Operational Characteristics of Linear Synchronous Actuator with Field-Cooled YBCO Bulk Secondary

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Abstract. It is expected that electric devices would be high efficiency, high output and downsized by using high-temperature superconducting (HTS) bulk materials. In the previous study, we have fabricated and tested a linear synchronous actuator with double-sided primary and YBCO bulk secondary; the linear actuator consists of a field-cooled YBCO bulk for secondary (mover) and copper windings with an iron core as a primary. The primary, which was excited by a three-phase VVVF (variable voltage variable frequency) power source to generate sinusoidal traveling magnetic fields, was divided into two sections: 1) the starting section in which the secondary is accelerated as an induction machine; and 2) the synchronous section in which the secondary moves with a specified synchronous speed. And we have evaluated both of the static and dynamic characteristics on this linear synchronous actuator. However, for practical use of linear actuator with field-cooled HTS bulk secondary, it is required to examine the distribution of magnetic field within the HTS bulk which is exposed to the traveling magnetic field in a realistic operational environment of linear actuator. Therefore, in this study, we repeated the mode of acceleration, constant-speed, deceleration and stop with the control circuit in the synchronous section. The direction of the mover can be turned automatically by the switching device and it made round-trip running possible. Then, we carried out many times round-trip operations and evaluated the change of the magnetic field on the surface of the YBCO bulk in various conditions with trapped field of the secondary and traveling magnetic field generated by the primary windings.

1. Introduction
It is expected that HTS bulk materials will be applied to various electric devices such as motors, flywheels and levitation systems, and so on [1]. Linear synchronous actuators with field-cooled bulk secondary have the potential to obtain larger magnetic field than conventional ones with permanent magnets. Therefore, it is expected that the linear actuator with field-cooled bulk secondary can generate larger thrust forces and can be designed with larger air gaps between primary and secondary compared with conventional ones.

Then, we designed and fabricated a model linear actuator with double-sided primary and YBCO bulk secondary. The linear actuator with double-sided primary is superior to that with single-sided primary in terms of generating larger magnetic field, while the magnetic attractive force between iron of primary and field trapped HTS bulk secondary can be cancelled [2]. The aim of fabricated model system is to investigate the dynamic characteristics as a synchronous linear actuator. Therefore, in this experiment, all primary windings were used as synchronous drive sections.
In this paper, first of all, we evaluated pull-in characteristics to synchronization as dynamic characteristics. And, we evaluated the change of the trapped magnetic field of the bulk to examine the distribution of magnetic field within the HTS bulk which is exposed to the traveling magnetic field in a realistic operational environment of linear actuator.

2. Model Actuator

2.1. Structure

A schematic drawing of a model linear synchronous actuator is shown in Fig. 1. The primary of the linear actuator are composed of copper windings with iron core in which the distributed and short-pitch windings are adopted. The secondary of the linear actuator consists of a plate-shaped field-cooled YBCO bulk. The primary was excited by a three-phase VVVF power source to provide a sinusoidal travelling magnetic field. The primary AC current of 1.5 A (effective value) generates a magnetic field of 0.02 T in the air gap. As shown in Fig. 1, the secondary takes the form of a “T”. The YBCO bulk plate are located vertically and fastened to the center of the secondary. To move the secondary smoothly, bearings are attached on both sides of the secondary. The length of the bulk plate in the driving direction is 28 mm (= \( \tau/3 \), where \( \tau \) is the pole pitch of primary). The YBCO bulk plate was immersed in a L.N2 bath during experiments. Specifications of the model linear actuator are listed in Table 1.

2.2. Field-cooling

We prepared solenoid coils arranged on the same axis for field trapping in the bulk as shown in Fig. 1. The coils, with an inner diameter of 60 mm, an outer diameter of 116 mm, and 13 mm thickness, were wound by 250 turns of copper wires and generates 0.09 T at the center at 15 A. The YBCO bulk was magnetized by field-cooling process. After field-cooling, the magnetic field distribution at points of 2mm from the surface of the YBCO bulk is 0.08 T at the center when coil current is 15A. After trapping a field, the YBCO bulk plate was fastened to the center of the secondary (mover).

