Ultra-precision machine system feedback-controlled using hexapod-type measurement device for six-degree-of-freedom relative motions between tool and workpiece

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Abstract

This study deals with a feedback-controlled precision machine system based on a hexapod-type measurement device for six-degree-of-freedom (6-DOF) relative motions between the tool and workpiece. The hexapod mechanism installed between the tool spindle and surface plate is passively actuated by a conventional machine. Then, the hexpod consisting of six extensible struts accurately measures the 6-DOF motions for the feedback control of the machine regardless with temperature fluctuation and external forces because each strut has a compensation device for elastic and thermal deformations of the joints and links. This paper describes the performance test for displacement measurement of the strut when the strut is expanded and contracted by a linear motion stage.

1 Introduction

In late years, to realize submicron-order volumetric accuracy of spatially-moving mechanisms for precise machining or coordinate measurement, a machine system generating accurately relative motion between its tool and the workpiece has been strongly required as well as the accuracy improvements of each element of the machine. In an actual machine, however, internal and external disturbances noticeably cause positioning errors. Thus, much improvement in guide element accuracy and structural stiffness has been achieved to decrease the motion error and the elastic deformation[1, 2]. However, increased mass along with such improvements has dynamically caused further motion error and elastic deformations. Further, no machine structure can be made infinitely stiff. On the other hand, to compensate for the thermal deformation, prediction methods have been investigated using temperature sensors and thermal deformation analysis[3, 4]. However, the thermal deformation is hard to predict precisely. In general, moreover, conventional feedback control of the machine has been implemented for each motion axis, which is based on one axis displacement measurement or one degree-of-freedom motion measurement. In such a case, 5-degree-of-freedom motion errors including three angular motion errors are not measured for compensating the Abbe errors caused by the angular motion errors and the Abbe offsets.

This study proposes a feedback control system based on a hexapod-type measurement device for six-degree-of-freedom (6-DOF) relative motions between the tool and workpiece[5, 6]. Because the measurement device measures the 6-DOF motions including angular motions around three axes, the arrangement of the sensor systems for the feedback control is not restricted by the Abbe alignment principle. Moreover, this measurement device is independent of any elastic and thermal effects and motion errors of the machine structure because the hexapod is separated from the machine's main mechanisms and its structure[9]. In other words, the machine system can compensate not only the systematic motion error caused by kinematic parameter errors or geometrical deviations of the machine elements but also non-repetitive motion errors caused by the elastic and thermal deformations if the 6-DOF motion can be precisely measured. This paper firstly describes the conception of the system. Moreover, when a strut of the hexapod-type measurement device was expanded and contracted by a linear motion stage, displacement measured by a linear scale unit installed in the strut was compared with a laser-interferometer length measurement system.

2 Machine system based on 6-DOF motion control

Figure 1 shows the principle of proposed machine system based on a measurement device for the 6-DOF motions between the tool and the workpiece.

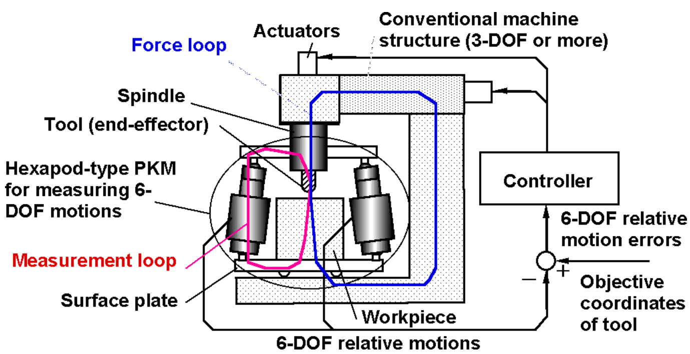

Figure 1: Fundamentals of proposed machine system using 6-DOF measurement device between tool and workpiece

This system consists of a hexapod-type parallel kinematic mechanism (PKM), a conventional machine structure, and a controller. To measure the relative 6-DOF motions, the base platform and the moving platform of the PKM are mounted on the surface plate and the machine spindle, respectively. Both platforms are connected through six extensible struts with prismatic joints. Since each strut has no actuator, the moving platform of the PKM is passively moved in three-dimensional space by the conventional machine. Because change in the length of each strut is measured by a displacement measurement unit or a linear scale unit, the 6-DOF motions can be calculated by the forward kinematics of the hexapod-type PKM. Consequently the controller compensates for the motion errors and accurately actuates the tool. In the coordinate measuring machine, the coordinates of the probe tip are directly measured by the PKM.

