Failure analysis of superconducting bearings

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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.

1. Introduction
High temperature superconductor bearings have been a subject of many investigations [1-3] to realize their applications in high-speed rotating machines such as gyroscopes, flywheels, turbines and novel devices like MEMS [4]. These passive bearings need no active control and are self-stabilizing. The stiffness of the bearing is a measure of its stability against external disturbances like rotor vibrations, imbalance, radial or eccentric loading. When used in the flywheel energy storage machines, these bearings are usually housed in vacuum chambers to provide thermal insulation and avoid windage losses. In this presentation we report on the failure-analysis measurements. The bearings would fail if the temperature of the superconductors rises above their critical temperature and the rotor supported by these bearings would 'touch-down'. How fast this happens is critically dependent on the rate of temperature rise in the superconductors. This can be triggered in two ways – either a loss of vacuum or a cryogenic failure. In a slow cryogenic failure scenario, the superconductors slowly warm above the critical temperature and in the event that the vacuum fails at the same time as the cryogen system, the superconductors would be subjected to a rapid warming. In this fast cryogenic failure scenario, as the vacuum fails, windage losses would result in dynamic loading. The dynamics of the rotor vis-à-vis the bearing characteristics have been investigated.

2. Experimental set-up
The bearing is housed in a bell-jar as shown in the picture in figure 1. The superconducting YBCO disk with 33mm diameter and 15mm thickness is cooled in a liquid nitrogen bath. A 0.4T ring magnet with 35mm OD, 25mm ID and a thickness of 8mm is fixed to an aluminum holder. This rotor assembly weighing about 64gm 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 a motor as shown in the figure. The bell jar is pumped out to lower the vapor pressure of liquid nitrogen which decreases the temperature below the liquid nitrogen boil-off point at 77K. As the pumping continues, the liquid nitrogen level decreases and the temperature of YBCO disk begin to rise. The temperature rise rate is proportional to the pumping speed. The YBCO disk is field-cooled at a distance of 2mm 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.

The force-displacement measurements were done on a commercially available Instron machine equipped with a 250N load cell. 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 figure 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 where \( K_{xx} \), \( K_{yy} \) and \( K_{zz} \) are along the principal axes and \( K_{xz} \), \( K_{yz} \) and \( K_{xy} \) are the cross coupling terms. For axisymmetric bodies \( K_{xx} = K_{yy} \), \( K_{xz} = K_{yz} \) and \( K_{xy} = 0 \), so we are left with three components viz. \( K_{xx} \), \( K_{zz} \) and \( K_{xz} \) called radial, axial and cross-coupling stiffness respectively. The values of \( K_{zz} \) and \( K_{xx} \) are estimated from the force-displacement curves shown in figures 3 and 4 and the cross coupling stiffness \( K_{xz} \) is determined from the axial force vs. radial displacement measurements. At 77K, \( K_{xx} = 0.4 \) N/mm, \( K_{zz} = 2.1 \) N/mm and \( K_{xz} = 0.75 \) N/mm. The stiffness values are related to the resonant frequencies by the equation \( K = m\omega^2 \) where \( \omega \) is the angular frequency at resonance. When the rotor is spun up and left to coast, it is expected to pass through these frequencies and as the rotor goes through one of the resonant frequencies, it begins to wobble thereby

![Figure 1. A picture of the experimental set-up.](image1)

![Figure 2. The bearing modelled as a system of springs.](image2)

![Figure 3. Force displacement curve of a bearing field-cooled at 77K and a height of 2mm](image3)

![Figure 4. Radial force vs. lateral displacement curve of a bearing field-cooled at 77K and a height of 2mm.](image4)
affecting the stiffness of the bearing and also incurring losses.

The spin-down time also provides an estimate of the frictional losses. The slopes of the spin-down curves (df/dt) are related to the coefficient of friction by the following equation [5]:

\[ \mu = \left( \frac{\pi R^2}{g R_d} \right) \frac{df}{dt} \]

R is the radius of the rotor and \( R_d \) is the radius at which the drag force acts and df./dt is the decay rate.

