Squeeze Film Dampers for High Temperature Superconducting Radial Magnetic Bearings

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ABSTRACT

Squeeze film dampers(SFDs) are designed and analyzed for radial superconducting bearings. The designed SFDs are mounted on the superconductors submerged in liquid nitrogen such that the dampers should supply additional damping to the relatively underdamped superconducting bearing support. Basic theory of SFD assembled with superconductors is introduced. Rotordynamic simulations are provided to support the feasibility of the superconducting bearings mounted on SFDs for a horizontal flywheel energy storage system.

Nomenclature

ρ : density of the fluid film
e : eccentricity of the journal
C : clearance of the SFD
μ : viscosity of the fluid film
P : pressure developed in the film
R : radius of the journal
Ω : rotational speed
c_s, c_f : damping coefficients of SMB and SFD
c_i : internal damping coefficient
k_s, k_f : stiffness coefficients of SMB and SFD

1. Introduction

Magnetic bearings suspend a spinning rotor without physical contact by utilizing magnetic field. Magnetic bearings find great applications in industry since they have many advantages over conventional bearings, such as less friction loss, no lubrication, operations at temperature extremes. Magnetic bearings are divided into two major categories: Active magnetic bearings and passive magnetic bearings.

Active electromagnetic bearings are most commonly used in industry. Active stiffness and damping properties of magnetic bearings make it possible to adjust rotordynamic properties while operating the rotor-bearing system. Furthermore, synchronous vibration due to imbalance can also be successfully reduced with automatic balancing. however, this all electromagnetic bearings consume substantial power in order to provide bias flux for linearization. There have been some efforts to develop hybrid type active magnetic bearings to minimize energy loss. Use of rare earth permanent magnets yields a very high efficiency when the permanent magnets are used as the source of bias flux to energize the air gaps and electromagnets are used to supply control fluxes in the active plane (Meeks [1]). Though there are many advantages on active magnetic bearings, reliability requirements limit active magnetic bearings from being used in many potential applications. Increasing reliability and reducing the complexity and cost of the system are still points of major concern in the field.

Passive magnetic bearings (PMB) using permanent magnets are based on inherently stable or dynamic phenomena so that they do not need either an active control or cryogenic systems to obtain contactless levitation. However, their dynamical performances are

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inferior to those of active magnetic bearings (AMB) or superconductor magnetic bearings. Static stable levitation is impossible to achieve without electronic control, or diamagnetic materials such as superconductors. However, a stable levitation is achievable if electrodynamic effects (eddy currents) are utilized (eddy current bearings).

Superconducting magnetic bearings are good substitutes for active magnetic bearings. Stable levitation can be realized by using a combination of strong permanent magnets and a bulk superconductors with high critical current density. The forces between superconductors and Nd-Fe-B permanent magnets act contactless and provide a passive stabilization caused by the flux pinning in the superconductors. The flux lines coming out of the permanent magnets are fixed by pinning centers to the bulk superconductors, that is, they are pinned and, therefore, the strength of stability relative to the levitation position works in both horizontal and vertical directions, resulting in stable levitation.

Superconducting magnetic bearings have many advantages. Tests performed in vacuum environment show that bearings constructed using superconductors have an extremely low frictional coefficient. Unlike active magnetic bearings, which require elaborate control system, superconducting bearings are completely passive. Therefore, superconducting magnetic bearings (SMBs) show fail-safe characteristics. In case of power failure, there is slow change in the temperature due to the heat capacity of the system and therefore no sudden change in the levitation force.

There are also some problems which must be addressed if superconductors are to be used in bearings. Superconducting bearings exibit strong force-displacement hysteresis, which causes unpredictability of the rotor equilibrium position. It is also shown that the force displacement hysteresis can stimulate the decay of the operational gap under the influence of the vibration. If a minor hysteresis loop is exited with large vibrations the bearing will then advance to a new equilibrium point. In other words the bearing gap will decay. The bearing then oscillate about the new equilibrium point. Even under steady load, conventional passive magnetic bearings using high-temperature superconductors exibit long term drift of the rotor position caused by so called magnetic flux creep in superconductors.

