An Ultraprecise Machining System with a Hexapod Device to Measure Six-Degree-Of-Freedom Relative Motions Between The Tool And Workpiece

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A machining system that generates accurate relative motions between the tool and workpiece is required to realize ultraprecise machining or measurements. Accuracy improvements for each element of the machine are also required. This paper proposes a machining system that uses a compensation device for the six-degree-of-freedom (6-DOF) motion error between the tool and workpiece. The compensation device eliminates elastic and thermal errors of the joints and links due to temperature fluctuations and external forces. A hexapod parallel kinematics mechanism installed between the tool spindle and surface plate is passively actuated by a conventional machine. Then the parallel mechanism measures the 6-DOF motions. We describe the conception and fundamentals of the system and test a passively extensible strut with a compensation device for the joint errors.

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1. Introduction

In recent years, demand has accelerated for highly accurate mechanisms with a positioning resolution on the order of nanometers and a positioning accuracy of less than 100 nm. This demand has been fueled by the high-precision machining required by high-technology manufacturers such as the semiconductor industry. To realize such an ultraprecise machine, a mechanism that generates highly accurate relative motions between the tool and workpiece is required, along with accuracy improvements for each element of the machine. In an actual machine, however, internal and external disturbances, as shown in Fig. 1, cause noticeable positioning errors. Thus, the structural and thermal stability of the entire machine is required in addition to the motion accuracy of each machine element. Although considerable improvements to the guide element accuracy and structural stiffness have been achieved to decrease the motion error and elastic deformation caused by external and internal forces,[1, 2] the increased mass caused by such improvements has dynamically introduced further motion errors and elastic deformations due to the increased inertial and frictional forces. In addition, a machine structure cannot be made infinitely stiff.

Prediction methods have been investigated by many researchers as a means of compensating for the thermal deformation of machine structures using a limited number of temperature sensors and a thermal deformation analysis.[3,4] However, thermal deformations are hard to predict precisely because sensors cannot measure the temperature of all the machine elements. Moreover, such predictions for a machine that includes a beam structure, such as an orthogonal slide mechanism, present great difficulties due to the complexity of the deformation in response to rapid fluctuations of the room temperature.

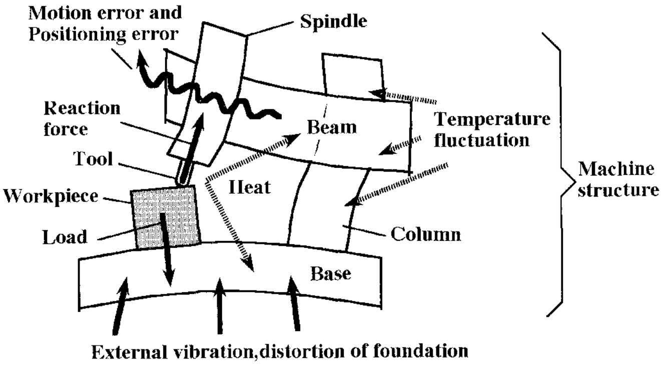


Fig. 1 Various causes of relative positioning errors between the tool and workpiece in conventional machine

We present a machine system equipped with a feedback sensor system to measure six-degree-of-freedom (6-DOF) motion errors between the tool and the workpiece. The 6-DOF relative motions are measured with a hexapod parallel kinematics mechanism (PKM) that consists of a base platform fixed on the machine surface plate, a