3 Extensible strut of PKM

Figure 2 shows an extensible strut of the PKM[7, 8]. Each strut has a mechanical compensation device both for elastic and thermal deformations of joints and links. Two rods connect the scale and the scale head of the linear scale unit to the two spherical joints at both ends of the strut. The scale head and the scale are guided by some linear bearings so that they can move only in the longitudinal direction. Thus, the scale unit can measure not only the displacement change of the prismatic joint but also the spherical joint errors and the link deformation in the longitudinal direction because each rod end is in contact with the master ball of the spherical joint. Further, because the rods are made of Super-Invar (thermal expansivity: approximately 0.5 ppm/K), each distance between the scale unit and a spherical joint is not influenced by any temperature change. Additionally, the distances are not influenced by any external forces because no external force is applied to the rods and the scale unit. To put it briefly, even if the strut is thermally or elastically deformed, the scale unit can accurately measure the length change of the strut.

4 Experimental apparatus

4.1 Extensible strut

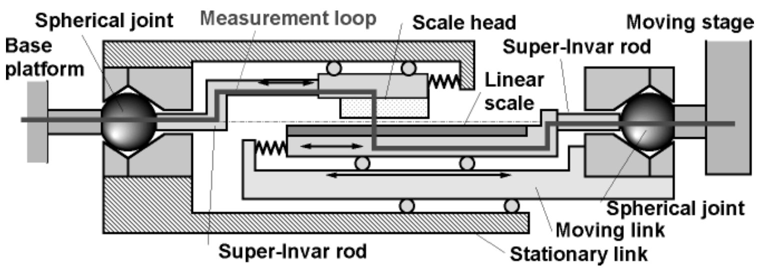

Figure 2: Extensible strut with compensation device for elastic and thermal deformation errors

Figure 3 shows a sectional view of the extensible strut with the compensation device mentioned above. The spherical joints are fixed at each end of the stationary link and the moving link. Moreover, Super-Invar rods connect a scale unit (Heidenhain LIP481R, with measuring length 270 mm and resolution 2 nm, nominal accuracy: ±0.5 µm) with the spherical joints. The scale unit head and the linear scale mounted on Super-Invar plates are guided by using simple notch-type linear springs to allow them to move only in the longitudinal direction. Two sets of rolling-element linear motion bearings mounted on the stationary link guide the moving link. The scale unit is installed on a straight line between the spherical joints so that the Abbe offset is minimized. Therefore, angular motion errors of these linear bearings have little effect on displacement measurement accuracy of the strut.

4.2 Spherical joint

As mentioned above, all parts along measurement loop shown in Figure 2, including the ball shanks of the spherical joint's, must be made of low thermal expansion materials. Thermal deformation of the ball shank will cause measurement error of change in distance between the spherical joints as shown in Figure 4(a). In other words, the scale unit cannot accurately measure the distance change. For example, in the previous study, material change of the ball shank from Super-Invar to steel worsened the strut's equivalent thermal expansion coefficient from 0.66 ppm/K to 1.89 ppm/K [6]. However, the Super-Invar ball is not practical because of its low hardness and low resistance to wear.

Figure 4(b) shows improved spherical joint using a Super-Invar ring with a conical inner surface. The conical surface is in contact with the master ball of

