Magnetic torque transferring study for bulk High-$T_c$ superconductors and permanent magnets

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Abstract. The torque transferring mechanism taking place in a superconducting mixer design has been studied. Several coupling magnetic arrangements were investigated for more details in the engineering design. A bulk superconductor sample was used to study the torque forces for various cooling gaps, and the twist angle dependence was also monitored for the rotational stiffness in stability. The experimental data with four permanent magnet configurations have been studied in the present work. The maximum torque forces are summarized for usage of engineering design with various gaps. The torque/gap characteristics for four configurations were also measured for the optimisation of the torque at a designed operating gap.

1. Introduction

One of the attractive properties of bulk RE-Ba-Cu-O (RE: rare earth elements) superconductors is that they can levitate a permanent magnet, and can firmly hold it in midair by virtue of flux pinning effect. Such levitation effect can lead to the applications to avoid the contact between materials and perfectly frictionless mechanism, for example, superconducting bearings, superconducting flywheel energy storage system, contact-less conveying system and levitated vehicles [1]. Superconducting materials can also provide torque forces when multi-pole magnetic fields were trapped inside the bulk superconductors. A mixing process without contamination can be performed with a superconducting mixer [2]. Such a device is attractive for medical applications where an ultra clean environment is required. In this study, we try to maximize the torque force between a bulk superconductor and permanent magnet in various configurations of magnetic poles. Furthermore, we studied the torque force as a function of gap in all the configurations.

The understanding of torque transferring mechanism is a goal of this study, which will lead us to develop a robust non-contact superconducting mixer that our research group have tackled in the previous studies [2, 3]. The new design of non-contact torque transferring mechanism was innovated as shown in Figure 1.

Bulk superconductors used in the present study were commercially available Dy-Ba-Cu-O bulk superconductors (Nippon steel) produced by a typical top-seeded melt-growth process. The chemical composition of the sample was DyBa$_2$Cu$_3$O$_{6.9}$ 75.0 wt%, Dy$_2$BaCuO$_{5.0}$ 24.5 wt% and Pt 0.5 wt%. The sample dimensions were 30 mm in diameter and 5 mm in thickness.

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The experimental study will verify the suitable configuration that will yield the optimum torque transferring characteristics. The operating gap dependence is also taken into account. However, uncomplicated arrangement of magnetic poles will be the first candidate to avoid the additive cost in practical applications.

2. Analytical model

Magnetic torque transferring characteristics have already been studied in various superconductor/permanent magnet configurations [4-6]. Tixador et al. [4] have studied the superconducting coupling device which is based on transverse force acting between multiple sets of superconductor/permanent magnet couples. However, they still need a rotational support to hold the coupling set of permanent magnets. Thus perfectly non-contact torque transferring was not achieved in their work.

Type-II superconductors can trap magnetic fields and thus behave like a permanent magnet in that the quantized fluxoids were pinned at normal conducting particles in a superconductor matrix. Physically, the pinning force which is induced by approaching a pole of permanent magnet toward a superconductor can repulse magnetic field, which leads to levitation and then free rotation in mid air. Therefore, we induced the pinning force of the superconductor with the different magnetic poles on the same face, which generated the torque coupling between them in a perfectly non-contact mode. However, we learned that the force between a permanent magnet and a bulk superconductor must be balanced in a vertical direction, because the repelling force of the superconductor against a permanent magnet was much higher than the attractive force at the designed gap.

In a radial direction, the total pinning force of an activated volume with the differential of magnetic flux in both radial and angular directions at various gaps have been studied. In this work we also tried to maximize the torque force by optimising the configuration of permanent magnets. The superconductor/permanent magnets interactions are considered based on Maxwell’s equation and Ampere’s law. Once we simplify by the magneto-quasi-static reduction thus we obtained,

$$\nabla \times B = \mu_0 J$$

(1)

In the torque coupling mechanism, however, the torque forces acting between a superconductor and permanent magnets will include the transverse force. To yield the maximum torque, the trapped pinning forces have to be induced as large as possible. Therefore, the transverse force between a superconductor and permanent magnet can be expressed as follows:

$$F_r = \int_{v_w} \mu_0 M(H) \frac{dH}{dr} dv$$

(2)
Then we applied the classical Bean model approximation to the magnetization in the case of full penetration field. We obtained thus

\[ F_r \approx \mu_0 J_c a \frac{dH}{dr} V_{act} \]  \hspace{1cm} (3)

