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Design, analysis and test of a long stroke fast tool servo

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Abstract

Fast tool servo (FTS) in precision machining is an efficient and reliable method for fabricating non-rotationally symmetric surfaces or microarrays with sub-micrometric form accuracy. Compared to slow tool servo, FTS can reduce the manufacturing time and has small tracking errors. In this paper, a novel long stroke FTS construction is designed where the voice coil motor is located inside the slide to reduce the total volume of the system. Air bearings are used to reduce kinetic frictions. Counter balance is adapted on the FTS system, which reduces the vibration from ±3 µm to ±0.2 µm. For the control subsystem, several control algorithms are applied to the physical system, including traditional PID, PID with velocity/acceleration feedforward, sliding mode control (SMC), active disturbance rejection control (ADRC). They all have different characteristics and adapted to different situations. The correspondences of the simulation model and physical model expand the possibilities of further algorithm developments. The system can reach 0.2 m/s and 4.3 g acceleration and has a maximum 0.5% tracking error when tracking the sinusoidal signal. The typical working performances are ±1 mm @ 30 Hz for long stroke and ±0.1 mm @ 80 Hz for high frequency. The relationships between mechanical subsystem and control subsystem are analysed from system stiffness and system bandwidth points of view. A comprehensive design method is presented which enables the modular design of fast tool servo systems.

Keywords: Fast tool servo, Air bearing, Counter-balance, Control algorithm, Tracking error

1. Introduction

Fast tool servo is an efficient method manufacturing non-rotation symmetric surface (NURBS) and the surface with microarrays. These surfaces are widely used in optical applications like varifocal lenses. FTS can monitor and make the cutting tool to do reciprocating motions with different frequencies and different strokes according to the surface topography. FTS can be divided into two types: Piezoelectric FTS which uses piezoelectric ceramics as driving source, this kind of FTS is suitable for short strokes (up to 100s µm level) but high frequency (several kilohertz) [1]. Kinetic Ceramics developed a series of products which can reach 10 µm at 20 kHz, 25 µm at 5 kHz, 25 µm at 1.5 kHz, 8 µm at 24 kHz separately [2]. This type of FTS is limited by the small stroke and it is hard to do the close loop control for the high frequency applications. Another type is the Lorentz force FTS, which is driven by the voice coil. It can achieve millimetre stroke but due to the large moving mass, the bandwidth of this kind system cannot reach to a high value, usually up to 100 Hz [3]. Moore Nanotech developed an FTS which can reach 2 mm at 100 Hz with counter-balance system [4]. The drawback of Lorentz force is the performances are limited by the large moving mass, and under-damping system is hard to control. Even there are commercial FTS products, there is no systematic design method for this type system. Most researches focus on one part of this technology, new mechanical structures or advanced control algorithms, but the relationships between different components are unclear, which motivates the development of the modular design of FTS.

The paper aims to develop an integrated fast tool servo system driven by the voice coil motor. With the systematic design method, FTS technology will has more application areas and increase the total manufacturing efficiency.The paper is divided into four parts: the design of mechanical subsystem, a new structure is adapted and a stiffness criterion and dynamic are presented based on this structure for further developments. The second part is the control subsystem design, in which four different control algorithms are designed and applied to the physical system. An accurate simulation model is expected for designing new control methods in the future. The third part is the counterbalance design, which aims to solve the vibration problem due to large acceleration. The final part is the processing experiments, which aims to verify the design in the previous parts.

2. Mechanical subsystem

The motion of the FTS system is the reciprocating motion, and it can be seen as a sinusoidal motion. The stroke, frequency, and the moving part mass determine the kinetic characteristics. The voice coil motor is the driving source. It generates the varying forces for the system and realizes the required motion. The governing equations are as follows:

$$X = Asin(\omega t) \tag{1}$$
$$F_{max} = ma_{max} = m\ddot{X}_{max} = -\omega^2 A \tag{2}$$

X - Displacement
A - Maximum displacement
ω - Frequency
a – Acceleration

The target performances are, the working frequency can reach up to 100 Hz, the maximum stroke is ±1.5 mm.