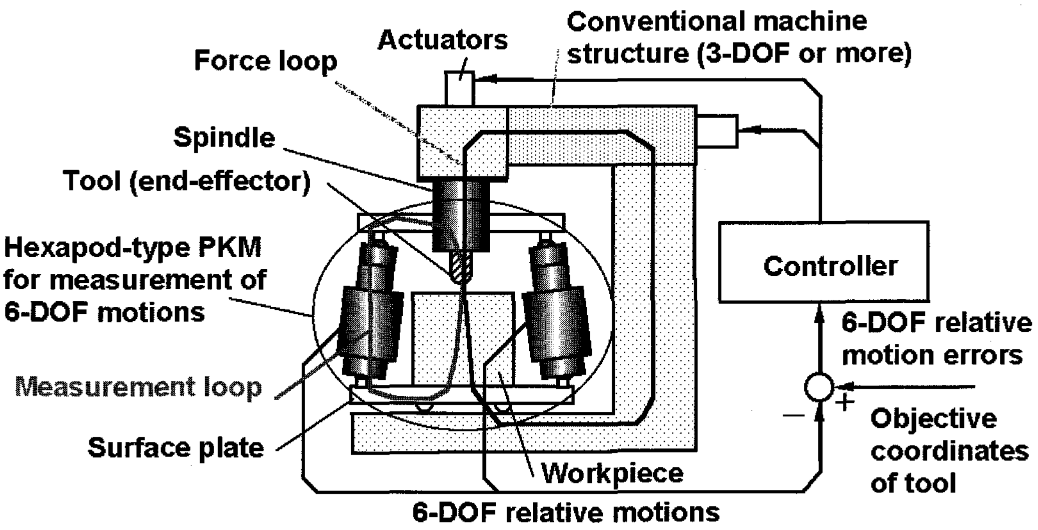


Fig. 2 Fundamentals of the proposed machining system using a hexapod measurement device for 6-DOF motions between the tool and workpiece

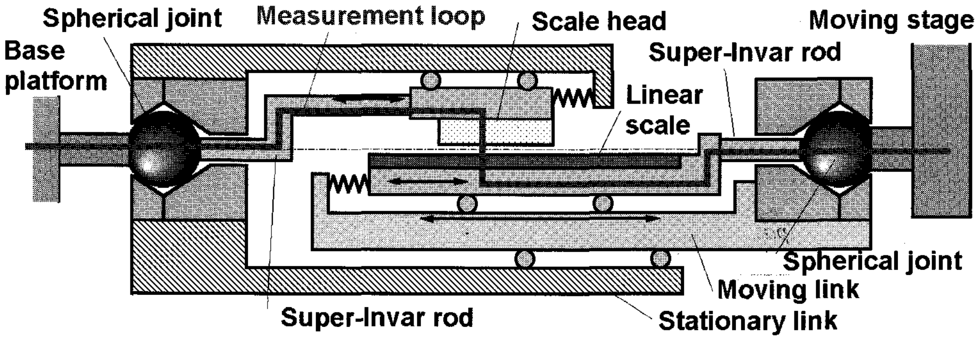


Fig. 3 Extensible strut with compensation device for errors arising from both the joint and the elastic and thermal deformations of the link

moving platform fixed on the machine spindle, and six passive extensible struts with linear scale units. We discribe the conception and fundamentals of the system and demonstrate a compensation method for the thermal deformation of spherical joints.

2. Fundamentals

2.1 Compensation system

Figure 2 shows a schematic illustration of the proposed machining system. It consists of a hexapod PKM, a conventional machining tool or a measuring machine, and a controller. To measure the relative 6-DOF motions between the tool spindle and the surface plate on which the workpiece is attached, 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 does not have an actuator, the moving platform of the PKM is passively moved in three-dimensional space by the conventional machine. Because changes in the length of each strut are measured by a displacement measurement unit installed in the prismatic joint, the 6-DOF relative motions can be calculated by the forward kinematics of the hexapod PKM. When moving, 6-DOF motion errors are calculated by comparing the measured motions with the objective tool motions. Consequently, the controller compensates for motion errors and accurately actuates the machine. The coordinates of the probe tip in the coordinate measuring machine are directly measured by the PKM.

