USE OF HIGH-TEMPERATURE SUPERCONDUCTING FILMS IN SUPERCONDUCTING BEARINGS *

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Submitted to Cryogenic Engineering Conf.
Montreal, Canada, July 12-16, 1999

*Work partially supported by the U.S. Department of Energy, Energy Efficiency and Renewable Energy, as part of a program to develop electric power technology, under Contract W-31-109-Eng-38.

DISCLAIMER

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ABSTRACT

We have investigated the effect of high-temperature superconductor (HTS) films deposited on substrates that are placed above bulk HTSs in an attempt to reduce rotational drag in superconducting bearings composed of a permanent magnet levitated above the film/bulk HTS combination. According to the critical state model, hysteresis energy loss is inversely proportional to critical current density, J_c, and because HTS films typically have much higher J_c than that of bulk HTS, the film/bulk combination was expected to reduce rotational losses by at least one order of magnitude in the coefficient of friction, which in turn is a measure of the hysteresis losses. We measured rotational losses of a superconducting bearing in a vacuum chamber and compared the losses with and without a film present. The experimental results showed that contrary to expectation, the rotational losses are increased by the film. These results are discussed in terms of flux drag through the film, as well as of the critical state model.

INTRODUCTION

The use of high-temperature superconductors (HTSs) in levitation applications, such as magnetic bearings has seen considerable development during the past decade [1-3]. The most common configuration for a HTS bearing has incorporated a rotatable permanent magnet (PM) stably levitated in close proximity to a stationary bulk HTS. The bulk HTS used is usually melt-textured Y-Ba-Cu-O in the form of single domains of up to $<\approx 10$ cm in linear dimension and with critical currents of $J_c > 10^4$ A/cm^2. The domains are typically oriented with the c-axis perpendicular to the HTS surface that faces the PM. These configurations are capable of providing levitation pressures >20 N/cm^2.

More recently, interest in the use of thin-film HTSs in superconducting bearings has increased [4-8]. Although YBCO thin films often have J_c values of >1 MA/cm^2 at 77 K, the thickness of these films is only ≈ 1 µm and they do not provide much levitation force. The magnetization quickly saturates, and it is possible to produce very large hysteresis loops if this occurs. However, when unsaturated, the stiffness of such films is often similar to that produced by bulk material of greater thickness [5,7].

The use of high-J_c thin-films in HTS bearings has long been thought to offer the potential for reduced rotational drag [9,10]. This conjecture is based on the generally accepted hysteretic loss mechanism for HTS bearings that is based on the critical-state model. Hysteretic loss is produced whenever there is a cyclic change in applied magnetic field, and the energy loss per cycle is [11]

$$E_h = K\mu_o(\Delta H)^3/J_c \qquad (1)$$

where E_h is the hysteretic energy loss per unit area per cycle, K is a geometric coefficient of order unity, $\mu_o = 4\pi \times 10^{-7}$ N/A^2 is the magnetic permeability of vacuum, $\Delta H = \Delta B/\mu_o$ is the peak-to-peak amplitude of the varying magnetic field, and J_c is the critical current density in the HTS. When a levitated PM spins over a HTS, there exists small rotational loss because of azimuthal inhomogeneities of the magnetic field of the PM, which causes a ΔB at a surface location on the HTS over a complete rotation of the PM. The amplitude of the ΔB increases if there is any appreciable whirl amplitude of the PM, in which case the radial gradient of the magnetic field also contributes to the ΔB. One may conceptualize the magnetics of the bearing system as the PM providing a constant magnetic field B that interacts with the HTS to provide levitation force and a circumferentially varying magnetic field ΔB that produces the rotational loss. In general the ΔB associated with inhomgeneity is much less than the constant magnetic fields B that provide the levitation force.

A further consequence of the critical-state model, beyond the energy loss described in Eq. (1), is that the interior of the HTS is shielded from the varying magnetic field, so that the hysteresis losses occur only on the surface of the HTS. Thus, it was conjectured that if a thin-film HTS were interposed between the PM and bulk HTS, the levitation force would remain approximately the same and most of the hysteretic loss would occur in the thin-film HTS. The thin-film HTS would shield the bulk HTS from the effects of the applied ΔB, so that the bulk HTS only experienced a constant applied magnetic field. Because J_c is so much higher in the thin-film, the total hysteretic loss, and therefore the rotational drag on the levitated PM, should be much smaller with the HTS film installed.

