pISSN 1229-3008 eISSN 2287-6251
Progress in Superconductivity and Cryogenics
Vol.25, No.1, (2023), pp.11~15 https://doi.org/10.9714/psac.2023.25.1.11

Experimental study on the interaction force between a permanent magnet and a superconducting roll stack

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(Received 5 January 2023; revised or reviewed 29 March 2023; accepted 30 March 2023)

Abstract

In recent years, the interaction force between a permanent magnet and a closed superconductor coil has been gradually investigated in depth. The principle and application potential of an energy storage/convertor composed of a magnet and a closed superconducting coil have been proved. However, the study on the force between a magnet and a non-closed superconducting coil (superconducting roll stack) has hardly been reported in previous literature. The behavior of this kind of interaction and its influence to the interaction force between a permanent and a closed superconducting coil are also still unclear. In this paper, first we investigated the interaction force between a magnet and a superconducting roll stack. Then, a series of experiments were designed and conducted to clarify the factors affected the interaction force, including the geometrical parameters of the superconducting roll stack and the magnetic field density at the roll stack. Moreover, the comparison of the interaction forces between the magnet and roll stack or a closed coil was also introduced.

Keywords: superconductivity, superconducting roll stack, permanent magnet, interaction force

1. INTRODUCTION

The interaction between a permanent magnet and a superconductor ring or closed superconductor coil have attracted research interest with the development and application of high temperature superconductor [1-6]. It has been found that the interaction force acting on the magnet does not always impede its motion. When an axially magnetized cylindrical magnet approaches the superconductor coil along the mutual axis of the magnet and coil, the magnet experiences an interaction force opposite to the direction of its movement. When the magnet passes through the coil and continues to move, the force acting on the magnet is in the direction of its movement [4]. Based on the interaction behavior, a superconducting energy storage/convertor composed of a permanent magnet and a closed superconductor coil can be built, which is promising for application in the field of vehicle regenerative braking, and also has the potential to be used in the field of EMALS (Electromagnetic Aircraft Launch System) and flux pump [7, 8].

Recently, we experimentally found that the interaction force between a permanent magnet and a superconducting roll stack is visually different from the force between the magnet and a closed superconducting coil. The superconducting roll stack can be considered as a non-closed superconducting coil with turn-to-turn insulation. It results in no induced current flowing through superconducting tape can be generated. However, there are few studies on the interaction force between a permanent magnet and a superconducting roll stack, and its effect on the interaction force between a permanent magnet and a closed superconducting coil is not clear yet.

In this paper, the interaction force between a permanent magnet and a superconducting roll stack was studied by experiment. We first introduced the experimental apparatus and specimens used for the investigation. Then, we conducted a series of experiments to investigate the interaction force and the factors affecting the interaction force using roll stacks with different geometrical parameters and magnets with different grades. Furthermore, the interaction forces between a magnet and a superconducting roll stack or a closed superconductor coil were also compared.

2. EXPERIMENTAL APPARATUS AND SPECIMENS

2.1. Experimental Apparatus

In this study, we conducted experiments on a 3D measurement system [9]. The system is shown in Fig. 1, it can be used for measuring forces in three dimensions by replacing proper load sensors, but we only used it for measuring the force in one dimension, *z*, in the following experiments. As shown in Fig. 1, a superconducting roll stack can be fixed in a sample container made of nylon. The container is bolted together with a sliding platform, which is made of aluminium. A permanent magnet is installed on a load sensor by means of a non-magnetic rigid rod. The load sensor is vertically installed on the suspension arm of the system. The suspension arm (along with the load sensor and magnet) is able to be driven by the servo-motor to move in *z*-axil, which is controlled with a computer. The (pulling and pushing) force acting on the magnet is measured with the load sensor and recorded with a computer.