Where \( H \) is the field created by the permanent magnets and \( V_{act} \) is the superconducting volume, which develops magnetization. In alternating magnetic poles excitation, the single domain grain size is considered large, so that \( a \) is equal to the elementary magnet width. Then the torque force will be a function of \( r \), leading to a fundamental equation:

\[ d\tau = dr \times F_r \]  \hspace{1cm} (4)

As for the definition of rotational stiffness, \( k \), is the derivative of the applied torque respect to the angle of distortion, \( \theta \), in particular when considering the stability limit of the mechanism.

\[ k = \left( \frac{\partial \tau_r}{\partial \theta} \right) \]  \hspace{1cm} (5)

Following the standard of International Electrotechnical Commission (IEC) code 61788-9/CDV, the measurements for bulk high temperature superconductors of magnetic field trapped was described in details [7]. Thus we followed the procedure of the standard, the \( J_c \) value will be calculated by the empirical equation as expressed below.

\[ B_z = C \left( (z + D) \ln \frac{R + \sqrt{R^2 + (z + D)^2}}{z + D} - z \ln \frac{R + \sqrt{R^2 + z^2}}{z} \right) \]  \hspace{1cm} (6)

where \( B_z \) = the trapped flux density
\( z \) = a gap between a superconductor and a magnetic sensor
\( D \) = the height of a superconductor
\( R \) = a radius of a superconductor
\( C \) = the constant related to \( \mu_0 J_c \)

The numerical evaluation in comparison to the experimental results is also necessary in the engineering design. Once the simulation method is established, one can estimate the torque forces for large devices in practical applications scale.

3. The experimental set up

We used commercially available Dy-Ba-Cu-O samples (Nippon Steel) produced by the top-seeded melt growth process, the detail of which is described in ref [1]. The chemical composition of the sample was DyBa2Cu3O6.9 75.0 wt%, Dy2BaCuO5.0 24.5 wt% and Pt 0.5 wt%. The samples were single-domain with dimensions of 30 mm diameter and 5 mm thickness in which \( c \)-axis was aligned parallel to the axial direction.

The magnetic field trapped by the sample have been investigated to estimate the \( J_c \) value by following the International Electrotechnical Commision standard number 61788-9/CDV. For instance, the sample was cooled in the presence of the external magnetic field at 77 K. The excited magnetic field was applied by Nd-Fe-B permanent magnet with the surface flux density of 0.45 T and remnant of 1.1 T. The magnets are concentrically set to the sample to apply the magnetic field parallel to the \( c \)-axis of the sample. The magnetic field trapped by the sample was measured after the removal of
As suggest in the standard, the trapped flux density values are those measured after at least 15 minutes of removal of external field [7]. We have designed an experimental set up which can be used for the trapped field measurements in a static field of a permanent magnet. The upper and lower stand can move in both ascending and descending modes smoothly controlled by a thread-levelling fixture. After cooled to a superconducting state in a field-cooled condition as explained above, a set of permanent magnets were removed from the sample. In this process, the field generated from the permanent magnet was trapped by the superconductor. Then, the field distribution trapped by the sample was measured by scanning a Hall probe sensor at every 1 mm pitch on the squared scanning area on the sample surface as the same in ref. [8].

The torque coupling measurements can also be performed using the configuration shown in Fig. 2. Here the upper magnet part is fixed to a torque measuring instrument aligned concentrically with the frame rods. The exciting set of permanent magnets will also be rigidly fixed with the torque measuring instrument that allows only the angular direction movement. The experiments were studied for four different configurations of Nd-Fe-B magnets such as, two poles conventional magnetic coupling, 2-poles bar shape, 2 poles square and 4 poles square permanent magnets, which are schematically shown in Fig. 3. The specification details of the components are summarized in Table 1.

