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Performance Optimization for Single-Point Diamond Turning Machines

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Abstract: This paper describes a new, rapid servo tool system designed to produce non-rotationally symmetric components using single-point diamond turning machines. A prototype system is defined, designed for versatile interfacing with traditional machine tool controllers, as well as performance testing data of tilted flat and off-axis conic parts. Techniques are addressed to control the piezoelectric actuator to an error of less than 1 percent. The output of a regular integral controller in the actuator performance Optimization of a Fast Tool Servo for single-point diamond turning machines shows a significant error due to hysteresis. By implementing two control schemes, an optimized proportional, integral, derivative controller, and a technique using a dynamic compensator module in conjunction with the linear controller, the effects of hysteresis have been reduced. The compensator measures the relationship between hysteretic voltages, displacement in real time and thereby modifies the effective gain. Results of the simulation show that system performance errors caused by hysteresis can be compensated and reduced by 90%. Experimental implementation results in the motion error caused by hysteresis being reduced by 80 percent, but peak-to-valley errors are limited by the compensation side effects.

Keyword: diamond turning, diamond turning machine, fast tool servo, precision actuator, single-point diamond turning.

INTRODUCTION

In the field of optical surface generation, single-point diamond turning machines (DTM) have found wide application. Machines were manufacturing surfaces for use in infrared in the 1970s and 1980s. In the late 1980s and 1990s, advances in machinery and tooling enabled diamond-turned reflective optics appropriate to be used at visible wavelengths. With the emergence of improved machines and processes, interest in a fast tool servo (FTS) system to increase the capacity and performance of existing machines has already been increasing. The Purpose of the FTS is to travel the tool small distances several times per part revolution into and out of the work piece. This resulting in non axisymmetric or error correction [1] [2] .

Many of the previous FTS systems have been used to correct different machine-related errors, such as spindle error motions or parasitic vibrations. New adaptations of fast travel mechanisms with very high resolution and rigidity addressed these needs and created new areas of application that were challenging. Ultra-precision surfaces that are now possible include special, non-rotationally symmetrical components such as secondary mirror correction, anamorphic optics, on-axis off-axis conic sections, and generalized surfaces.

In advanced systems, tilted and excentric pupil systems are increasingly being used to improve performance and to avoid diffraction effects caused by obscuring concentrated reflective and catadioptric systems. These devices are very suitable for development with ultra-precise diamond turning machines, used in combination with self-aligning designs. Wide application can be found in commercial, research, and military systems, including optical systems of the interceptor class, scientific instruments, and optical platforms and analyzers based on space.

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In advanced systems, tilted and excentric pupil systems are increasingly being used to improve performance and to prevent diffraction effects caused by obscuration in concentrated reflective and catadioptric systems. These devices are very suitable for development with ultra-precise diamond turning machines, used in combination with self-aligning designs. Broad application can be found in industrial, scientific, and military systems, including optical systems of the interceptor class, scientific instruments, and optical platforms and analyzers based on space [3].

The FTS mentioned in this paper manufactures optical off-axis elements on the rotation axis by moving the cutting tool twice every revolution in and out of the optic plane. This approach significantly reduces the system size needed when the optical element is small enough to fit on the computer, but requires a high bandwidth and accuracy actuator. An FTS system enables the DTM to work close to the center of its capability, improving the precision, repeatability and smoothness of the resulting surface. These manufacturing schemes often avoid the wide, difficult to balance fixtures that decrease the stiffness of the loop near the extremes of slide travel when machining critical surfaces [4].

METHODOLOGY

Actuator Description:

The FTS described here was designed and referred to as the MAC-100 by the Precision Engineering Center, North Carolina State University, Raleigh. The device displayed in Fig. 1 and 2, based on an earlier version with a much smaller travel and consisting of a rigid piezoelectric transducer (PZT) stack made of titanium lead zirconates. The design's salient features include the use of a high-resolution, high bandwidth, closed-loop capacitance feedback probe, an extended travel long PZT stack, and an active cooling system to eliminate hysteretic heating.

