Performance assessment of an ultraprecision machine tool positioning system with a friction drive

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The positioning system for an ultraprecision machine tool must be accurate to the order of a nanometer. Various feed drive devices have been proposed to achieve this resolution; currently, most attention is directed towards hydrostatic lead screws and friction drives. It has been reported that a positioning resolution accurate to an angstrom can be achieved using a twist-roller friction drive. Therefore, we manufactured an ultraprecision positioning system driven by a twist-roller friction drive and assessed its performance when defining problems and finding solutions. Our study showed that the twist-roller friction drive is mechanically suitable for ultraprecision positioning, but some considerations are required to obtain a higher resolution.

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1. Introduction

Ultraprecision machining technology is widely used to manufacture optical and semiconductor components, such as high precision mirrors and lenses, and silicon wafers. Today, the components of optical devices and semiconductors have become micro-sized, and thus the size of the workpieces manufactured using ultra-precision machining methods have become much smaller. To machine smaller and more precise components, a system is required that has a positioning technique that is accurate to the order of a nanometer[1]. To control such an ultraprecision positioning system, the drive mechanism must also be accurate to the order of a nanometer[2].

Currently, attention is focused on two possible drive mechanisms among the many that are available: hydrostatic leadscrews[3] and friction drives[4]. In particular, an ultraprecision positioning system has been described that has a friction drive that is accurate to the resolution of an angstrom[5]. Friction drives also have other merits, such as easy design and manufacturing capabilities, no backlash, a high resolution, and a long stroke.

In this study, an ultraprecision positioning system with a twist-roller friction drive was manufactured and its performance was assessed. Several problems and solutions are described, and a system that can be used to manufacture components with a resolution that is accurate to the order of a nanometer is proposed.

2. Twist-roller Friction Drive

2.1 Principle of the friction drive

As shown in Fig. 1(a), when a driven roller contacts the drive shaft at an angle of α, it advances by $L = \pi D \tan\alpha$ during one rotation of the drive shaft. This situation is depicted in Fig. 1(b). The driven roller requires a support that allows it to rotate only about its axis in order to convert the rotational motion of the drive shaft into a linear motion in the direction of the drive shaft. The support does not rotate and only guides the linear motion of the driven roller.

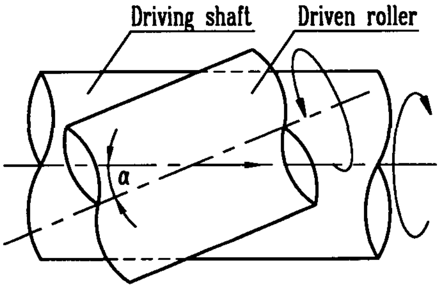

Fig. 1(a) Principle of the twist-roller friction drive

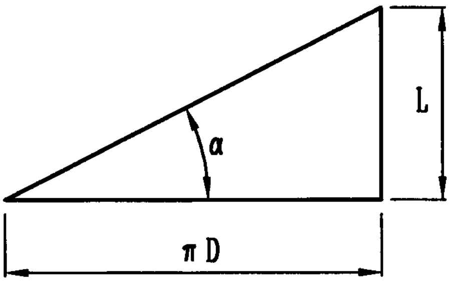

Fig. 1(b) Moving trajectory of the driven roller

2.2 Manufacturing of the friction drive

Figure 2 shows the manufactured twist-roller friction drive. A schematic diagram of the friction drive is presented in Fig. 2(a) and a photograph of the manufactured friction drive is shown in Fig. 2(b).