The above considerations motivated us to test create the experimental arrangement, shown schematically in Fig. 1, to measure the rotational drag of a PM levitated over a combination of bulk HTS with a thin-film HTS covering the bulk. This article reports the detailed arrangement and results of these tests. A theoretical interpretation of the results is also provided.

ROTATIONAL DRAG MEASUREMENTS

The experimental apparatus for rotational drag measurements is shown in Fig. 1. A NdFeB PM disk rotor was levitated over a HTS in a vacuum chamber, with an oil-diffusion pump reducing the pressure to <100 μPa [12]. The HTS was inside a room-pressure cryochamber, through which liquid nitrogen flowed from a gravity feed at ≈3 kPa. The cryochamber walls and top were electrically insulating fiberglass to avoid eddy-current losses while the PM was rotating. The cryochamber was covered on the top and sides with three thin layers of aluminized Mylar to reduce radiation heat input. Before cooling the HTS, the PM was held by a thin flat plate that was movable in the z (vertical) direction and rotatable around its support post.

Following HTS cooldown and positioning of the PM rotor, the support plate was moved away from the rotor to prevent interference during the spin tests. The PM rotation was accelerated and decelerated by a cold gaseous nitrogen jet impinging approximately tangentially on the PM perimeter from a small-diameter copper tube. The nitrogen gas, supplied from a pressurized bottle through a regulator, was cooled by passing it through a heat exchanger submerged in liquid nitrogen before it entered the vacuum chamber; this averted a possible temperature rise in the HTS. Such a temperature rise would decrease the J_c and possibly decrease the levitation height. Once the PM reached the desired speed, the gas jet was shut off. The rotation of the PM was continuously monitored by a tachometer. To obtain good statistics, the PM was allowed to freely spin down for 3-5 minutes after acceleration, and speeds were recorded at 5 second intervals. When we were interested in details of resonance behavior, we recorded the data every second. Linear regression was used on the data from the free-spin period to calculate the slope of the rotational frequency versus time function (df/dt), which in turn was used to calculate the coefficient of friction [12].

The height of the levitated PM was measured with a traveling telescope at intervals throughout the experiment, and no change in height from the initial levitation value was observed to within 10 μm. The levitation height in these experiments includes the thickness of the cryochamber (3.5 mm) and the gap between the PM and the top of the cryochamber. The height was recorded after the system had cooled, so as to avoid obfuscation by any changes due to thermal contraction.

Three configurations of HTS were used: (1) bulk HTS, (2) thin-film HTS, and (3) thin-film HTS over bulk HTS.

The bulk HTS is a melt-textured Y-Ba-Cu-O cylinder with the c-axis aligned along the vertical, $J_c = 20$ kA/cm^2, critical temperature $T_c = 92$ K, diameter of 32 mm, and thickness of 22 mm. The disk-shaped thin-film HTS has $J_c = 3.7$-4.1 MA/cm^2, critical temperature $T_c = 89.2$-89.6 K, diameter of 51 mm, and thickness of 350 nm. The film is deposited on a La-Al-O_3 substrate with a thickness of 0.5 mm. When the film is used together with the bulk, they are coaxial with the film immediately above the bulk.

Degradation of the thin-film HTS by contact with moisture was a concern. The thin-film and substrate was therefore encased by a thin, sealed polyethylene bag. In addition, before cooling with liquid nitrogen, the cryochamber was evacuated with a mechanical pump and then backfilled with gaseous nitrogen at ambient temperature. We also flowed liquid nitrogen through the inlet line for some time before directing it to the cryochamber, so that most of the trapped air in this line would be removed.

