Dependence of Horizontal Vibration Characteristics on Load Weight Distribution in Magnetic Levitation Type Seismic Isolation Device

著者	津田　理
journal or publication title	IEEE Transaction on Applied Superconductivity
volume	18
number	2
page range	832-835
year	2008
URL	http://hdl.handle.net/10097/46507

doi: 10.1109/TASC.2008.920794

Dependence of Horizontal Vibration Characteristics on Load Weight Distribution in Magnetic Levitation Type Seismic Isolation Device

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***Abstract*—We have developed a magnetic levitation type seismic isolation device. The device could remove any horizontal vibrations very effectively. Three-layer structure was adopted in the device. The bottom layer was composed of permanent magnets. The middle layer comprised HTS bulks and permanent magnets. The top layer consisted of HTS bulks. The horizontal vibration characteristics in the middle layer depended on the air gap between the bottom and middle layers; the air gap was closely related to the load weight distribution in the top and middle layers. Inhomogeneous load weight distribution caused the different air gap in each bulk. Horizontal levitation against the inhomogeneous load weight distribution, however, could be obtained by adjusting the initial offset angle of each bulk in field-cooling process. The smaller initial air gap was effective in realizing horizontal levitation; the difficulty of horizontal levitation increased with the initial air gap. Independent of the load weight distribution, almost the same characteristics of horizontal vibration were obtained in the small initial air gap.**

***Index Terms*—Horizontal vibration, HTS bulk, magnetic levitation, seismic isolation device.**

I. Introduction

REDUCING vibration transmission from the ground to structures during earthquake is necessary to avoid the damage in general house, building and nuclear power plant, and the destruction of valuable furniture, art object and antique. Recently, seismic isolation device has attracted attention as a means of avoiding the damage and the destruction. A large number of studies of the seismic isolation device have been performed for a long time [1], [2].

The current seismic isolation device is generally equipped with the bearing and damper elements. The following technical problems in the current seismic isolation device are still unsolved: 1) ineffectiveness against small vibration amplitude; 2) no immediate damping after earthquake; and 3) small effect in the lightweight structure. To solve these problems, we have devised magnetic levitation type seismic isolation device [3].

The device has three-layer structure and consists of HTS bulk and permanent magnet. Theoretically, arbitrary horizontal vibration can be completely removed by the device. In a practical use of the seismic isolation device, multiple devices are required to sustain the structure with heavy load. Load weight distribution of the structure is not necessarily always homogeneous; it seems likely that different load is applied to each device. It is not easy to apply the current seismic isolation device to the structure with inhomogeneous load weight distribution. On the other hand, it is likely that the magnetic levitation type seismic isolation device is effective for the structure with inhomogeneous load weight distribution. In the magnetic levitation type seismic isolation device, the air gap differs with each device, when the load weight of the structure is inhomogeneous and the same initial air gap in field-cooling process of HTS bulk is adopted. This means that the structure with inhomogeneous load weight distribution would be tilted without any adjustments of the initial air gap. It is likely that the tilt angle is closely related to the characteristics of magnetic stiffness in the pitch direction of the bulk. Therefore, the characteristics of magnetic stiffness in the pitch direction and the suitable field-cooling condition of the bulk for horizontal levitation should be investigated.

Even if horizontal levitation could be achieved by selecting the suitable field-cooling condition, the characteristics of magnetic stiffness in the "horizontal" direction may differ with each device. This means that the horizontal vibration characteristics in the structure with inhomogeneous load weight distribution may be different from those of homogeneous distribution. Therefore, dependence of the horizontal vibration characteristics on load weight distribution should be clarified in consideration of the magnetic stiffness in the pitch direction.

II. Experiment

A. Magnetic Stiffness in the Pitch Direction

We investigated magnetic stiffness in the pitch direction using a model system composed of an YBCO bulk and Nd-Fe-B permanent magnets shown in Fig. 1. The diameter, thickness, and weight of YBCO bulk were 30 mm, 10 mm, and 50 g, respectively. The bulk was fixed in the bottom of Styrofoam container with 180 mm long, 50 mm wide and 50 mm height. Nd-Fe-B permanent magnets, 9 mm square and 3 mm thick, are fixed on an iron plate to compose a permanent magnet unit. The magnetic flux density on the top surface of a permanent magnet was 360 mT. The magnetic poles in the top surface of permanent magnet unit were arranged in alternately different polarities (NSNS) in the transverse direction, while the same polarities in the longitudinal direction. Therefore, when the bulk is field-cooled above the permanent magnet unit, the bulk can move

Manuscript received September 28, 2007. This work was supported in part by Okumura Corporation.

