Contactless Mechanical Power Transmission Through the High- T_c Superconducting Pinning Effect

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Abstract

Mechanical power transmission (MPT) components are almost indispensable for every engineering equipment with motions. In order to satisfy some rigorous requirements, such as contamination free and zero leakage in the mixing process of bio-medical solutions, a contactless MPT mode was proposed in this study based on the high- T_c superconducting flux pinning mechanism. It makes the stirring container with the driven part inside that can be totally isolated from the external environment. The physical principle of superconducting flux pinning effect was discussed firstly to explore a feasible structural scheme, which can completely restrain all the six degrees of freedom (DOFs) by the linkage of magnetic flux lines. Then, a measurement device was established to verify and investigate the proposed contactless MPT mode. The motion can be transferred synchronously from the superconducting driving part to the permanent magnet driven part since they are unified as an integrity through the pinned flux lines. The influence of driving speed, cooling clearance, and magnet arrangement on the transmitted torque was analyzed. The verified contactless MPT mode also has the advantages of self-stability and overload protection, which can avoid the drawbacks of traditional permanent magnetic transmission mode.

Keywords Mechanical power transmission · Contactless · High- T_c superconducting pinning mechanism · Magnetic flux lines

1 Introduction

There are various approaches to generate power, but it is almost impossible to generate power just right where it is needed or in the exact right forms or directions [1]. In order to ensure the energy can be transferred from where it's produced to a place where it is used to perform working, it is necessary to pay lots of attentions to mechanical power transmission (MPT) elements when designing motion machines [2]. The reliable transmission of motion and torque through these MPT elements is the most important foundation of modern mechanical equipment. Therefore, it is

meaningful to concentrate on the performance upgradation of the existing MPT modes and the development of novel modes. Till now, the most frequently used MPT elements in engineering include coupling, screw, gear, belt, chain, and so on [3, 4]. Through the rigid or flexible mechanical linkage between the driving part and the driven part, they can pass the mechanical power reliably. However, when adopting these elements in some special situations, such as the mixing of medicine solutions or the stirring separation of nucleic acid of COVID-19, the requirements of ultra-clean and zero-leakage cannot be fulfilled very well. The MPT components must penetrate the stirring container with the accompany of bearings and seals [5]. The bearings will inevitably cause wear debris and the seal cannot realize the absolute isolation [6]. The only way to realize contamination free and zero leakage is to make the stirring container with the driven part inside that can be totally isolated from the external environment. Therefore, the direct mechanical linkage must be replaced by other alternatives.

The permanent magnetic transmission elements by adopting the interaction effect of unlike poles attract while like poles repel each other, such as magnetic gear and magnetic

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coupling [7–9], were proposed accordingly. The motion and torque are transmitted through the mediation of magnetic energy and can realize the requirement of mechanical contactless. Especially the finding of $\text{Nd}_2\text{Fe}_{14}\text{B}$ magnet with a maximum magnetic energy product of about 365 kJ/m^3 , the development of permanent magnetic transmission elements is increasingly concerned by researchers [10]. Nevertheless, due to the intrinsic instability of permanent magnetic levitation [11], it is also necessary to apply auxiliary bearings to ensure the operation stability of the driven part, which would still cause the contamination of wear debris and cannot well fulfill the ultra-clean mixing of biomedical solutions. Fortunately, type-II high- T_c superconducting levitation system can realize self-stable suspension in external inhomogeneous magnetic field [12]. Such type of superconductors has lots of microdefects and nonsuperconducting centers which allow the magnetic flux to enter in quantized packets surrounded by a supercurrent vortex and realize the flux pinning state [13]. The macro behavior of flux pinning is that a superconductor can be pinned in space above a magnet or a magnet levitates in space above a superconductor [14]. Under this state, the superconductor and the magnet are linked together by magnetic flux lines not just the coupling interaction of magnetic poles. Some researchers [15–18] have already applied the superconducting pinning mechanism into the space docking of CubeSat sized spacecraft. However, they use concentric cylindrical superconductor and permanent magnet for simulation and experiments, which cannot completely restrain the six degrees of freedom (DOFs). If the system is used to transmit torque and motion, magnets or superconductor arrangement should be reconsidered to ensure all the six DOFs can be restrained [19, 20].