The same PM rotor was used in all the tests. The PM rotor is a cylinder with diameter of 25.4 mm, height of 6.35 mm, and mass of 35.59 gm. The levitation force provided by the thin-film HTS was too small to levitate this PM. The levitational force was augmented by placing a stationary PM above the rotor in an Evershed configuration, so that there is an attractive force between the two PMs [13]. The distance between the two PMs was adjusted to that the upward force due to magnetic attraction was slightly less than the gravitational force downward.

RESULTS

Rotational loss of an HTS bearing is evidenced by the decay rate of the rotational frequency f and is characterized by the coefficient of friction (COF)

$$COF = -[2\pi R_\gamma^2/(gR_D)]\ df/dt \tag{2}$$

where R_γ is the radius of gyration of the rotor, g is the acceleration of gravity, t is time, and R_D is the weighted mean radius at which the drag force acts and is given by [14]

$$R_D = \Sigma\, r_i\, (\Delta B_i)^3 / \Sigma\, (\Delta B_i)^3 \tag{3}$$

where r_i is the radius for the ith term and ΔB_i is the peak-to-peak value of the variation of the vertical component of magnetic field measured in the circumferential path at r_i at the surface of the HTS. For the PM used in our experiments, R_D = 10.78 mm.

COF versus f at different heights for the three HTS configurations, bulk only, film only, and bulk plus film, are shown respectively in Figs. 2-4. In all cases, COF increases with decreasing levitation height. Each data set is characterized by a peak in COF that corresponds to a resonance in the radial vibration amplitude that is readily observed visually. The behavior of the rotational losses are thus divided into three regions: below the resonance, resonance region, and above the resonance. For rotation rates away from the resonance, the loss is mostly independent of frequency, which is consistent with a hysteretic energy loss. Below the resonance, the rotational loss is caused only by circumferential inhomogeneity in the magnetic field of the PM. The COF is higher above the resonance than below the resonance due to rotation about the PM center of mass, rather than its center of magnetism. Here there is an additional angular variation in magnetic field seen by the HTS, due to the radial gradient of the PM magnetic field combined with the whirl amplitude about the center of mass.

Figures 2-4 also show that the resonant frequency shifts to higher values as the levitation height decreases. This is expected, because more magnetic flux lines are trapped in the HTS at lower field-cooling heights, and thus the magnetomechanical stiffness is higher. Figure 4 shows a slight dip in the COF immediately before the resonance region for all three heights. Figures 2 and 3 do not show this behavior.

In Figs. 5-7, the data sets are rearranged to show the behavior for each HTS configuration at approximately the same levitation height. For all the levitation heights, the resonant frequency is consistently lowest for the bulk alone and highest for the combination of bulk and film. For all the levitation heights, both above and below the resonance, the minimum loss occurred when bulk HTS was used alone, and the loss was maximum when the bulk and film were used together. In these regions, the COF of the bulk and film is approximately equal to the sum of the COFs for the bulk alone and the film alone.

DISCUSSION

The results of the rotational loss measurments are At this time, we are unable to present a complete theory of the rotational loss when HTS films are used. However, we discuss here the germane physical concepts that we believe govern the behavior and are consistent with the results obtained.

The critical-state calculation of Fig. 1 is generally valid when the magnetic field is parallel to the HTS surface. When the magnetic field is perpendicular to the surface of a film, the aspect ratio plays an important part in determining the behavior of the penetration of the field [15-17]. Experimentally, the hysteresis loss of an HTS film can be almost 3 orders of magnitude higher with the field perpendicular to the film surface, compared with the case of the field parallel to the surface [16]. The case of a thin disk in a uniform field has received considerable analysis, but the configuration of our experiment is considerably more complicated and seemingly not susceptible to elementary analysis. The experimental configuration can be conceptualized as a spot of flux being dragged in a circle over the surface of the HTS film. The diameter of the spot is considerably smaller than the diameter of the film, the flux has components parallel and perpendicular to the film surface, and part of the flux may be shielded out while part of it may be dragged through.

