Zhihan Hong

Paper title:

Long-stroke fast tool servo and a tool setting method for freeform optics fabrication

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1. Introduction

A freeform fabrication method with higher frequency and lower cost based on diamond turning by fast tool servo (FTS) has been explained in Fig. 1. FTS is mounted on a diamond turning machine (DTM), which can move along x direction and the work-piece is clamped on the spindle. FTS can translate diamond tool in and out of the workpiece several time per resolution to obtain a freeform surface.[1-5]

In 1980s, Patterson and Magreb in Lawrence Livemore National Laboratory designed a micro-feed system for error compensation, and the concept of FTS was first introduced. Massachusetts Institute of technology et al. have devoted resources to developing FTS technology.

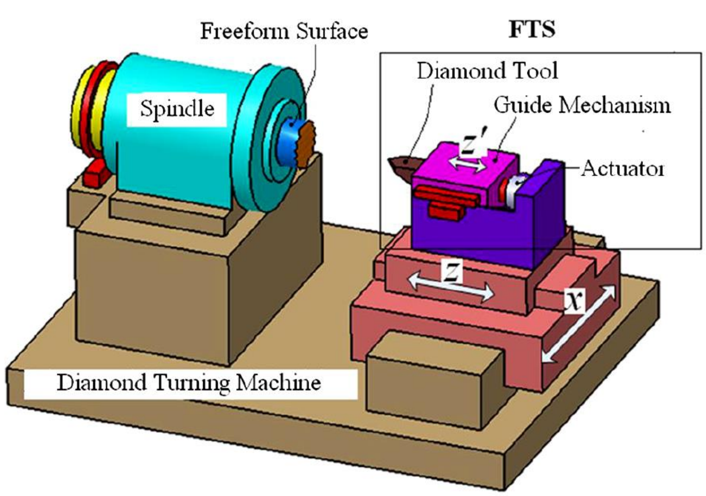

Fig. 1 Working principle of fast tool servo (FTS)-assisted diamond turning.

An FTS system is an independent closed-loop working system mainly consisting of an FTS device and controller. And for better motion resolution, the toolpath for given freeform surfaces and machining parameters must be calculated and optimized, which means that FTSs system should be fixed on DTM and a perfect calibration in order to develop the low cost and high-precision long-stroke one.

2. Long-Stroke FTS System Design

A BEI Kimco VCM is chosen as the driving element. The displacement of FTS is measured by a Reinshaw linear encoder with resolution of 0.01 um. The readhead is installed on the base and the scale is pasted on the moving part of the FTS. Cross-shape flexure hinges providing high stiffness in the x and y directions are designed to guide tool motion.

The parameters of the cross-shape hinge are shown in Fig. 2. The stiffness in z direction (Kz) can be calculated follows:

$$K_z = \frac{F}{z} = \frac{4Ebh^3}{l^3}$$

The flexure hinge stiffness in x and y direction is:

$$K_{x,y} = \frac{2Ebh^3}{l^3} + \frac{2EA}{l}$$

Where A=b*h is the cross-sectional area of the flexure hinge. The parameter values and calculation results are shown in Table 1.

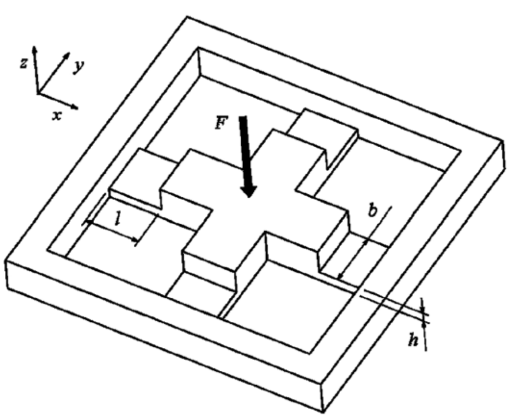

Fig. 2 The cross-shape hinge structure.

Table 1 Parameter values of the flexure hinge.

	b	h	E	K_z	$K_{x,y}$
[illegible] mm	12 mm	0.5 mm	190 GPa	107.6 N • mm^{-1}	134.4 × 10^3 N • mm^{-1}

Another characteristic of the chosen VCM used is an about 12.7mm diameter

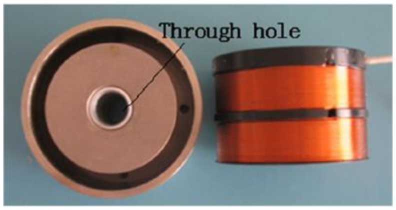

Fig. 3 The chosen voice coil motors of the FTS.

