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# A newly developed zero-gravity vertical motion mechanism for precision machining

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ABSTRACT

Gravity load deteriorates positioning performance on a vertical motion stage. A counterweight or a fluidic cylinder is conventionally used for gravity compensation; however, these solutions may induce new problems. This paper presents a novel zero-gravity vertical motion mechanism for precision machining. The proposed mechanism employs a linear motor and the magnet yoke has rolling guideway, thus the yoke is also used as counter mass. Because inertia of the moving parts is doubled for disturbance, the mechanism can effectively minimize the influence of machining force. The performance evaluation results confirm that the mechanism provides superior driving characteristics to vertical motion stages.


## 1. Introduction

In recent years, as the demand for precision machining of complicated and precise shape has increased, high speed and precise positioning of both tool and workpiece under the effect of machining force is required in a variety of industrial sectors. To meet this requirement, a lot of positioning systems for machine tools have been studied and developed so far [1]. It is important to realize not only the horizontal positioning but also the vertical positioning for machining of complicated and precise shapes. There are many proposals and development of positioning systems in the horizontal plane [2–4], consequently, they can provide superior positioning performance. However, there has been little reported research or proposals on vertical positioning. The most different technical point between the horizontal and vertical positioning is that the gravity load of the moving part acts in the same direction of positioning, thus support of gravity load is indispensable for achieving high performance in vertical positioning. A vertical *X–Y* stage for X-ray lithography [5] was supported by a counterweight, a vertical wafer stage for high vacuum applications [6] was supported by stepper motors, and a positioning system for nano machining [7] employed noncontact seal type vacuum cylinders for gravity compensation.

To materialize high speed and precise feed system, applications of linear motor to the driving axis as an actuator have been increasing. Linear motors can provide rapid and precise motion because it is a direct drive mechanism and can drive in a noncontact condition; however, it may excite undesirable vibration in the machine structure due to the reaction force of rapid change of driving force. In order to solve the vibration issues, jerk-decoupling technology [8] and a master-slave control technique using two linear motors [9] have been reported.

This paper presents a newly developed positioning mechanism for the linear motor-driven vertical axis of a machine tool. This mechanism can provide unique functions of compensating for gravity load, eliminating undesirable excited vibration, and decreasing the influence of disturbance without any complicated control.

## 2. Gravity compensation

### 2.1. Conventional mechanism

There are only a few mechanisms to support the gravity load of the moving parts in the vertical positioning. One of the simplest ways is to support the mass of the table with a driving actuator for positioning. In this mechanism, it is not necessary to install an additional unit in the vertical positioning system and is flexible to the change of the gravity load; however, this mechanism has disadvantages such as large amount of heat generation, risk of fall when an unexpected power outage occurs, and so on. Therefore, a gravity compensation mechanism is normally installed into a vertical axis in addition to a driving actuator. A balancing mechanism with fluidic cylinder or counterweight is widely used in a machine tool system. The entire system can be compact by using fluidic cylinders because it can generate a large supporting force easily, however the supporting force may fluctuate during high speed driving. The counterweight mechanism that cancels the gravity load of the moving objective requires no electric power, hence it can work even during a power outage. However, this mechanism requires a large actuator because the total driven mass doubles.

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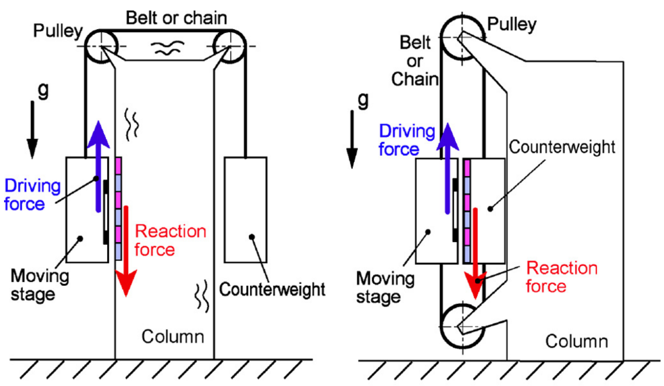
In all conventional mechanisms, reaction force of the driving actuator excites structural vibrations when in rapid motion. In particular, when a driving element is a linear motor, that issue becomes conspicuous in precise applications. Therefore, it is required to combine a gravity compensation function with a vibration decreasing function.