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Digital Object Identifier 10.1109/TASC.2008.920794

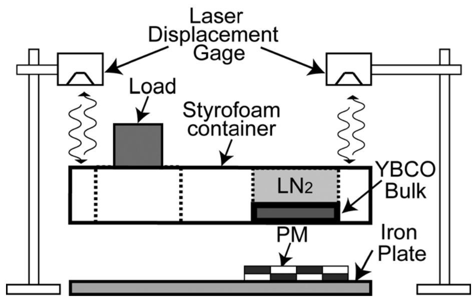

Fig. 1. Schematic drawing of an experimental setup for magnetic stiffness in the pitch direction of an YBCO bulk in single bulk system.

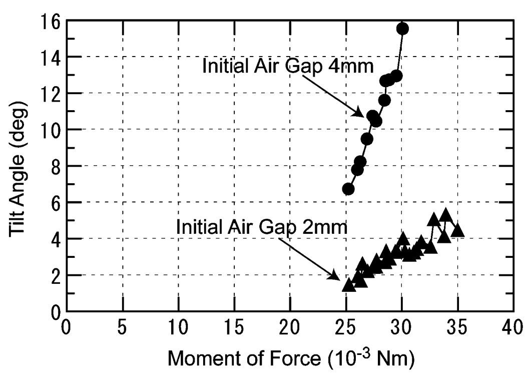

Fig. 2. Experimental results of tilt angle of an YBCO bulk as a function of moment of force in single bulk system.

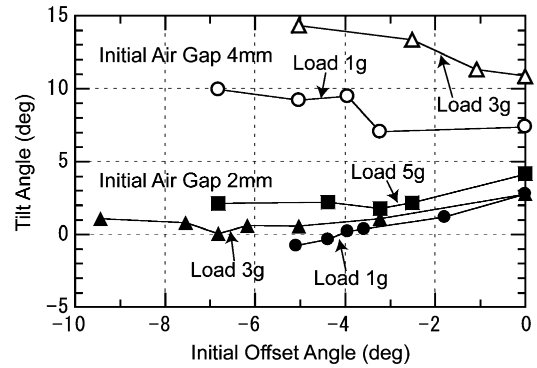

Fig. 3. Experimental results of tilt angle for horizontal levitation as a function of initial offset angle in single bulk system.

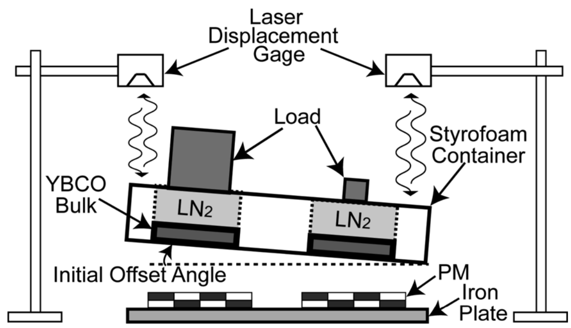

Fig. 4. Schematic drawing of an experimental setup for magnetic stiffness in the pitch direction of YBCO bulks in two-bulk system.

freely in the longitudinal direction of the permanent magnet unit, while fixed in the transverse direction.

The experiment proceeds through the following steps: 1) put an adjustable-height spacer on the permanent magnet unit and then put the Styrofoam container with a load on the spacer; 2) cool the bulk by LN_2 and let the Styrofoam container levitate by removing the spacer; 3) measure the tilt angle from a horizontal plane by using laser displacement gage. The characteristics of magnetic stiffness in the pitch direction depend on not only the load weight but also the distance between the load and the bulk. Therefore, we investigated the relationship between the tilt angle and the moment of force about the center of the bulk.

The experimental results of the moment of force and the tilt angle are shown in Fig. 2. Note that the counterclockwise direction of the tilt angle is defined as positive. The Styrofoam container was tilted according to the load weight and the distance. The relationship between the moment of force and the tilt angle was approximately linear. The slope at the initial air gap of 4 mm was much larger than that of 2 mm. This is because magnetic stiffness in the pitch direction decreases with initial air gap due to the decrease of magnetic flux density.