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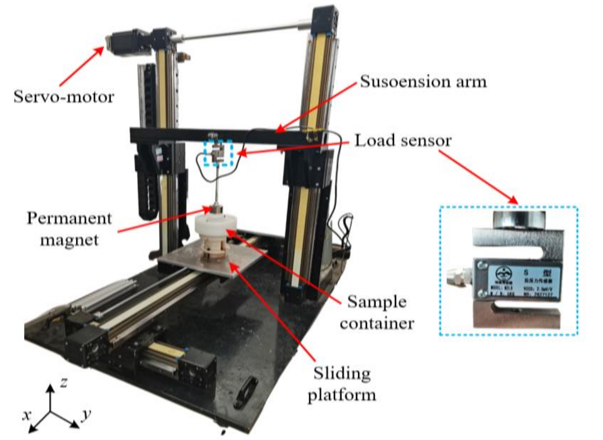

Fig. 1. Photo of the experimental apparatus.

The specifications of the measurement system and the load sensor are listed in Table I. These parameters show that the measurement system has high accuracy and small error, and it is reliable for studying the interaction force between a magnet and a superconducting roll stack.

2.2. Specimens Used in Experiments

In order to make the critical currents of the used superconducting tapes as equal as possible, we used the same batch of Bi-2223 superconducting tapes produced by Sumitomo Electric Industries for all the experiments in this study.

Five superconducting roll stacks were fabricated with the superconducting tapes which were wrapped with polyimide insulation tapes in advance. The parameters of them are listed in Table II. As shown in Fig. 2, we take roll stack 4 including two pancakes as an example. *h* is the height of the roll stack. Since the width of the superconducting tape (4.5 mm) determines the height of each pancake of the roll stack, we can only increase the *h* to multiple of 4.5 mm by increasing the number of pancakes. *w* is the width of the roll stack, *r* is the inner radius of the roll stack, and r_{ave} is the average radius of the stack.

TABLE I
KEY SPECIFICATIONS OF THE APPARATUS.

Parameters	Sliding platform (z-axis)	Load sensor
range	900 mm	5 kg
accuracy	0.05 mm/m	2 g/kg
comprehensive error	±0.01 %F·S	±0.03 %F·S

TABLE II
GEOMETRICAL PARAMETERS OF THE SPECIMENS.

Specimens	Parameters			
	h	w	r	r_{ave}
roll stack 1	4.5 mm	18 mm	31.5 mm	40.5 mm
roll stack 2	9 mm	4.5 mm		33.7 mm
roll stack 3	9 mm	9 mm		36 mm
roll stack 4	9 mm	18 mm		40.5 mm
roll stack 5	18 mm	18 mm		40.5 mm

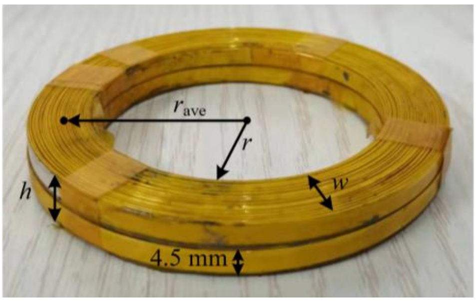

Fig. 2. Photo of the superconducting roll stack 4.

Three permanent magnets with the same dimensions but different grades were used in this study. All the magnets have the shape of cylindrical, material of Nd-Fe-B, height of 30 mm, and diameter of 50 mm. Fig. 3 is the photo picture of magnet I. The magnetic field densities at the center of the surface are 830 Gs for magnet I, 1630 Gs for magnet II, and 3970 Gs for magnet III.

2.3. Experimental Procedure

During the experimental preparation, we controlled the sliding platform to move along the *x*-axis and *y*-axis until the magnet and the superconducting roll stack were coaxial. From here on, we no longer moved the sliding platform in the *xy*-plane, but only drove the magnets to move along the *z*-axis.

When proceeding experiment, we installed one magnet on the one end of the rigid rod, and fixed a roll stack into the container. The magnet was moved to a starting position. The roll stack was cooled with liquid nitrogen. Then, we drove the magnet in a specified trajectory (from the starting position to an ending position) with speed of 5 mm/s to complete force measurement. Meanwhile, the force acted

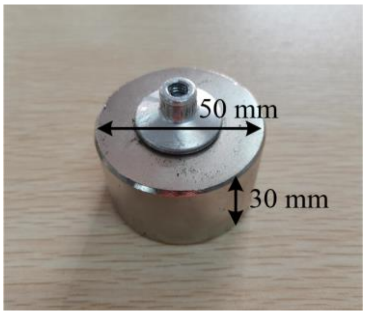

Fig. 3. Photo of magnet I.