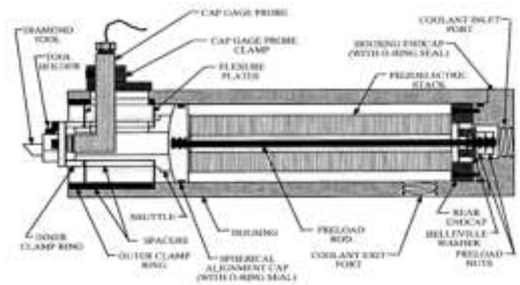

Fig.1: Section of the FTS

In the tool holder, which is an integral part of the shuttle shown in the figure 2, a short shank diamond tool is mounted. The shuttle is supported at the end of the piezoelectric stack by two annular flexures that hold it preloaded against the spherical alignment shield. The flexure plates provide high radial rigidity while allowing the axial movement required. The distance between the two end caps is increased as the stack is energized. Because the housing covers the rear end cap, the end cap of the alignment is pulled outwards, causing the device to be displaced.

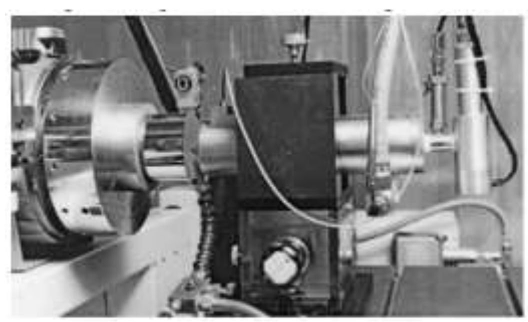

Fig.2: Installed FTS

A Trek, Inc. is moving the piezoelectric stack. Model P0617 High-voltage amplifier with a maximum output of 1000 V dc at 1 A. A steel preload rod passing through the middle of the stack is preloading the PZT stack between the alignment cap and a rear end cap. It prevents the PZT from working under stress, which for the ceramic material can be disastrous. The stack is 13 cm long and has an open-loop stiffness of about 70 N / m to achieve the 100-m range against the preloaded pin. Belleville springs are included in the preload rod series to reduce the thermal expansion and contraction effects and the preload is set at a nominal load of 1000 N. The PZT stack produces up to 60 W of heat under normal operating conditions, and cooling is required in the actuator. Therefore, O-ring seals are located in each end cap on the PZT stack to allow coolant to enter the rear of the actuator, travel through the stack's center annulus to the outer jacket, and exit through the bottom refrigerant port. The actuator system installed is displayed in Fig. 2; Table 1 contains a description of relevant device requirements [5].

Table.1: Important FTS System Specification

Update Speed	100 Microsecond
Resolution	0.024 microsecond
Operating range	100 micrometers
Design Band width	100 Hz
Stiffness	70×10^{6} Newtons/meter

Performance Testing:

The surface finish was measured for the conditions listed in Table 2. The test was performed with copper specimens to mitigate material effects. The measurements of roughness were taken with a Chapman MP2000 noncontact profilometer perpendicular to the machining grooves over a spatial distance of 2–200 m. For comparison, a reference was machined using a standard tool post instead of the FTS. As can be seen in the table, until closed-loop control is activated, no significant change in surface roughness is noticed. The relatively rough surface created by the FTS is largely due to the feedback capacitance probe's 250-A resolution maximum. While the present resolution is sufficient for position accuracy at 100 Hz bandwidths, a high-resolution feedback sensor, such as a laser interferometer, could improve surface smoothness [1] [6].

Table.2: Roughness Evaluation of Fast Tool Servo under Various Operating Conditions

Condition	RMS Surface Roughness
Reference	112
FTS off	88
Open loop control at 500 V	98
Open loop control tilted flat,60 µm travel	111
Closed loop control tilted flat, 100 µm travel,1000 rpm ,5 µm/rev	156

Surface Accuracy Estimation:

A benchmark was designed to test the performance of the MAC-100 FTS, requiring full-range actuator displacement while simultaneously providing an easily measurable work piece. The test involves cutting at 1000 r / min (16.7 Hz) a 100 m tilted flat in a copper work piece with a diameter of 75 mm. A setup schematic diagram is displayed in Fig. 3. The tilted flat requires the FTS to move the tool at full amplitude as a sine wave, while providing a nominally flat surface that can be easily measured with an interferometer laser [7].