2.1. Air bearing and system arrangements

After the main driving source is chosen, air bearing is chosen as the support components. It uses the high-pressure air to form an air film, with certain stiffness but no frictions. In the FTS design, the stiffness of the air bearing is a very important index. Higher stiffness gives the system higher mechanical bandwidth and then system bandwidth increases. An air bearing with 7 orifices was designed and manufactured for the system. The maximum stiffness was measured to be 31 N/µm when the air film height was 12 µm as shown Figure 1. From air bearing stiffness curve, the air bearing has a optimum stiffness point which is a useful value during air bearing installation.

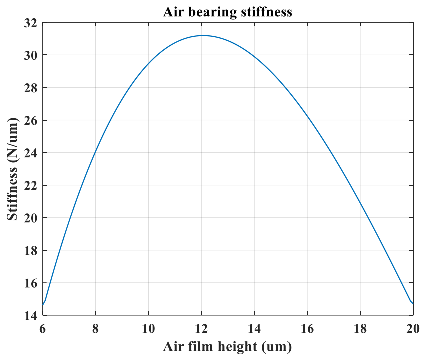

Figure 1. Air bearing stiffness curve

To reduce the total volume of the system, there are no transmission components in this design. The voice coil motor is connected with a square-hollow slide. Four air bearings are arranged at the outside of the slide and connected with the outside shell with ball-headed screws (air bearing connections), the section view and front view of FTS system are shown in Figure 2(a) and 2(b):

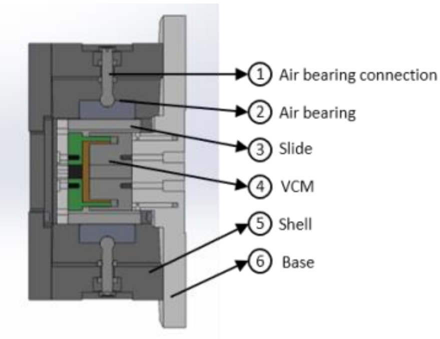

Figure 2(a). Section view of designed FTS system

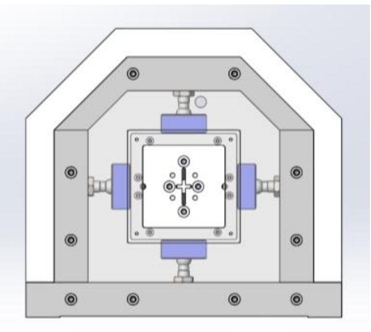

Figure 2(b). Front view of designed FTS system

A design criterion is made for the air bearing used in the FTS system. To ensure the stable operation and prevent misalignment, the air bearing should have the ability to absorb the motor force and keep the air film unchanged. Considering the machining tolerance, the air bearing stiffness criterion can be desired as:

$$K \geq \frac{1}{2} \times \frac{F}{\frac{1}{3} \times h - fl_s - fl_a} \tag{3}$$

K – Air bearing stiffness
h – Air film installation height
F – Continuous force of voice coil motor
fl_s – Slide flatness of air bearing installation surface
fl_a – Air bearing flatness

The final length of the FTS system is 140 mm, this arrangement can decrease the installation dimensions of the system.

2.2. System dynamic properties

Modal analysis and harmonic response analysis were performed to the system. Model analysis shows the first natural frequency of the system is 369.14 Hz, and this should be three times more than the designed maximum working bandwidth (100 Hz). The second and third natural frequencies represent the stiffness in vertical directions of air bearings. If the stiffness of air bearings is increased, all the modal frequencies are increased. Figure 3 and 4 show the modal analysis results of the system, the first-order modal is the twist of the whole system and the second and third modal are the offsets of the air film. This means the weakness points of the system are the air bearing film and the connections.