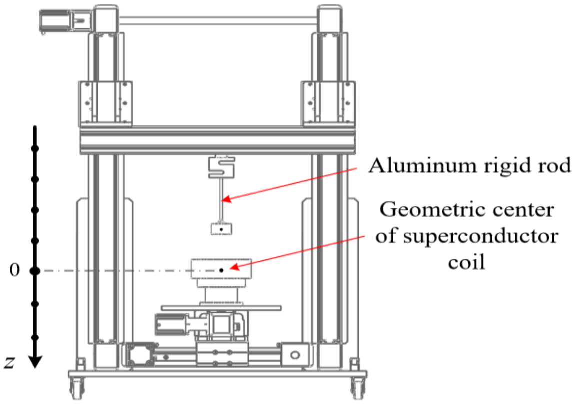

Fig. 4. Definition of the coordinate.

on the magnet was measured and recorded.

For analysis, we define the coordinate as in Fig. 4. The geometric center of the superconducting roll stack is set to be the coordinate origin, and the position of the origin changes with the height of the stack. The positive direction of *z*-axis is illustrated in Fig. 4. The interaction force on the magnet is taken as positive if it is downward.

3. INTERACTION FORCE BETWEEN PERMANENT MAGNET AND SUPERCONDUCTING ROLL STACK

In this section, we carried out experiments with the roll stacks and magnets to study the interaction force between a permanent magnet and a superconducting roll stack, and clarify the factors affecting the interaction force.

We conducted the first test with roll stack 4 and magnet II. The position of z = -70 mm is taken as the starting position, and z = 70 mm as the ending position. We performed the test with the experimental procedure described in Subsection 2.3. The interaction force, F_L, between the magnet and the roll stack was recorded in real time.

The result of the test is plotted in Fig. 5. From the F_L-z curve, in the process of the magnet approaching and passing through the roll stack, the interaction force impedes the motion of the magnet most of the time, and the amplitude of the force curve increases as the distance between the magnet and the roll stack decreases. The pattern of the curve looks complicated and has no symmetry, and the two peak values of the curve are -1.8 N and -4.3 N, respectively, at z = -22 mm and z = 6 mm.

Based on the investigations of the force of superconductor bulk or bulk stack in external magnetic field, both the dimensions of superconductor and the magnetic field have much influence on the force [10-16]. Thus, we believe that the interaction force is affected by the geometrical parameters of the superconducting roll stack and the magnetic field density at the stack. In order to clarify the effect of these factors on the interaction force, another three sets of experiments are conducted respectively. To reduce the effect of noise on the graphical display of the experimental results, the sampling frequency is reduced appropriately in the following three tests.

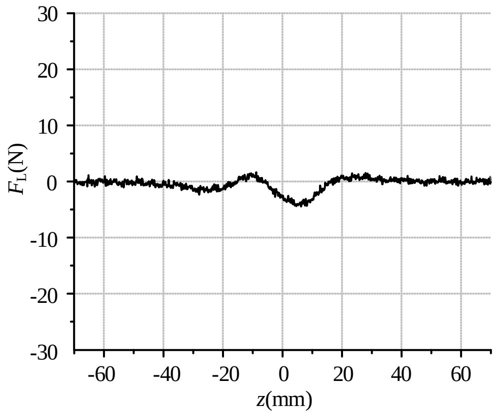

Fig. 5. Curve of interaction force between the magnet and the superconducting roll stack.

3.1. Experiments with Different Height of Roll Stack

We used magnet II to conduct tests with roll stack 1, 4, and 5 respectively. Each test was carried out with the experimental procedure in Subsection 2.3, and the magnet's moving trajectory was taken as z = -70 mm → z = 0 → z = 70 mm. The results for these three tests are shown in Fig. 6.

