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Dynamics of superconductor bearings in a cryogenic failure

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Abstract

The dynamics of superconductor bearings in a cryogenic failure scenario have been analyzed. As the superconductor warms up, the rotor goes through multiple resonance frequencies, begins to slow down and finally touches down when the superconductor goes through its transition temperature. The bearing can be modelled as a system of springs with axial, radial and cross stiffness. These springs go through various resonant modes as the temperature of the superconductor begins to rise. We have presented possible explanations for such behaviour.

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Keywords: Superconducting bearings; Levitation; Bearing stiffness and spin-down

1. Introduction

Superconducting bearings have been extensively analyzed to explore their use in high speed machines such as flywheels [1–5] and in low speed devices like gyroscopes for space applications [6] and micro-electromechanical systems [7]. A distinct advantage of these bearings despite their low stiffness is that they are entirely passive, self-damping and incur negligible losses [1]. Many prototype machines have been proposed wherein a typical set up consists of a stator element housing the superconducting pucks and a rotor element carrying reinforced magnetic rings made up from NdFeB [2,3]. In most of the designs, the bearings operate at liquid nitrogen temperatures of 77 K and the superconducting element is field-cooled for operational practicalities. The whole system is housed in a vacuum chamber to reduce windage losses, to provide thermal isolation and it also acts as containment for the spinning rotor. The bearing is expected to be robust enough against thermal and mechanical loads. There have been investigations of the bearing stiffness over a wide range of temperatures and it was reported by Hull et al. [6] that for small amplitudes, the bearing stiffness does not change and that the thermal loading below 77 K marginally influences it. However, at higher temperatures the effects of thermal loading are expected to become more pronounced. In a dynamic situation, the amplitude of vibrations around the resonant modes of the rotor would be considerably higher. The oscillations due to rotor whirl and pitching will affect the balance of forces acting up on the bearing. Our investigations are focused on the dynamics of the bearing during a cryogenic failure. We have considered an extreme case where failure of the vacuum system as well as the cryogenic cooling leads to a rapid warm up of the superconductor elements and a quick slow down of the spinning rotor. This results in the rotor going through its resonant modes in conjunction with a change of bearing stiffness.

2. Experimental set-up

The bearing is housed in a bell-jar as shown in the picture in Fig. 1. The melt-grown superconducting YBCO disk with 33 mm diameter and 15 mm thickness is cooled

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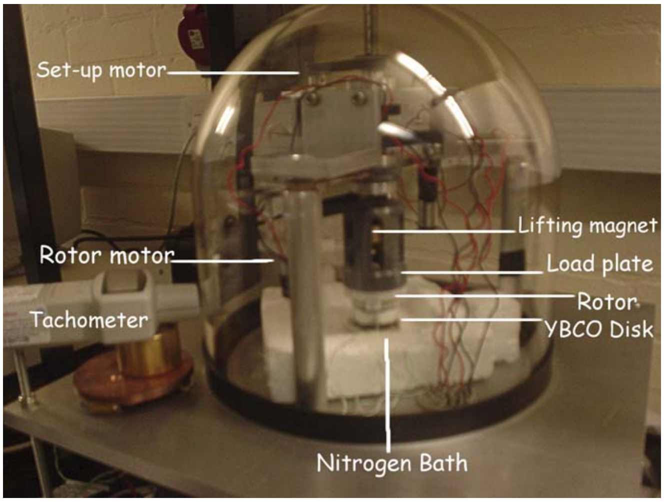

Fig. 1. A picture of the experimental set-up.

in a liquid nitrogen bath. A ring magnet with 35 mm OD, 25 mm ID, a thickness of 8 mm and a surface field of 0.4 T is fixed to an aluminum holder. This rotor assembly weighing about 64 gm is attached to a load plate and is held by a similar ring magnet mounted over the shaft. The whole set-up can be moved up and down by a set-up motor. The load plate is driven by another motor as shown in Fig. 1. The bell-jar is pumped out to lower the vapor pressure of liquid nitrogen which decreases the temperature below 77 K. As the pumping continues, the liquid nitrogen level decreases and the temperature of the YBCO disk begin to rise. The rate of temperature rise is proportional to the pumping speed. The YBCO disk is field-cooled at a distance of 2 mm from the ring magnet to levitate the rotor. The rotor is then set spinning and the load plate is moved away leaving the rotor levitated and freely spinning. A digital photo tachometer monitors the speed of rotation. Rotor speed during a spin-down is plotted against spin-down time.