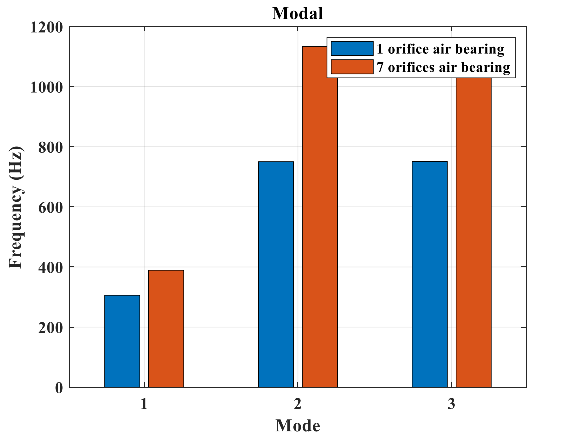

Figure 3. modal frequencies for system with different air bearings

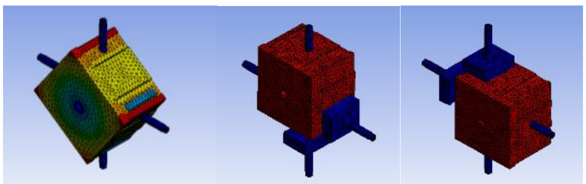

Figure 4. Modal analysis results for the first three orders

Harmonic analysis can calculate the overall stiffness of the whole system, using a 5 N force from XYZ directions to simulate the cutting resistance force. From the results: the air bearing stiffness is 31 N/µm, the stiffness for air bearing connection is 135 N/µm, the total stiffness in X/Y direction (whole FTS mechanical subsystem) is 50.4 N/µm. Therefore, the system can be simplified as: the ball-head screw connects in series with the air bearing and then connect in parallel with the other side.

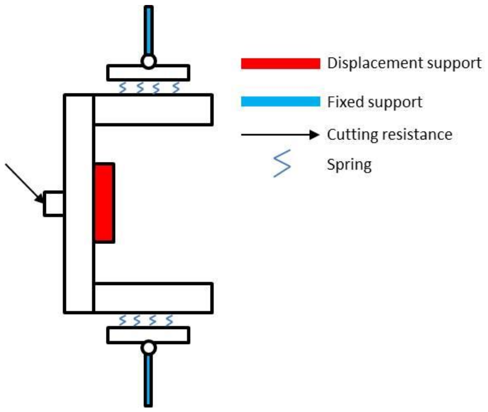

Figure 5. Harmonic analysis set up sketch

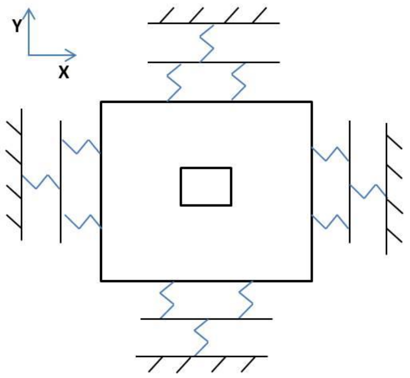

Figure 6. System stiffness simplified model

Figure 5 is the set up of the harmonic analysis, the air film is equivalent to spring, a zero displacement support is applied on the motor to represent the enable state. Figure 6 is the system stiffness simplified model, it can be used for modular design in the future.

3. Control subsystem

The control subsystem is the key to realize the designed objectives. The designed system is the underdamped system due to the usage of the air bearing. Therefore, a well-designed control system is needed to help the system achieve its designed goals. A system control simulation is carried out to give a basic understanding of how the system should works. The mechanical subsystem can be simplified as a second-order system. A precision motion controller (Omron CK3M) and a motor driver (Elmo) have been chosen to build the control system for the designed FTS system. Figure 7 is the control block diagram of the system:

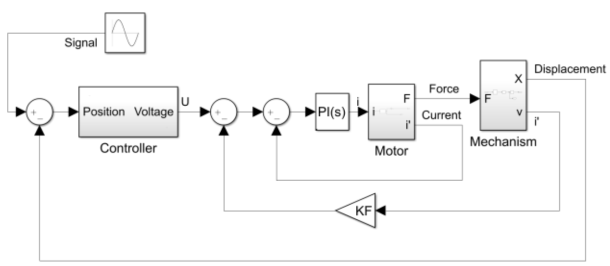

Figure 7. System simulation model

The whole system is designed as a double close loop system: current loop and position loop. Traditional PI control is used in the current loop and provides up to 3 kHz bandwidth. For the position loop, four different control algorithms are tested on the physical model: velocity/acceleration feed forward, sliding mode control (SMC) and active disturbance rejection control (ADRC).