Fig.3: Experimental Set-up for Fabrication of Tilted Flat Benchmark Test

Performance Enhancement:

Four areas have been studied to improve the performance of the MAC-100 FTS. These areas would include a baseline checkout, an analysis of cutting parameters, enhancement of control gains and improved performance using a linearization module for hysteresis. Important performance improvements were found by optimizing the gains of the controller and implementing the linearization module for hysteresis. These methods, however, often resulted in residual surface errors taking on very different shapes.

The study of the cutting parameter also indicated that although the surface error improves with reducing spindle speed, it is the spindle speed (revolutions per minute) that has been studied that affects as well as the cutting time and the forming error. Each work piece was shown the effects of FTS travel range on the form error, as the tilted flat program required the amplitude to decrease to zero as the tool approached the work piece center. It is therefore possible to extract the effect of reducing the FTS travel from any tilted flat. Such experiments were carried out using two different PID controllers on the MAC100, and for each controller the results were standardized to the shape errors at 1000 r / min. This normalization eliminated the controller effects and separated the spindle velocity effects [5].

The efficiency of the MAC 100 FTS was measured by a baseline checkout. The baseline test was cut at 1000 r/min with a 5 mm /min feed rate and a cutting depth of 4 m. using an integrated controller, the reference controller operates at a sampling frequency of 10 kHz.

In order to determine their effects on shape error, various cutting parameters were experimentally varied. The key parameter measured is the speed of the spindle (revolutions per minute), which influences both the time of cutting and the error of shape. The work piece was shown the effects of FTS travel range on the shape error, as the tilted flat system allowed the amplitude to decrease to zero as the device approached the work piece core. It is therefore possible to extract the effect of reducing the FTS travel from any tilted flat. These tests have been carried out using two separate PID controllers on the MAC 100 and for each controller the results were standardized to the form errors at 1000 r/min. This normalization removed the controller effects and isolated the spindle velocity effects.

A standardized software controller routine was developed to allow controller gains optimization and different controller concepts to be implemented. The routine allows for the implementation of input gains for a number of controller architectures, including PID, lead / lag, and zero / pole positioning. It also has an option in the piezoelectric actuator to dynamically linearize the system to reduce the effects of hysteresis. One major drawback to the generic controller is that, depending on the controller's calculations, the sampling speed must be reduced from the default of 10 kHz to either 8 or 5 kHz. Reducing the speed of the sampling increases the surface error, but it also enables the controller gains to be optimized. Once the gains are optimized, it is possible to increase the sampling rate depending on the amount of additional computations required by the controller technique chosen.

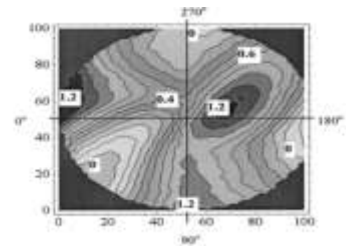

Fig.4: Interferogram Showing from Error in Benchmark Tilted Flat

A simulation of the MAC-100 FTS was conducted to establish the effect of the PZT hysteresis on the system response. The time difference between these tests and the previous study was about one year, so a new case for comparison was cut. Without compensation, there was a P–V form error of 2.4 waves (1.5 m) at 1000 r / min in the work piece cut with uncompensated integral control (s, sampling frequency kHz). The type error shape is same as shown in Fig. 4.

CONCLUSION

Dynamic assessment of the MAC-100 FTS system suggests a substantial increase in range and accuracy compared to earlier devices and shows that these systems can be used to fabricate segments of far off-axis mirrors on existing DTMs. The MAC-100 was optimized in two independent tests, improving the gains of the controller and adding a compensation module to reduce the actuator's nonlinearities. Each made substantial improvements.

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