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ROTORDYNAMIC CHARACTERIZATION OF A HYBRID SUPERCONDUCTOR MAGNET BEARING

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ABSTRACT

A hybrid superconductor magnet bearing uses magnetic forces between permanent magnets to provide lift and the flux pinning force between permanent magnets and superconductors to stabilize against instabilities intrinsic to the magnetic force between magnets. We have constructed a prototype kinetic energy storage system, using a hybrid superconductor magnet bearing to support a 42 lb. flywheel at the center. With five sensors on the periphery of the flywheel, we have monitored the position and attitude of the flywheel during its spin down. The results indicate low values of stiffnesses for the bearing. The implications of this and other consequences will be discussed.

INTRODUCTION

A rotary bearing is a device designed to provide an interface between a rotating shaft (rotor) and a stationary structure (stator) that allows the transmission of normal thrust but not shear forces. With commonly encountered bearings such as ball bearings, this interface is made up of metallic spheres that roll on well lubricated tracks. Thrust forces are transmitted from the stator to the rotor via contact forces between the metallic spheres and the track, but dissipative shear forces, present as friction wherever there is relative motion between two solid bodies in physical contact, are still not entirely eliminated despite lubrication. This direct contact between the surface of a rotating solid object and the surface of a stationary object can be replaced by an indirect contact mediated by a fluid in motion. Hydrodynamical forces due to the fluid motion are responsible for the transmission of normal thrust support from the stator to the rotor, while creating a small gap that keeps them slightly apart at the same time. Dissipative shear forces across the fluid interface now appear in the form of viscous forces inherent in the motion of the fluid, but is generally much reduced in magnitude from frictional forces encountered with direct contact. Fluid film bearings, air bearings and fluid lubricants for roller bearings, all operate by the same phenomena.

Contact between the rotor and the stator is further reduced in magnetic bearings. When operating in vacuum, aerodynamic drag forces can be reduced to a minimum depending on the lowest pressure that can be attained. Normal thrust force is exerted via magnetic flux linkages between the rotor and the stator. These same magnetic flux linkages are also another potential source of dissipative shear forces, if their penetration through any surrounding metallic parts is not engineered to be axisymmetric about the axis of rotation of the rotor. However, the most serious difficulty lies in the harmonic nature of the forces between magnets for time independent situations. Embodied in Earnshaw's theorem[1] as a special case, it implies that a stable equilibrium configuration cannot be with magnetostatic forces alone. Thus, alternating currents through coils are employed in passive magnetic suspension systems and active control circuitry is often found in the magnetic bearings of today. In these devices, the very means of maintaining stability requires some expenditure of energy.

With the advent of high temperature superconductivity, a new avenue to circumvent the inherent instability with magnetic systems becomes more readily accessible. The interaction between magnets and superconductors gives rise to two distinct effects which can be exploited for stable magnetic levitation. One is the Meissner effect; the other, the flux pinning effect. In the Meissner effect, the superconductor behaves as a perfect diamagnet and excludes magnetic fields completely from within its volume. As a result, a repulsive force develops between a superconductor and a magnet. The Meissner effect is dominant at lower magnetic fields (below the first critical field, $H_{c1}(T)$), and hence yields lower forces in general. Under higher magnetic fields, the superconductor allows partial or complete penetration of the external applied magnetic field into its interior. However, the rate of penetration of the field can be characterized as slow under most circumstances, and the behavior can be qualitatively described with the model of an almost perfect conductor. One consequence of this is that the superconductor develops a mechanical force opposing any motion that tends to change the magnetic field in its interior.[2] Thus, the force that develops between the superconductor and a magnet can be attractive or repulsive, depending on their relative position and orientation, and how they were brought into their present state.