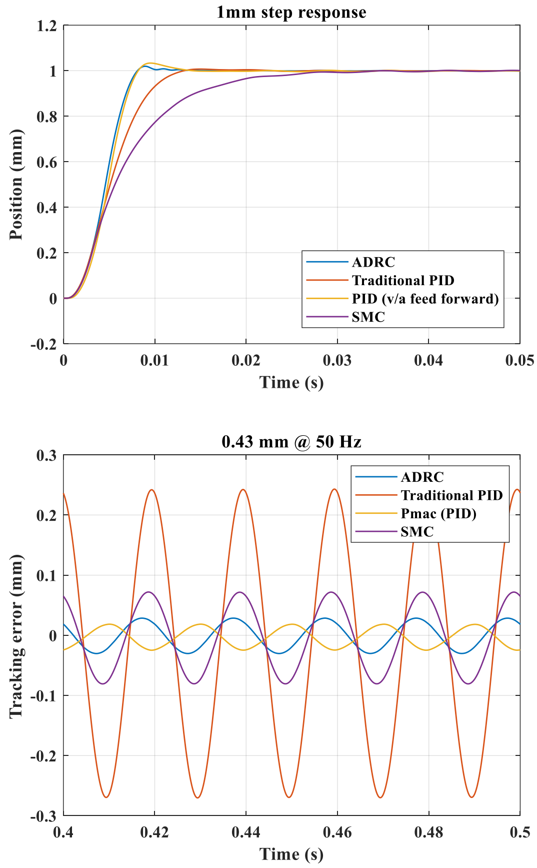

Figure 8. Step and sine responses of different control algorithms

The PID with velocity/acceleration feedforward control and ADRC control have better performances. Like the step and sine response results which are shown in Figure 8, the PID with velocity/acceleration feedforward control has the shortest settling time. When tracking the sine signal (0.43 mm @ 50 Hz), it can achieve the minimum tracking error ±20 µm. But note that these are the results of preliminary testing without machining, different control algorithms could suit different cutting processes.

Also, the correspondences of the simulation model and physical model expand the possibilities of further algorithm developments. The output of the controller in the physical model are in good agreement with results obtained from the simulation model. Like shown in Figure 9, the controller output in the simulation model and physical model shares the similar values, the differences are acceptable due to the ideal condition of the simulation model (no external disturbances).

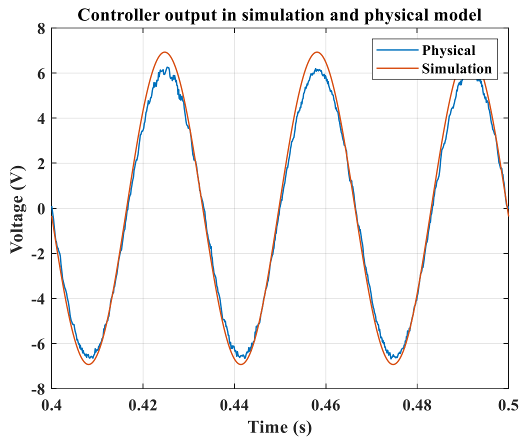

Figure 9. Comparison of voltage output in simulation and physical model

The system performance result is tested as follows: the maximum velocity is 0.2 m/s and the maximum acceleration is 4 g. For long stroke is 1 mm @ 30 Hz. For high frequency is 0.1 mm @ 80 Hz. The maximum tracking error is 0.5%.

Table 1 shows some achieved performances of designed FTS system with the velocity/acceleration feedforward control method.

Table 1 Achieved performances of designed FTS

Frequency (Hz)	Stroke (mm)	Tracking error
30	1	0.01%
40	0.68	0.088%
50	0.43	0.047%
60	0.3	0.067%

4. Counter-balance

Counter-balance is a method that solves the vibration problem caused by the large acceleration of the large moving mass. A back-to-back design is adapted, a counterbalance mass is used to do the same motion with the main moving mass, the total acceleration can be considered as zero for the whole system.