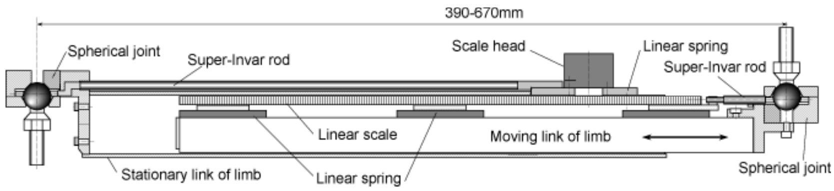

Figure 3: Passive PKM strut with compensation device

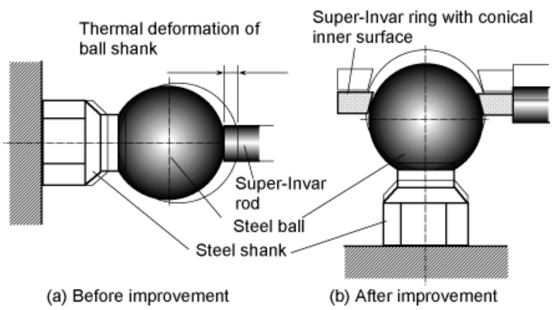

Figure 4: Improved spherical joint

the joint. Moreover, the ring is connected to the linear scale unit through a Super-Invar rod. When the temperature of the ball shank rises, the ring translates in the perpendicular direction of the strut's axis. This means that the thermal deformation of the ball shank has little effect on the measured displacement of the linear scale unit. Moreover, a tungsten carbide ball having a sphericity less than 0.16 µm is brazed with Super-Invar shank. This ball shank is more effective to eliminate the thermal deformation because an expansion coefficient of the tungsten carbide is 4.6 ppm/K, or approximately 40% of steel's one. A brass holder and a lid with conical surfaces contain the ball, and are mounted on each platform as shown in Figure 8. Some compression springs press the ring against the ball.

4.3 Experimental setup for displacement measurement of strut

In the previous paper, the strut was mounted on the test bed so that the strut length was fixed to be 530 mm. Measurement stability of the strut was reported when the strut was subjected to the gravity change and room temperature fluctuation. As a result, the compensation device improved the measurement stability from 2.3 µm to 0.24 µm (10.4%) when the elevation angle of the strut changed from 30˚ to 61˚ to horizontal angle. Moreover, the thermal expansion coefficient of the strut was improved from 20.2 to 1.21 ppm/K(6.0%).

In this paper, when the strut is expanded and contracted by a linear motion stage (Nippon Thompson IKO CTLH220H-3030A, Stroke: 300 mm), the linear scale unit built in the strut measures change in the length of the strut as shown in Figure 5. A laser-interferometer length measurement system (Renishaw ML-10) is also employed to measure the displacement of the moving stage. Basically, the difference between readings of these two displacement measurement systems represents the measurement error of the passive strut. Before preliminary measurement experiment, parallelism between the laser beam and the strut was adjusted within 0.1 mm by using a QPD (Quadrant Photodiode Detector) because 0.5-mm parallelism potentially causes the cosine error of 0.46 µm in the displacement measurement.

Moreover, it is expected that pitch error of the stage cause the Abbe error because there are an offset in z direction of approximately 57 mm between axes of the laser beam and the strut. On the other hand, in this arrangement, yaw error of the stage has a little effect on measured displacement because of no offset in y

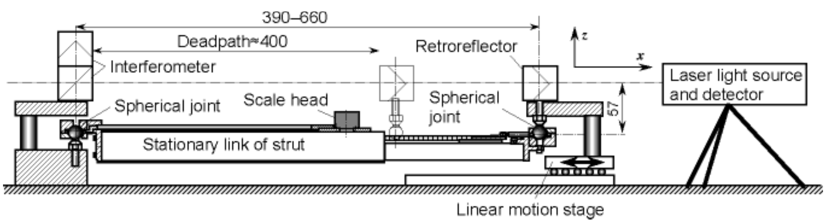

Figure 5: Experimental setup for measuring displacement of linear stage

direction. Figure 6 shows the pitch errors of the stage, measured five times by the laser interferometer measurement system (Renishaw ML-10) when the stage traveled in the positive direction. Similar result of the pitch errors was obtained in the negative direction. Although each pitch error was less than ±10 μrad, this error has possibility to provide the Abbe error of ±0.57 μm in the positioning direction or *x* direction. However, the Abbe error can be decreased to less than ±0.1 μm by compensation with averaged pitch error because non-repetitive pitch error is less than ±1.6 μrad and 0.50 μrad_σ (standard deviation) as shown in Figure 7.

