Structural Design of a Newly Developed Ultraprecision machine Tool "ANGEL"

(Reprint from Proceedigns of ISUPEN2011)

Hayato Yoshioka[1] , and Hidenori Shinno[1]

[1] Tokyo Institute of Technology, Yokohama, Japan

Abstract – Demands for fabricating micro- and nano-structured surfaces have rapidly increased in the advanced science and engineering fields. In order to meet such requirements it is necessary to develop an ultraprecision machine tool with both nanometer-level machining accuracy and a large machining area. This paper presents a newly developed ultraprecision machine tool for enabling nano-machining over large work area. In order to remove the principal error factors caused by machine structure, the machine tool developed employed a perfect non-contact structure excluding the machining point. In addition main components of the system were arranged symmetrically to eliminate thermal and dynamic error factors. The performance evaluation results confirm that the developed system provides superior performances for nano-machining.

***Key Words*:** Machine tool, Ultraprecision machining, Design concept, Structural configuration

1. Introduction

Demands for ultraprecision machining process have increased in the advanced science and industrial fields [1-3]. In particular, structured surfaces with micro- and nano-patterns have recently been required for various industrial sectors. In order to meet the requirements, it is necessary and indispensable to realize an ultraprecision machine tool with both nanometer order machining accuracy and a large work area. In our research project, therefore, an ultraprecision machine tool is newly developed for nano-machining over large work area. The developed machine tool is composed of some originally designed structural components such as an X-Y planar positioning table and a Z vertical positioning stage [4-7]. This paper describes the basic concept of ultraprecision machine tool and the structural components. In addition, typical examples of performance evaluation are also described.

2. Design concept of the developed machine tool

Figure 1 shows a basic design concept for a thermally and dynamically stable machine tool structure. In order to realize a stable machine tool structure, thermal and mechanical disturbances from within and without should be considered. Furthermore, it is important to minimize, isolate, and control principal error sources for eliminating influence on performance effectively. In particular, these design concepts are indispensable to ultraprecision machine tools with a large working area.

Figure 2 shows a structural design concept of a newly developed ultraprecision machine tool. It is design to do nano-machining over a large work area, and it is consequently named "Advanced Nano-pattern GEnerator with Large work area (ANGEL)." ANGEL is basically a vertical type machining center, and has an X-Y planar positioning table for workpiece motion and a Z vertical positioning stage for tool motion.

The whole machine structure is symmetrically designed with respect to the vertical center axis (Z axis). Therefore a machining point is located at the structural center of the entire system. Furthermore feedback sensors for all positioning mechanisms are

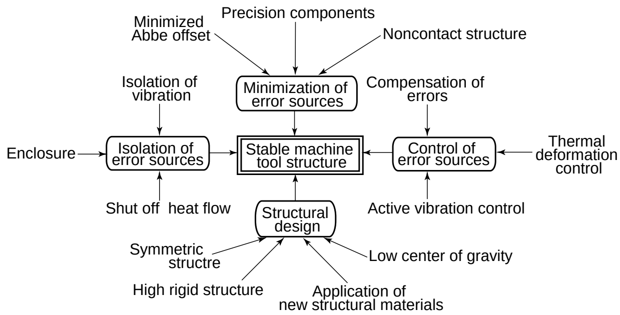


Fig. 1 Design concept for the stable machine tool structure

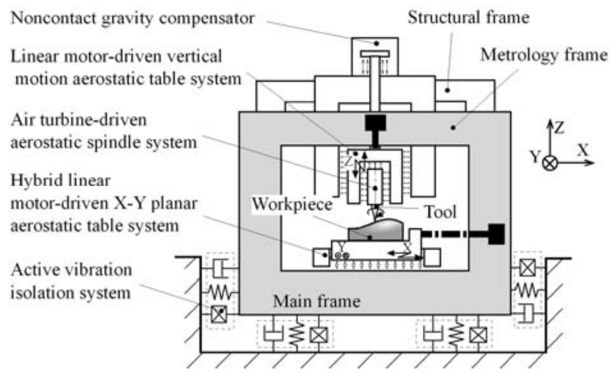


Fig. 2 Structural design of the developed ultraprecision machine tool

arranged so that a cross point of their measuring axes agrees with the machining point to minimize Abbe error including feedback position. Principal structural parts, e.g., a main bed, columns, beams, and moving bodies are made of low thermal expansion material. All the positioning mechanisms with nano-positioning capability are supported and driven in a perfect noncontact condition. The entire system is installed in a temperature-controlled enclosure and is supported by an active vibration isolation system to isolate external thermal and dynamic disturbance. In addition, to isolate internal vibration disturbance the system has two of frames; a structural frame with driving components and a metrology frame with measuring components.