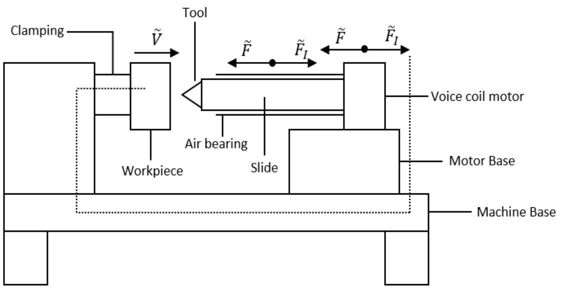

Figure 10. Sketch of counter-balance problem

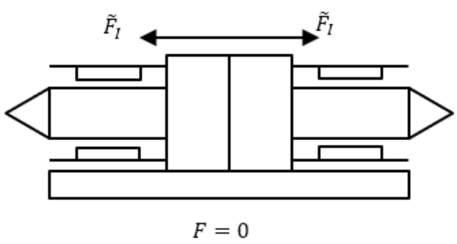

Figure 11. Back-to-back solution for counter-balance

Figure 10 shows the counter-balance problem, the inertia force generated from the moving components is transferred to the base plate. The vibration in base plate has a side effect on the manufactory of the workpiece. Figure 11 is the back to back design, the same system is installed at the back of the main system.

With the designed mechanical and control subsystem, the overall system with counterbalance can be easily set up. It functions as a gantry structure. A laser displacement sensor is used to test the vibration of the base plate. The vibration has the same frequency with main FTS motion. The amplitude is decreased from ±3 μm to ±0.2 μm like shown in Figure 12:

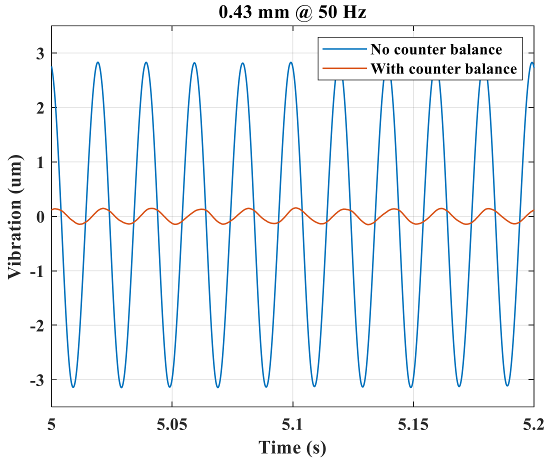

Figure 12. The comparison of using counter balance

5. Conclusions and future work

This work has achieved three goals: For the mechanical subsystem, a mechanical stiffness design criterion is presented and the simplified model is concluded for further modular design. For the control subsystem, a mature control system is built, the simulation model is developed corresponding to the physical model. Also, four different control algorithms are tested, and PID with velocity/acceleration achieves the best performance prior machining tests, which enables the system to achieve ±1 mm @ 30 Hz for long stroke and ±0.1 mm @ 80 Hz for high frequency with the maximum tracking error less than 0.5%. For counterbalance, the vibration of the system is reduced to from ±3 μm to ±0.2 μm.

Future developments will focus on machining experiments and verify all the conclusions from the preliminary tests.

References

[1] Linlin Zhu et.al, "Review on fast tool servo machining of optical freeform surfaces," The International Journal of Advanced Manufacturing Technology, vol. **95**, pp. 2071-2091, 2018.

[2] Kinetic Ceramics, "Ultra-Fast Tool Servos," Kinetic Ceramics, 2021. [Online]. Available: https://www.kineticceramics.com/products/ultra-fast-tool-servos/. [Accessed 1 2 2021].

[3] L. X. Trumper, David L., "Fast Tool Servos: Advances in Precision, Acceleration, and Bandwidth," in Toward Synthesis of Micro-/Nano-systems, London, Springer, 2007, pp. 11-19.

[4] Precitech, "Fast tool servo," 2019. [Online]. Available: https://www.precitech.com/product/accessoriesoverview/fasttoolservo. [Accessed 4 2 2021].