A Newly Developed Long-Stroke Vertical Nano-Motion Platform with Gravity Compensator*

Motohiro TAKAHASHI**, Hayato YOSHIOKA** and Hidenori SHINNO**

**Precision and Intelligence Laboratory, Tokyo Institute of Technology, 4259 Nagatsuta, Midori-ku, Yokohama, 226-8503, Japan
E-mail: takahashi.m.ah@m.titech.ac.jp

Abstract
Demands for three-dimensional nano-positioning are increasing in a wide range of industries. In order to meet such demands, it is necessary to realize a stable long-stroke vertical nano-motion. In long-stroke vertical motion control, the minimization of gravity load is one of the most important issues. In addition, it is important to minimize error factor from nonlinear phenomenon such as friction, vibration and heat transfer. In general, however, it is difficult to support gravity load of the moving part and to ensure that the vertical motion platform is free from such error factors which may occur during its nano-positioning. In this study, therefore, a novel vertical motion platform with a noncontact counterbalancing mechanism is developed for achieving long-stroke vertical nano-motion. The developed platform is characterized by a noncontact drive with a voice coil motor, by levitation with aerostatic guideways, by a counterbalance with noncontact vacuum cylinders, by an overall structure made of ceramics and by a symmetrical structural configuration. The positioning performance of the developed platform is evaluated through a series of vertical positioning experiments. The experimental results demonstrate that the developed platform has a superior positioning performance.

Key words: Nano Positioning, Vertical Motion, Noncontact Counterbalancing, Stage, Noncontact Drive, Vacuum Cylinder

1. Introduction
Demands for nano-positioning have been recently increasing in a wide range of industries. In particular, three-dimensional nano-positioning technology has been required for measuring complicated micro-structures such as aspheric micro lens and optical reflection devices. In order to meet such requirements, it is necessary and indispensable to develop an effective vertical nano-positioning system as well as a horizontal planar motion table system (1-2). In such a vertical motion system, one of the most important issues is to minimize gravity loads. In order to balance the gravity load in the vertical direction, counterweights and counterbalances (3-5) have been widely used so far. Those typical gravity compensation mechanisms have, however, a lot of error factors in nano-positioning. In this study, therefore, a novel long-stroke vertical nano-motion platform was developed for achieving nano-positioning. The platform developed was integrated with a gravity compensator. The overall platform was installed on both the structural and the metrology frames (6-8), which are parallel allocated to each other. The performance evaluation of the developed vertical nano-motion platform was performed and then the
experimental results confirmed that the platform has remarkable performance.

2. A Developed vertical nano-motion platform

2.1 Basic concept of a proposed platform

Figure 1 shows a basic design concept of the proposed vertical nano-motion platform equipped with gravity compensator. The proposed platform consists of a moving stage, a voice coil motor, a pair of aerostatic guideways, and a pair of vacuum cylinders.

The overall platform structure was symmetrically designed with respect to the vertical driving axis. A voice coil motor was mounted at the center of the parallel-allocated guideways to drive the moving stage at the center of gravity, so that the angular error could be minimized. In addition, thermal deformation could be significantly reduced to minimize the horizontal positioning error. The position of the moving stage could be measured using a laser interferometer with the reference mirror mounted on the center of the stage in order to reduce the Abbe error in the vertical direction. The moving stage can move along a pair of aerostatic guideways and is supported by a pair of noncontact vacuum cylinders in a perfect noncontact condition.

2.2 Design concept of gravity compensator

Counterweights with pulleys and counterbalances with pneumatic cylinders have been widely used to minimize gravity loads. Such typical counterweights and counterbalances include, however, a lot of error factors, i.e., friction and force fluctuations.

In this study, a noncontact vacuum cylinder was used as gravity compensator, as shown in Fig. 2. The moving mass was supported by the vacuum attraction force. A piston connected with the moving stage freely moves upward and downward in the vertical direction. Pressure fluctuation in vacuum cylinder was quite smaller than that in pneumatic cylinder used in conventional counterbalances because absolute pressure in
cylinder is almost zero. In addition, a noncontact seal inhibited both vibration and heat transfer transmitted to the moving stage.

Equation (1) shows pressure change of air in the noncontact vacuum cylinder. The leakage of the noncontact seal can be expressed as Eq.(2). On the other hand, the exhaust air by the vacuum pump can be expressed as Eq.(3). Design of gravity compensator was optimized with the pressure change simulation results based on the above equations in order to minimize force fluctuation of the vacuum cylinder.

\[
\frac{dP_c}{dt} = \frac{P_c}{V_c} \frac{dV_c}{dt} + \frac{Q_s - Q_p}{V_c} 
\]

\[
Q_s = \frac{\pi D a^3}{12 \mu L} (P_a^2 - P_c^2) 
\]

\[
Q_p = \frac{\pi d^4}{256 \mu d} (P_c^2 - P_p^2) 
\]

where,
- \(a\) : Gap of noncontact seal [m]
- \(L\) : Seal length [m]
- \(D\) : Diameter of piston [m]
- \(l\) : Exhaust pipe length [m]
- \(d\) : Diameter of exhaust pipe [m]
- \(P_a\) : Pressure of atmosphere [Pa]
- \(P_c\) : Pressure of cylinder [Pa]
- \(P_p\) : Inlet pressure of vacuum pump [Pa]
- \(V_c\) : Total inner volume of the cylinder [m³]
- \(Q_s\) : Leakage of noncontact seal [Pa⋅m³/s]
- \(Q_p\) : Exhaust air of vacuum pump [Pa⋅m³/s]
- \(\mu\) : Coefficient of viscosity [Pa⋅s]