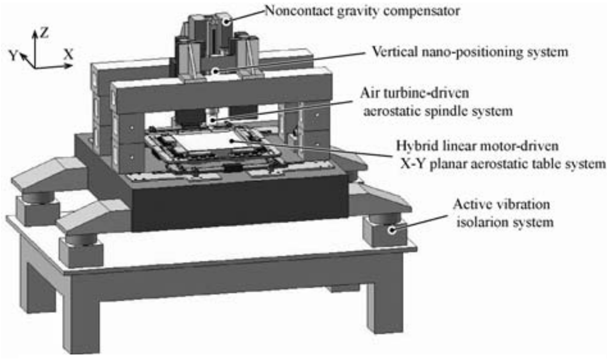


Fig. 3 Structural configuration of ANGEL

Table 1 Specifications of ANGEL

Machine size [mm]	1450(H) x 1640(W) x 1000(D)
Mass of machine [kg]	1350 (approx.)
Stroke [mm]	200(X,Y), 100(Z)
Max. workpiece size [mm]	230 x 230 x 70
Position sensor resolution [nm]	0.6(x), 0.3(Y), 0.6(Z)
Max. feed speed [mm/s]	250(X,Y), 150(Z)
Spindle speed [rpm]	~60000
Control frequency [kHz]	10 (Simultaneous control)

In consequence, various nonlinear phenomena such as friction and stick slip can be removed from machine structure, and error factors in the overall system can be minimized.

As mentioned above, ANGEL can be summarized by the following attributes:

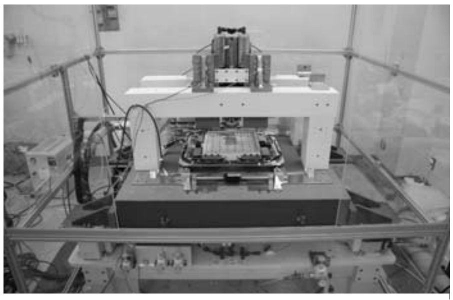
(1) Symmetrically designed structure,
(2) Abbe error offset-minimized structure,
(3) Motion error-minimized structure,
(4) Thermal deformation-minimized structure,
(5) X-Y planar positioning table with large work area,
(6) Z vertical positioning stage with gravity compensation,
(7) Air turbine-driven aerostatic spindle system.

3. Structural configuration of the developed machine tool

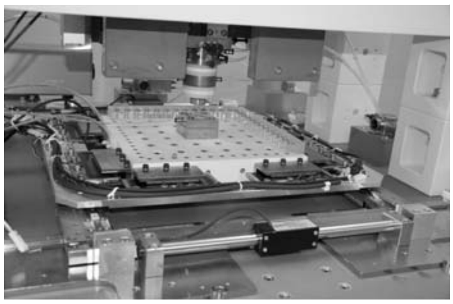
3.1 Machine structure

The structural configuration of the developed machine tool ANGEL is shown in Fig. 3. The main body of ANGEL consists of a large flat bed, two of columns, and two of top beams. An X-Y planar positioning table and a Z vertical positioning stage are also installed in the main structure. The fundamental structural modules such as the main bed, columns, top beams, and positioning systems are made of alumina ceramics (Al_2O_3) because of its low thermal expansion coefficient, high Young's modulus, and low density.

Figure 4 shows appearance of the developed machine tool ANGEL. The overall system is mounted on a pneumatic type active vibration isolation system and is installed into the temperature-controlled enclosure within 23±0.2 degrees Celsius. Table 1 shows the basic specifications of the ANGEL. The mass of the whole system is relatively light because most of components are made of ceramics.