To illustrate these properties, let us consider a magnet being brought to the vicinity of a cold (ie. below T_c, the temperature at which the superconductor changes from normal state to superconducting state) superconductor (melt-textured $YBa_2Cu_3O_7$) from a point far away. A continuously increasing repulsive force develops all the way. This could be interpreted as a consequence of the Meissner effect, and it is true at moderate distances, when the magnetic field at the superconductor due to the magnet is still lower than the first critical field. At smaller distances, however, the situation would have to be understood in terms of the flux pinning effect, which is only partially excluding the intensifying magnetic flux from the approaching magnet. This contention is supported by the following two observations: first, if we stop advancing the magnet towards the superconductor, the repulsive force gradually diminishes, signalling a reduction in the magnetic stress as the magnetic field continues to penetrate into the superconductor even though the magnet has stopped coming closer; and second, if we reverse the motion of the magnet, the repulsive force drops to values less than that recorded on the advance, and may reverse in direction to become an attractive force under certain circumstances.[3] Thus, the force between a superconductor and a magnet is not only dependent on its relative position and orientation, but also on the history of their relationship. As we shall see next, the attractive force is a signature of the flux pinning force as the Meissner effect can only give rise to repulsive forces.

The superconductor in the experiment described above was prepared in a zero field cooled condition, since it was already cold before the magnet started approaching. To contrast and compare, we can cool the superconductor after the magnet has been brought to the vicinity of the superconductor. This is called the field cooled condition. No appreciable force develops between the magnet and the superconductor, indicating that the magnetic field that was present in the superconductor is not expelled to any considerable extent as the superconductor is cooled down through the transition temperature. Now, if we push the magnet closer towards the superconductor, a repulsive force develops; but if we pull the magnet away from the superconductor, an attractive force ensues. The same happens if we displace the magnet in the lateral directions.[4] This is in full accordance with the expectations of the flux pinning effect in which the superconductor resists any attempts to change the magnetic flux that was present at the moment when it last became superconducting. Here, we may note that although the force developed under field cooled conditions is much less than that developed under zero field cooled conditions, the magnetic stiffnesses developed are comparable.

Ever since the discovery of high temperature superconductors, there have been many schemes to harness the levitation force of superconductors on magnets for the fabrication of nearly frictionless bearings. These operate on the same principle as the magnetic bearings, with the superconductor replacing one of the magnets, usually that in the stator. Normal thrusts are now carried by a combination of flux pinning forces and diamagnetic repulsive forces from the Meissner effect.[5,6] More importantly, there will be no resistance against rotation if the magnet has been carefully crafted to be axisymmetric about the axis of rotation on the rotor, for this motion produces no changes in the magnetic field anywhere.[3]

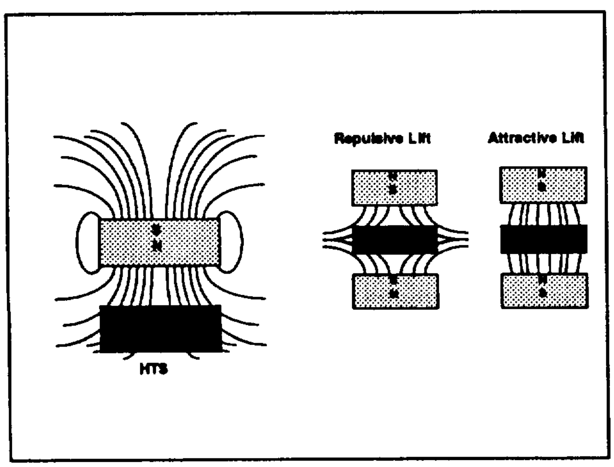

Fig. 1 On the left is an illustration of a superconductor magnet bearing. On the right are two versions of the hybrid concept. In the repulsive lift version, only the top magnet is freely levitated. In the attractive lift version, only the bottom magnet is freely suspended. All other components are presumed fixed.

At this point, we have to decide how we intend to put the magnet and the superconductor together to form the bearing. Field cooling is more natural and convenient, but it yields practically no thrust. However, even with zero field cooling, the levitation pressure that we can get is rather limited, to somewhere around 10 to 20 psi, and both short term stability and long term reliability are potential problems. On the contrary, levitation achieved with field cooled conditions appears to be more robust. So we decided to patch up the only shortcoming with the field cooled state by using additional magnets in the stator to provide the thrust needed.[7,8] With this hybrid approach, we gained the further advantage of the capability to achieve higher levitation pressure with less material. We do pay a price for this, as we have compromised the stability of the magnet superconductor configuration with the instability inherent in the magnetic force between the rotor magnet and the newly introduced stator magnet. As we shall soon see, we can lower this price to a small, acceptable level. This hybrid concept is illustrated in fig. 1.

