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The design considerations for a superconducting magnetic bearing system

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ABSTRACT

In this paper a high temperature superconducting magnetic bearing is studied with various design considerations. The design of the bearing consists of a rotor with 7.5 kg mass. The stable levitation of the rotor is provided with the Evershed type and superconducting components. The dynamic stability of the rotor is strengthened with the electromagnetic and electrodynamic levitation techniques. The force on the rotor is predicted in terms of semi-analytical frozen image model. The designed driving system sustains stable levitation during the rotation of the rotor and achieves higher rotational speed than that of the torque driver. The results indicate that the designed rotor and driving system have potential solutions for the development of the superconducting flywheel energy storage.

1. Introduction

High temperature superconductors (HTS) have many engineering applications. These applications generally focus on the magnetic properties of the superconductors [1,2]. Superconducting flywheel energy storage is one of the prominent technologies, which consist of designing efficient bearing system, power electronics and composite materials for the high speed rotor. This technology has potential to provide various industrial applications, integration the intermittent energy (wind turbines and solar energy) with the energy storage devices (superconducting magnetic and flywheel energy storage devices) through smart grids.

Magnetic bearings have advantageous over the mechanical bearings from various points, such as low friction and no need for lubricant. Introducing superconductivity to magnetic bearing and flywheel technology provides additional advantage such as passive control, which is simpler and cheaper to maintain. Flywheels are used to transform electrical energy into mechanical energy and use this energy to regenerate electricity as needed. Conventional flywheels have 3–5 percent energy loss of per hour [3]. Superconducting flywheels may offer to operate at less than 0.1% loss per hour, providing potential suitability for the industrial applications [4].

The superconducting bearing technology is still in the developing stage. The projects generally focused on the levitation of larger weights and manage their control at high speeds. In 2000, the research in Cambridge University provided that the rotor mass of 35 kg was levitated and able to pass the dynamic tests [5]. The Boeing Company developed a flywheel system, which was 132 kg and it has promising future [6]. More recently, ATZ Company is working on a flywheel system which has a rotor mass of 600 kg, with a roundtrip efficiency of 85–90% and expected cycle lifetime as 10^6–10^7 cycles.

This study concerned on the small scale application of superconducting bearing. The objective is to improve the levitation characteristics and driving mechanism of the bearing. In the present design the associated power electronics is simpler compared the existing bearing applications announced by Boeing [6] and ATZ superconducting flywheel energy storage systems [7]. In this paper the rotor design for the bearing is configured according to superconductor and permanent magnet (PM) interaction. By using previously designed non-contact torque mechanism, additional forces in the bearing are considered via electromagnetic and electrodynamic levitations, which in turn improved the bearing characteristics in levitation and operation speed (up to 70 Hz) compared to previous work [8]. This is done via correlating the levitation, lift and drag forces with various design parameters, such as the speed of bearing rotor, driving torque and stability of the rotor.

2. Experimental design and procedure

The design calculation of the study is focused on the stable levitation and driving of the rotor for the superconducting magnetic

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bearing. The picture of the experimental setup is shown in Fig. 1(a) and the schematic view is given in Fig. 1(b), where the corresponding bearing components are numbered. The rotor is constructed from brass with a total mass of 7.5 kg with a 50 mm radius and 100 mm height. In order to drive the rotor with eddy current mechanism, an array of 16 permanent magnets is placed on the 80 mm perimeter of an aluminum disc. More detailed description of the experimental setup is given elsewhere [8].

The superconductors placed on the base of the bearing are melt textured Yttrium Barium Copper Oxide (YBCO) samples purchased from ATZ Company. The rotor of the bearing is levitated with an Evershed type [9]. In this type of levitation the majority of the weight is lifted by the attractive force between the permanent magnets placed on the rotor and lifting shaft. Once levitated, the radial and vertical stability of the rotor is achieved passively, which is provided by a restoring force existing between the PM on the rotor and the HTS in the base. The magnetic system configured with this arrangement forms weak stability and thus requires effective use of available levitation techniques. In addition, the force between the PM and HTS is not sufficient due to flux creep and its associated levitation drift problem [10]. For this reason, the Evershed type is supported by electromagnetic and electrodynamic levitations.

The rotor is accelerated by applying a torque from the top surface of the rotor, shown as 5 in Fig. 1(b). The torque on the rotor is provided by the PM driver disc, indicated by 8 in Fig. 1(a), via drag force [11,12]. A synchronous speed is reached as soon as the drag force overcomes the moment of inertia of the rotor. The lift and drag forces on the rotor is measured by using load cells. Once the optimum levitation distance (gap) is determined, the rotor is driven up to high speed and its free spin is performed, which will be discussed in Section 4.