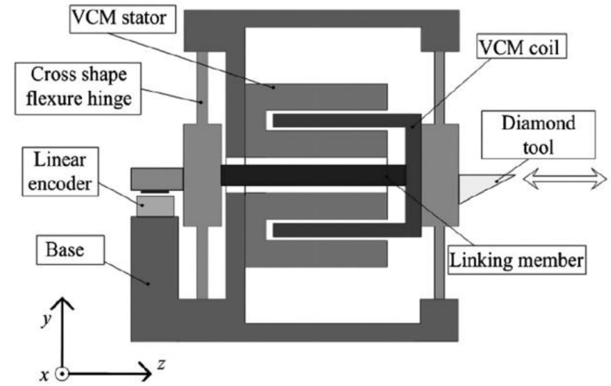

Fig. 5 The designed FTS system working principle.

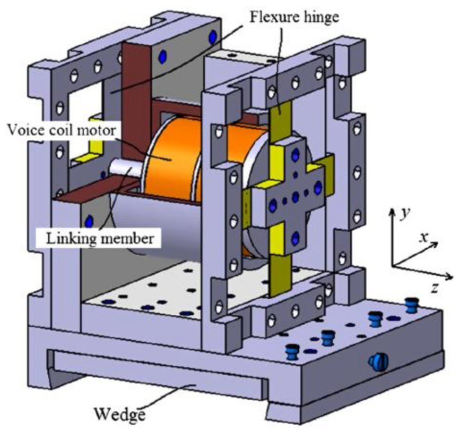

Fig. 4 The details of the FTS.

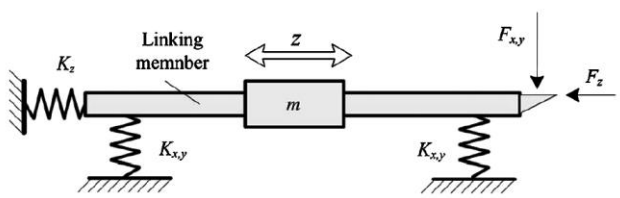

Fig. 6 The simplified schematic diagram of the FTS flexure structure.

through hole in the VCM stator as shown in Fig. 3. The FTS system details are shown in Fig. 4 and the working principle is explained in Fig. 5.

Considering the 12mm linking member to be a rigid body, we shown the diagram of FTS flexure structure is designed in Fig. 6. High stiffness as it designed in x and y direction before, the xy plane force Fx,y, including cutting force and other disturbance forces, can be compensated by close-loop control. Most of the moving mass distributes between the two fulcrums in order ensures that FTS can keep stabilization and high precision.

Mechanical resonance frequency f of the FTS is express as:

$$f = \frac{1}{2\pi\sqrt{\frac{k}{m}}}.$$

Where m is the FTS moving parts mass, which is around 443 g. Since using two flexure hinges, z direction stiffness of the FTS k is 2*Kz. Others are calculated based on the theoretical stiffness and mass, the resonance frequency of the FTS is around 110.98 Hz.

3. Off-Line Testing Results and Discussion

3.1 The open-loop test was carried out, and the result is shown in Fig. 8. The damping coefficient is determined by the equation:

$$D = 2\xi\sqrt{K * m}$$

Where ξ is the damping ratio, which is given by $\xi = 1/[2j\pi \ln(x_i/x_{i+j})]$; x_i and $x_j$is the amplitude from the impact response curve . D influences the stabilization time and overshoot of FTS system, and further influences the response frequency and tool positioning accuracy, and it can be improved by the controller or damping structure. Resonance frequency is the harmful element in FTS diamond turning causing machining error and distortion to the work-piece. As we can the result shown in Fig. 9, since the continuously changing value in the cutting process, FTS must work below the first resonance frequency.

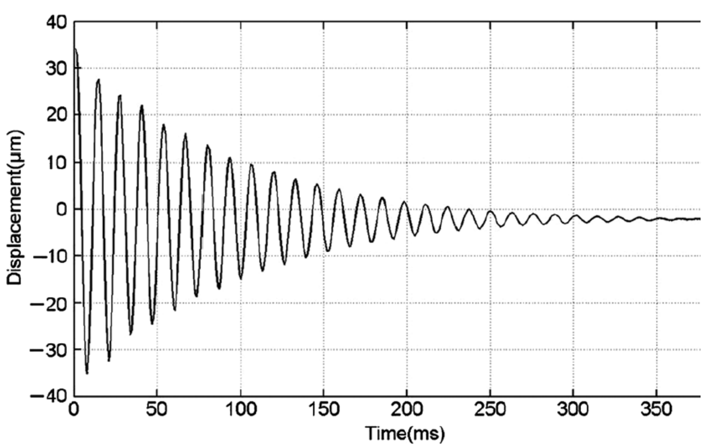

Fig. 8 The open-loop response of the new FTS.