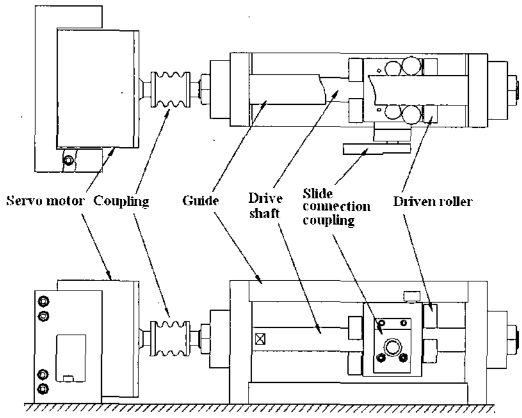

Fig. 2(a) Schematic diagram of the twist-roller friction drive

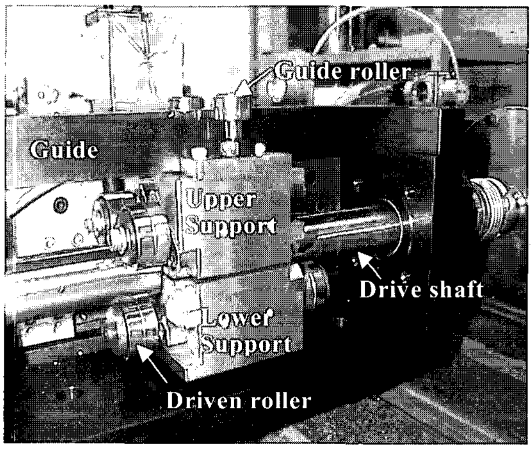

Fig. 2(b) Photograph of the twist-roller friction drive

To distribute the preload force between the driven rollers and the drive shaft equally, the three driven rollers are separated from each other by 120°. The support is composed of two parts (upper and lower), which allows easy assembly and easy preloading. Two springs in the support ensure that each driven roller maintains close contact with the drive shaft. A guide is connected to the two bearing housings of the drive shaft, and the two guide rollers that are attached to the upper portion of the support are reciprocally moved through this guide.

3. Manufacturing of the Ultraprecision Positioning System

The ultraprecision positioning system with a twist-roller friction drive is shown in Fig. 3. The rotation of the servomotor generates a linear motion in the friction drive. Then the friction drive moves toward the air-bearing table, which is coupled to it.

The position of the table is fed back to the system using laser interferometry (Zygo ZMI). Therefore, a plane mirror is attached to the table. The resolution of the laser interferometry was 5 nm, and its output was an AQuadB signal like in an encoder. The entire positioning system was mounted on an air bed to eliminate the effects of external vibrations.

Closed loop control was performed using a PC and a pc-nc control board (MEI PC-DSP). A flexible coupling (Mayr) was used to connect the DD motor and the friction drive. The connector between the friction drive and the air table was designed to have 5 degrees of freedom so as to reduce the motion errors from machining and the assembly errors of the friction drive.

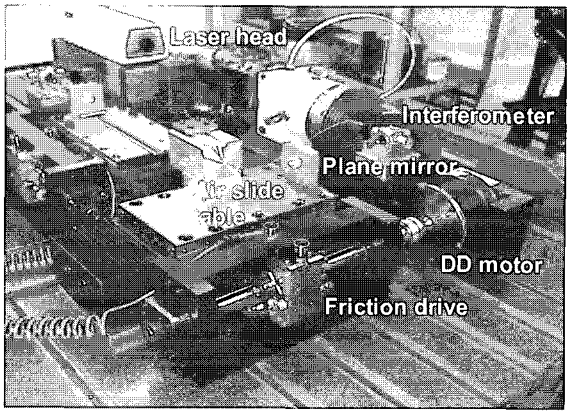

Fig. 3 Photograph of the feeding system

4. Experimental Methodology and Results

4.1 Experimental methodology

4.1.1 Motion accuracy

We used a laser interferometer (HP 5529A) to estimate the motion accuracy of the ultraprecision positioning system with a friction drive. The interferometer retroreflector was placed at the center of the table and used to measure the vertical straightness, horizontal straightness, yaw error, and pitch error of the positioning system. The measured stroke was 50 mm. To analyze the motion of the friction drive, it was necessary to measure the errors in the motion of the air-bearing slide when it was not connected to the friction drive. Therefore, we disconnected the table from the friction drive and connected it to another stepping motor using a wire. The motion accuracy of the air-bearing table itself, driven by the stepping motor, was measured using laser interferometry, as well as the motion accuracy of the friction drive.

To determine the properties of the 5 degree of freedom (DOF) coupling system, shown in Fig. 4(a), the system was replaced with a leaf spring shown in Fig. 4(b) and the motion errors were measured again.

4.1.2 Microstep response

The resolution and step response of the ultraprecision positioning system with a friction drive were measured with a capacitive gap sensor (ADE Microsense 3401). The sensor was placed at the same position as the laser interferometer plane mirror and used to measure the step response after various step distances were applied. The total measuring time was 26 s and the sampling rate was 100 Hz.