(a) Overall



(b) Machining point

Fig. 4 Exterior appearance of ANGEL

3.2 X-Y planar positioning table

The X-Y planar positioning table of ANGEL is driven by hybrid linear motors to realize both nano-positioning and long range motion. Fig. 5 shows the structural configuration of the developed X-Y table. The moving table is driven by eight voice coil motors (VCM) arranged around the table in both the X and Y directions. Although VCM can generate quick and accurate driving force, its effective stroke is limited by size of permanent magnets. In order to realize a large working area, shaft type linear motors which have long stroke over several hundred millimeters are installed into the driving system with two stacking rectangular frames. In this mechanism the shaft type linear motors drive a coil of VCM independently of a main feedback loop so as to keep a relative distance within a stroke of VCM. In consequence, the nano-motion control system of the moving table drives the VCM without considering the stroke of the VCM.

The square moving table is levitated by five porous aerostatic bearings which are preloaded by vacuum attraction force. Eight VCMs are symmetrically arranged around the square moving table so as to drive the center of gravity of the moving table in both the X and Y directions. The moving table on the flat base is supported and driven in a non-contact condition. The rectangular frame structure with the VCM coils and the relative displacement sensor are driven by the shaft type linear motors.

The table position in both the X and Y directions can be measured using a laser interferometer fixed on the flat bed. The intersection point of the laser beams for the X and Y measurement is allocated at the machining point to minimize the Abbe's error.

3.3 Z vertical positioning stage

In order to achieve vertical nano-motion control, it is one of the most important issues to support gravity load of the moving part. Counter mass and counter balance mechanisms with pneumatic