To illustrate the situation, we perform several simplified example calculations. First, consider the bulk HTS with $J_c = 20$ kA/cm^2 and calculate what is the ΔB required to produce a COF of 2×10^{-7}. We assume an HTS surface area of 270 mm^2, equivalent to a radial swath of ≈4 mm around the perimeter of the HTS upper surface. The weight of the PM is $F_L = 0.36$ N, so the drag force is $F_D = 72$ nN. The hysteretic energy loss per revolution is then 4.9 nJ, and according to Eq. (1), the associated ΔB is 146 μT. This value is consistent with measured values of ΔB_z for the PM.

Next, consider application of the 146 μT field over the entire top surface of the film. The surface area is about 8 times higher, but J_c is 200 times higher. Based only on these relations, one would expect the COF to be lower by at least a factor of 25. That COF is not lower for the film, plus the nearly complete lack of shielding of the bulk HTS by the film, leads one to investigate the 3-dimensional nature of the currents in the film. If a magnetic dipole were oriented perpendicular to the film surface, it should be possible to shield the field out of the film interior with currents running only in the plane of the film. However, if the dipole moment is oriented parallel to the film surface, then currents must flow perpendicular to the film surface to shield the interior of the film. This creates a counterflowing current on the back side of the film, which would account for the lack of shielding of the bulk HTS, since from the bulk's point of view, the currents flowing in the film would essentially cancel the magnetic field produced. If current flows perpendicular to the film surface, it will do so at a greatly reduced J_c, resulting in a larger hysteresis loss in the film.

The difference in shielding of a perpendicular dipole versus a parallel dipole by a thin-film HTS is an experimentally testable hypothesis, and we hope to perform such experiments in the future.

One may show that dragging of flux through the film is probably not occurring. Consider a spot of perpendicular flux of radius R_f and mean magnetic induction B that is dragged in a circle of radius R_D through the HTS film. The force per unit volume is [18]

$$F = B\, J_c, \tag{4}$$

which yields

$$COF = \pi R_f^2 h B\, J_c / F_L \tag{5}$$

where h = 350 nm is the film thickness. Consider a 10 μT field and a spot size of 1 mm. The calculated COF in this case is 1.2×10^{-6}. Even with the small values considered, the COF is too large.

CONCLUSIONS

We have experimentally measured the rotational drag of a permanent magnet (PM) levitated above a high-temperature superconductor (HTS). We examined HTS configurations of bulk, thin-film, and a combination of thin-film over a bulk. The loss in the thin-film HTS was significantly higher than predicted by a simplified critical-state model, and the film did not shield the bulk HTS from magnetic-field inhomogeneities of the PM. A comprehensive theory of this phenomena is not available, but we believe that the 3-dimensional nature of the currents in the film provide a plausible physical explanation for the increased losses.

ACKNOWLEDGMENTS

This work was partially supported by the U. S. Dept. of Energy, Energy Efficiency and Renewable Energy, as part of a program to develop electric power technology, under Contract W-31-109-Eng-38. Author Cansiz gratefully acknowledges the support of the Turkish government. The authors are grateful to K. Salama for providing the bulk HTS used in the experiments and to Markus Getta for providing the thin-film HTS.

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FIGURE CAPTIONS

Fig. 1. Schematic of apparatus for rotational drag measurements.

Fig. 2. COF vs frequency at different heights for PM levitated over bulk HTS.

Fig. 3. COF vs frequency at different heights for PM levitated over thin-film HTS.

Fig. 4. COF vs frequency at different heights for PM levitated over combination of bulk HTS and thin-film HTS.

Fig. 5. COF vs frequency at 9.4-9.6 mm height for PM levitated over HTS in various HTS configurations.

Fig. 6. COF vs frequency at 10.1-10.4 mm height for PM levitated over HTS in various HTS configurations.

Fig. 7. COF vs frequency at 8.0-8.1 mm height for PM levitated over HTS in various HTS configurations.