5 Experimental results

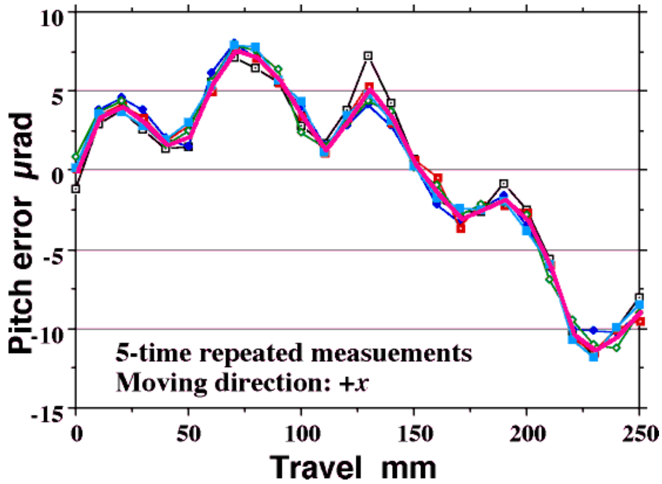

Figure 6: Pitch error of linear motion stage

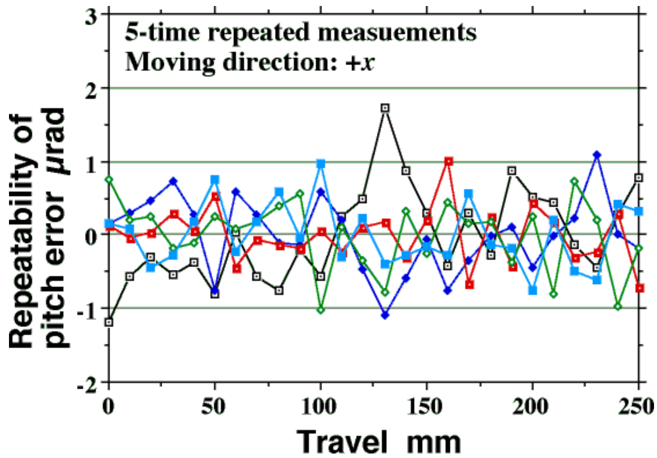

Figure 7: Nonrepetitive pitch error of linear motion stage

5.1 Constant-temperature test

First, the displacement measurement described in Figure 3 was carried out in a thermostatic room. Figure 8 shows stage positioning errors measured by two displacement measurement systems when the strut expands in +x direction. After compensating the laser interferometer's displacement with the averaged pitch error of the linear motion stage, the difference between two displacements ranged from –0.5 µm to 0.3 µm. These displacement measurements were repeated two times in each direction of the linear motion stage. In Figure 9, a similar tendency of the measurement error was seen both in forward and backward directions. Considering the nominal accuracy of the linear scale unit,

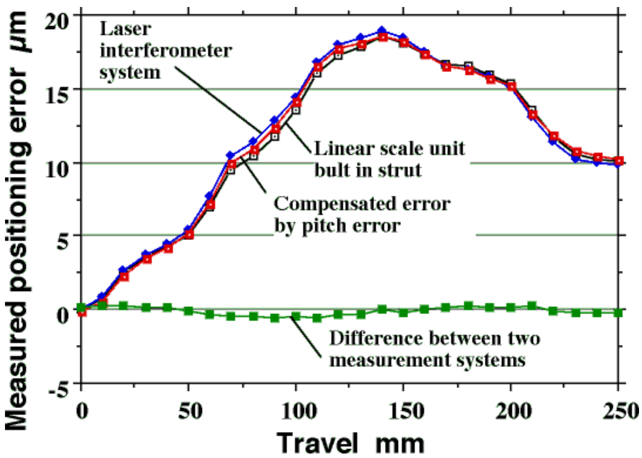

Figure 8: Positioning errors measured by two measurement systems

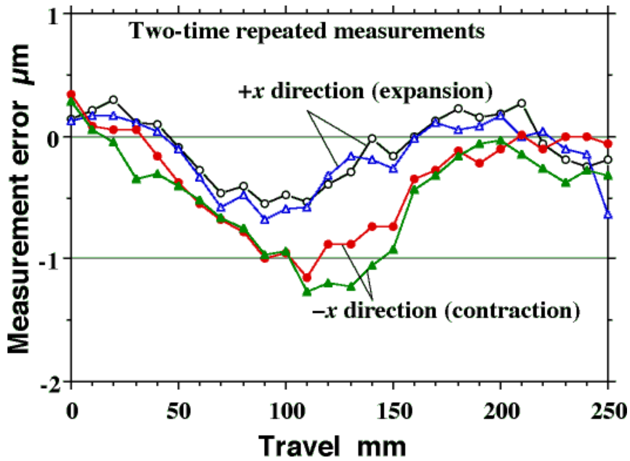

Figure 9: Measurement error in forward and backward directions

i.e. ±0.5 µm, the measurement error in Figure 9 seems reasonable figure. Although the difference between two directions approaches to approximately 1 µm, the measurement repeatability of each direction is less than 0.6 $\mu m_{p\text{-}p}$ and 0.15 μm_{σ} (standard deviation). It is possible to decrease this error by compensating with averaged error because a systematical error dominates this error.

5.2 Fluctuated-temperature test

Next, to investigate an influence of temperature fluctuation on the measurement uncertainty, the setting of room temperature was changed from 20˚C to 25˚C just before the stage travels in forward direction. Figure 10 shows temperature changes of the room and the strut. The length measurement accuracy of the strut is strongly influenced by the heat unless the strut has compensation device described in section 3. For instance, provided the average temperature rise of the strut is 3.695$K_{p\text{-}p}$, calculated thermal expansion of the aluminum-made strut 660 mm long reaches 56 µm.