Superconducting bearings also have very low stiffness as well as very low damping [2-3], which may cause rotordynamic problems. With this extremely low damping it is difficult to pass critical speeds without severe vibrations. This paper presents a novel squeeze film damper (SFD) which is designed and mounted on the superconducting magnetic bearing. Liquid nitrogen are used for a lubricant in the damper while it provides cooling of the superconductors. The SFD may provide an additional damping to the extremely underdamped rotor system supported by superconducting bearings.

2. Design of a Squeeze Film Damper on a Superconducting Magnetic Bearing

One of a good application of SMBs is flywheels for energy storage. With the introduction of passively stable frictionless magnetic bearings, the efficiency of flywheels for energy storage could be increased to an economically useful level. Figure 1 shows the schematic drawing of the SMB mounted on a SFD. The superconducting magnetic bearing consists of a Nd-Fe-B ring magnet embedded into the superconductor flywheel rotor and YBCO bulk superconductors mounted inside a closed continuous flow liquid nitrogen cryostat. The high temperature superconductors are attached on the inner side of the squeeze film damper. The superconductors as well as the SFD are submerged in liquid nitrogen. The rotor and bearing housing are installed in a vacuum environment.

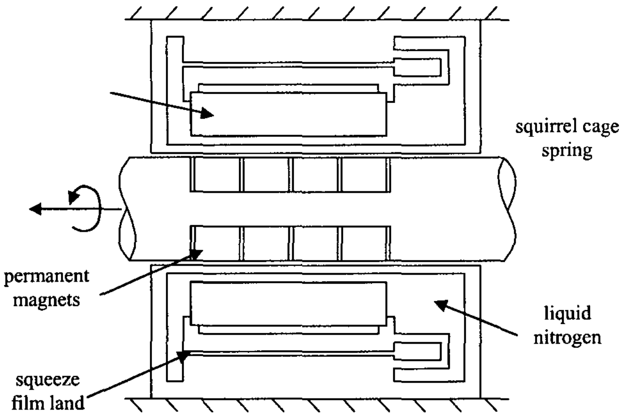

Fig. 1 HTSMB mounted on a SFD

This vacuum environment minimizes air drag due to high speed as well as strengthens the cooling system by preventing heat transfer from the outside. The permanent magnets are press-fitted on the rotor part. When the superconductors work by supplying sufficiently cooling, the flux from the permanent magnets generates restoring forces if the rotor moves.

The squeeze film damper then reacts by squeezing liquid film inside the film land. This series of reactions generates additional fluid damping forces.

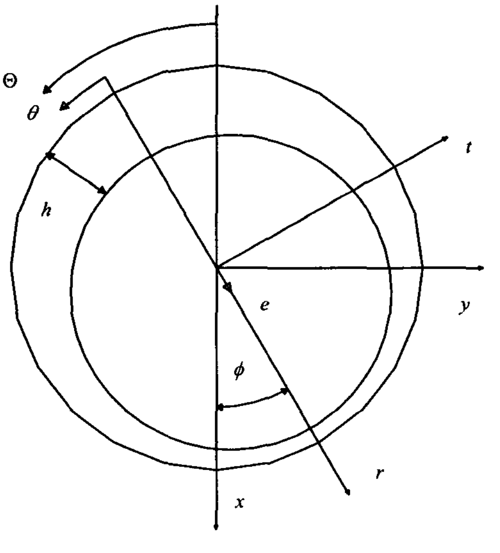

Fig. 2 Geometry of the Squeeze Film Damper

Figure 2 shows the geometry of squeeze film fluid between the journal and the damper housing. The classical Reynolds equation in polar coordinate for compressible flow is