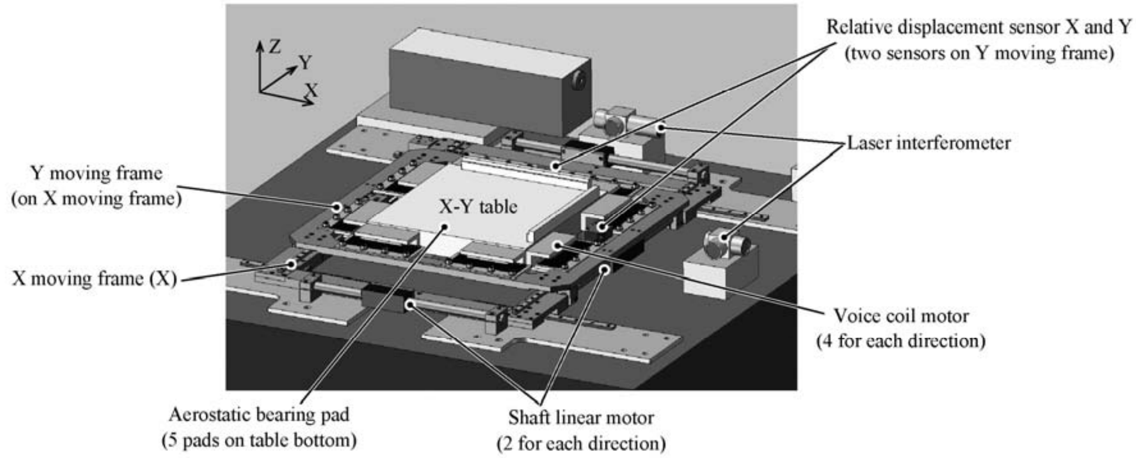


Fig. 5 Structural configuration of the X-Y planar positioning table

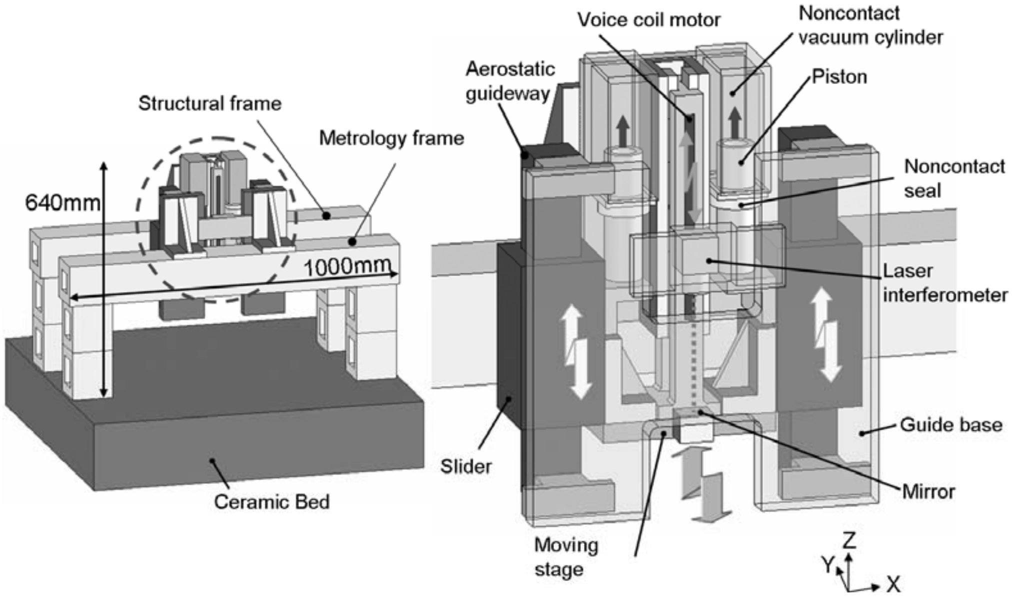


Fig. 6 Structural configuration of the Z vertical positioning stage

cylinder are generally used for gravity compensation in conventional machine tool structure, while use of those mechanisms deteriorates the performance due to vibration, low response or pressure fluctuation. By contrast, pressure fluctuation in vacuum cylinder during piston movement is significantly lower than that in pneumatic cylinder because the absolute pressure in vacuum cylinder is negligibly small.

Figure 6 shows the structural configuration of the developed Z vertical positioning stage. The moving body with tools is guided by aerostatic guideways which are vertically allocated in parallel and driven at the center of gravity of the moving body by a VCM. A pair of pistons of the developed gravity compensators is fixed on the moving stage, and there is small gap between the pistons and vacuum cylinders to remove friction at seal.

In addition, in order to isolate the excited vibration of the top beam caused by the reaction force of the VCM, the guideways and the laser interferometer of the Z positioning stage were separately installed on the structural frame and the metrology frame respectively, as shown in Fig.6.

4. Performance evaluation

In order to evaluate the performance of ANGEL, some positioning experiments were performed under a free load condition. Figure 7 shows a 1nm stepwise positioning of the X-Y planar positioning table and the Z vertical positioning stage. The X-Y table and the Z stage are supported and driven in a non-contact condition to eliminate nonlinear phenomena such as friction, stick slip, backlash, etc. In consequence, clear stepwise nano-motions in both directions can be observed in all driving axes.

Figure 8 shows a result of circular motion test in the X-Y plane with a diameter of 100mm and a feed speed of 62.8mm/s. There was no quadrant glitch in the obtained circular motion and the maximum radial error during the driving was less than 4.5nm. From this result a smooth nano-motion can be realized over large working area by using the hybrid linear motor.

To evaluate basic machining capability of ANGEL, some cutting experiments were performed. A single crystal diamond tool was fixed on the Z vertical stage, while a workpiece of oxygen free copper was fixed on the X-Y planar positioning table.