In this study, a contactless MPT mode is proposed by the usage of high- T_c superconducting flux pinning mechanism in Y–Ba–Cu–O system. Through the theoretical discussion of flux pinning, a feasible structural scheme with six DOFs totally restrained is given. The feasibility and performance of such contactless MPT mode are investigated on a self-established device. The influence of magnet arrangement is also taken into consideration.

2 Structural Scheme of the Contactless MPT Mode

2.1 Physical Principle of Superconducting Pinning Mechanism

In type-II superconductors, flux pinning is originated from the interaction between spatial inhomogeneities and the external magnetic field. These spatial inhomogeneities consist of the crystal defects during fabrication and artificially doped nonsuperconducting inclusions. The latter one is a frequently adopted technical method to strengthen the pinning effect [21]. Figure 1 displays a typical microstructure of Y–Ba–Cu–O superconductors, which are fabricated by top seeded melt-textured process. The precursor powders include YBaCuO_{7-x} and Y_2BaCuO_5 powders. The former powders are used to grow the superconducting domain while the later nonsuperconducting powders are acted as pinning inclusions [22]. It can be found that numerous microcrystal defects and artificially doped Y_2BaCuO_5 particles distributed in the superconducting matrix. These nonsuperconducting inclusions would generate various regions with suppressed critical transition temperature of superconductors. Accompanied with the microdefects, preferred low energy sites for vortex occupation will be produced, which can allow the external magnetic flux lines penetrate these sites. Physically, pinning effect can only occur when the sizes of spatial inhomogeneities are close to the length of either superconducting coherent length ξ or flux penetration depth λ [23]. Otherwise, they will be treated as distinct phases in the external magnetic field. ξ or λ of Y–Ba–Cu–O superconductors is usually around several nanometers. It has been clarified that interfaces of Y_2BaCuO_5 inclusions, and defects are the dominant part of pinning sites [24].

According to the Maxwell–Faraday law and the E (the electric intensity)– J (the current density) current law, currents induced in the superconductor are a function of the variation rate of the local magnetic flux lines [25, 26]. For

Fig. 1 Typical microstructure of a melt-textured Y–Ba–Cu–O superconductor with numerous spatial inhomogeneities

Fig. 2 Six DOFs of a cylindrical magnet above a superconductor cannot be restrained completely by the pinning force

instance, the magnetic field of a cylindrical permanent magnet has a vertical axis of symmetry. The magnet will cause no change in the magnetic field if it rotates around this axis. As a result, the trapped magnetic flux lines by the pinning sites cannot resist that rotation, and this DOF is in a free state. This phenomenon can be easily demonstrated by a simple experiment, as shown in Fig. 2. A cylindrical permanent magnet is pinned above a cylindrical Y–Ba–Cu–O superconductor. The superconductor is cooled into superconducting state among the magnetic field. Then, the superconductor with the cooling container will conduct rotation in a speed of w_1 , driving by a

servo motor downward. It can be observed that the magnet does not follow the rotation and keeps static suspension at first. After a relative long time, it will carry out a rotation around its own vertical axis of symmetry in a speed of w_2 . Besides, the rotational axes of the superconductor and magnet are not parallel to each other. This experimental phenomenon indicates that the vertical rotation axis of the magnet is not restrained by the pinned flux lines. And such system cannot be applied for the contactless mechanical power transmission in engineering. The cylindrical magnet should be replaced by other arrangements, which can cause the changes of magnetic field while rotating around the axis of symmetry. Since it is quite difficult to fabricate large-size cube-shaped permanent magnet, a good alternative can be the usage of several cylindrical permanent magnets or magnet balls in special arrangement.

2.2 Structural Scheme of the Proposed MPT Mode

Based on the above physical discussion of high- T_c superconducting pinning mechanism, the mechanical power can be successfully transmitted only when all the six DOFs of the permanent magnet driven part are totally restrained by the pinned flux lines. The flux lines are able to penetrate the nonmagnetic container nondestructively and realize contactless transmission. Figure 3 displays a schematic diagram of the proposed contactless MPT mode. One cylindrical superconductor is installed into the center of the cooling container to form the superconducting driving part. This part will be connected to a servo motor to achieve motion and torque. The permanent magnet driven part is constituted by several cylindrical magnets or magnet balls in special arrangement. It could be circumference shape or Halbach arrangement. The driven part will provide motion and torque for the execution component. To enhance the pinning effect, the superconductor must be cooled into superconducting state under a strong external magnetic field and the clearance between the

Fig. 3 Schematic diagram of the proposed contactless MPT mode based on superconducting pinning mechanism

upper surface of the superconductors and the bottom of the magnet H should be small enough. Since the superconductor in the new flux-pinned superconductor-magnet system resists any change in the magnetic flux lines it has pinned, the system can exhibit stiffness and damping in all the six DOFs and resist any relative motion from the established equilibrium position.

