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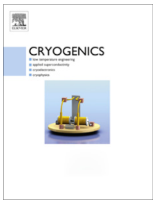

Research paper

Effect of reciprocating motions around working points on levitation force of superconductor-magnet system

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ABSTRACT

In order to simulate vibration around working points in practical operation of superconducting levitation system, magnet in a simple superconductor-magnet system are conducted reciprocating motions around static height in this study. Two YBCO cylindrical samples with different grain orientations are used to investigate the effect of reciprocating motions of magnet on superconducting magnetic force. The *c*-axis of sample S1 is perpendicular to the top surface while sample S2 is parallel to the top surface. The initial cooling processes for the superconductors include zero-field-cooled (ZFC) and filed-cooled (FC). Compared to the levitation force before reciprocating motions, the ZFC levitation force at static height becomes smaller after reciprocating while the FC force presents opposite phenomenon. It is found that levitation force at static height tends to be stable after several times of reciprocating under ZFC and FC conditions and its time-decay phenomenon is suppressed in some extent, which is meaningful for the practical application of superconducting levitation system. Based on vortex dynamic, some physical discussions are presented to the experimental results.

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1. Introduction

Because of their advantages of being friction-free and self-stable, high-T_c superconducting levitation systems have demonstrated fascinating prospects in flywheel energy storage system [1,2], maglev transportation [3,4] and other fields [5,6]. The interaction force F_L and its stiffness K_L between a superconductor and a magnet are very important for the stable operation of these systems, and have been one of the fundamental research subjects during the past three decades [7–11]. F_L is closely related to critical current density J_c of superconductor [12]. J_c of type-II high-T_c superconductors is a comprehensive effect between vortex-density gradient caused by pinning and the gradient decays with time as a result of a thermally activated motion of flux lines, namely trapped magnetic field and flux creep. In practical application, it's important that magnetic flux (or vortex) be frozen in the superconductor. Otherwise, F_L would slowly decrease with time. Flux state in YBCO has a different behavior at different temperatures or magnetic field [13]. The vortex phases are divided into flux liquid, vortex glass and vortex lattice. It should be noted that the temperature of 77 K envisaged for most of the applications of YBCO corresponds to vortex lattice state, which is not a very strong pinning state for flux line. Therefore, time-decay in levitation force, caused by flux creep or magnetic relaxation, is a conventional phenomenon in the practical applications. This phenomenon has been studied by many research groups worldwide [14–20]. Relaxation in levitation force follows logarithmic approximately and becomes stable finally. The decrease in levitation force would significantly affect the safe operation of systems. Therefore, it's meaningful to suppress flux creep in superconductor as much as possible. The magnetic relaxation rate has a dramatic decrease when the cooling temperature for superconductor is lower [21,22], which is known as flux annealing effect. Preload method [23–25] or using ferromagnet [26] is also effective to suppress relaxation. Beasley et al. [27] found that magnetic flux remained unchanged for a long time after small reverse of external magnetic field for the first time. After the discovery of high temperature superconductor, this reverse method was developed in more detail [28,29].

It is worth noting that the experimental procedures in these works on reverse method may not coincide with practical situations. For an example, Zhang et al. [30] try to found a working point with weakest flux creep by the reverse method. But the working point in their study becomes lower gradually. Reciprocating motion or vibration around working points of magnet due to variation of external loads is a typical phenomenon during the operation process of levitation system. The motions of magnet are fully

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controlled in most published works instead of simulating practical situations. Till now, F_L and K_L of typical superconducting levitation system are not very enough for industrial-level applications with relative high static and dynamic loads [4,31]. Due to hysteresis characteristics, K_L of typical superconducting levitation system is limited to some extent. The first industrial-level superconducting bearing (SMB) has a stiffness of 5.1×10^6 N/m [32]. However, stiffness of conventional hydrodynamic bearing in many rotating machinery can reach to 10^8–10^9 N/m [33] and the load capacity can be very high with the same size of SMB. In our previous works [34,35], a kind of novel superconducting compound bearing with high-stiffness was proposed for the development of a new generation of liquid rocket engine in China. In order to provide fundamental data for the manufacturing of this compound bearing, practical vibration around working points is simulated on a simple superconductor-magnet system through the reciprocating motions of magnet around static height. Moreover, the magnet is kept at static height for a certain time to observe relaxation of magnetic force. Two YBCO cylindrical samples with different grain orientations are used and the difference in F_L caused by anisotropy in superconductor and matching field effect is discussed. The effect of reciprocating motions and reciprocating times on levitation force and stiffness is investigated in this paper. The experimental procedure in this study is close to practical situations and the results are meaningful for the design of practical systems. Some physical discussions based on vortex dynamic are presented to the experimental results accordingly.

2. Experimental procedure

All the experiments are conducted on a superconducting levitation measurement system developed by Northwest Institute for Non-ferrous Metal Research, as shown in Fig. 1. Servomotor realizes the movement of a permanent magnet through screw and the speed is set as 1.25 mm s^{-1}. Displacement sensor is used to obtain the clearance between the bottom of magnet and the surface of superconductor. Pull-pressure sensor is used to obtain the levitation force between superconductor and magnet, include repulsive and attractive force. The superconductors are directly cooled by liquid nitrogen. The minimum height for measurement is 1 mm above the top surface of YBCO samples. If the height is less than this, magnet would touch the liquid nitrogen and levitation force would change significantly [36,37]. Low temperature would enhance the magnetization of NdFeB magnet [38]. Moreover, the liquid nitrogen film formed under small clearance would affect the accuracy of measurement.