Figure 11 shows positioning errors measured by two displacement measurement systems, i.e. the scale unit built in the strut, and the laser interferometer system. This indicates that the compensation device implemented in the strut suppressed the difference between the readings of two systems from 56 µm to 5.99 $\mu m_{p\text{-}p}$, 10.7% of the expected thermal deformation of the strut. This measurement error of the strut is considerably small considering that the temperature of the strut rose 3.695K. This indicates that the expansion coefficient of the strut has improved from 23 ppm/K to 2.454 ppm/K. Consequently, it is necessary to control the strut temperature within ±0.31K for suppressing its thermal deformation to a value less than ±0.5 $\mu m_{p\text{-}p}$.

6 Discussions

In the section 5.2, the measurement error of the passive strut reached approximately 6 µm when the averaged temperature rose 7.55K. Moreover, the equivalent expansion coefficient of the strut, 2.454 ppm/K, became worse than twice of that in the previous paper, i.e. 1.21 ppm/K. However, it is expected that this measurement error contains the deadpath error caused by a change in the environment during the measurement. In the experimental setup illustrated in Figure 5, the deadpath reached approximately 400 mm. According to the Edlen's equation on the refractive index of air, a change in room temperature from 20˚C to 28˚C changes the refractive index by approximately -8 ppm even if the humidity and air pressure are constant. Thus, this has the potential to increase the error by approximately 3 µm. Considering that the change in difference of the measured displacements in Figure11 resembles the change in room temperature in Figure 10, the deadpath error could be a big part of the measurement error.

7 Conclusion

We described an ultra-precision machine system based on 6-degree-of-freedom motion feedback control between the tool and workpiece. A passive hexapod-type PKM consisting of six extensible struts with a linear scale unit is used as a feedback sensor system to measure the relative motions and orientations of the tool spindle and the workpiece surface table regardless of any temperature change and external forces because of a compensation device installed in the strut. Performance tests for displacement measurement of the strut were carried out by comparing with a laser interferometer length measurement system when the strut was expanded and contracted by a linear motion stage. From the results

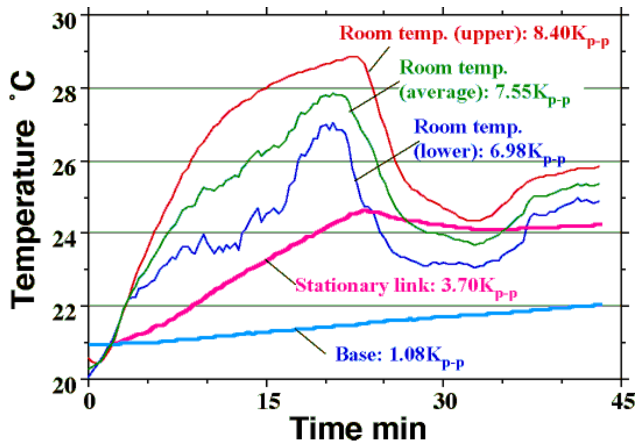

Figure 10: Temperature fluctuation during measurement

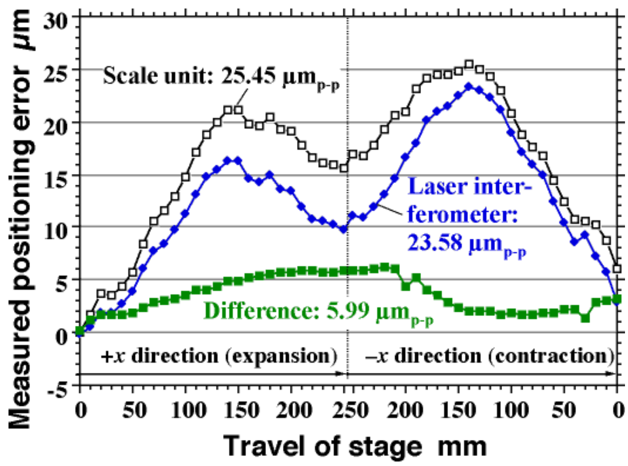

Figure 11: Positioning error measured during temperature disturbance

of repeated experiments, it was found that when the length of the strut changed by 270 mm the displacement measurement accuracy was approximately 1 $\mu m_{p\text{-}p}$ in the thermostatic room.

8 Acknowledgments

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