectric actuators that require charge control to avoid hysteresis and creep [12–14]. The lack of wearing components eliminated mechanical friction losses and led to high reliability rates. As a result very stable plant parameters were guaranteed during amplifier and controller design. Unlike piezoelectric actuators, voice coil actuators do not provide inherent system stiffness, and the controller design becomes critical for sufficient stiffness during the cutting process.

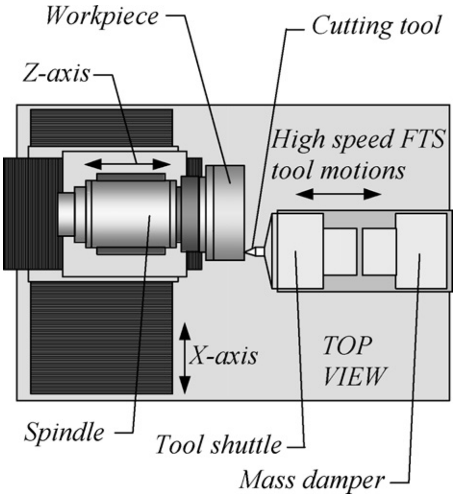

Fig. 1. Fabrication of a multilobed part on a DTM using an FTS.

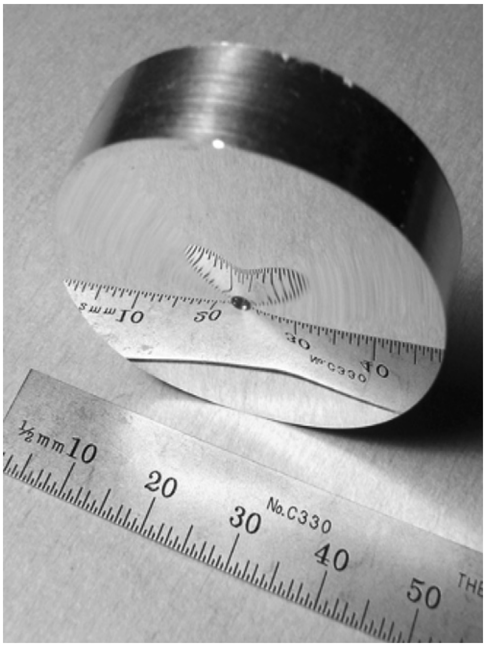

Fig. 2. Aluminum test part machined with the long-range FTS system on a DTM. The part has three lobes cut across the face with 250 μm amplitude.

Fig. 4 shows the actuator and an earlier flexure mechanism installed in the FTS enclosure. The mass damper shown to the right is almost identical to the tool servo. To reduce error motions the actuator was aligned such that the actuation forces went through

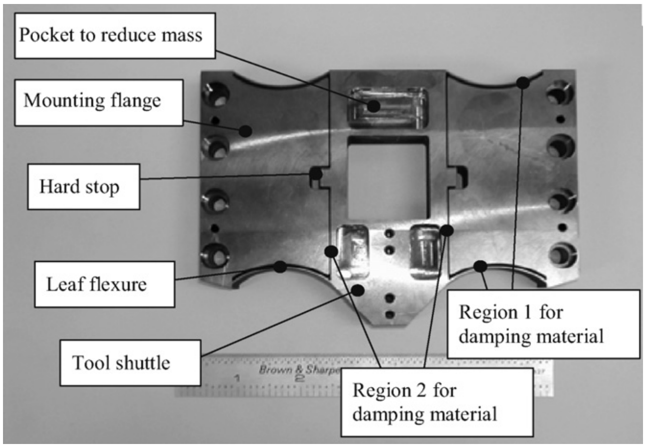

Fig. 3. Flexure mechanism that carries the cutting tool. Extra damping material can be applied between stationary and moving parts.