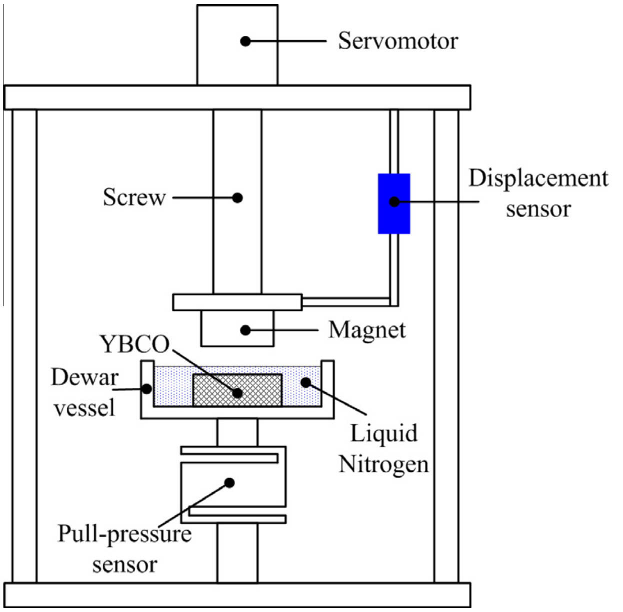

Fig. 1. Schematic diagram of superconducting levitation measurement system.

The superconductor-magnet system studied in this paper consists of a bulk YBCO superconductor and a bulk NdFeB permanent magnet. Two YBCO samples with different grain orientations are chosen from a mall batch of samples prepared by top-seeded melt textured growth (TSMTG) process [39]. As shown in Fig. 2, a certain proportion of Y123, Y211 and CeO_2 powders are compacted into cylindrical sample before crystal-growth by TSMTG. The $Sm_1Ba_2Cu_3O_{7-x}$ seed is placed on the center of the sample surface. The cylindrical samples S1 and S2 are of nearly the same size $\Phi 29 \times 18$ mm. The c-axis of sample S1 is perpendicular to the top surface while c-axis of sample S2 is parallel to the top surface. The permanent magnet has a diameter of 26 mm and a thickness of 25 mm. Furthermore, it is axially polarized with the concentrating surface magnetic flux density of up to 0.5 T. The superconductor and the magnet are arranged in a coaxial and symmetrical configuration during the measurement of levitation force.

The experimental procedures, used to simulate vibration of magnet around working points, are summarized in Fig. 3. When the initial cooling process is ZFC, magnet is moved from $h_0 = 50$ mm to the static height h_{zfc} and is kept till t_{s1}. Then, servomotor drives the magnet to conduct reciprocating movement: $h_{zfc} \to 1\ \text{mm} \to h_0 \to h_{zfc}$, and keeps the magnet at h_{zfc} till $t_{s1} + t_{s2} + t_{s3}$. When the initial cooling process is FC, experimental data begins to be recorded as the levitation force tends to be stable and till t_{s1}. Then, the magnet is driven to conduct reciprocating movement: $h_{fc} \to 1\ \text{mm} \to h_0 \to h_{fc}$, and be kept at h_{fc} till $t_{s1} + t_{s2} + t_{s3}$. The maximum times of reciprocating in this study is 4 and the levitation force versus time is recorded.

3. Results and discussion

3.1. ZFC condition

Fig. 4 shows the experimental results of levitation force F_L versus time t during four times of reciprocating around static height h_{zfc}. The initial cooling process for YBCO samples is ZFC. The static heights h_{zfc} are 10 and 5 mm, respectively. The circular symbol is for F_L of sample S1 and rhombic symbol is for sample S2. At first, the magnet is moved from $h_0 = 50$ mm to h_{zfc} and be kept at h_{zfc} till $t = 200$ s. Then, magnet is conducted reciprocating motions around h_{zfc}. The total measurement time is 1400 s and reciprocating times are 4. Focus on F_L at h_{zfc}, the force decreases sharply after the first time of reciprocating, and becomes stable after several times of reciprocating. F_L at h_{zfc} of sample S1 and S2 decreases by 4.5 N and 1.7 N respectively after the first time of reciprocating when h_{zfc} is 10 mm. The decrease values are 4 N and 1 N respectively when h_{zfc} is 5 mm. Since the experiments in this study are close to

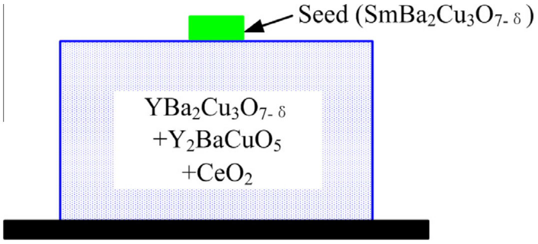

Fig. 2. Layout of YBCO sample for TSMTG process.

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