One of the effective methods for reducing the tilt angle is adjustment of the initial offset angle from a horizontal plane. Therefore, the tilt angle was measured as a function of the initial offset angle. The experimental results of the initial offset angle and the tilt angle are shown in Fig. 3. Note that the counterclockwise direction of the initial offset angle is defined as positive. At the initial air gap of 2 mm, horizontal levitation was achieved at the load weight of 1 g and 3 g by selecting the initial offset angle of -6.8 deg and -4.1 deg, respectively. The required initial offset angle for horizontal levitation increased with the load weight; the maximum load weigh for horizontal levitation was 4 g at the initial air gap of 2 mm. On the other hand, at the initial air gap of 4 mm, horizontal levitation could not be obtained independent of the initial offset angle. Theses results show that the smaller initial air gap is desirable for horizontal levitation. This is because magnetic flux density around the bulk decreases with the initial air gap.

B. Horizontal Levitation in Multiple Bulk System

It is likely that magnetic stiffness in the pitch direction in multiple bulk system is different from that of single bulk system. The suitable initial offset angle for horizontal levitation in the multiple bulk system would also differ from that of the single bulk system. Therefore, the relationship between the initial offset angle and the tilt angle in multiple bulk system was investigated experimentally. As shown in Fig. 4, two YBCO bulks were fixed in the bottom of Styrofoam container and two loads with different weight were put on the Styrofoam container. The tilt angle at the initial offset angle of 0 deg and the initial offset angle at the tilt angle of 0 deg were measured as a function of the weight of the left-hand side load in Fig. 4. Note that the weight of the right-hand side load was fixed to be 1 g in the measurement.

The experimental results of the tilt angle at the initial air gap of 2 mm and 4 mm are shown in Fig. 5. The absolute value of the tile angle increased with the weight of the left-hand side load. At the initial air gap of 2 mm, the load weight of 1 g generated

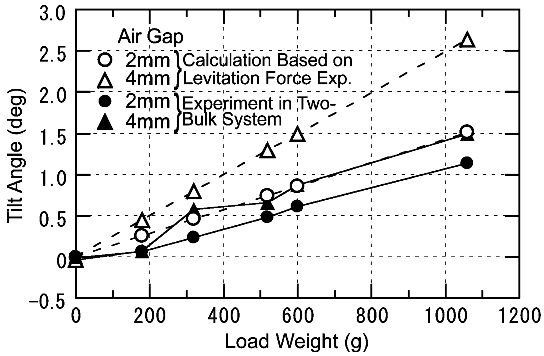

Fig. 5. Experimental and analytical results of tilt angle of YBCO bulks at initial offset angle of 0 deg as a function of load weight in two-bulk system.

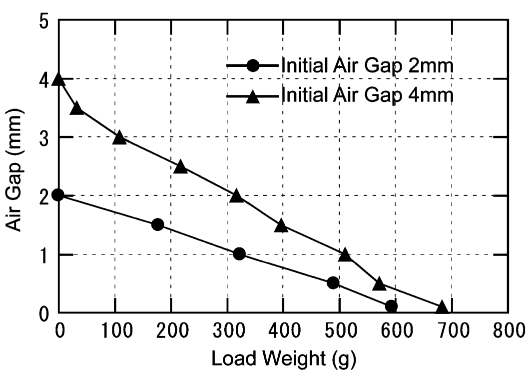

Fig. 6. Experimental results of air gap between an YBCO bulk and permanent magnets as a function of load weight in single bulk system.

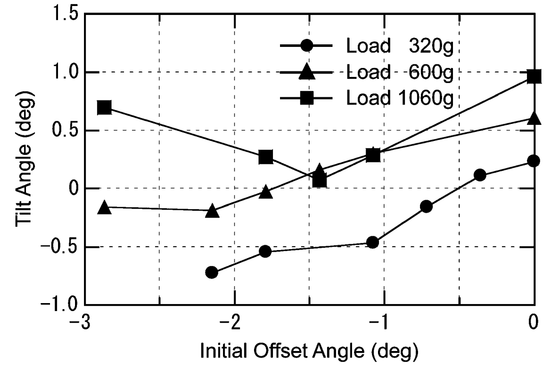

Fig. 7. Experimental results of tilt angle for horizontal levitation at initial air gap of 2 mm as a function of initial offset angle in two-bulk system.