2.2 Extensible strut of the PKM

Figure 3 shows the extensible strut of the PKM. Each strut has a mechanical compensation device for both joint errors and link deformations.[5,6] Recent studies have reported that the translational error of a joint in the direction of the strut strongly affects the motion error of the moving platform PKM.[7,8] In other words, the distance between the spherical joints located on both ends of the strut, *i.e.*, the length of the strut, is very important for accurately positioning and measuring the moving platform. Errors in the other directions, which are perpendicular to the strut axis, have little effect on the length of the strut because these become the cosine error. Two rods connect the scale and scale head of the linear scale unit to the two spherical joints, as shown in the figure. The scale head and the scale are guided by 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. Since the rods are made of Super-Invar (thermal expansivity: approximately 0.5 ppm/K), the distance between the scale unit and a spherical joint is not influenced by temperature changes. The distances are not influenced by any external forces, compressive or tensile, because external forces are not applied to the rods and the scale unit. Thus, even if the strut is thermally or elastically deformed, the scale unit can accurately measure the change in the length of the strut. To accurately measure the 6-DOF relative motions between the tool and workpiece, all of the parts in the measurement loop shown in the figure, including both platforms, must be made of low thermal expansion materials. Previous studies have shown that the scale unit in this prismatic joint

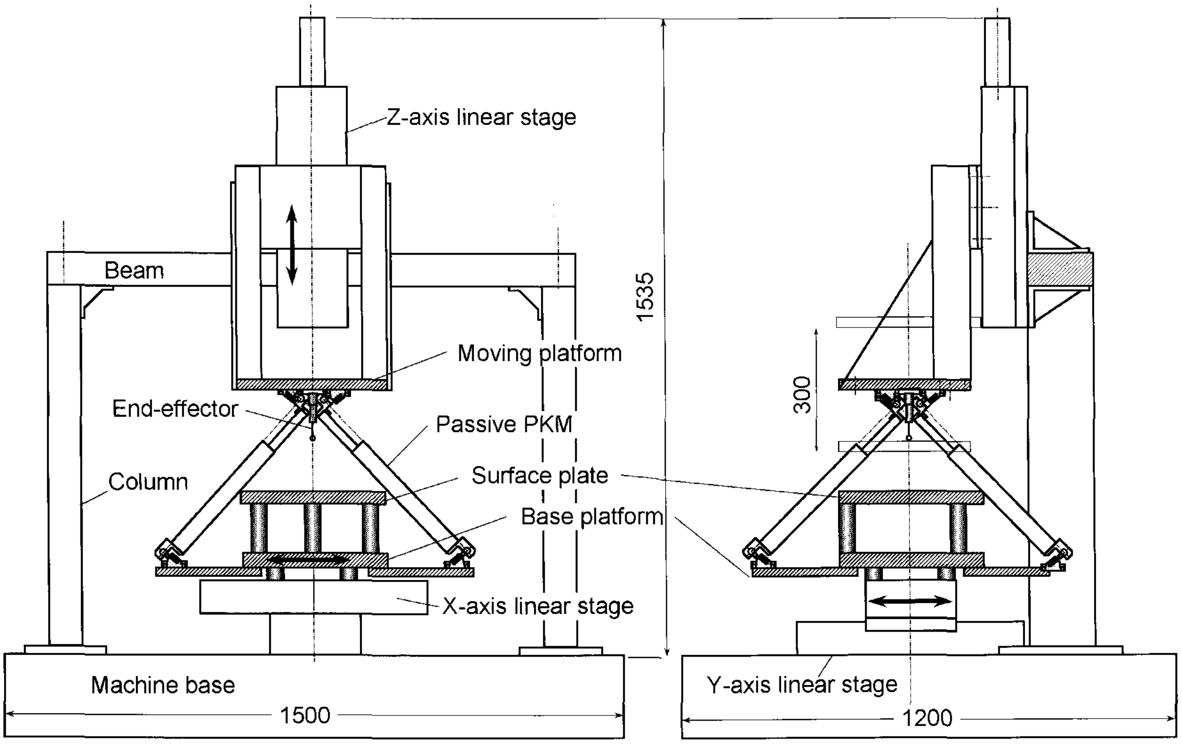


Fig. 4 Experimental ultraprecise machine consisting of a conventional orthogonal mechanism and a hexapod passive PKM for measuring 6-DOF motion errors between the tool spindle and surface plate

