# Realization of Lateral Flux-path Control Magnetic Suspension Using Rotational Mechanism

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## Abstract

A magnetic suspension system using rotational flux-path control mechanism is developed. In the developed flux path control mechanism, a pair of gear-shaped flux control plates are attached to the top and bottom of a permanent magnet (magnetic source); they are surrounded by a ferromagnetic outer yoke with teeth facing the control plates. The gear-shaped control plate is rotated to change the relative angle to the teeth of the outer yoke. The attractive force acting on the ferromagnetic floator is adjusted by rotating the control plates. Stable suspension is achieved in the developed apparatus.

***Keywords:*** *Magnetic suspension, Magnetic bearing ,Flux-path control, Variable flux path, Rotational mechanism*

## 1. Introduction

Magnetic suspension is one of the most promising methods of achieving non-contact suspension. It has various applications taking advantage of unique characteristics (Jayawant, 1981; Schweitzer and Maslen, 2009). In some applications, a large gap between a magnetic source and a suspended object (floator) is required. Flux-path control magnetic suspension has been proposed to achieve such large-gap suspension with small energy (Mizuno et al., 2007). In the original flux-path control mechanism, ferromagnetic control plates are inserted into the gap between the magnetic source and the ferromagnetic floator.

The authors proposed a novel configuration of flux-path control magnetic suspension named as lateral control type (Ishibashi et al., 2017). In this system, control plates were located around the magnetic source and moved vertically. To study its characteristics experimentally, an apparatus was developed which has three flux-path control mechanisms (Mizuno et al., 2019). Noncontact suspension with three-dimensional motion control was achieved in the apparatus.

However, the size of the apparatus was rather large mainly because each flux-path control mechanism enlarged the motion of the control plate by using see-saw mechanism. Such enlargement was necessary to vary the control force sufficiently to achieve stable suspension. In this work, a novel rotational flux-path control mechanism is developed to make the suspension system smaller. The developed flux-path control mechanism needs no mechanical magnification to obtain sufficient control force for stable noncontact suspension.

## 2. Flux-path control magnetic suspension systems

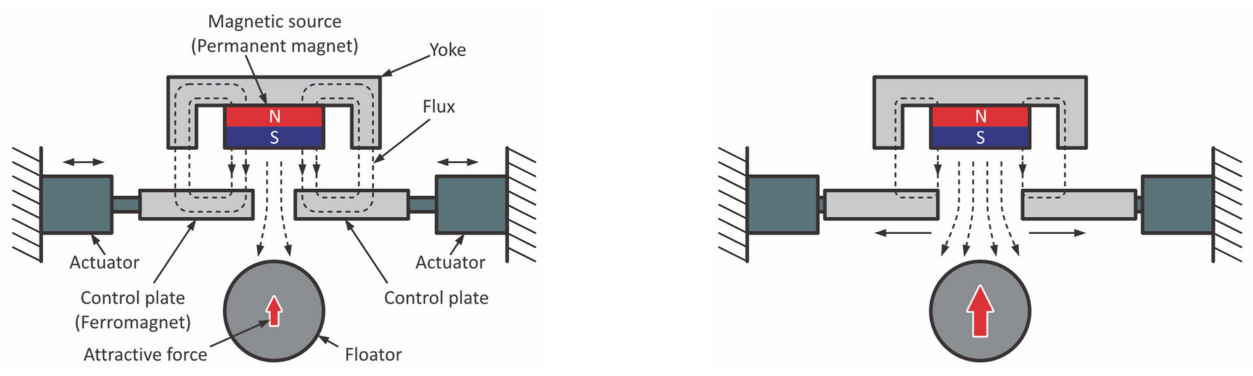
### 2.1 Flux-interrupted type

Figure 1 shows a basic configuration of the original flux-path control suspension system (Mizuno et al., 2007). A pair of ferromagnetic control plates are inserted into the gap between the magnetic source and the floator. When the distance between the control plates becomes wider, more flux reaches the floator from the magnetic source, and the attractive force acting on the floator becomes stronger as shown by Fig.1(b), and vice versa. The suspension system with such configuration is called as flux-interrupted type because the control plates interrupt the flux path from the magnetic source to the floator.