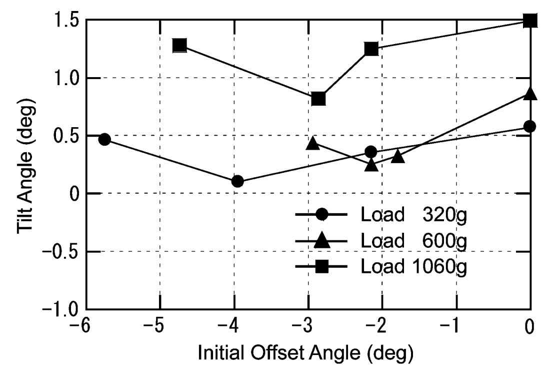

Fig. 8. Experimental results of tilt angle for horizontal levitation at initial air gap of 4 mm as a function of initial offset angle in two-bulk system.

the tilt angle of 2.8 deg in the single bulk system, while much smaller tilt angle of 1.1 deg was obtained at the load weight of 1060 g in the two-bulk system. The big difference in these results is caused by the difference of the distance between the load and the bulk. Since the bulk did not exist under the load in the single bulk system, the load weight of 1 g could not be directly sustained from under the load. On the other hand, the bulk could directly sustain the load weight of 1060 g from just under the load in the two-bulk system. These results imply that reducing the distance between the load and the bulk is effective in sustaining heavy load weight and reducing the tilt angle.

In the two-bulk system, the weight of 1060 g in the left-hand side load would be sustained by not only the left-hand side bulk but also the right-hand side bulk. Therefore, we investigated influence of the interaction of restoring force between the bulks on the tilt angle. The air gap in the single bulk system was measured as a function of load weight. The measured air gap is shown in Fig. 6. Acceptable maximum load weight was 640 g and 680 g at the initial air gap of 2 mm and 4 mm, respectively. The acceptable maximum load weight was much less than the weight of 1060 g in the experiment of the two-bulk system. This means that the right-hand side bulk greatly contributed to sustain the load weight of 1060 g.

We calculated the tilt angle in the two-bulk system as a function of the weight of the left-hand side load. Note that the weight of the right-hand side load was fixed to be 1 g in the calculation. The tilt angle was calculated according to the following steps: 1) estimate the air gap between each bulk and permanent magnet unit by using the experimental results in Fig. 6; 2) calculate the vertical distance between the bulks by using the estimated air gap in step 1; and 3) calculate the tilt angle using the horizontal distance between the bulks and the calculated vertical distance in step 2. The calculated tilt angle is added to Fig. 5. The measured tilt angle was apparently smaller than that of calculation. This is because not only the restoring force in the left-hand side bulk but also that of the right-hand side bulk reduced the displacement in the pitch direction.

Based on the results of Fig. 5, we investigated the suitable initial offset angle for horizontal levitation. The tilt angle was measured as a function of initial offset angle. The experimental results of the tilt angle at the initial air gap of 2 mm and 4 mm are shown in Fig. 7 and Fig. 8, respectively. At the initial air gap of 2 mm, horizontal levitation could be achieved, while no horizontal levitation at the initial air gap of 4 mm. This is because magnetic stiffness between the bulk and the permanent magnet unit decreases with the initial air gap.

C. Dependence of Vibration Characteristic on Load Weight Distribution

The schematic drawing of an experimental setup for horizontal vibration is shown in Fig. 9. To investigate influence of load weight distribution on the vibration characteristics, we measured the horizontal displacement between the permanent magnet unit and the Styrofoam container as a function of vibration frequency. The experiment was performed in the following

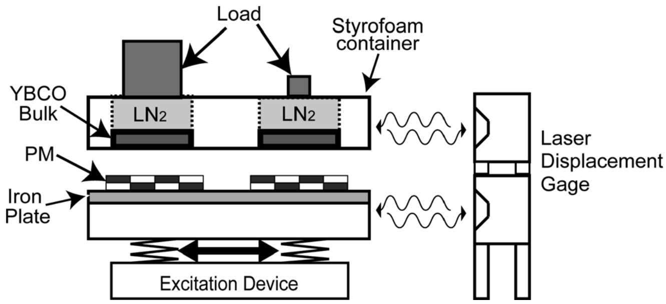

Fig. 9. Schematic drawing of an experimental setup for horizontal vibration characteristics in two-bulk system.