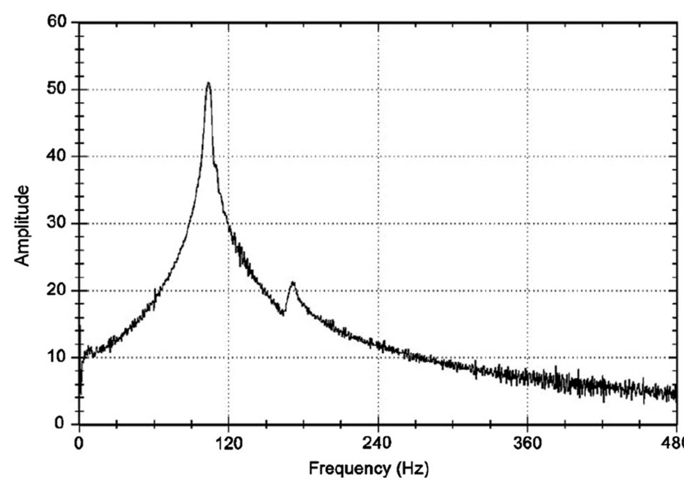

Fig. 9 The FFT of the open-loop response.

3.2 Closed-Loop Test are carried to verify the performance of the FTS system. With amplitude of 1mm, tool working frequency is around 30 Hz.

The resolution is main target for the design of FTSs that is lower than the theory. As shown in Fig. 10, a stair control signal is applied to the FTS, and the displacement is recorded by the linear encoder. System noise is up to 40 nm larger than environment noise. For analyzing this problem of directly bring to the work-piece, testing the response of FTS. As we can see the tracking in the Fig. 11, the movement of that start causes error in the middle, which means that a high performance amplifier and controller are needed.

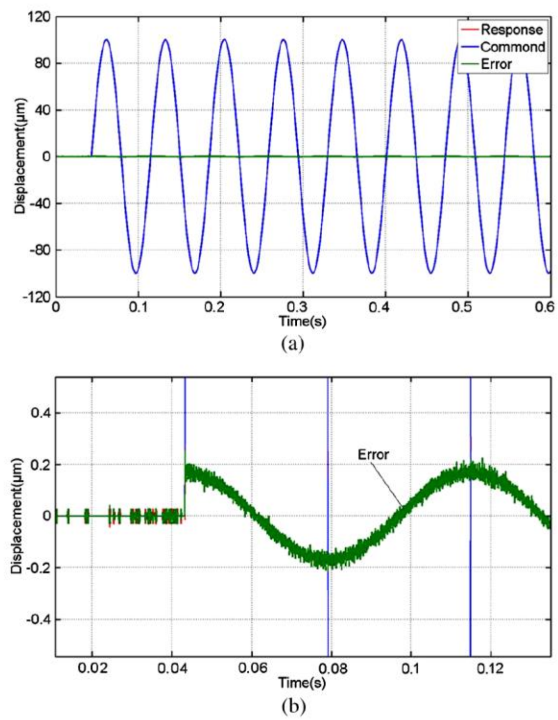

Fig. 11 Tracking performance of the FTS system. (a) Tracking performance. (b) Partial enlarged drawing.

4. Available adjustment

As we mentioned before, the rotationally symmetric is usually machined first; the tool height is adjusted first. A flat surface is needed with a good surface finish. 1. Keeping the spindle still, the slide moves along x direction, bringing the tool across the work-piece to draw a line on the surface as shown in Fig. 12. These two line length might be different, as we can see from Fig. 13.

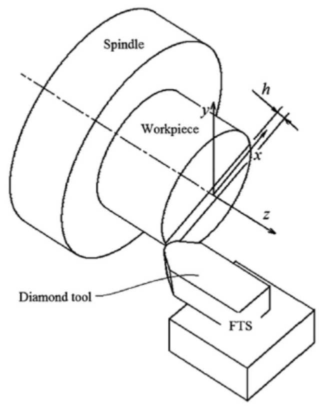

Fig. 12 The schematic diagram of the vertical direction tool center adjustment.

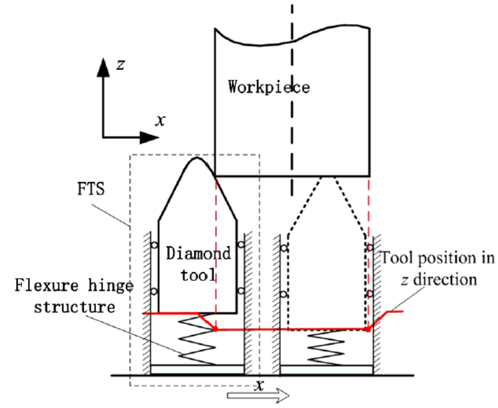

Fig. 14 The schematic diagram of the horizontal direction tool center adjustment.