accurately measures changes in distance between both spherical joints, regardless of any temperature change.[5,6] This compensation system has remarkably improved the equivalent thermal expansion coefficient of the strut from 15.4 to 0.66 ppm/K when the master ball and ball shank in the spherical joint are made of Super-Invar, which closely approximates a system in which all parts of the strut are made of Super-Invar. However, a Super-Invar ball shank is not practical because of its low hardness and low resistance to wear relative to a steel ball shank. Therefore, an improved spherical joint will be described in Section 3.3.

2.3 Advantages of the compensation system

The proposed machining system has several advantages over conventional methods used to improve machining accuracy.

(1) The measurement system is separated from the machine structure so that the 6-DOF motions are measured regardless of any external or internal forces.[9]

(2) The measurement device measures the 6-DOF motions so that the arrangement of the displacement sensor systems is not restricted by the Abbe alignment principle.

(3) The system can compensate non-repetitive motion errors caused by elastic and thermal deformations in addition to systematic motion errors caused by kinematics parameter errors or geometrical deviations of the machine elements.

(4) Neither predictions nor analyses for thermal deformations are required.

(5) A precise thermostatic environment is not needed, although if the system is operated in a thermostatic chamber, a more highly accurate machine will be achieved.

3. Experimental apparatus

3.1 Machine

Figure 4 depicts the experimental ultraprecise machine. It consists of a conventional Cartesian-coordinate-geometry mechanism and a hexapod passive PKM. The former mechanism employs three commercial ballscrew-driven linear positioning stages equipped with AC servomotors and rotary encoders. An X-Y system of stages is mounted on the machine base. The PKM' base platform and the surface plate, which are made of low expansion cast iron, are mounted on an X-axis stage, and a Z stage is mounted on a beam supported by two columns. This bridge-type frame is made of aluminum and mounted on the machine base. The PKM moving platform is suspended from the Z-axis stage. Six passive extensible struts are installed between the base and moving platforms. The PKM is moved passively in three-dimensional space by the XYZ mechanism. The relative position and orientation between the end-effector and surface plate are then calculated by the forward kinematics of the hexapod PKM.