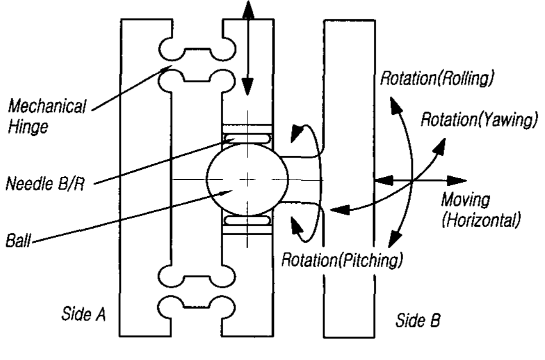

Fig. 4(a) Five degree-of-freedom type coupling

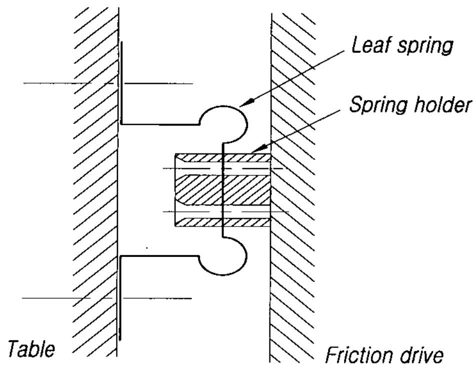

Fig. 4(b) Leaf spring type coupling

4.2 Results and discussions

4.2.1 Motion accuracy

Figure 5 shows the motion accuracy of the air-bearing slide table when it was not attached to the friction drive, while Fig. 6 shows the motion accuracy of the friction drive. The high frequency portion shown in Fig. 5 was caused by the hydrodynamic effect of the air-bearing[6]. As shown in Fig. 6, all of the motion errors produced large oscillations over the lead period (0.91 mm) of the friction drive. This was because of a misalignment between the drive shaft and the driven rollers.

Figures 7 and 8 show the motion accuracy of the air-bearing table driven by the friction drive with the 5 DOF coupling system and the leaf spring coupling system, respectively. As shown in Fig. 7, the 5 DOF coupling system could not isolate the oscillations from the friction drive lead period. However, the leaf spring coupling system, shown in Fig. 8, effectively isolated the oscillations, with the result that the motion errors of the drive were almost equal to the positioning errors of the table itself.

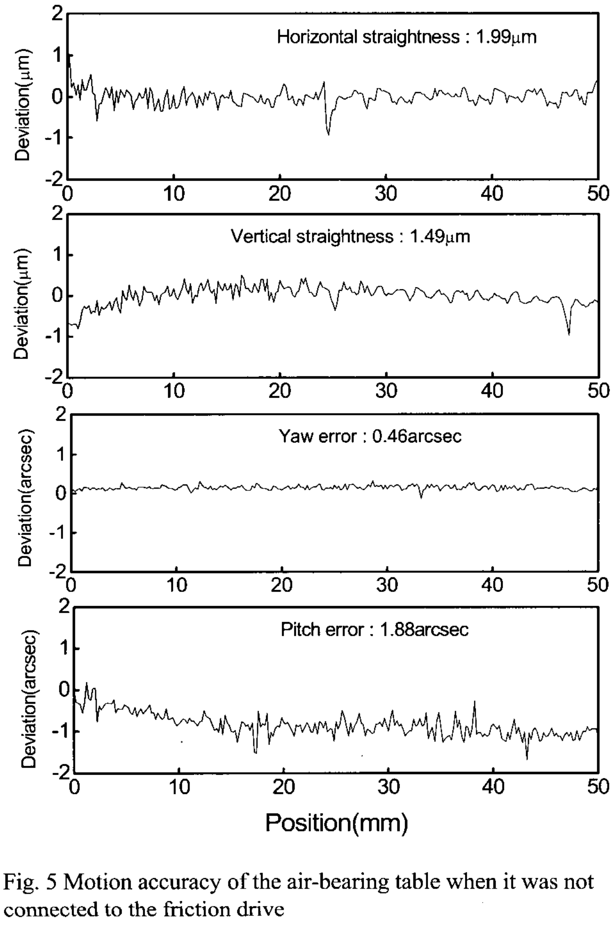

Fig. 5 Motion accuracy of the air-bearing table when it was not connected to the friction drive