This type has an advantage over the conventional active magnetic suspension with an electromagnet in achieving large-gap suspension mainly because the actuator drives the control plate instead of the floator itself. However, the attractive force action on the floator decreases by inserting the control plates.

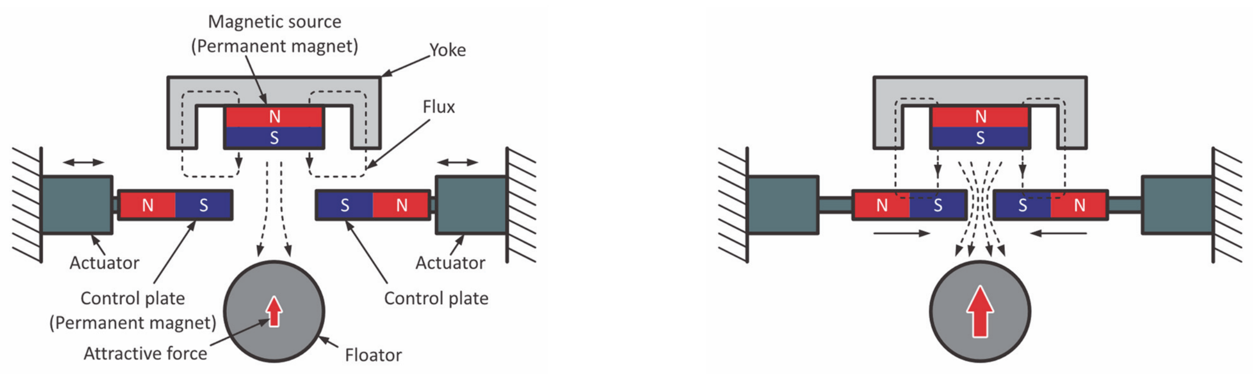
### 2.2 Flux-concentrated Type

Figure 2 shows a basic configuration of the flux-concentrated control suspension system (Mizuno et al., 2013). The control plates are made of permanent magnet instead of ferromagnetic material. This type is superior in producing intensive force to the flux-interrupted type. In addition, the relation of the suspension force to the distance between the



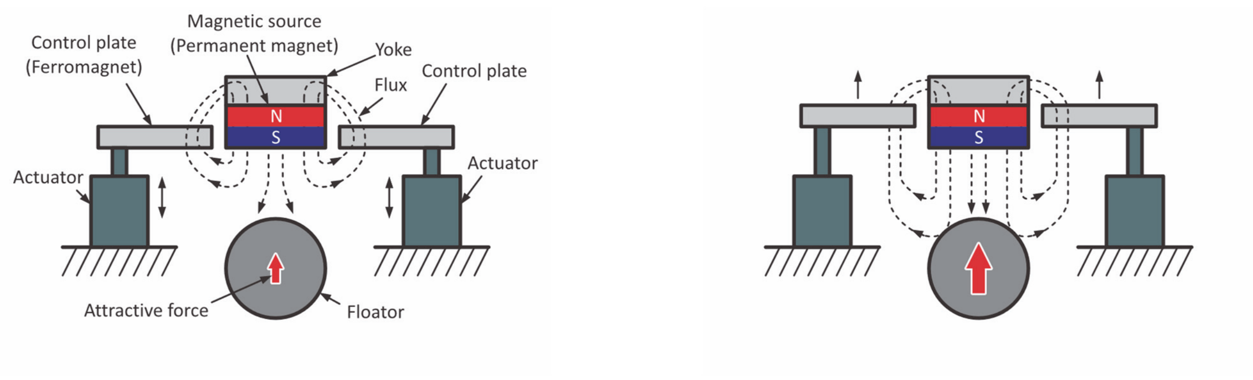

*(a) Basic structure* *(b) Control plates opened*

*Figure 1 Flux-interrupted flux-path control magnetic suspension system*




*(a) Basic structure* *(b) Control plates closed*

*Figure 2 Flux-interrupted flux-path control magnetic suspension system*




*(a) Basic structure* *(b) Control plates raised*

*Figure 3 Laterally controlled flux-path magnetic suspension system*

control plates is contrasting. When the distance between the control plates becomes smaller, more flux is concentrated in the gap so that the attractive force acting on the floator becomes stronger, and vice versa.