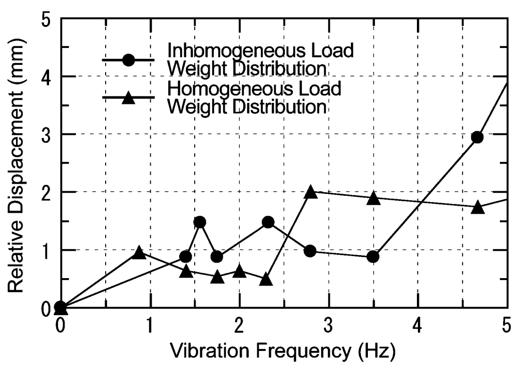

Fig. 10. Experimental results of relative displacement between YBCO bulks and permanent magnets as a function of vibration frequency in two-bulk system.

two cases. One is about inhomogeneous load weight distribution. The weight in the left-hand side load was 520 g and that of the right-hand side load was 1 g. The initial offset angle and the tilt angle used in the experiment were -1.3 deg and 0 deg, respectively. The other is about homogeneous load weight distribution. Both loads were put on the center of the Styrofoam container. The measured horizontal displacement is shown in Fig. 10. The same level of the displacement was obtained in the experiment. This implies that seismic isolation effect in magnetic levitation type device can be obtained independent of the load weight distribution of the structure.

III. Analysis

It was demonstrated that magnetic stiffness in the pitch direction contributed to reduce the tilt angle of the structure with inhomogeneous load weight distribution. To clarify the details of magnetic stiffness in the pitch direction, we investigated electromagnetic behavior within the bulk analytically. Analytical model based on the stored energy within the bulk was adopted to evaluate the restoring force against a displacement in the pitch direction [4]. The restoring force in the x-direction, for example, can be obtained by:

$$F_x = \frac{-S^2}{L}\left(\sum(B_x - B_{x0})\frac{\partial B_x}{\partial x} + \sum(B_y - B_{y0})\frac{\partial B_y}{\partial x} + \sum(B_z - B_{z0})\frac{\partial B_z}{\partial x}\right) \quad (1)$$

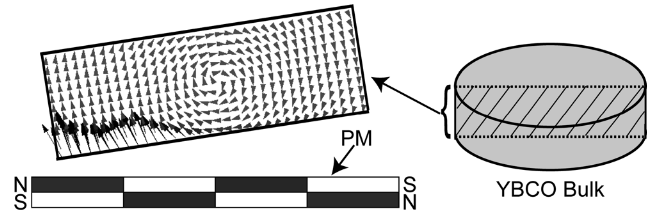

Fig. 11. Numerical result of restoring force distribution in a rectangular cross-section of YBCO bulk tilted in the pitch direction.

where S and L are the area and the self-inductance of a supercurrent loop in each element, respectively; B_{i0} and B_i are the magnetic flux density in the i direction $(i = x, y, z)$ before and after the displacement, respectively. The bulk was divided into many infinitely small elements and restoring force was evaluated by calculating electromagnetic energy stored in each element.

The restoring force distribution in a rectangular cross-section of the bulk is shown in Fig. 11. The initial offset angle of 0 deg and the tilt angle of 10.3 deg were adopted in the analysis. These parameters were obtained in the experiment of the single bulk system at the load weight of 2 g and the initial air gap of 4 mm. The restoring force concentrates in the left-hand side bottom of the bulk. This is because the magnetic flux density in the left-hand side of the bulk is much larger than that of the right-hand side. The direction of the restoring force is clockwise. This is because in the experiment the bulk was tilted in the counterclockwise direction due to the inhomogeneous load weight distribution.

IV. Conclusion

Dependence of horizontal vibration characteristics on load weight distribution in magnetic levitation type seismic isolation device was investigated in consideration of magnetic stiffness in the pitch direction. Inhomogeneous load weight distribution caused the different air gap in each bulk, so that the levitated bulks were tilted. Horizontal levitation, however, could be obtained by adjusting the initial offset angle in the field-cooling process of each bulk. The smaller initial air gap was effective in adjusting the initial offset angle for horizontal levitation. Reducing the distance between the load and the bulk was effective in sustaining the heavy load weight and reducing the tilt angle. The horizontal vibration characteristics were almost independent of the load weight distribution.

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