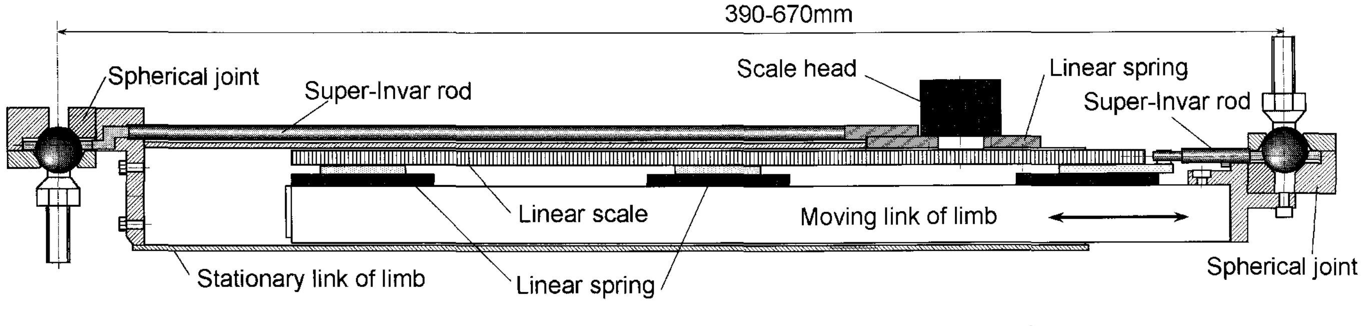


Fig. 5 Passive PKM strut with a compensation device using Super-Invar rods

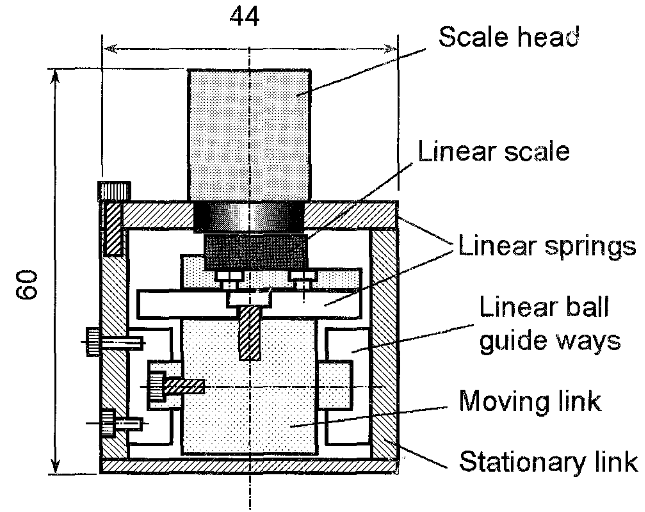
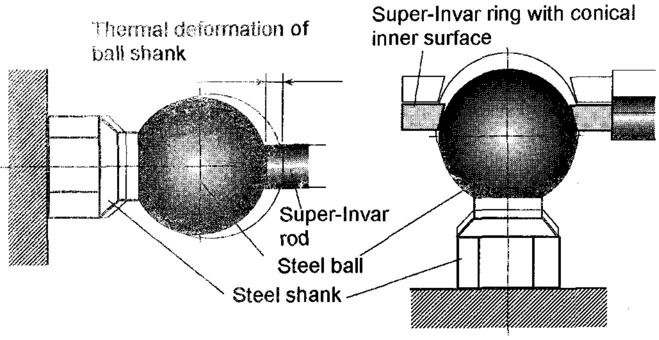


Fig. 6 Cross-sectional view of extensible strut with compensation system

3.2 Extensible strut

Figure 5 shows a sectional view of the extensible strut with the compensation device described in Section 2. The spherical joints are fixed at each end of the stationary and moving links. Super-Invar rods connect a scale unit (Heidenhain LIP481R with a measuring length of 270 mm and a resolution of 2 nm) to the spherical joints. The scale unit head and linear scale mounted on Super-Invar plates are guided using simple notch linear springs so that they can only move in the longitudinal direction. Figure 6 shows a cross-sectional view of the strut. Two sets of 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, the angular motion errors of the linear bearings have little effect on the accuracy of the displacement change measurements of the prismatic joint.

3.3 Improved spherical joint



(a) Before improvement (b) After improvement

Fig. 7 Spherical joints before/after improvement

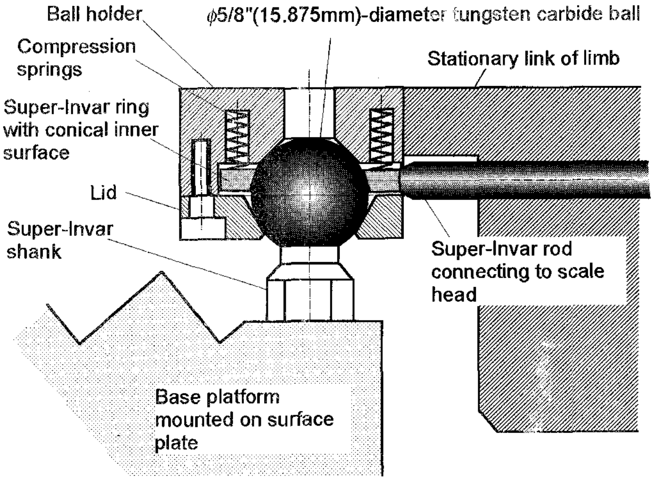


Fig. 8 Improved spherical joint consisting of tungsten carbide ball and Super-Invar ring