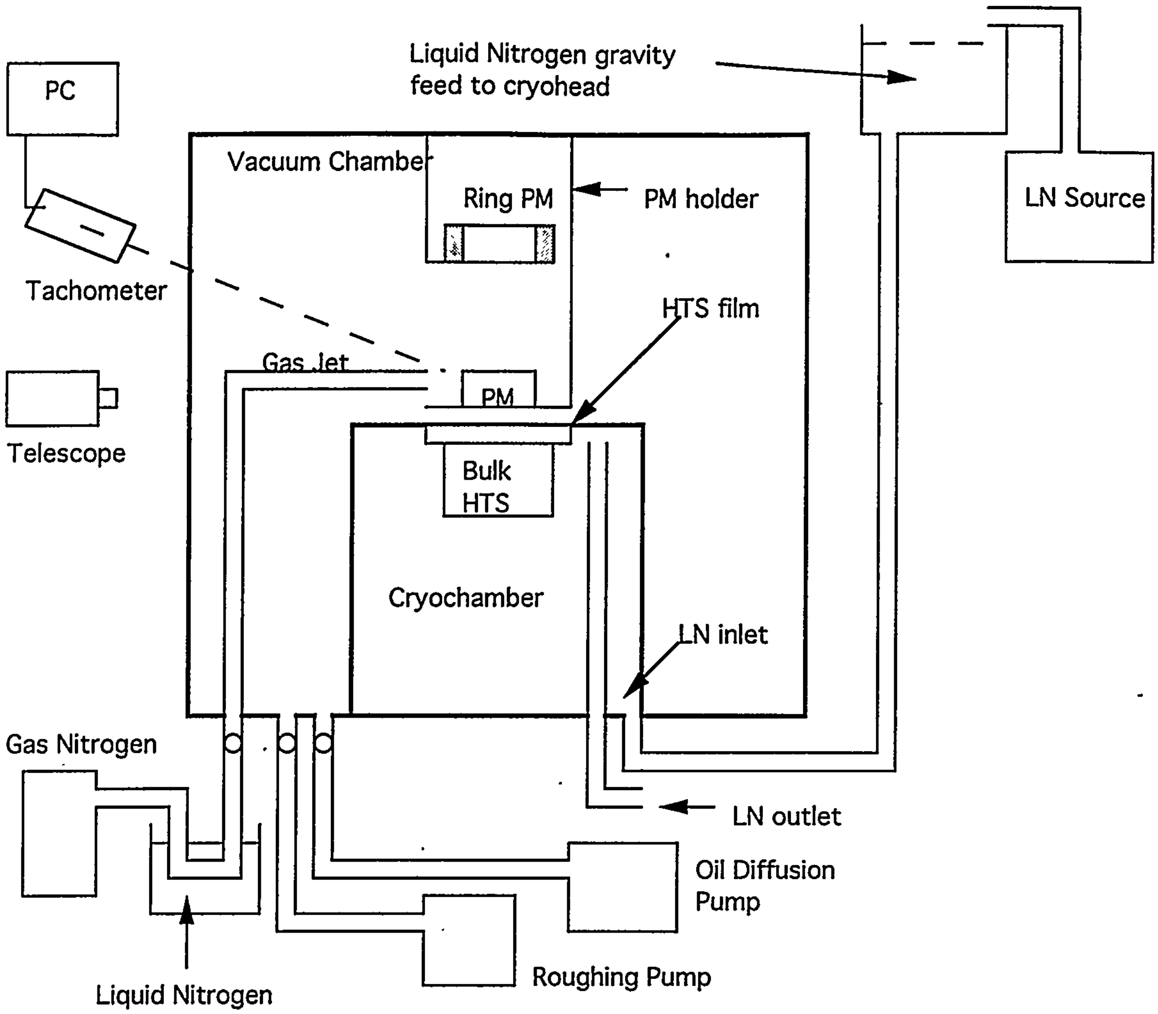
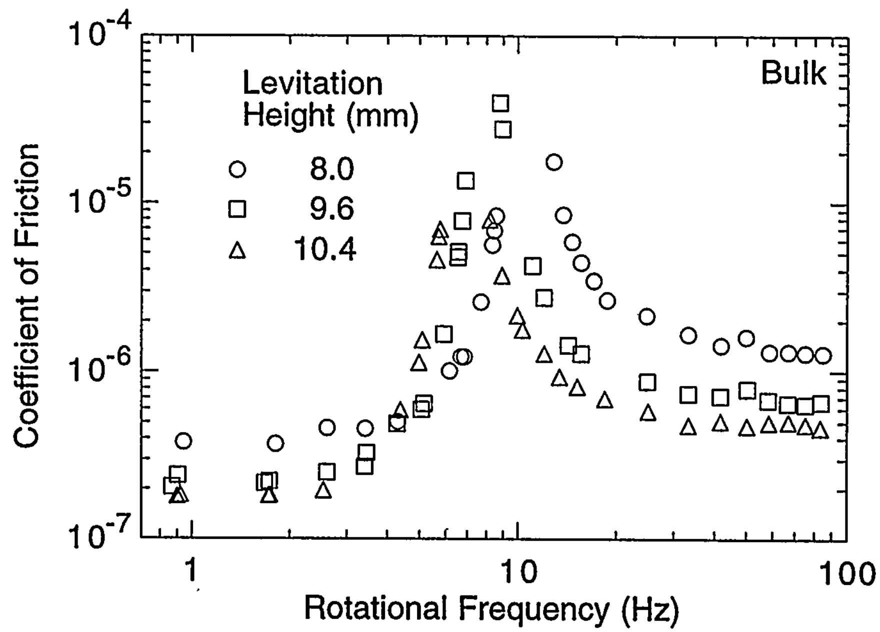