## 2.3 Lateral control type

In both former types, the control plates are inserted between the floator and the magnetic source (permanent magnet). It decreases the effective gap. In the lateral control type, control plates are placed in the lateral of the magnetic source (Ishibashi et al., 2017). The attractive force is adjusted by moving the control plates in the vertical direction beside the permanent magnet. Thus, the effective gap equals that between the floator and the magnetic source. Figure 3 shows

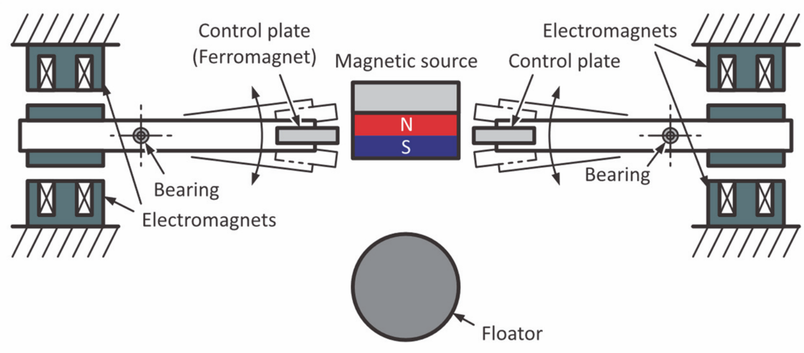



*Figure 4 Schematic drawing of magnetic suspension system with fabricated flux-path control mechanisms*

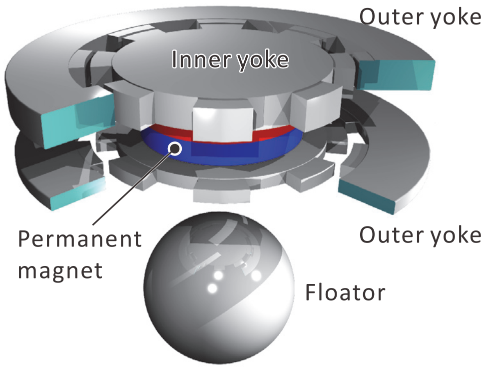



*Figure 5 Magnetic suspension with a rotational flux-path control mechanism*

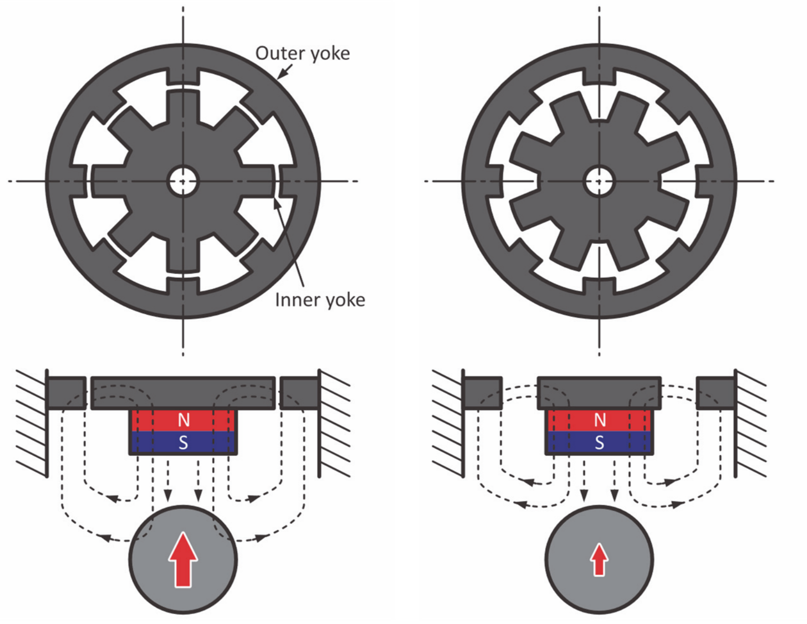
the principle of adjustment of the attractive force. When the control plates are placed at the lowest position where the bottom of the control plates is aligned with that of the permanent magnet, more flux flows into the control plates, and the attractive force becomes smaller. When the control plates are placed at the highest position, where the top of the control plates is aligned with that of the permanent magnet, the attractive force becomes larger because the control plates work as yoke.

