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Improvement of Levitation Force Characteristics in Magnetic Levitation Type Seismic Isolation Device Composed of HTS Bulk and Permanent Magnet

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Abstract. Magnetic levitation type seismic isolation device composed of HTS bulks and permanent magnets can theoretically remove horizontal vibration completely. It is, however, not easy to generate the large levitation force by using only the levitation system composed of HTS bulk and permanent magnet (HTS-PM system). We focused on a hybrid levitation system composed of the HTS-PM system and the PM-PM system composed of only permanent magnets and investigated the suitable arranging method of the hybrid system for improving levitation force and obtaining stable levitation. In order to clarify the most suitable permanent magnet arrangement in the PM-PM system for the levitation force improvement, repulsive force between permanent magnets was measured in various kinds of the PM-PM system. The maximum repulsive force per unit area in the PM-PM system was at least three times larger than the levitation force per unit area in the HTS-PM system, so that the levitation force in the hybrid system was larger than that of the HTS-PM system. Stable levitation was also achieved in the hybrid system. This is because repulsive force in the PM-PM system against horizontal displacement was much smaller than restoring force in the HTS-PM system.

1. Introduction
Earthquake-resistant technology is generally adopted in buildings and structures to protect them from earthquake destruction. A recent earthquake in Japan, however, gave serious damages to a nuclear plant as well as general houses. This means that adopting only the conventional earthquake-resistant technology is not enough to avoid such the damages of buildings and structures. Seismic isolation device composed of bearing and damper elements has recently attracted attention as a higher level of protection for buildings and structures. In the current device, however, vibration cannot be damped immediately and seismic isolation effect cannot be obtained sufficiently against small vibration amplitude and lightweight buildings and structures. Therefore, we have devised magnetic levitation type seismic isolation device composed of HTS bulks and permanent magnets [1]. The seismic isolation device has a three-layer structure and can theoretically remove horizontal vibration completely. It is, however, generally difficult to obtain large levitation force in the magnetic levitation system composed of HTS bulk and permanent magnet (HTS-PM system). Moreover, much use of HTS bulk for generating large levitation force is economically disadvantaged. In terms of levitation force, the magnetic levitation system composed of only permanent magnets (PM-PM system) would be preferable to the HTS-PM system. This is because the repulsive force between permanent magnets is generally larger than the levitation force between an HTS bulk and a permanent magnet.
Earnshaw's theorem, however, states that stable levitation of a permanent magnet above another permanent magnet is impossible without an additional force for stabilization. Hybrid levitation system composed of HTS bulk system and PM-PM system is one of the suitable methods for achieving levitation force improvement and stable levitation. The magnetic levitation system composed of HTS bulk and permanent magnet has been already investigated experimentally and numerically [1]-[7]. The suitable arranging method of the hybrid system realizing large levitation force and stable levitation, however, has not been investigated sufficiently yet. Therefore, we investigated the suitable arranging method for improving levitation force and obtaining stable levitation in the hybrid system composed of the HTS-PM system and the PM-PM system.

2. Magnetic levitation type seismic isolation device
The magnetic levitation type seismic isolation device has a three-layer structure as shown in figure 1. The bottom and top layers are composed of permanent magnets and an HTS bulk, respectively. The middle layer consists of HTS bulks and permanent magnets fixed to an iron plate. Horizontal vibration in the y-direction of the bottom layer is removed between the bottom and middle layers and that of the x-direction of the middle layer is removed between the middle and top layers. This is because magnetic field applied to the bulk in the middle layer does not change even if the permanent magnet in the bottom layer moves in the y-direction. This means that restoring force is not generated within the bulk in the middle layer against vibration in the y-direction of the bottom layer. Based on this theory, we can remove arbitrary horizontal vibration completely by using this device.

3. Levitation force improvement
It has been reported that levitation force in HTS-PM system depends on initial air gap in the field-cooling process of HTS bulk [1][2]. It is not easy to generate the large levitation force that corresponds to the weight of building and structure. One of the methods for obtaining such large levitation force is adopting multiple HTS-PM systems. Instead of the HTS-PM system, however, PM-PM system should be used as many as possible, because HTS bulk is much more expensive than permanent magnet. Therefore, we investigated the suitable arranging method of permanent magnets in the PM-PM system for obtaining the large levitation force effectively.