3. Levitation and stability of the superconducting bearing: hybrid levitation

According to the Earnshaw theorem it is not possible to obtain passive stable levitations by conventional magnetism, which consists of permanent magnets only [13]. For this reason, in order to obtain an efficient levitation in the bearing system various levitation techniques are analyzed. As there is no energy storage device satisfying all the technical and economical requirements for the industrial applications, the existing levitation techniques necessitate to be configured simultaneously. For example, a superconducting flywheel energy storage based on the bearing application may be a strong candidate for storing the energy when the superconducting, electromagnetic and electrodynamic levitation techniques are considered all together.

3.1. Electromagnetic levitation due to alternating current

For a system consisting of a time varying magnetic field near a conducting plate, the governing equation is obtained by solving the Maxwell equations [14]. Assuming that the magnetic field is applied to the surface of a conducting plane located in x–y direction and neglecting the displacement field due to low frequency regime, the magnetic diffusion equation provides the solution in the form of

$$\mathbf{B} = \mathbf{a}_x B_0 e^{-z/\delta} e^{j(\omega t - z/\delta)} \tag{1}$$

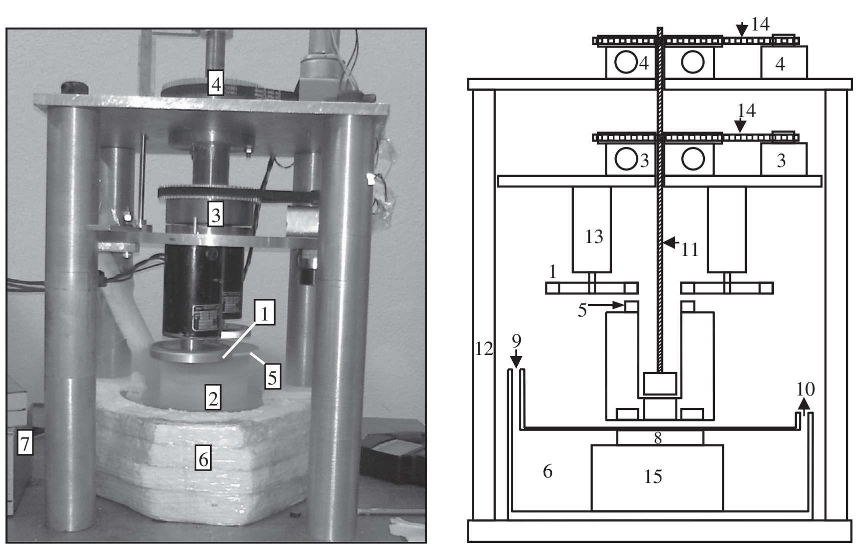
where $\delta = \sqrt{2/\mu\sigma\omega}$ is the penetration depth, μ is the permeability, ε is the permittivity, σ is the conductivity of the medium and ω is the angular frequency of varying field with an amplitude B_0. Assuming the current density in a segment of conducting plane is $\mathbf{J}$, the total force (Lorentz force) is obtained by integrating over the volume,

$$\mathrm{F} = \int_v \mathbf{J} \times \mathbf{B} dv \tag{2}$$

The current density in Eq. (2) is obtained from $\nabla \times \mathbf{H} = \mathbf{J}$. Using $\mathbf{F} = \mathrm{Re}(\mathbf{J}) \times \mathrm{Re}(\mathbf{B})$, the force per unit volume is obtained as

$$\mathrm{F} = \mathbf{a}_z \frac{B_0^2}{2\mu\delta} e^{-2z/\delta}\left[1 - \sqrt{2}\sin(2\omega t - 2z/\delta - \pi/4)\right] \tag{3}$$

The non-zero average electromagnetic levitation from Eq. (3) strengthens the net levitation force on the rotor during the drive. Eq. (3) also indicates the oscillation of the magnitude of the force



(a) (b)

Fig. 1. (a) Superconducting bearing picture and (b) schematic view of the bearing components: 1: Driving PM discs, 2: Rotor, 3: Lift motor mechanism, 4: Setup motor, 5: Copper disc, 6: Liquid nitrogen tank, 7: Control unit, 8: HTS, 9: Liquid nitrogen inlet, 10: LN outlet, 11: Shaft, 12: Aluminum columns, 13: Driver motor, 14: Belt and 15: Base plate.