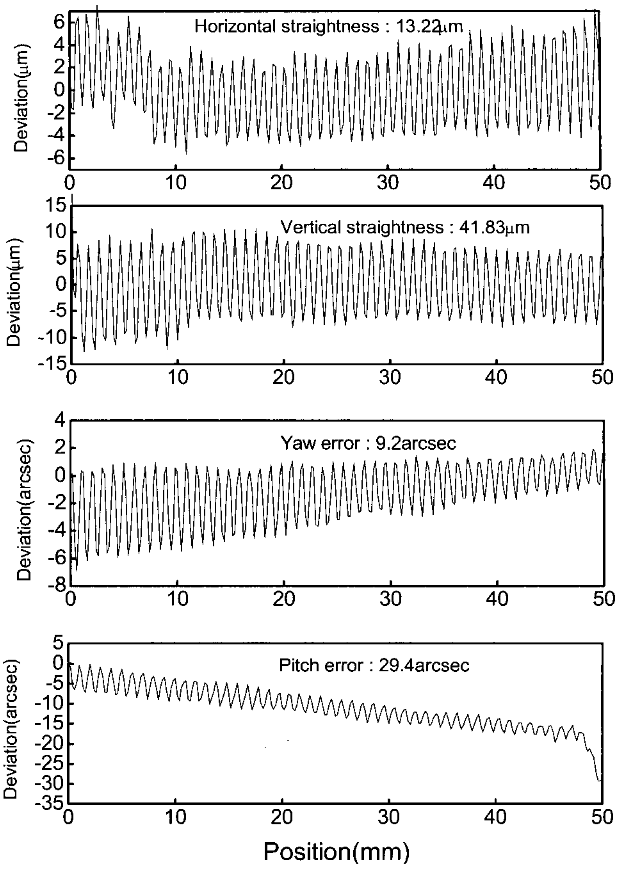

Fig. 6 Motion accuracy of the friction drive

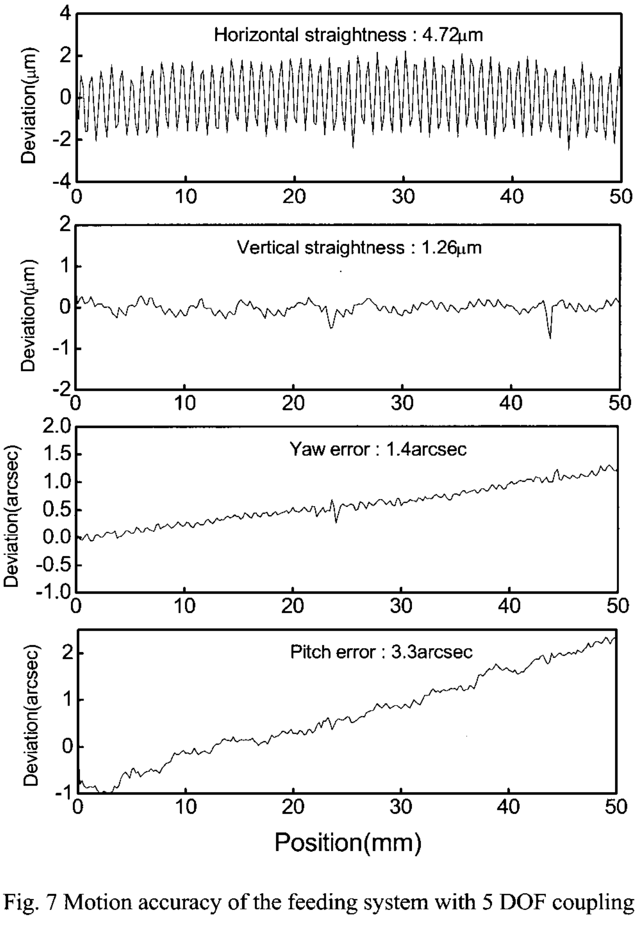

Fig. 7 Motion accuracy of the feeding system with 5 DOF coupling

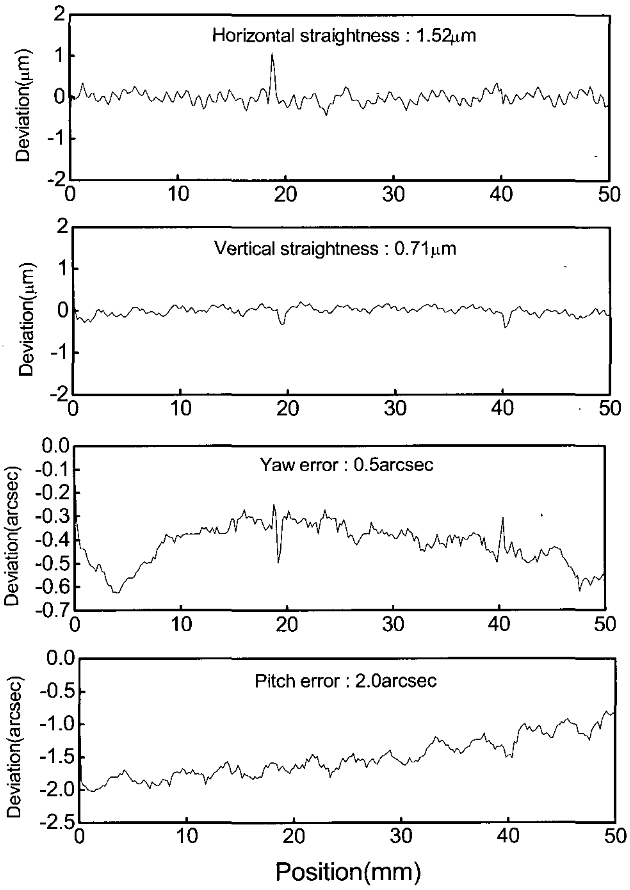

Fig. 8 Motion accuracy of the feeding system with leaf spring coupling

4.2.2 Microstep response

Figure 9 shows the microstep response of the table with the friction drive. A 5 DOF coupling and a gap sensor (ADE Microsense 3401) were used. As shown in the figure, the response to a step distance of 30 nm and 20 nm was relativity accurate, but the response to a step distance of 10 nm was not. It is therefore reasonable to state that the resolution of the ultraprecision positioning system was 20 nm.

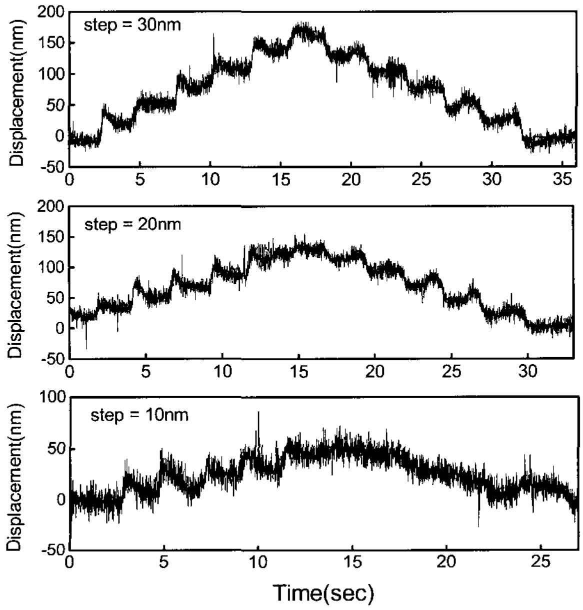

Fig. 9 Microstep response of the feeding system

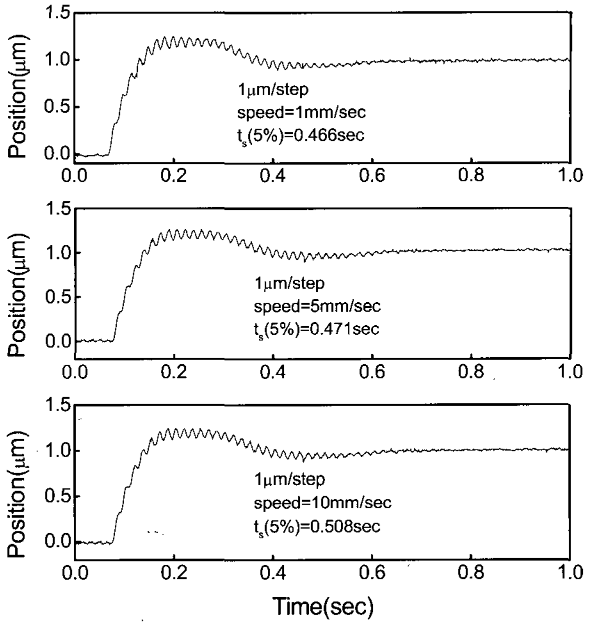

Fig. 10 Step response of the feeding system

Figure 10 shows the microstep response of the air table for three different velocities: 1 mm/s, 5 mm/s, and 10 mm/s. In these three cases, the settling times were 0.466 s, 0.471 s, and 0.508 s, respectively. The microstep response results indicate that the settling time of the air table was restricted to 0.5 s, even though the velocity reached 10 mm/s, which is at the upper limit of typical ultraprecision cutting speeds. This indicates that the ultraprecision positioning system with a twist-roller friction drive had stable control characteristics.

5. Conclusions

In this study, an ultraprecision positioning system driven by a twist-roller friction drive was manufactured and its performance was assessed in order to find problems and their solutions. The following conclusions can be drawn.

(1) There were large oscillations in the motion accuracy of the friction drive itself, and these oscillations were transmitted to the air table through the 5 DOF coupling.
(2) A leaf spring coupling reduced the oscillations.
(3)The microstep response tests demonstrated that the positioning system had a 20-nm resolution.
(4) The ultraprecision positioning system had a 0.5-s settling time at speeds normally used for ultraprecision cutting. Thus this system had stable control characteristics.

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