Figure 4 shows a schematic drawing of the fabricated flux-path control mechanism (Mizuno et al., 2019). In this mechanism, a ferromagnetic control plate is fixed on one end of a lever made of non-magnetic material. The lever is supported by a ball bearing to rotate about a horizontal axis. A pair of electromagnets are placed at an end of the lever. The motion at the electromagnets is mechanically amplified approximately five times at the control plates. Such a structure inevitably made the apparatus rather large (Mizuno et al., 2019).

### 2.4 Rotational flux-path control type

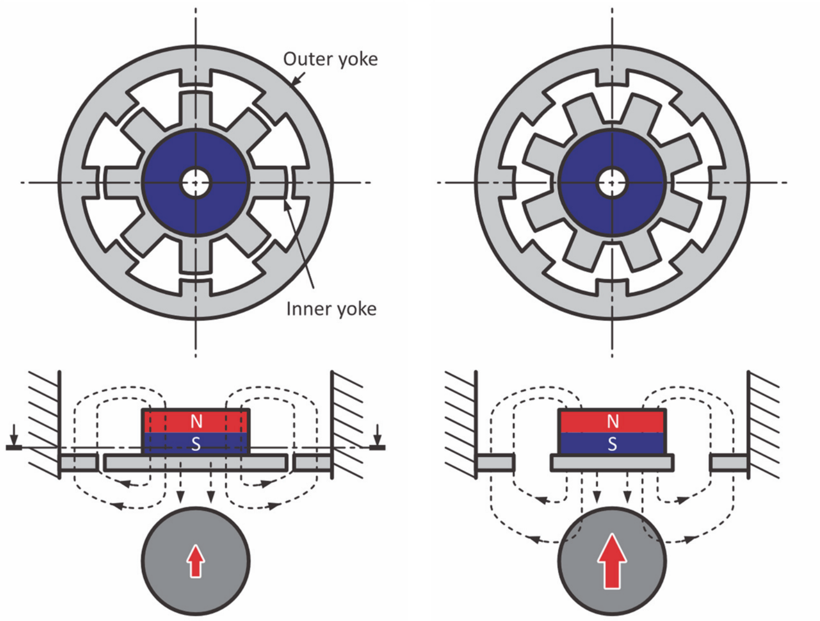
To reduce the size of suspension system, rotational flux-path control mechanism has been proposed (Kurosawa et al., 2019; Mizuno et al., 2020). Figure 5 shows a conceptual diagram of the proposed magnetic suspension system with a rotational flux-path control mechanism. A gear-shaped ferromagnetic yoke (inner yoke) is attached on the top of a disk-shaped permanent magnet (magnetic source). It is surrounded by a gear-shaped plate (upper outer yoke). The inner yoke is rotated by an actuator to vary the relative angle between a magnetic tooth of the inner yoke and that of the outer yoke. A ferromagnetic sphere (floator) is located under the magnetic source. The attractive force acting on the floator can be adjusted by the angle, which will be explained by Fig.6 where the number of teeth is assumed to be eight. When the teeth face each other (relative angle is 0 deg.) as shown by Fig.6a, flux flows in the outer yoke most and the attractive force is maximum as a result. In contrast, when the tooth of the inner yoke is at the middle of the teeth of the outer yoke as shown by Fig.6b, flux flows in the outer yoke least and the attractive force is minimum. When the number of the teeth is *n*, the corresponding relative angle $\theta_r$ is 180/*n* deg

Another gear shaped inner yoke and the corresponding outer yoke are placed below the permanent magnet as shown by Fig.5 and Fig.7. In this case, when the teeth face each other (relative angle is 0 deg.) as shown by Fig.7a, flux flows in the outer yoke most, which leads to minimum attractive force instead. In contrast, when the tooth of the inner yoke is at the middle of the teeth of the outer yoke as shown by Fig.7b, flux flows in the outer yoke least and leads to maximum attractive force.




*(a) Relative angle: 0 deg* *(b) Relative angle: 22.5 deg*

*Figure 6 Control plate on the top of magnetic source*




*(a) Relative angle: 0 deg* *(b) Relative angle: 22.5 deg*

*Figure 6 Control plate at the bottom of magnetic source*

In the developed apparatus, both upper and lower yokes are combined to maximize the variation of the attractive force (control force). The relative angle between the upper and lower is set to be 180/$n$ deg.