In the figure, the black circle plot shows the result of the test with the roll stack whose h is 4.5 mm, the red triangle plot shows that with whose h is 9 mm, and the green square plot shows that with whose h is 18 mm. The maximum interaction forces in the three tests are -3.1 N, -6.2 N, and -10.4 N respectively. It means that the interaction force increases almost proportionally with the height of the superconducting roll stack. In addition, the acting distance of the interaction force also increases with the height.

3.2. Experiments with Different Width of Roll Stack

In this section, roll stack 2, 3, 4 with different w and magnet II were used. The experimental process is the same as that of the test in the last subsection. The experimental results with w of 4.5 mm, 9 mm, and 18 mm are plotted in Fig. 7.

In the figure, as w increases, the maximum values of the experimental curves are -3.4 N, -5.3 N, and -5.8 N respectively. The red triangle plot and the green square plot are nearly coincident, while the amplitude of the black

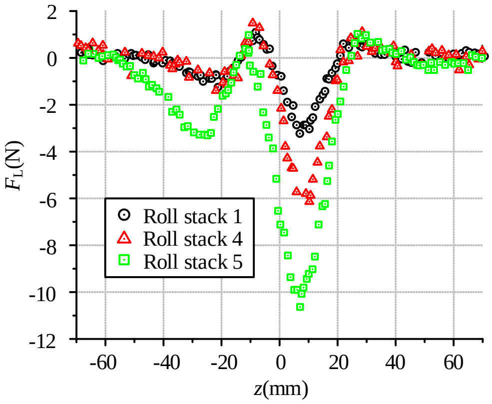

Fig. 6. Experimental results on the factor h.

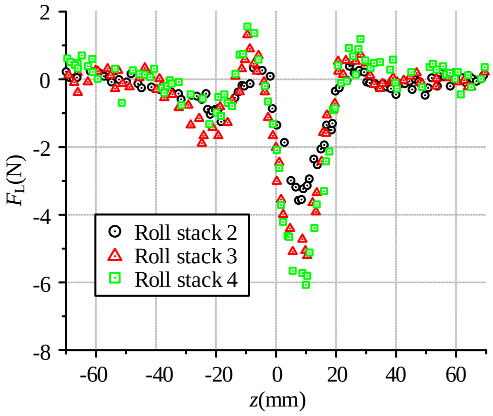

Fig. 7. Experimental results on the factor w.

circle plot is smaller than that of the other two. It can be attributed to the shielding effect of the inner layers of the superconducting roll stack, making the outer portion of the roll stack almost does not interact with the permanent magnet. Therefore, for a magnet, when the width of the roll stack is smaller than a certain value, w_0, the interaction force increases as the width of the roll stack. When the width of the roll stack is larger than w_0, the interaction force no longer increases with w increases. The outer layers contribute little to the increase in interaction force, and the force no longer increases with the width of the roll stack.

3.3. Experiments with Different Magnetic Field Density at Roll Stack

We used roll stack 4 and magnet I, II, and III for this set of experiments. To quantify the magnetic field density (B) at the stack brought about by different magnets, we placed the magnets at the origin respectively at room temperature, and measured the magnetic field at the position of average radius of the roll stack, r_{ave}. We obtained that they are 400 Gs for magnet I, 560 Gs for magnet II, and 830 Gs for magnet III.

For each test, the roll stack and one of the magnets were installed on the measurement system to complete the force measurement with the experimental procedure described above. Then, we plotted the experimental results in Fig. 8.

From the results, the maximum values of the curves with B = 400 Gs, 560 Gs, 830 Gs are -3.8 N, -6.1 N and -10.1 N respectively. Obviously, the interaction force is proportional to the magnetic field density at the roll stack.

4. DISCUSSIONS

To compare the interaction forces between a permanent magnet and a superconducting roll stack or a closed superconducting coil, we soldered the two taps of roll stack 4 to form a closed coil, and then repeated the first test with the closed coil and magnet II. The interaction force, F, between the magnet and the closed coil was recorded and plotted in Fig. 9.