4. Failure analysis

Figure 5 shows a spin-down curve for a field-cooled bearing at 63K. There are two resonant frequencies at 30Hz and 18Hz corresponding to the stiffness values of 2.3 N/mm and 0.82 N/mm. The former is the axial stiffness Kzz and the latter is the cross-coupling stiffness Kxz [6]. The third resonance should be occurring around 8Hz but we don’t observe it. The coefficient of friction estimated from the decay rate (df/dt = 3.25\times10^{-2}/sec\(^2\)) is 1.75\times10^{-4}.

In the next experiment the YBCO disk is warmed up during the spin-down to simulate cryogenic failure. Figure 6 shows the frequency decay along with the temperature rise. The decay rate in this case was 4.4\times10^{-2}/sec\(^2\), increased by almost a third of that at a constant temperature of 63K before the rotor started to drop down around 11Hz. The temperature rise rate was 3.3 K/min. There were two resonant frequencies occurring quite closely at 29 and 23 Hz. In another experiment shown in figure 7 the first resonance was observed at 32 Hz and as the temperature rose at a rate of 6 K/min, two more resonances were observed at 26 Hz and 18Hz. The decay rate in this case was 6.3\times10^{-2}/sec\(^2\), almost double the rate at a constant temperature. In the final experiment shown in figure 8, the superconductor started warming up just before the resonance at a rate of 7.4K/min. The decay rate in this case was 6.9\times10^{-2}/sec\(^2\) and we observed a resonance width of more than 10 Hz.

5. Discussion

The dynamics of the bearing can be explained by considering a system of springs. The stiffness components along the axial (Kzz), radial (Kxx) and cross-coupling (Kxz) are related to the corresponding resonant frequencies. These components must be dependent on the temperature of the superconductor forming the bearing and as the superconductor warms up due to a cryogenic failure the stiffness values would be changing accordingly affecting the rotor dynamics. We have observed that the rotor goes through a broad resonance spread over 10Hz or more and up to three resonances before touching down at the critical transition temperature around 90K. As the stiffness value changes with temperature, it is possible to get a broad resonance region with a merger of various resonant frequencies into one band. There could be another explanation for this behaviour. During the resonance, the levitated rotor wobbles over the superconductor and this wobbling is similar to a

![Figure 5. Spin-down curve at 63K](image1)

![Figure 6. Spin-down and temperature rise curves showing two closely occurring resonances.](image2)
magnet vibrating with a certain frequency over the superconductor. In an experiment to simulate wobbling a similar magnet is set vibrating for 500 cycles at different frequencies with amplitude of 0.25 mm over a superconductor field-cooled at height of 2 mm. Figure 9 shows force-displacement curves for 2, 5, 10 and 15 Hz. For clarity, the data for first five cycles are presented. It is worth noting that the stiffness of the bearing decreases with the increasing frequency. This decrease would be further amplified by the increasing temperature. Appearance of multiple resonances during warm up suggests a sudden change in the stiffness of the bearing. At this point we can only speculate that melting of the pinned flux lines might result in this behavior. Further work to understand the dynamics of the bearing during a cryogenic failure is in progress.

References
[1] Hull J R 2000 Supercond. Sci. Tech.13 R1-R15 (and references cited therein).
[2] Coombs T A, Campbell A M, Storey R and Weller R 1999 IEEE Trans. Appl. Supercond. 9 831-34.
[3] Rastogi A, Coombs T A and Campbell A M 2003 IEEE Trans. Appl. Supercond. 15, 2242-44.
[4] Coombs T A, Samad, I, Ruiz-Alonso, D and Tadinada K 2005 IEEE Trans. Appl. Supercond. 15, 2312 –15.
[5] Rastogi A, Alonso D R, Coombs T A and Campbell A M 2003 IEEE Trans. Appl. Supercond. 13, 2267-70.
[6] Hull J R and Canzis A, 1999 J. Appl. Phys. 86 6396-6404.