$$\frac{\partial}{\partial t}(\rho h)+\frac{\partial}{\partial \Theta}\left(\frac{\Omega}{2}\rho h\right)= \frac{1}{R^2}\frac{\partial}{\partial \Theta}\left(\frac{\rho h^3}{12\mu}\frac{\partial P}{\partial \Theta}\right)+\frac{\partial}{\partial Z}\left(\frac{\rho h^3}{12\mu}\frac{\partial P}{\partial Z}\right) \tag{1}$$

where

$$h = C + e\cos\theta \tag{2}$$

$$\Theta = \theta + \phi \tag{3}$$

In case for incompressible flow, which is the case for the SFD with liquid nitrogen, the Reynolds equation in Eq. (1) reduces to

$$\dot{e}\cos\theta + e\left(\dot{\phi}-\frac{\Omega}{2}\right)\sin\theta = \frac{1}{R^2}\frac{\partial}{\partial \theta}\left(\frac{h^3}{12\mu}\frac{\partial P}{\partial \theta}\right)+\frac{\partial}{\partial Z}\left(\frac{h^3}{12\mu}\frac{\partial P}{\partial Z}\right) \tag{4}$$

If L/D goes to infinity, the axial flow of the bearing is effectively very small. The term $\frac{\partial P}{\partial Z}$ in Eq. (4) then goes to zero, which leads to

$$\dot{e}\cos\theta + e\left(\dot{\phi}-\frac{\Omega}{2}\right)\sin\theta = \frac{1}{R^2}\frac{\partial}{\partial \theta}\left(\frac{h^3}{12\mu}\frac{\partial P}{\partial \theta}\right) \tag{5}$$

Equation (5) is so-called long bearing solution The long bearing solution provides a good approximation for tightly sealed SFDs of any L/D. If L/D goes to zero with no end seals (open-ended), the circumferential flow is effectively very small. The term $\frac{\partial P}{\partial \theta}$ in Eq. (4) then goes to zero. The reduced Reynolds equation is

$$\dot{e}\cos\theta + e\left(\dot{\phi}-\frac{\Omega}{2}\right)\sin\theta = \frac{\partial}{\partial Z}\left(\frac{h^3}{12\mu}\frac{\partial P}{\partial Z}\right) \tag{6}$$

Equation (6) is a good approximation for journal bearings with short axial length (short bearing solution).

The squeeze film damper with no end seals is used for the configuration of the SMB mounted on a SFD. The direct damping coefficient for a SFD executing circular centered orbits (short bearing solution) in a closed form is calculated as;

$$c_{sfd} = \frac{\mu R L^3}{C^3} \frac{\pi}{\left(1-\varepsilon^2\right)^{3/2}} \tag{7}$$

The designed SFD has film land length L of 0.06 m, film land diameter D of 0.17 m, film clearance C of 0.00025 m. The eccentricity ε of the vibrations is assumed as 0.2. The viscosity μ of the liquid nitrogen is 0.256 centistokes. The calculated damping coefficient of the SFD is then 1004 N-s/m. The designed squirrel cage spring coefficient for the SFD is 1,000,000 N/m.

3. Rotordynamic Coefficients of Rotor-SFD-SMB Model

Figure 3 describes a simplified model of the superconducting bearing mounted on a squeeze film damper shown in Fig. 1.

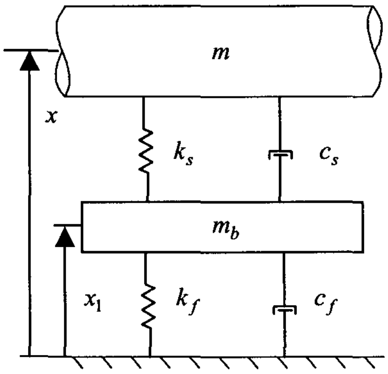

Fig. 3 SMB-SFD Model

The equations of motion for the rotor supported on SFD-SMB are [4]

$$m\ddot{x} + c_s(\dot{x} - \dot{x}_1) + k_s(x - x_1) = 0 \tag{8}$$

$$\begin{aligned} m_b\ddot{x}_1 &+ c_s(\dot{x}_1 - \dot{x}) + c_f\dot{x}_1 \\ &+ k_s(x_1 - x) + k_f x_1 = 0 \end{aligned} \tag{9}$$