3 Experimental Investigations

3.1 Experimental Device

In terms of the proposed schematic diagram, an experimental device is established to verify the feasibility and investigate the performance of the contactless MPT mode. As displayed in Fig. 4, the overall structure of the device consists of three portions. The upper portion includes a WN-2 torque-meter, which is used for measuring the transmitted torque. The middle portion consists of the installation platform, the permanent magnet driven part, the inlet pump for

adding liquid nitrogen, and the rotational speed sensor. It can be observed from Fig. 4(c) that the driven part is composed of four $\text{Nd}_2\text{Fe}_{14}\text{B}$ magnet balls with a superficial magnetic field of 0.6514 T, and the diameter of each one is 10 mm. The centers of sphere are arranged in a circle of approximately 14.14 mm. Above the magnet balls, a connected output rotor provides a plug-in interface for the measure head of the torque-meter. When measuring the transmitted torque, the rotation of the driven part will be restricted by the torque-meter, and the value of torque will be obtained. The photo-electric reflective speed sensor can monitor the transmitted motion without the restriction of the torque-meter. The lower portion consists of the superconducting driving part and the servo motor. A cylindrical Y-Ba-Cu-O superconductor with a diameter of approximately 28 mm is installed into the center of the cooling container by four fastening bolts in the circumferential directions, which can make the experimental device adapt to another bulk superconductor with a different size. The motion and torque of the driving part come from the servo motor, and its torque is a constant value when the speed is below 500 r/min. In

Fig. 4 (a) Three-dimensional model, (b) practical photograph, and (c) details of permanent magnet driven part of the experimental device

order to avoid the splashing of liquid nitrogen from the uncovered container during rotation, the maximum speed for experiments is set as 100 r/min, which is still indeed a usual working speed in the stirring of biomedical materials. In the future, the speed can be improved increasingly with necessary protection or the usage of chilling unites instead of liquid nitrogen.

3.2 Experimental Results

The transmitted motion from the superconducting driving part to the permanent driven part is displayed in Fig. 5. The field cooling clearance between the upper surface of the superconductor and the lowest point of magnet balls H is 5 mm, which can be observed through the scale ruler. A local region of the output rotor is covered by a reflective sticker. The output key phases of the photo-electric

reflective rotational speed sensor for covered and uncovered areas are quite different. The transmitted rotational speed value can be calculated from the time span of two changing points in the key phase. The driving rotational speed values for the measurements include 50 r/min, 75 r/min, and 100 r/min. It can be observed that the rotations of the driving part and the driven part are synchronous, even accompanied with the friction torque of the rolling bearing shown in Fig. 4(c). The two parts are unified as an integrity by the pinned superconducting flux lines. The calculated rotational speed values based on time spans are exactly equal to 50 r/min, 75 r/min, and 100 r/min, respectively. All the six DOFs of the driven part are completely restrained, which verify the feasibility of the proposed contactless MPT mode through the superconducting flux pinning mechanism.

Fig. 5 The transmitted motion detected by photo-electric reflective rotational speed sensor when the rotation speed of the driving part is (a) 50 r/min, (b) 75 r/min, and (c) 100 r/min

After the measurement of transmitted motion, the torque-meter will be connected to the output rotor of the driven part by a plug-in linkage to monitor the transmitted torque. The field cooling clearance H is kept as 5 mm. During the measurements, the torque-meter would restrain the rotation of the driven part although the superconducting driving part keeps rotating. Therefore, the superconducting pinning state will be broken and reform continuously. Figure 6 displays the transmitted torque from the driving part to the driven part under different values of driving speed. It is also a characterization of the shear strength for the pinned superconducting magnetic flux lines. As the output torque of the servo motor is a constant value below 500 r/min, the maximum transmitted torque values under different speed values are basically around 0.008 N·m. The slight deviations are attributed to the variation of cooling temperature and random errors. It can be found that the measured torque has two directions, which indicates the driven part can rotate

in opposite direction of that of the superconducting driving part after the reformation of new pinning state. Indeed, if disconnecting the torque-meter and the output rotor, the driven part will conduct quiver motion occasionally, and the pinned state is unstable. The connection between the driving part and the driven part through flux lines can easily be destroyed by external disturbances, such as the friction torque of rolling bearing. The transmitted torques with opposite direction of the driving motion are originated from the twisted flux lines after re-pinning, as shown in Fig. 7. Each flux line must penetrate the superconductor through a large number of pinning sites and these sites usually are not on a straight line [27]. As a result, a torque with the opposite direction of the driving part may be generated at some time.