All parts in the measurement loop shown in Fig. 3, including the ball shanks of the spherical joints, must be made of low thermal expansion materials. Thermal deformation of the ball shank will introduce measurement errors, as shown in Fig. 7(a), since the scale unit cannot accurately measure the change in distance between the spherical joints. When the ball shank material was changed from Super-Invar to steel in a previous study, the equivalent thermal expansion coefficient of the strut worsened from 0.66 to 1.89 ppm/K.[6] However, a Super-Invar ball shank is not practical because of its low hardness and low resistance to wear.

Figure 7(b) shows an improved spherical joint using a Super-Invar ring with a conical inner surface. The conical surface is in contact with the master ball of the joint, and 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 direction perpendicular to the axis of the strut. This means that the thermal defo

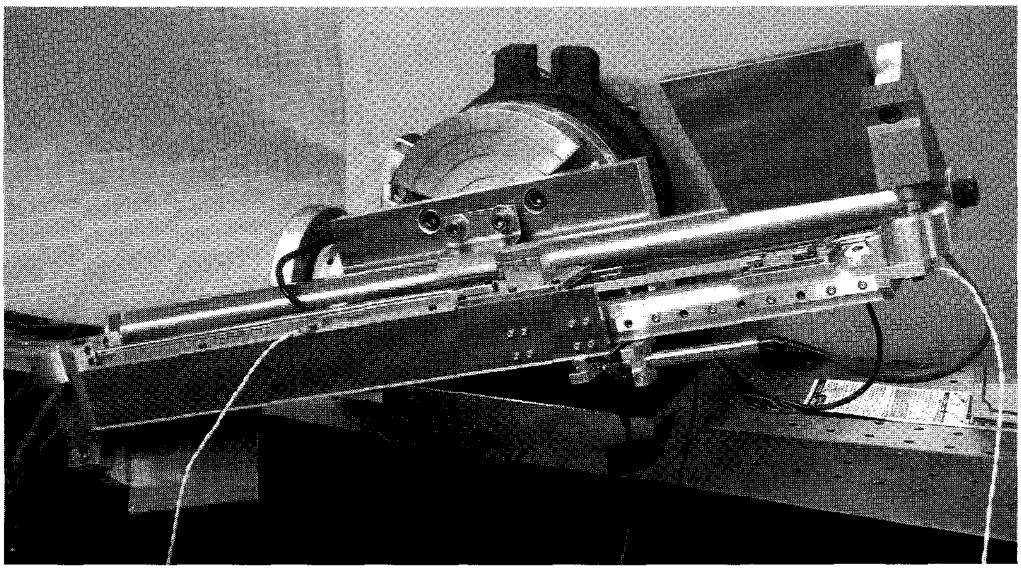


Fig. 9 Strut with compensation device and electrical comparator, mounted on the test bed equipped with index table