3.1. Levitation force in HTS-PM system
In order to investigate effectiveness of adopting hybrid system on levitation force improvement, levitation force in hybrid system should be compared with that of HTS-PM system. Therefore, we measured the levitation force in an HTS-PM system composed of YBCO bulks and Nd-Fe-B permanent magnets. Schematic drawing of an experimental setup for levitation force measurement is shown in figure 2. The diameter, thickness, and weight of a disk-shaped YBCO bulk by QMG process are 15mm, 10mm, and 50g, respectively. Two bulks were fixed in the bottom of a Styrofoam container with 180mm long, 50mm wide and 50mm height. Nd-Fe-B permanent magnets, 9mm square and 3mm thick, were fixed on an iron plate to compose a permanent magnet unit by placing the permanent magnets in four rows. Magnetic poles in the top surface of the permanent magnet unit were arranged
in alternately different polarities (NSNS) in the x-direction, while the same polarity in the y-direction. The experiment proceeded through the following steps: 1) put Styrofoam container on a spacer and cool the bulks by LN$_2$; 2) remove the spacer and let the Styrofoam container levitate; and 3) measure levitation force by load cell as a function of air gap between the bulk and the permanent magnet unit. The experimental results of levitation force per unit area of the bulks are shown in figure 3. The levitation force increased with the initial air gap. The maximum levitation force per unit area of 17kN/m$^2$ was obtained at the initial air gap of 6mm and the air gap of 0.3mm.

3.2. Repulsing force in PM-PM system

In order to clarify the most suitable permanent magnet arrangement in PM-PM system for improving levitation force in hybrid system, we measured repulsive force between the permanent magnets in various kinds of permanent magnet arrangements. As a precondition of the permanent magnet arrangement, we assumed that the permanent magnets in the lower part were arranged in the same polarity in the y-direction to obtain the seismic isolation effect against horizontal vibration. The permanent magnet in the upper part was placed just above that of the lower part so that permanent magnets of the same polarity were facing each other. The permanent magnet in the upper part was fixed to a load cell and the repulsive force was measured by the load cell.

3.2.1. Influence of number of permanent magnet rows in lower part on repulsive force.

The repulsive force was measured as a function of number of permanent magnet rows in the lower part. One permanent magnet was fixed in the upper part. The experimental results of repulsive force per unit area of the permanent magnet in the upper part are shown in figure 4. The maximum repulsive force was obtained in the PM-PM system with one permanent magnet row and the repulsive force decreased with the number of permanent magnet rows. The repulsive force per unit area in the three permanent magnet rows, however, was larger than the levitation force at the initial air gap of 6mm in the HTS-PM system. This means that even the PM-PM system composed of one permanent magnet in the upper part and the three permanent magnet rows in the lower part was better than the HTS-PM system. These results show that adopting PM-PM system is much more effective in improving levitation force in the magnetic levitation type seismic isolation device than adopting extra HTS-PM system.

3.2.2. Influence of number of permanent magnets in upper part on repulsive force.

Dependence of the repulsive force on the number of permanent magnets in the x-direction of the upper part was investigated experimentally. Three permanent magnet rows were adopted in the lower part. The experimental results of repulsive force per unit area of the permanent magnets in the upper part are shown in figure 5. Independent of the number of permanent magnets in the upper part, almost the same repulsive force per unit area was obtained at the air gap of 3mm or more. This means that the repulsive force increased proportionally to the number of permanent magnets in the upper part at the
air gap of 3mm or more. On the other hand, the repulsive force at the air gap of 3mm or less decreased with the air gap in one magnet or three magnets in the upper part, while increased with the air gap in two magnets. The repulsive force in three magnets in the upper part and three magnet rows in the lower part was smaller than that of one magnet in the upper part and one magnet row in the lower part. We finally inferred from these experimental results that the most suitable arrangement in the PM-PM system for improving levitation force was one permanent magnet in the upper part and one permanent magnet row in the lower part. The maximum repulsive force per unit area in the PM-PM system was at least three times larger than the levitation force per unit area in the HTS-PM system.

Influence of number of permanent magnets in the y-direction of the upper part on repulsive force was also investigated experimentally. One permanent magnet in the x-direction of the upper part and one permanent magnet row in the lower part were adopted in the experiment. The results of repulsive force per unit area of the magnets in the upper part are shown in figure 6. Almost the same level of repulsive force per unit area was obtained independent of the number of permanent magnets in the y-direction; the repulsive force increased with the number of permanent magnets in the y-direction. This means that increasing the number of permanent magnets in the y-direction of the upper part is an effective and reliable method for improving levitation force.