Assuming solutions of the form $x = \hat{x}e^{i\Omega t}$ Eq. (9) is solved for x_1 in terms of x and substituted into Eq. (8), which leads to;

$$m\ddot{x} + c_e\dot{x} + k_e x = 0 \tag{10}$$

where

$$\begin{aligned} c_e = c_s&\left(1 - \frac{k_s(k_s + k_f - m_b\Omega^2) + \Omega^2 c_s(c_s + c_f)}{(k_s + k_f - m_b\Omega^2)^2 + \Omega^2(c_s + c_f)^2}\right) \\ &- k_s\left(\frac{c_s(k_s + k_f - m_b\Omega^2) - k_s(c_s + c_f)}{(k_s + k_f - m_b\Omega^2)^2 + \Omega^2(c_s + c_f)^2}\right) \end{aligned} \tag{11}$$

$$\begin{aligned} k_e = k_s&\left(1 - \frac{k_s(k_s + k_f - m_b\Omega^2) + \Omega^2 c_s(c_s + c_f)}{(k_s + k_f - m_b\Omega^2)^2 + \Omega^2(c_s + c_f)^2}\right) \\ &+ c_s\Omega^2\left(\frac{c_s(k_s + k_f - m_b\Omega^2) - k_s(c_s + c_f)}{(k_s + k_f - m_b\Omega^2)^2 + \Omega^2(c_s + c_f)^2}\right) \end{aligned} \tag{12}$$

The stiffness and damping coefficients of the superconducting magnetic bearing used in this paper are 200,000 N/m and 20 N-s/m, respectively. Effective stiffness k_e and damping c_e with respect to the rotational speed Ω are shown in Fig. 4.

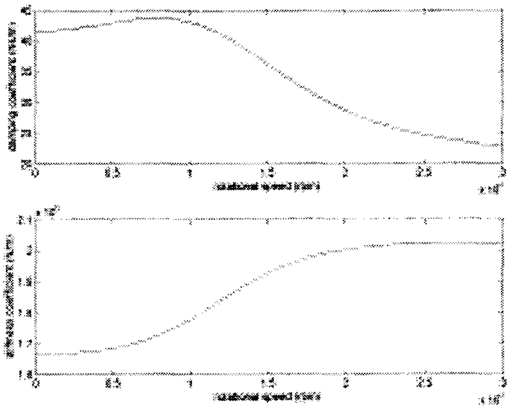

Fig. 4 Effective Stiffness and Damping

Effective damping to the rotor rolls off with respect to the rotating speed while effective stiffness converges to the superconducting bearing stiffness.

The flexible built-up rotors which have many press-fitted parts are susceptible to have internal friction. Internal friction is known as one of the destabilizing mechanism for an underdamped rotor-bearing system. The damping from the SFD helps to increase the threshold speed of instability if there exist some internal friction.

4. Conclusion

Superconducting magnetic bearings are used in flywheel energy storage system since they have relatively low friction coefficients and provide passively stable magnetic suspension. However, relatively low bearing stiffness and damping of the superconducting bearing may cause some rotordynamic problems if the rotor-bearing system has an instability mechanism such as internal damping. A squeeze film damper is designed and mounted on the superconducting magnetic bearing in order to provide extra damping to the extremely underdamped system. Effective damping to the rotor is related with the stiffness ratio of the SMB and SFD, and reduced with respect to the rotational speed. This extra damping may help to suppress excessive vibration at the critical speed in the low speed region, and also increases the threshold speed of instability at high speed if there exist substantial internal damping in the system.

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