Table 1. Specification details of components

| Component     | Material       | Dimensions (mm) | Surface flux density (T) |
|---------------|----------------|------------------|--------------------------|
| Superconductor| Dy-Ba-Cu-O     | ∅30 x 5t         | N/A                      |
| 2 poles coupling | Nd-Fe-B   | ∅40 x 10t       | 0.466                    |
| 2 poles bar   | Nd-Fe-B       | 40x20x10         | 0.457                    |
| 2 poles square | Nd-Fe-B    | 40x40x10         | 0.394                    |
| 4 poles square | Nd-Fe-B    | 40x40x10         | 0.472                    |
The relationship between the torque force and the gap has also been studied by varying the gap in the field-cooling mode at every 1 mm. The torque forces were measured with a digital programmable torque-measuring instrument with a resolution of 0.001 Nm. The data have been recorded at every 10-degree angle of twist.

4. Results and Discussion

Figure 4 shows the trapped field distribution of Dy-Ba-Cu-O sample, which shows the peak trapped field value of 0.323 T. Following the empirical equation expressed in IEC standard as shown in eq.(6), the average $J_c$ value over the volume of the sample was calculated to be 4.36 kA/cm$^2$ at 77 K by 0.45 T of external field $H_{//c}$-axis.

A single peak and symmetric field distribution at the height of 1 mm over the sample confirmed that the sample is a single domain without any appreciable defects [8]. Furthermore, we also measured the trapped magnetic field distribution of the same sample when excited by 4 poles permanent magnets and the result is shown in Fig. 5, which shows that the sample can also trap the magnetic flux in different poles symmetrically.

The torque forces were also measured at various gaps in every 1 mm step in the field-cooling mode until the measured torque values were reduced below 5 N⋅cm. The results are plotted in Figs. 6 (a) to (d) for type A, B, C, and D configurations, respectively. The torque force decreases gradually with increasing the cooling gap. The maximum torque yields at different angle up to the poles configuration. The type A, B and C configurations, which have 2 magnetic poles on the coupling surface, exhibited the maximum torque force at about 60 degree twist. In contrast, the type D configuration of 4 magnetic poles yields the maximum torque at about 45 degree twist. The different of the maximum torque values are an effect of the arrangement of magnetic coupling configuration, which can useful for an engineering design of further mechanism.

The maximum torque forces for all the configurations are summarized in Fig. 7. The results clearly show that the torque forces decreased with increasing the cooling gap. The torque force achieved at 1mm cooling gap was the highest for the type D configuration, however the force decreased more rapidly with gap than the other configurations. It is interesting to note that the gap dependences of the torque forces for types A, B and C configurations are similar, which suggests that these gap dependences reflect the characteristics of 2 poles configuration.
In addition, the results of a conventional coupling configuration type A showed that its torque force is similar to that obtained in the 2 poles bar like shape configuration (type B). Since the conventional coupling configuration has the wider poles pitch, however, unstable rotation has occurred during the agitating process. A similar situation was observed in the experimental mixing process in that the levitated component centrifugally dropped and touched the ground. In contrast, the 4 poles square shape never experienced such a drop in the levitating component in the mechanism. The higher in the poles pitch was the smaller the torque force, which was also found in the work of Zheng et al. [5]. Furthermore, we achieved higher torque force in a quite similar coupling type as compared to their work, presumably due to the fact that the present superconductor exhibited stronger flux pinning.

5. Summary

We have studied the torque transferring mechanism between a bulk superconductor and permanent magnets with four useful configurations. The designed operating gap and torque coupling force have to compromise with the permanent magnets array. The 4 poles configuration produced the highest torque of about 32 N·cm at 1mm gap, however the force decreased significantly with increasing the gap. At the larger gaps, the stronger coupling force can be obtained from 2 poles square configuration. It was also found that the configuration those have more magnetic poles on the surface exhibited the maximum torque at lower twist angles, however, the torque force reduces more rapidly than the lesser magnetic poles array. The qualitative comparison of the results led us to the conclusion that one can design a superconducting mixer that can stir the liquid level of 30ℓ at 5 cm operating gap.

Figure 4. Trapped field distribution of Dy-Ba-Cu-O measured at 1 mm above the sample excited by a single pole magnet.

Figure 5. Trapped field distribution of Dy-Ba-Cu-O measured at 1 mm. above the sample excited by 4 poles magnet.
Figure 6  Plots of torque-gap relation against twist angles for four configurations of experiments: (a) 2 poles conventional coupling, (b) 2 poles bar, (c) 2 poles square, and (d) 4 poles square. Here FC1-8 denote the field cooling gap of 1 to 8 mm.

Figure 7. Maximum torque plotted against the cooling gap for four types of magnetic couplings.
6. References

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