PC
Liquid Nitrogen gravity
feed to cryohead
Vacuum Chamber
Ring PM
PM holder
LN Source
Tachometer
HTS film
Gas Jet
PM
Telescope
Bulk
HTS
Cryochamber
LN inlet
Gas Nitrogen
LN outlet
Oil Diffusion
Pump
Roughing Pump
Liquid Nitrogen

Fig. 1

Fig. 2



Levitation
Height (mm)
8.0
9.6
10.4
Bulk
Coefficient of Friction
10-4
10-5
10-6
10-7
1
10
100
Rotational Frequency (Hz)

Fig. 3

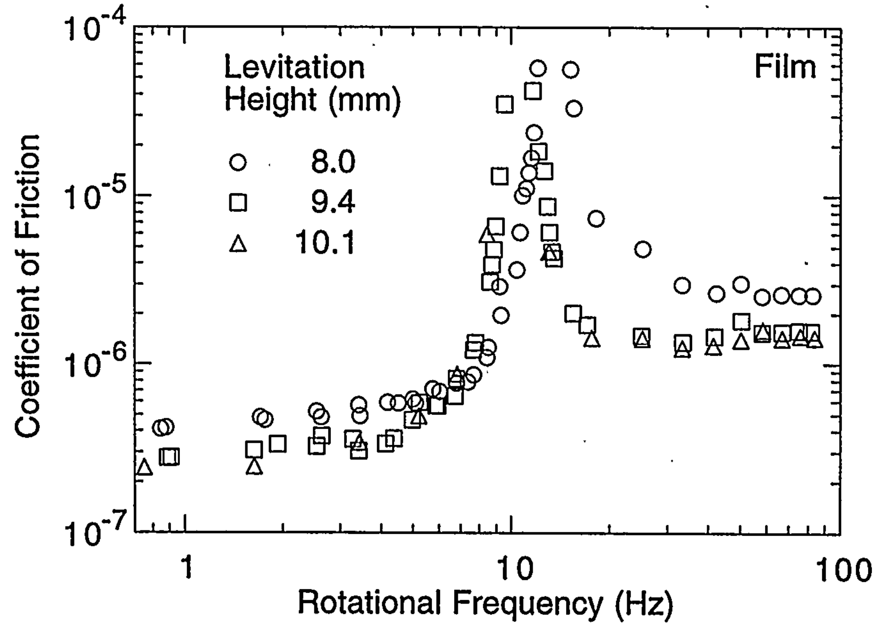

Levitation
Height (mm)
8.0
9.4
10.1
Film
Coefficient of Friction
10^{-4}
10^{-5}
10^{-6}
10^{-7}
1
10
100
Rotational Frequency (Hz)