The force–displacement measurements were done on a commercially available Instron machine equipped with a 250 N load cell and a data acquisition system. Forces are measured at various positions of the magnet with respect to the superconducting disk. Stiffness of the bearing can be estimated from the slope of the force–displacement curves.

3. Rotor dynamics and bearing characteristics

As mentioned before, in our experiments the rotor is levitated by field-cooling the YBCO disk. The bearing thus formed can be modeled as system of springs with its principal axes x, y and z shown in Fig. 2. The stiffness along the three axes is defined by the equation:

$$[K]y + [M]\ddot{y} = 0$$

where K and M are the stiffness and mass matrices. The stiffness matrices are split into various components as follows:

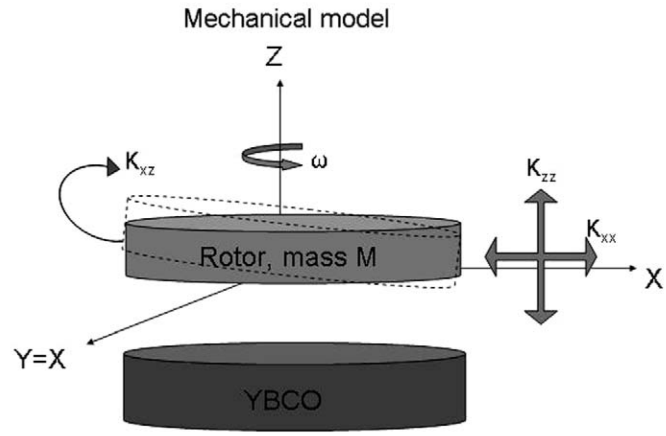

Fig. 2. The bearing modelled as a system of springs.

$$\begin{bmatrix} Kxx & Kxy & Kxz \\ Kyx & Kyy & Kyz \\ Kzx & Kzy & Kzz \end{bmatrix} \approx \begin{bmatrix} Kxx & 0 & Kxz \\ 0 & Kxx & Kxz \\ Kxz & Kxz & Kzz \end{bmatrix},$$

the eigenvalue matrix $K_{\text{eigen}} = \begin{bmatrix} K1 \\ K2 \\ K3 \end{bmatrix}$

where Kxx, Kyy and Kzz are along the principal axes and Kxz, Kzx, Kyz, Kzy, Kyz and Kxy are the cross-coupling terms. For axisymmetric bodies $Kxx = Kyy$, $Kxz = Kyz$ and $Kxy = 0$, so we are left with three components viz. Kxx, Kzz and Kxz called radial, axial and cross-coupling stiffness respectively. The values of Kzz and Kxx are estimated from the force–displacement curves shown in Figs. 3 and 4 and the cross-coupling stiffness Kxz is determined from the axial force vs. radial displacement measurements [9]. At 77 K, $Kxx = 0.4$ N/mm, $Kzz = 2.1$ N/mm and $Kxz = 0.75$ N/mm. The stiffness values are related to the resonant frequencies by the equation $K = m\omega_{\text{res}}^2$ where ω_{res} is the angular frequency at resonance. The eigenvalues calculated from the above-said stiffness components are

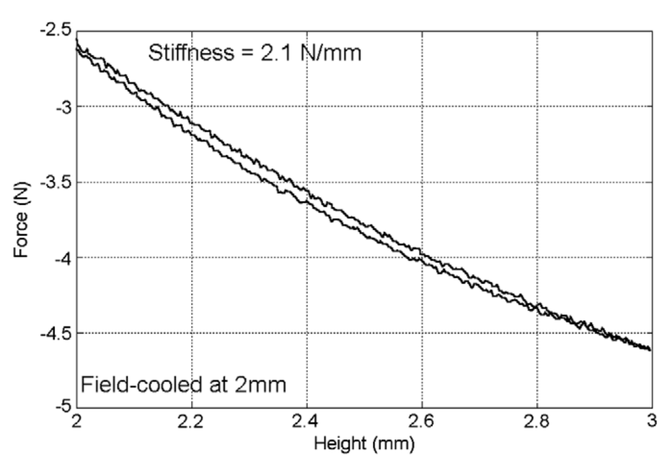

Fig. 3. Force–displacement curve of a bearing field-cooled at 77 K and a height of 2 mm.