From the F-z curve, the direction of the interaction force is opposite before and after the magnet passes through the origin. The interaction force reaches peak values are -26.7 N and 25.6 N at z = -13 mm and z = 14 mm respectively.

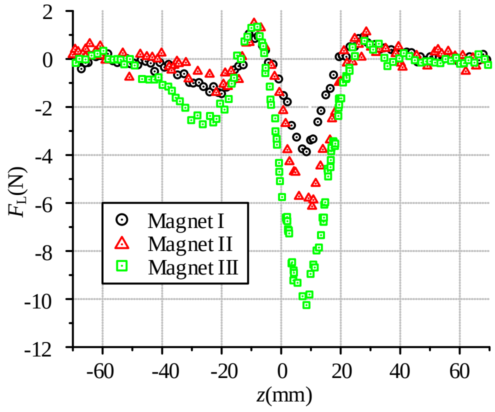

Fig. 8. Experimental results on the factor B.

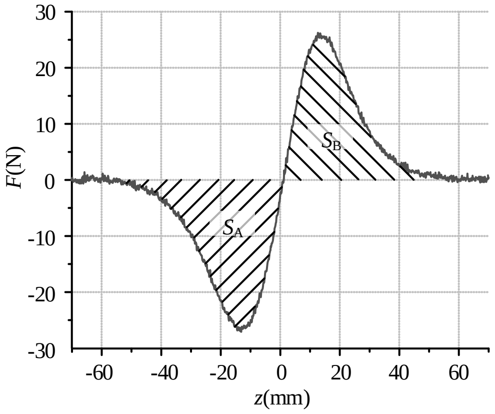

Fig. 9. Curve of interaction force between the magnet and the closed superconducting coil.

Comparing the curves in Fig. 9 and Fig. 5, the patterns of the curves are dramatically different. The reason for the difference is that there is an induced current flowing through the closed coil during the experiment, but not in the superconducting roll stack. In more detail, the values of F_L at z = -13 mm and z = 14 mm are 1 N and -3 N, which is nearly an order of magnitude smaller than the values of F at the same positions. This indicates that the value of F_L has an impact on F, but it is relatively small. Moreover, we calculated the areas of the shaded parts in Fig. 9, S_A=642.06 N·mm and S_B=574.72 N·mm. We have proved that the joule loss on the joint resistance takes unshirkable but not all responsibility for $S_B < S_A$ from the perspective of energy conversion [4,5]. Since the direction of F is opposite before and after x = 0 but the direction of F_L is almost unchanged, we believe that the interaction force from the roll stack also plays a role in the contribution to $S_B < S_A$. Therefore, the influence of the interaction between magnet and roll stack is small on the magnitude of interaction force between a permanent magnet and a closed superconducting coil, but takes effect in improving the conversion efficiency of the energy storage/convertor.

Form the previous analysis, we believe that for a closed superconducting coil with certain number of turns, the coil with larger w but smaller h is better for the energy storage/convertor.

5. CONCLUSION

In this study, we have conducted experiments to study the interaction force between a permanent magnet and a superconducting roll stack. The factors affecting the interaction force in superconducting roll stack have been studied, including the geometrical parameters of the roll stack and the magnetic field density at the roll stack. The experimental results show that the interaction force is almost proportional to the height of the roll stack and the magnetic field density at the roll stack, and it also increases with increasing width of the roll stack until the width exceeds a certain value.

Moreover, the comparison of the interaction forces between a permanent magnet and a superconducting roll stack or a closed superconducting coil is conducted. The results demonstrated that the configuration with the permanent magnet and the closed coil can be used as an energy storage/convertor device, while the configuration with the permanent magnet and the roll stack cannot. It also can be concluded that the interaction force between a permanent magnet and a superconducting roll stack affects the force between the magnet and a closed superconducting coil, but the effect should be relatively small.

ACKNOWLEDGMENT

This work was supported in part by the Tianjin Research Innovation Project for Postgraduate Students (grant no. 2021YJSB157).

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