## 3. Experiment Apparatus

Figure 8 shows a picture of the developed apparatus. In this apparatus, the inner yokes sandwiching the permanent magnet are rotated. The number of the teeth is eight so that $\theta_r = 22.5\,\text{deg}$. Figure 9 shows schematic views of the

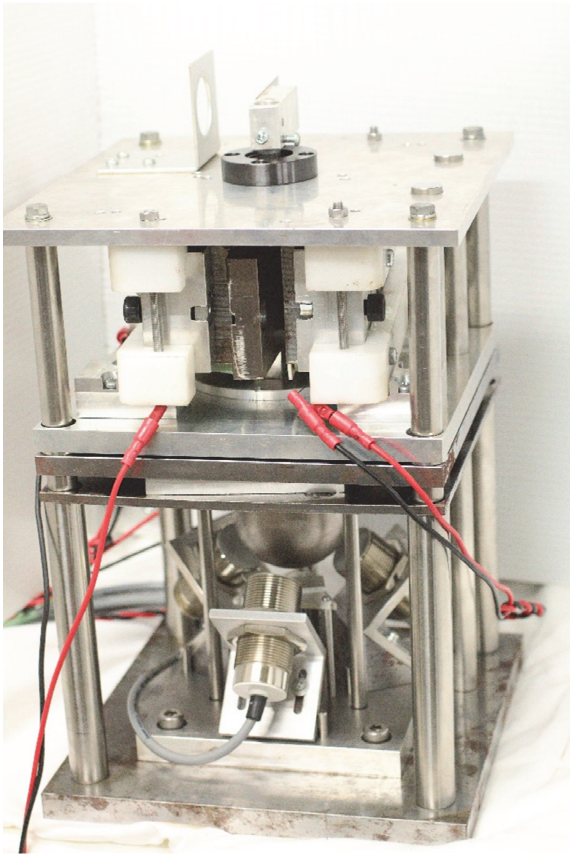


*Figure 8 Picture of apparatus*

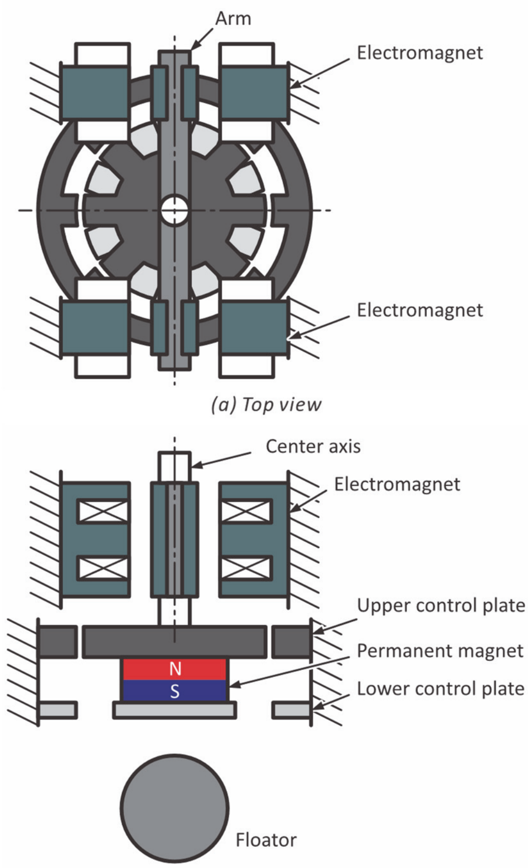



*Figure 9 Schematic drawing of rotational flux-path control mechanism*

rotational mechanism. An arm is connected to the rotational axis of them. The arm is driven by two pairs of differentially operated electromagnets. They are located above the inner and outer yokes.

## 4. Experimental Results

The designed controller has a double-loop structure that is similar to that used in the previous work (Mizuno et al., 2018). In the inner loop, the motion of the lever is locally fed back in the flux-control mechanism. In the outer loop, the displacement of floator in the vertical direction is also fed back. In the inner loop, PD control is applied to provide the flux-path control mechanism sufficient stiffness and damping property to suspend the floator. In the outer loop, PD control is also applied to stabilize the suspension system.

Figure 10 shows a measured frequency response of the rotational mechanism (inner loop). In the measurement, a sinusoidal signal was added to the control signal and the output was the angular displacement of the arm. It is found that the resonant frequency is approximately 35 Hz.