3.3. Levitation force in hybrid levitation system

Based on the experimental results of repulsive force in the PM-PM systems, we constructed a hybrid levitation system composed of the HTS-PM system, shown in figure 2, and the PM-PM system composed of one permanent magnet in the upper part and one permanent magnet row in the lower part. Levitation force in the hybrid system was measured as a function of initial air gap in the field-cooling process of YBCO bulks. The schematic drawing of the experimental setup for the levitation force measurement is shown in figure 7. As well as the experimental results in the HTS-PM system, the results of levitation force per unit area of two YBCO bulks and one permanent magnet in the hybrid system are shown in figure 8. Independent of the initial air gap, the levitation force per unit area in the hybrid system was larger than that of the HTS-PM system. This means that it is effective in improving levitation force to add PM-PM system to HTS-PM system.

The interaction between PM-PM system and HTS-PM system was investigated by using the experimental results of levitation force in the HTS-PM system and repulsive force in the PM-PM system. The levitation force in the hybrid system was compared with the sum of levitation force in the HTS-PM system and repulsive force in the PM-PM system. The ratio of levitation force in the hybrid system to the sum of levitation force and repulsive force is shown in figure 9. The interaction between the two systems existed independent of the initial air gap. The synergistic effect between the two systems, however, was not obtained at the initial air gap of 6mm and the air gap of 2mm or less. This means that relative distance between HTS-PM system and PM-PM system is also important parameter to obtain large levitation force effectively.
4. Horizontal vibration characteristics in hybrid system

Permanent magnet in the upper part of PM-PM system cannot be levitated stably. This implies that the PM-PM system reduce stability of levitation in the hybrid system. In the design of the hybrid system we should consider not only levitation force but also stability. Therefore, we investigated the stability in the hybrid system by measuring relative displacement between the lower and upper parts against horizontal vibration in the lower part. Schematic drawing of the experimental setup is shown in figure 10. The lower part was vibrated by an excitation device. The displacement in the upper and lower parts was measured by laser displacement gages to evaluate the relative displacement. In the hybrid system we adopted the PM-PM system composed of one permanent magnet in the upper part and one permanent magnet row in the lower part. The experimental results of relative displacement in the HTS-PM system and the hybrid system at the initial air gap of 2mm are shown in figure 11 and figure 12, respectively. In the HTS-PM system the small constant relative displacement was obtained at the vibration frequency of 2.5 Hz or less, while the displacement increased at the frequency of 3Hz or
more. The same tendency was observed in the hybrid system. This means that stable levitation can be achieved even if the PM-PM system that generates large repulsive force is added to HTS-PM system.

In order to investigate mechanism of stable levitation in the hybrid system, we measured restoring force in the HTS-PM system and repulsive force in the PM-PM system against a displacement in the x-direction from an equilibrium position. In both systems the upper part was fixed to a load cell. The upper part with the load cell was moved in the negative x-direction and magnetic force was measured by the load cell. The experimental results of restoring force in the HTS-PM system and the repulsive force in the PM-PM system at the air gap of 2mm are shown in figure 13. Especially in the small displacement, the restoring force in the HTS-PM system was much larger than the repulsive force in the PM-PM system. This means that the upper part in the hybrid system was very stable against horizontal displacement. The stability, however, would decrease with the amount of permanent magnets in the upper part of the PM-PM system. Therefore, the maximum acceptable amount of permanent magnets should be considered carefully in the design of the hybrid system.

5. Conclusion
We investigated the suitable method for improving levitation force in magnetic levitation type seismic isolation device. Hybrid system composed of HTS-PM system and PM-PM system is a promising candidate for the most suitable system for improving levitation force effectively. Repulsive force in the various kinds of permanent magnet arrangement in the PM-PM system was evaluated and the suitable arranging method for improving levitation force in the HTS-PM system was clarified. Using the most suitable arrangement of permanent magnet, we constructed a hybrid system and demonstrated that the PM-PM system was effective in improving the levitation force. Stability in the hybrid system was also investigated by evaluating horizontal vibration characteristics. Stable levitation was observed in the hybrid system. This is because the restoring force in the HTS-PM system was much larger than the repulsive force in the PM-PM system against a horizontal displacement. The PM-PM system can achieve both levitation force improvement and stable levitation.

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Figure 13. Experimental results of restoring force in an HTS-PM system and a hybrid system and repulsive force in a PM-PM system at the air gap of 2mm.