### 2.2. Proposed mechanism for zero-gravity vertical motion

Fig. 1 shows a proposed concept of a gravity compensation mechanism for zero-gravity vertical motion. This mechanism consists of a moving stage, counterweight with the same mass as the moving stage, a pair of pulleys, and a connecting belt or chain. Effective pretension is applied to connecting such elements for tight connections. Furthermore, the moving stage is driven by a linear motor whose magnet yoke or coil is fixed to the counterweight. The mechanism proposed in this paper provides the following advantages in comparison with conventional mechanisms:

- No need to consider compensation for the gravity load of the moving parts in a positioning controller, because it is mechanically supported by the counterweight.
- The reaction force of the actuator drives the counterweight in the opposite direction of the main stage motion. Thus, undesirable vibration of the column can be eliminated during driving.
- Displacement due to disturbance force to the moving stage decreases because the mass for external disturbance is doubled.
- These functions are mechanically realized, and hence it is not necessary to apply additional sensors, actuators, controllers, and energy.

From these advantages, the mechanism is suitable for a vertical axis in machining systems.




(a) Conventional mechanism (b) Proposed mechanism

**Fig. 1.** Concept of the proposed zero-gravity mechanism for vertical motion.

## 3. Analysis of the proposed mechanism

### 3.1. Mathematical model of the mechanism

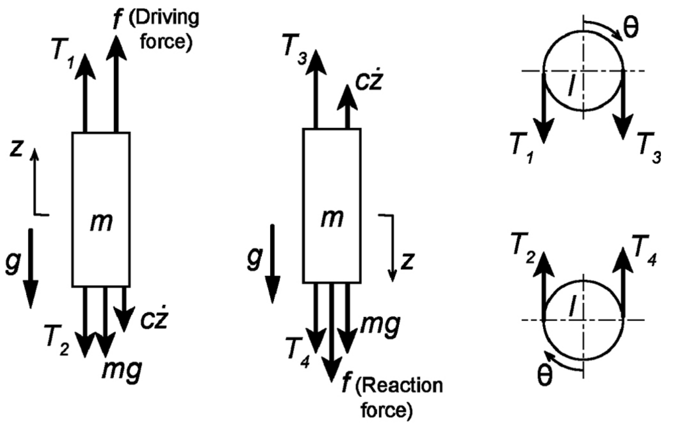
Fig. 2 shows mechanical models of system components of the proposed zero-gravity mechanism. Driving force $f$ to the moving stage and reaction force $f$ to the counterweight is same amplitude in the opposite direction. Based on Fig. 2, the equations of motion about each component are expressed as follows:

$$\text{Moving stage}: \quad m\ddot{z} = f + T_1 - T_2 - mg - c\dot{z} \tag{1}$$

$$\text{Counterweight}: \quad m\ddot{z} = f + T_4 - T_3 + mg - c\dot{z} \tag{2}$$

$$\text{Upper pulley}: \quad I\ddot{\theta} = T_3 r - T_1 r \tag{3}$$

$$\text{Lower pulley}: \quad I\ddot{\theta} = T_2 r - T_4 r \tag{4}$$




(a) Stage (b) Counterweight (C) Pulley

**Fig. 2.** Mechanical models of components.

where $z$ is vertical motion, $\theta$ is rotational motion, $m$ is the mass of the stage, $I$ is inertia of the pulley, $r$ is radius of the pulley, $c$ is the coefficient of proportional damping of guideway, $T_i$ is the force due to the tension in the belt, respectively. Here both the expansion of the belt and the slip between the pulley and belt are ignored.

From these equations, the transfer function $G(s)$ from driving force to displacement is given as a following equation:

$$G(s) = \frac{Z}{F} = \frac{1}{(m + (I/r^2))s^2 + cs} \tag{5}$$

When a conventional mechanism using a counterweight is used, the reaction force $f$ of the actuator in Fig. 2(b) does not act on the counterweight. Therefore, the transfer function $H(s)$ from driving force to displacement is given by the following equation:

$$H(s) = \frac{Z}{F} = \frac{1}{2}\frac{1}{(m + (I/r^2))s^2 + cs} \tag{6}$$

In comparison, it is clear that the transfer function of the newly proposed mechanism is twice that of a conventional mechanism. This means that the proposed mechanism can reduce the size of a driving actuator and also the responsiveness of the system does not decrease even when the counterweight is employed.

### 3.2. Disturbance response of the stage

Disturbance force such as cutting force may deteriorate positioning performance of the stage during the machining process. Therefore, it is important to ensure high stability of the system against the disturbance.

Disturbance is usually treated as an external force, and it acts not on the counterweight but on the moving stage. Stage motion is affected by the disturbance force; however, the proposed mechanism can reduce the influence of disturbance, because the stage is connected to the counterweight and the pulleys therefore the inertia of the moving parts is larger than that of the conventional mechanism. External disturbance to the proposed mechanism is the same situation as the driving force in the conventional mechanism, as shown in Fig. 2(b). Thus, the proposed mechanism acts like the system that has no counterweight to driving force and has twice the inertia to external disturbance.

## 4. Performance evaluation

### 4.1. Structural configuration of the developed vertical stage

In order to verify the proposed mechanism, an actual positioning system was developed. Fig. 3 shows the structural