The transmitted torques under different field-cooled clearances are presented in Fig. 8. The clearances include 3 mm, 5 mm, and 7 mm. The driving speed value is kept as 100 r/min. A smaller field-cooling clearance can obtain a

Fig. 6 The transmitted torque when the rotational speed of the driving part is (a) 50 r/min, (b) 75 r/min, and (c) 100 r/min, respectively

Fig. 7 The twisted magnetic flux lines pinned by the superconductor

stronger pinning state due to the stronger external magnetic field for the superconductor. The maximum torque is about

0.01 N·m and 0.006 N·m when the clearance is 3 mm and 7 mm, respectively. It is worth mentioning that the diameter of the superconductor is quite small. It is appropriate to adopt large-size high-performance superconductor or several superconductors together for pursuing larger transmitted torque.

In this study, the influence of the magnet arrangement on transmitted torque is also taken into consideration. As displayed in Fig. 9, thirty cube-like permanent magnets are arranged into a Halbach array. Each magnet with a size of 4.76 mm × 4.76 mm × 4.76 mm and the concentrated superficial magnetic field is about 0.505 T. These magnets are installed in a three-printed disc component and will be fixed by structural glue. The details of the magnet poles are presented in the figure.

After replacing the magnet balls by the new Halbach magnet array, the transmitted torques under different field-cooled clearances are measured again. The

Fig. 8 The transmitted torque when field-cooled clearance H is (a) 3 mm, (b) 5 mm, and (c) 7 mm, respectively

Fig. 9 A Halbach magnet array for measurement of the transmitted torque

driving speed value is kept as 100 r/min. According to Fig. 10, the maximum torque is about 0.0167 N·m and 0.0130 N·m when the clearance is 3 mm and 5 mm, respectively. Most importantly, the transmitted torque can maintain a relative long time during the measurements. It indicates that the Halbach magnet array can produce a much more concentrated magnetic field even with the magnet having a lower super superficial magnetic field. Since the diameter of the superconductor is about 28 mm, the average pinning force in the circumferential direction F_p or the shear strength can be simply calculated. This force can characterize the stability of

pinning state under external torsional force. For instance, when the torque is 0.0167 N·m, F_p is about:

$$F_p = 0.0167N \cdot m / 0.007m = 2.4N \quad (1)$$

The proposed contactless MPT mode has been verified experimentally. Thanks to the self-stability of superconducting maglev system, the transmission of mechanical power is featured with high-reliability. Additionally, such MPT mode also can realize the effect of overload protection because of the flexibility of magnetic flux line. It has fascinating prospects in special situations with requirements of contamination free and zero leakage.

Fig. 10 The transmitted torque by the replacement of the Halbach magnet array when the filed-cooled clearance is 3 mm and 5 mm, respectively

4 Conclusions

In this study, a novel contactless mechanical power transmission mode is proposed by using the high- T_c superconducting pinning mechanism to avoid the drawbacks in the traditional and permanent magnet transmission modes. Based on the physical discussion of superconducting pinning effect, a schematic diagram which can restrain all the six DOFs of the driven part through the magnetic flux lines is given. The magnetic flux lines are able to penetrate the nonmagnetic container nondestructively and realize contactless transmission. The feasibility of the schematic diagram is verified on a self-established measurement device. The rotations of the driving part and the driven part are synchronous, even accompanied with the friction torque of the rolling bearing. The influence of field-cooled clearance, the driving rotational speed and magnet arrangement on the transmitted torque is experimentally investigated. By adopting the Halbach magnet array, the maximum transmitted torque under the field clearance of 3 mm is about 0.0167 N·m, and the approximate average pinning force in the circumferential direction is about 2.4 N. The new transmission mode can fulfill the requirements of contamination free and zero leakage, which can be used for the mixing of medicine solutions or the stirring separation of nucleic acid of COVID-19.

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