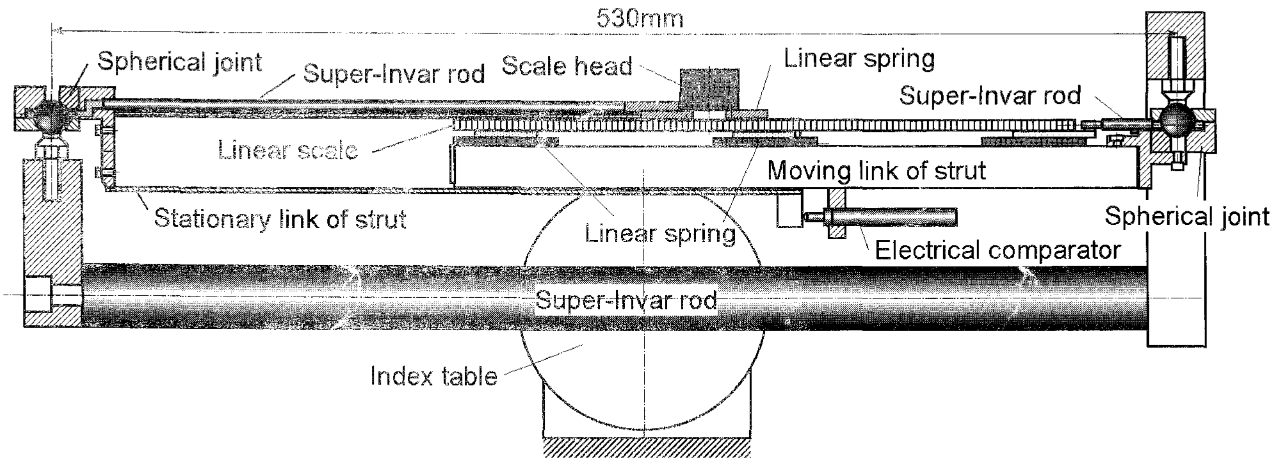


Fig. 10 Experimental setup for testing the strut with improved spherical joints

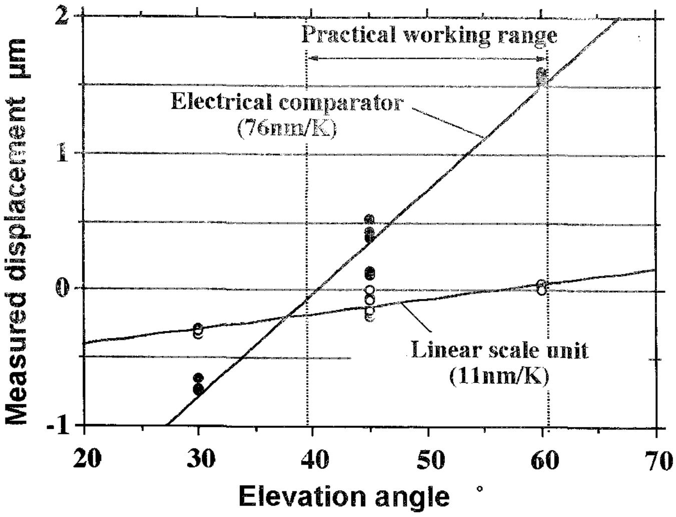


Fig. 11 Influence of elevation angle of strut on displacements measured by two measurement systems

-rmation of the ball shank has little effect on the measured displacement of the linear scale unit. In addition, a tungsten carbide ball with a sphericity less than 0.16 µm is brazed with the Super-Invar shank. This ball shank is more effective at eliminating the thermal deformation because the expansion coefficient of the tungsten carbide is 4.6 ppm/K, or approximately 40% that of steel. A brass holder and a lid with conical surfaces contain the ball, and are mounted on each platform as shown in Fig. 8. Compression springs press the ring against the ball.

4. Experiments

Figure 9 shows the passively extensible strut and its test bed, and Fig. 10 presents a schematic diagram of the experimental setup. Most parts of the strut test bed were made of low thermal expansion cast iron (expansivity: 0.8 ppm/K) and Super-Invar to eliminate the influence of their thermal expansion. The strut was mounted on the bed with the spherical joints. The distance between both spherical joints was fixed at approximately 530 mm. An electrical comparator (Mahr 1201IC+P2004M) measured the relative displacement between the stationary and moving links of the strut. This measured displacement represented the thermal deformations of both links when the temperature fluctuated. However, since the distance between the spherical joints was constant, the displacement measured by the linear scale unit must ideally be zero. A thermometer (Technol Seven D642, with a measurement accuracy ±0.02 K and a resolution 0.01K) was used to measure the room temperature near the strut and the temperatures of the stationary and moving links.