Fig. 4

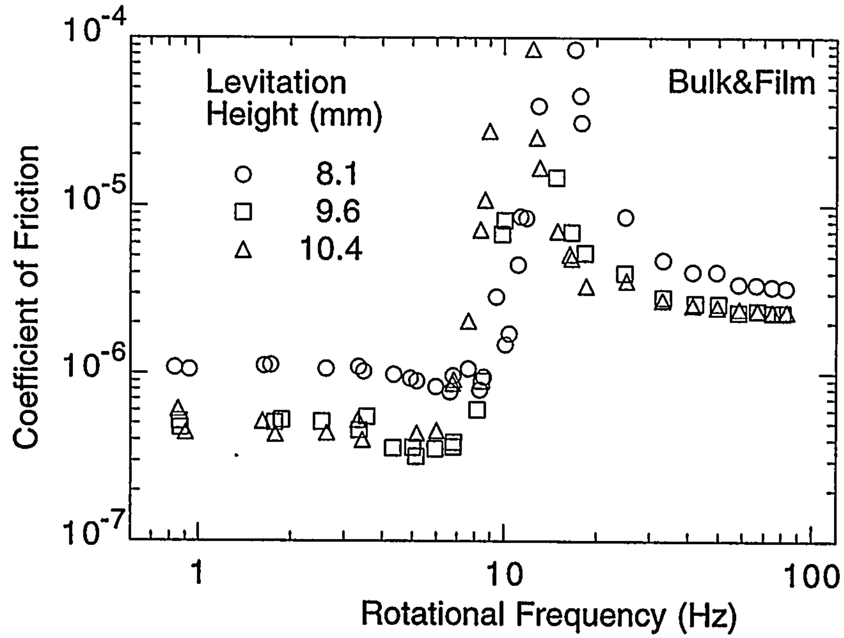
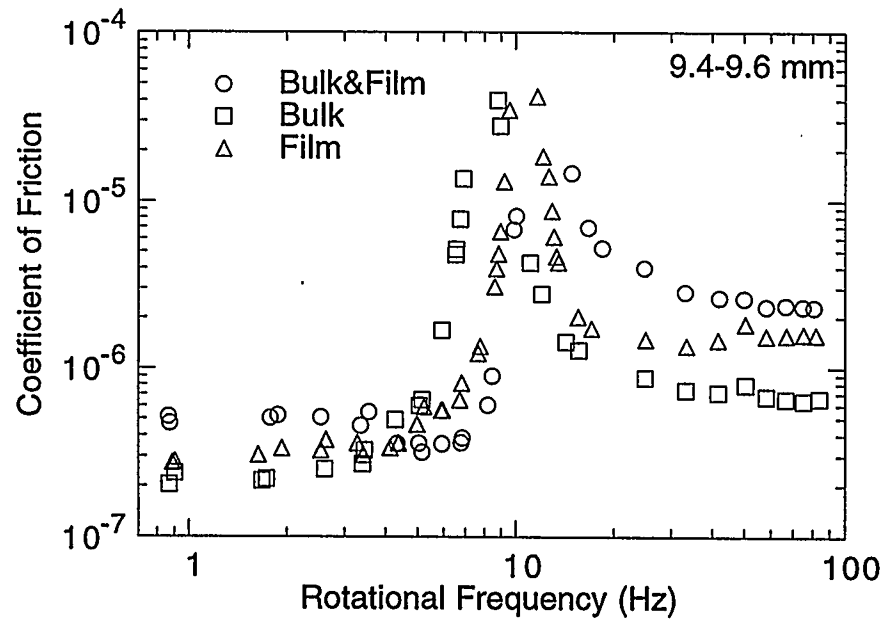
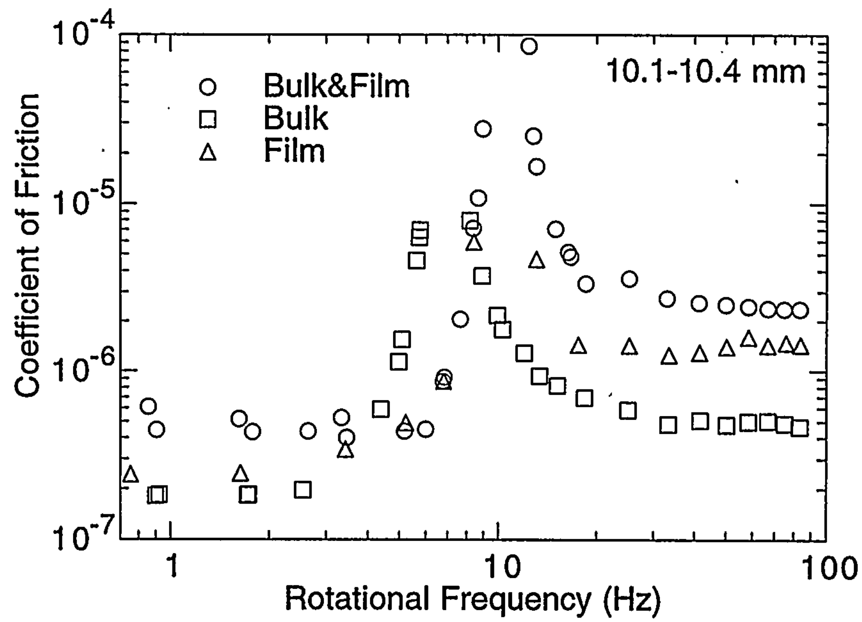