Stable suspension was achieved with the designed controller. Figure 11 shows the motions of the floator and the arm during levitation. The floator levitates at the position of 14.05 mm below the magnetic source. It was experimentally certified that the suspension was maintained in the presence of small disturbances.

## 5. Conclusions

A rotational flux-path control mechanism was introduced to reduce the size of laterally controlled magnetic suspension system. In the developed flux path control mechanism, two gear-shaped flux control plates were attached to the top and bottom of a magnetic source. Each of them was surrounded by a ferromagnetic outer yoke with teeth. The attractive force acting on the ferromagnetic floator was adjusted by changing the relative angle between the inner and outer yokes. Stable suspension was achieved in the developed apparatus.

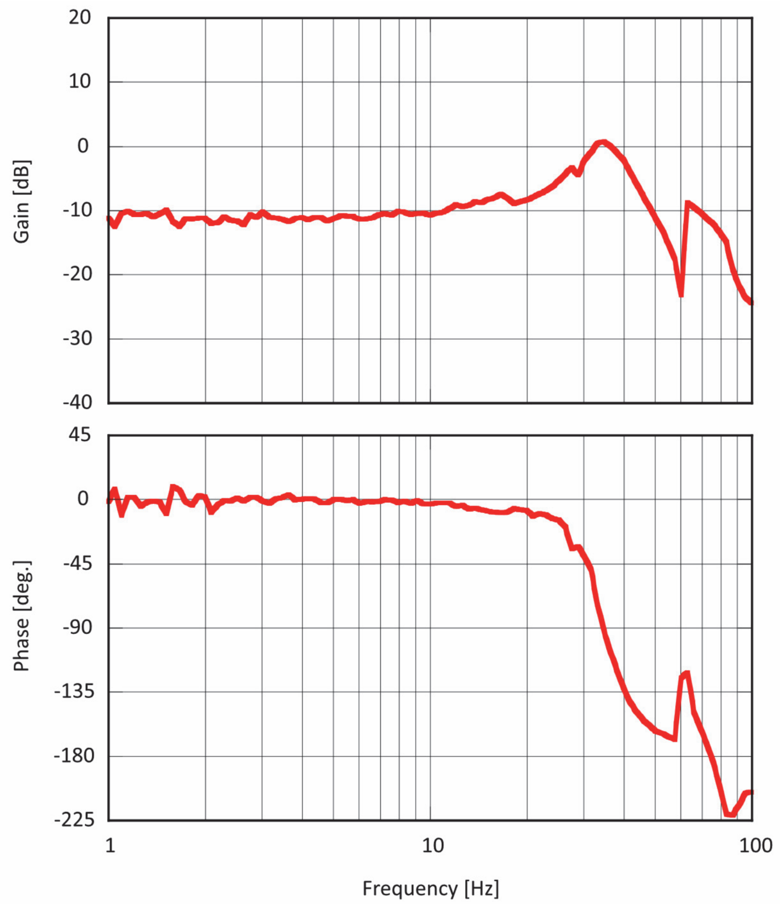
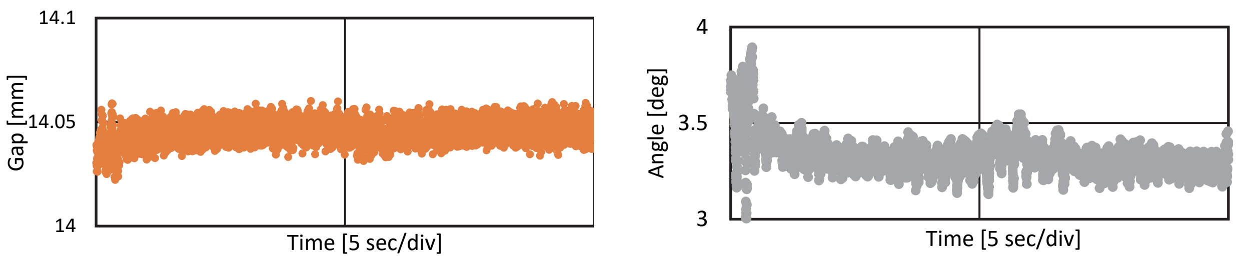



*Figure 10 Frequency response of rotational mechanims*




*(a) Floator* *(b) Angular displacement of arm*

*Figure 11 Motions during levitation*

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