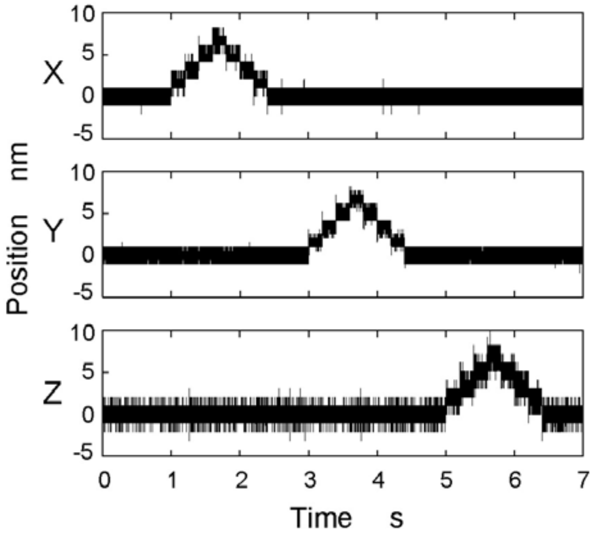


Fig.7 1nm stepwise response of ANGEL

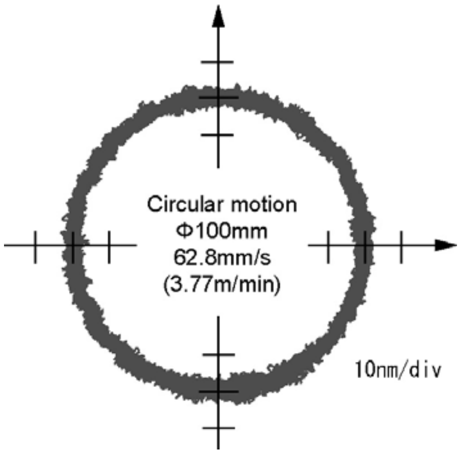


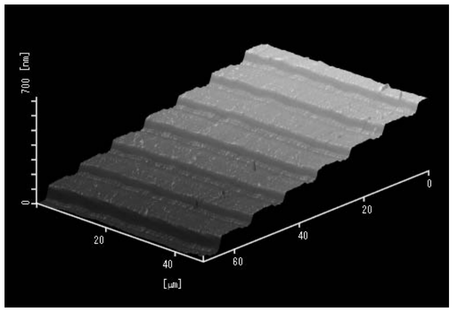
Fig.8 Circular motion test of X-Y planar positioning table

Feed and pick-feed motions were provided by the X-Y planar positioning table, while the depth of cut was given by the Z positioning stage. Figure 9 shows typical examples of machined surface observed with a scanning probe microscope. As shown in this figure, clear stepped-shape with height of 50nm and 20nm can be observed. These results confirmed that the developed positioning systems of ANGEL can realize nano-motion under machining condition and ANGEL has high stiffness and high stability for achieving nano machining capability.

5. Conclusions

This paper presents a newly developed ultra-precision machine tool "ANGEL" for achieving nano-machining over a large work area. Typical examples of performance evaluation results are discussed. As a result, the following conclusions can be drawn:

(1) The design concept proposed for ultra-precision machine tool provides dynamically and thermally stable machine tool structure.
(2) The ultra-precision machine tool based on the proposed structural configuration can achieve nano-machining over a large work area.
(3) The performance evaluation results confirmed that the developed ultra-precision machine tool has nano-machining capability.


(a) 50nm step height

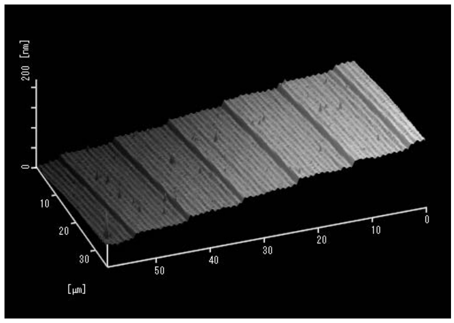

(b) 20nm step height

Fig.9 SPM images of stepped surface

Acknowledgements

This research project was financially supported by the Japan Society for Promotion Science (JSPS) Grants-in-Aid for Scientific Research (A) No.19206017, the Machine Tool Foundation, and the Electro-Mechanic Technology Advancing Foundation.

References

[1] Moriwaki,T., Multi-functional Machine Tool, CIRP Annals, Vol57, No.2, 2008, pp.736-749.
[2] Takeuchi,Y., Sakaida,Y., Sawada,K., Sata,T., Development of 5-Axis Control Ultraprecision Milling Machine for Micromachining Based on Non-Friction Servomechanism, CIRP Annals, Vol.49, No.1, 2000, pp.295-298.
[3] Sriyotha,P., Nakamoto,K., Sugai,M., Yamazaki,K., Development of 5-Axis Linear Motor Driven Super-Precision Machine, CIRP Annals, Vol.55, No.1, 2006, pp.381-384.
[4] Shinno,H., Hashizume,H., High Speed Nanometer Positioning Using a Hybrid Linear Motror, CIRP Annals, Vol.50, No.1, 2001, pp.243-246.
[5] Shinno,H., Hashizume,H., Yoshioka,H., Komatsu,K., Shinshi,T., Sato,K., X-Y-θ Nano-Positioning Table System for a Mother Machine, CIRP Annals, Vol.53, No.1, 2004, pp.337-340.
[6] Shinno,H., Yoshioka,H., Taniguchi,K., A Newly Developed Linear Motor-Driven Aerostatic X-Y Planar Motion Table System for Nano-Machining, CIRP Annals, Vol.56, No.1, 2007, pp.369-372.
[7] Takahashi,M., Yoshioka,H., Shinno,H., A Newly Developed Long-Stroke Vertical Nano-Motion Platform with Gravity Compensator, Journal of Advanced Mechanical Design, Systems, and Manufacturing, Vol.2, No.3, 2008, pp.356-365.