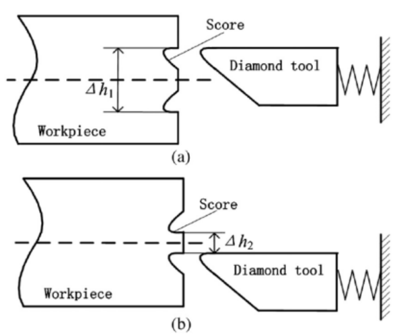

Fig. 13 Two cases of the two parallel lines.

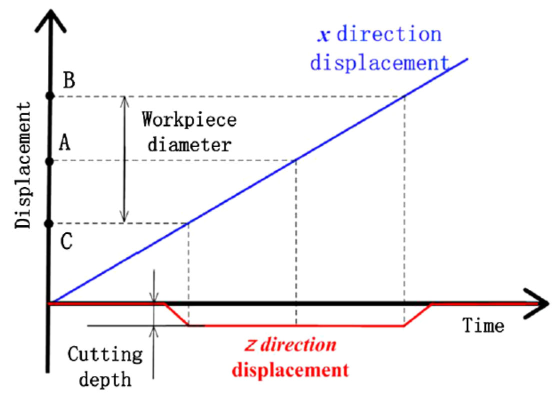

Fig. 15 Displacement changes during horizontal direction tool center adjustment.

Then adjust the horizontal direction, the work-piece has been considered to be a standard cylinder in this method. So its centerline should be the spindle centerline. After the tool height is adjust, x-center is conformed, which means that the FTS working principle can be simply describe in Fig. 14. When the tool draws across the work-piece along x direction, the tool position in z direction will be changed when the tool is contacting and leaving the work-piece, as Fig. 15 shows.

5. Cutting experiment

Adjust the horizontal and x-direction to be symmetry.

Since the paper mentioned leave the adjustment problem without perfectly resolved as we can see in the Fig. 17. And the improved result has been shown in the Fig. 18, we can get a tool height error is 2.7 um larger than ideal value of 0.5 um.

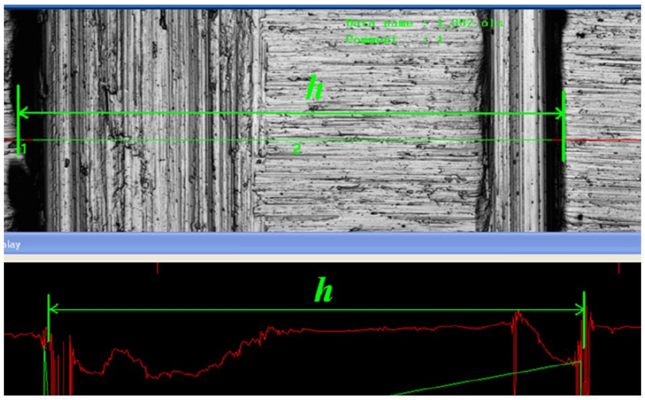

Fig. 17 The two lines for tool height adjustment.

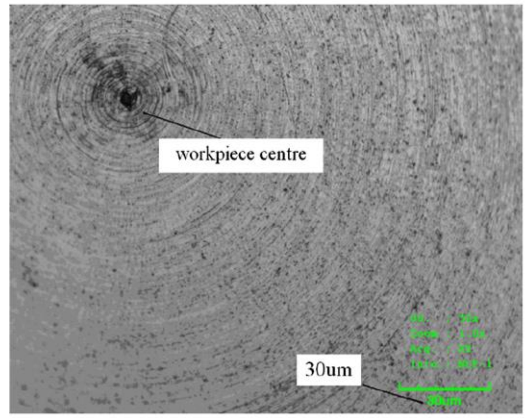

Fig. 18 Tool center error after the adjustment.

6. Conclusion

The paper focuses on the hardware quality analyzing and adjustment. It shows that the advantages of high resonance frequency and high stability, with working stroke exceeding 1mm. The resolution of the FTS is around 0.1 um that is an available accuracy for lower cost and high speed.

7. Discussion

In my opinion, whatever the cutting and high-precision mechanisms is working for a constant working process, as a suggestion for improvement, software compensating is still necessary. The author consider the material to be rigid that is the biggest assumption at first, which means they refused to consider the influence of thermal and other effect. Besides the tool that author mentioned the process without the tolerance setting process of different material and designed shape. A data base should be made to guide the process.

Even the paper focus more on the hardware, complete the project still need to add more control for the error. The author mentioned some of the error and analyzed the possibility of them that is significantly helpful for the real process and future software compensating that I mentioned before.

8. Reference

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