First, an index table tilted the test bed to investigate the effect of gravity on the measured displacement of the scale unit. The elevation angle was changed from 30° and 60° to horizontal. The results are shown in Fig. 11. The elastic deformation of the spherical joints and links generated a relative displacement between the stationary and moving links that reached 2.3 µm when the strut was tilted at a 30° to 60° angle. However, the displacement measured by the linear scale unit was less than 0.33 µm, or 14% of that measured by the comparator, confirming that the linear scale unit with the compensation device accurately measured the change in distance between both ball shanks of the spherical joints regardless of the elastic deformation of the links and joints. If the strut were installed in the machining system shown in Fig. 4, the elevation angle would be between 39° and 61°. Therefore, the measurement error of each strut is estimated to be less than 0.24 µm during operation. This displacement includes the test bed elastic deformation caused by the changing of direction of the load placed on the test bed.

Next, the strut was heated for 7 minutes until its surface temperature rose several degrees to investigate the influence of the temperature fluctuation. Subsequently, the strut was allowed to cool. The strut was lengthened so that it would be strongly influenced by the heat. Figure 12 shows the temperature change of the strut and the displacements measured by both the comparator and the scale unit. When the surface temperatures of the stationary and moving links rose 3.19 K and 1.59 K, respectively, the relative displacement between the stationary and moving links reached 25.48 µm. Provided the average temperature change of the strut is 2.38 K, the calculated

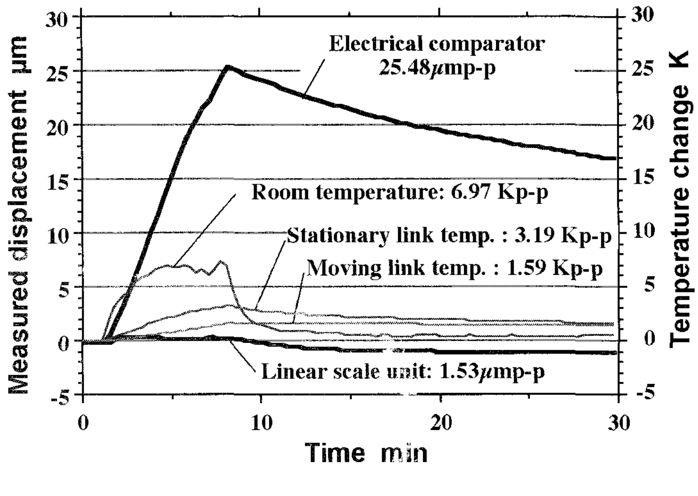


Fig. 12 Displacements measured by two measurement systems and strut temperatures

thermal expansion coefficient of a 530 nm-long strut is 20.2 ppm/K, almost equal to the coefficient of aluminum.

However, the displacement measured by the linear scale unit was less than 1.53 μm, indicating that the scale unit with the compensation device accurately measured the change in distance between both spherical joints, regardless of the temperature change, and that the expansion coefficient of the struts has improved from 20.2 to 1.21 ppm/K (6.0%). Consequently, the change in strut temperature must be controlled to within ±0.16 K to suppress its elongation to a value less than ±0.1 μm. A thermal environment meeting this criterion can be easily created using a standard thermostatic chamber.

5. Conclusion

We described an ultraprecise machining system that compensates 6-DOF relative motion errors between the tool and workpiece. A passive hexapod PKM consisting of six extensible struts with linear scale units was installed between the tool spindle and surface plate of a conventional Cartesian-coordinate-geometry mechanism. The PKM measured the relative positions and orientations of the tool and workpiece regardless of any temperature change and external forces because of the compensation device installed in the strut. Details of this compensation device and the improved spherical joints were also described. The passively extensible strut with a linear scale unit and compensation device accurately measured the change in length of the strut regardless of its change in orientation or temperature.

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