![Fig.2 Principle of a proposed gravity compensator](image-url)
2.3 Structural configuration of the developed platform

Figure 3 shows the structural configuration of the developed platform integrated with the gravity compensator. All the structural modules were made of alumina ceramics with light mass, high stiffness and low thermal expansion coefficient. In addition, the objective platform was mounted on the parallel-allocated stable frames, i.e., a structural frame and a metrology frame. The latter frame was used to isolate the measuring system from the various error factors. The basic specifications of the platform are given in Table 1. Fig. 4 shows appearance of the advanced nano-pattern generator (ANGEL) integrated with the developed platform. The overall system was supported by an active vibration isolation system, as shown in Fig. 4(a).

![Diagram of the developed platform](image-url)
(a) Advanced nano-pattern generator with large work area (ANGEL)

(b) Side and front views of the vertical nano-motion platform

Fig. 4 Appearance of the long-stroke vertical nano-motion platform
3. Vertical nano-motion control system

There is no nonlinear phenomenon in the mechanism of the developed platform as mentioned above. Consequently, the linearized system dynamics of the platform is simple in principle. A full closed-loop control system with the laser interferometer feedback was used together with PID and acceleration feedforward compensators in the vertical nano-motion control system. Fig. 5 shows a block diagram of the vertical nano-motion control system. The control system was operated at a sampling frequency of 10kHz. The thrust force of a voice coil motor can be determined by the coil current. In this control system, the coil current was provided by the current amplifier with a high speed current feedback function. As a consequence, the control system provided the reference command to the current amplifier. Each gain of the PID controller was tuned experimentally through a trial and error process so that a phase margin was around 20 degrees.

4. Performance evaluation of the vertical motion platform

4.1 Evaluation of the gravity compensator

In order to evaluate the dynamic behavior of the gravity compensator integrated into the developed platform, the pressure fluctuations of the vacuum cylinder were measured during the stage moving upward and downward with a payload mass. The static pressure of the cylinder was adjusted to each payload mass, as shown in Table 2. Fig. 6 shows typical examples of force fluctuations of the gravity compensator over the vertical 50mm-stroke at a speed of 50mm/s. The attraction force could be calculated from the pressure of the cylinder. The maximum force change was less than 1.5N and the value was less than
Table 2  Adjustment of the vacuum cylinder

<table>
<thead>
<tr>
<th>Payload mass [kg]</th>
<th>0.5</th>
<th>4.2</th>
<th>6.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static pressure [kPa(G)]</td>
<td>-67.7</td>
<td>-84.2</td>
<td>-92.6</td>
</tr>
</tbody>
</table>

0.64% compared with the static force when the payload mass was 6.8kg. In consequence, stable gravity compensation could be realized even during the stage moving.

4.2 Nano-positioning performance

Positioning performance of the vertical nano-motion platform was evaluated. Fig.7 shows the result of a 0.6nm stepwise response in the vertical direction. As shown in this figure, a clear 0.6nm stepwise response could be observed. This high positioning resolution could be achieved by eliminating all nonlinear behavior in the system. In such a platform design, the system robustness against external shock and vibration at steady state could be achieved by quick response, by a direct drive and by a drive at the center of gravity with the voice coil motor.

In order to evaluate tracking errors of the moving stage, nano-motion experiments were performed. Fig.8 shows the motion trajectory at a speed of 20nm/s over a 10nm stroke. The tracking error was clearly less than 1.2nm. Fig.9 shows an example of tracking error
over the vertical 50 mm-stroke at a speed of 10mm/s. The tracking error of less than 11nm was achieved. The relationship between the payload and the tracking error was observed, as shown in Fig.10. The static pressure of the vacuum cylinder was adjusted to actual payload mass in advance. The tracking error during the stage moving decreased with the increase in the payload mass on the moving stage. This result was due to the decrease of pressure fluctuation caused by the increase in the payloads.

These results confirmed that the platform developed has a remarkable performance in vertical nano-positioning.

Fig.7 Response for a 0.6nm stepwise positioning

Fig.8 Motion trajectory at a speed of 20nm/s

Fig.9 Tracking errors during long-stroke motion
5. Conclusions

A vertical nano-motion platform integrated with gravity compensator was developed for achieving three-dimensional nano-positioning. In addition, the performance of the platform was demonstrated. As a result, the following conclusions could be drawn.

1. The developed vertical nano-motion platform could achieve a long stroke vertical motion of a nanometer order.
2. The developed gravity compensator with vacuum cylinders provides an effective supporting function of the gravity load in a noncontact condition.
3. Experimental results confirmed that the platform developed has high potential making it applicable for vertical nano-positioning.

Acknowledgements

This study was supported by JSPS Grants-in-Aid for Scientific Research (A) No.19206017 and the Machine Tool Engineering Foundation.

References