2.3. Principle of Drive

We prepared VVVF power sources for the synchronous section. The YBCO bulk secondary is accelerated as a synchronous machine. And we repeated the mode of acceleration, constant-speed, deceleration and stop with the control circuit. Constant-speed section is energized by low-frequency source (2 Hz). Synchronous speed is 0.336[m/s] when operating by 2Hz. The direction of the mover can be turned automatically by the switching device and it made round-trip running possible.

![Figure 1. Schematic drawing of (a) model linear actuator, (b) coil system for field-cooling.](image-url)
Table 1. Specifications of model linear actuator.

| Primary        |                         |         |
|----------------|--------------------------|---------|
| Iron core      |                          |         |
| pole pitch     | [mm]                     | 84      |
| primary iron length | [mm]           | 4200    |
| primary iron width  | [mm]                  | 30      |
| primary iron thickness | [mm]          | 60      |
| teeth width    | [mm]                     | 7       |
| slot width     | [mm]                     | 7       |
| slot depth     | [mm]                     | 35      |
| Copper winding |                          |         |
| number of turn |                          | 50      |
| Resistance     | [Ω]                      | 0.55    |
| supplied frequency | [Hz]                | 2       |

| Secondary      |                          |         |
| Field-cooled HTS bulk |                   |         |
| Length         | [mm]                     | 28      |
| Width          | [mm]                     | 30      |
| Thickness      | [mm]                     | 5       |

3. Experiments

3.1. Dynamic characteristics

In this experiment, we set the frequency at constant-speed to 2 Hz, the synchronous speed was 0.336 m/s in the constant-speed section. We observed the synchronous process in the various cases. The ratio of primary current and field-cooling current was changed, and we experimentally evaluated the characteristics of pull-in to a synchronous speed. Fig. 2 shows speed in synchronism. It can be seen in Fig. 2 that pull-in to synchronization has succeeded. Fig. 3 shows the results of experiments under various conditions. From the result, pull-in characteristics to synchronization improved by enlarging field-cooling current or primary current and when the value in which primary current is crossed to field-cooling current is more than a certain constant value, it is possible to pull-in.

![Figure 2. Speed in synchronism. (field-cooling current 15A, primary current 1.5A)](image1)

![Figure 3. Result of pull-in characteristics.](image2)
3.2. Distribution of trapped field

We repeated the mode of acceleration, constant-speed, deceleration and stop with the control circuit in the synchronous section. Then, we carried out many times round-trip operations and evaluated the change of the magnetic field on the surface of the YBCO bulk in various conditions with trapped field of the secondary. We installed Hall probes on the surface of the bulk of the secondary, and measured the change of the trapped magnetic field of the bulk while the round-trip drives with the oscilloscope. The magnetic field on the surface of the bulk was measured by using the 10 Hall probes. The Hall probes were arranged from a central part of the bulk along to the traveling direction. Fig. 4 shows the magnetic field distribution of the YBCO bulk after 50 times round-trip drives. From the results, distribution of trapped magnetic field of the bulk didn’t changed so much, and almost constant regardless of strength of magnetization.

4. Conclusion

We designed and constructed a double-sided primary and short-secondary type of linear synchronous actuator with synchronous operation. And, we examined the distribution of magnetic field within the HTS bulk which is exposed to the traveling magnetic field in a realistic operational environment of linear actuator. Synchronizing characteristics and magnetic field characteristics were examined in the model linear actuator. The results are summarized as follows;

1) When the value in which the product of primary current and field-cooling current is greater than a certain constant value, it is possible to pull-in.

2) Trapped magnetic field of field-cooled HTS bulk didn’t changed for 50 times round-trip operation regardless of the strength of magnetization.

References

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