Levitation
Height (mm)
8.1
9.6
10.4
Bulk&Film
Coefficient of Friction
10^{-4}
10^{-5}
10^{-6}
10^{-7}
1
10
100
Rotational Frequency (Hz)

Fig. 5



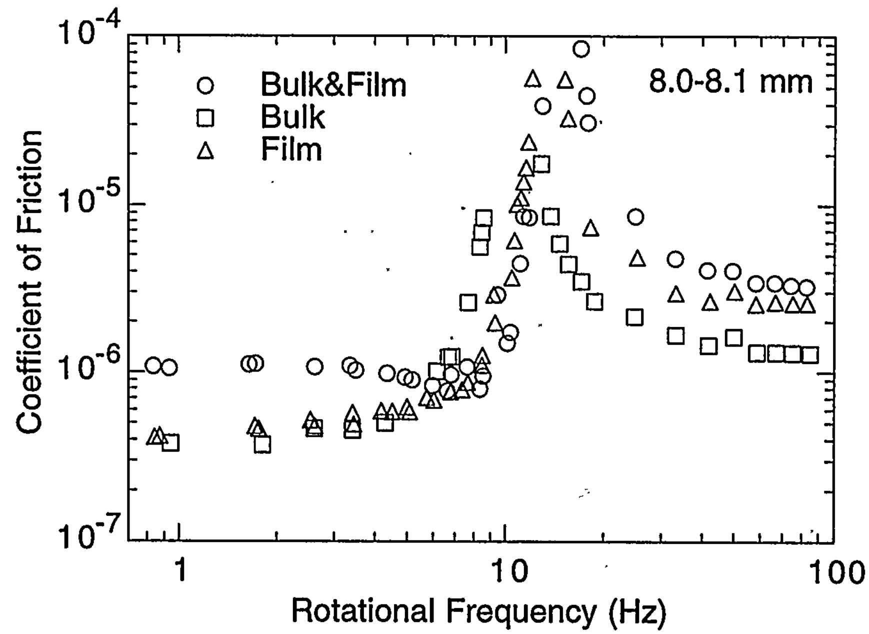
Coefficient of Friction
10-4
10-5
10-6
10-7
1
10
100
Rotational Frequency (Hz)
Bulk&Film
Bulk
Film
9.4-9.6 mm

Fig. 6



Bulk&Film
Bulk
Film
10.1-10.4 mm
10^{-4}
10^{-5}
10^{-6}
10^{-7}
Coefficient of Friction
1
10
100
Rotational Frequency (Hz)

Fig. 7


Bulk&Film
Bulk
Film
8.0-8.1 mm
Coefficient of Friction
Rotational Frequency (Hz)
10^{-4}
10^{-5}
10^{-6}
10^{-7}
1
10
100