We can arrive at this hybrid concept from the starting point with magnetic bearings also. Magnetic forces utilized in magnetic bearings can deliver sizable thrusts. The only thing that spoils this is their inherent instability which has to be overcome by means of active control. The hybrid approach simply replaces the active control circuitry with the passive differentially diamagnetic response of the high temperature superconductivity. Thus, we have combined the best of both worlds: the high thrust from the magnetic forces between magnets and the stability from the flux pinning forces between a magnet and a superconductor, all in a passive context in the sense of an absence of direct consumption of energy[4]. The one question that remains is whether the stability endowed by the magnet and superconductor combination is sufficient to overcome the instability of the magnet to magnet pair.

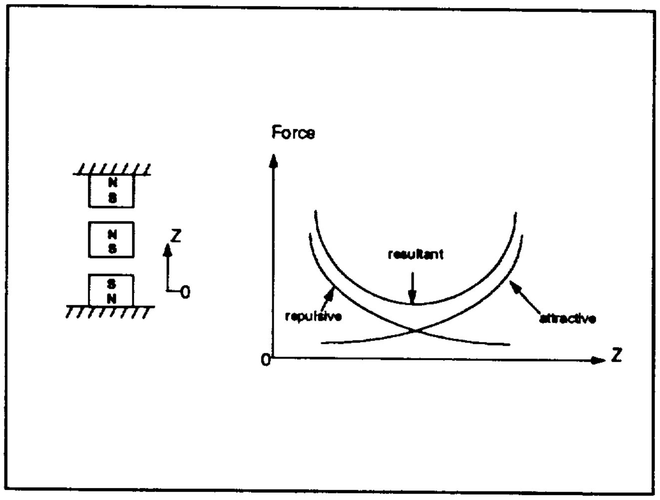

Fig. 2 Illustrating an example of a zero stiffness scenario. If the weight of the magnet exactly matches the value of the minimum resultant force at the midpoint, the magnet could be suspended in neutral equilibrium at that point.

In this tug of war between the instability of the magnet to magnet forces versus the stability coming from the flux pinning forces between the magnet and the superconductor, we can tip the balance towards stability either by increasing the flux pinning forces or decreasing the instability of the magnetic forces. The flux pinning forces are manifested in the critical current densities that the superconductors can carry, and limitations are set by intrinsic materials properties and processing techniques. On the other hand, although magnetic forces are inherently unstable, there is no lower bound to the magnitude of the instability. In other words, we can reduce the instability to a value as small as we please, in principle. We call this the zero stiffness concept, which is further illustrated in fig. 2.[9] What we have shown in this work is that in practice, we can reduce the instability in a magnet system capable of supporting a significant load down to a level that can be stabilized with a limited amount of superconducting material.

DESCRIPTION OF PROTOTYPE KINETIC ENERGY STORAGE SYSTEM

To demonstrate the practical utility of the hybrid magnet superconductor bearing, we have built a prototype kinetic energy storage system incorporating such bearings.[8] Being an energy storage system, it only makes sense to keep all source of energy loss down to a minimum. An extremely low loss is one of the potential benefits of the hybrid bearing. At the same time, the capacity for energy storage is also dependent on the mass involved, and the weight of this mass goes directly into the load on the bearing. Thus, for a device with useful energy storage capacity, the load on the bearing will also be substantial. This is where the high load carrying capability of the hybrid bearing becomes crucial.

The main component in a kinetic energy storage system that carries out the function of storing energy is the flywheel. In our prototype, the flywheel is composed of an aluminum disk, 12 in. in diameter, 1 in. thick, with two curvilinearly tapered stainless steel caps attached, one to each of both flat surfaces of the disk, making a total height from top to bottom of 7 in. The total weight of the flywheel comes out to 42 lbs. This load is shared almost equally between the top and bottom sets of magnets. The top set of magnets consists of a hollow cylinder magnet embedded in the top stainless steel cap on the rotor that is attracted to a similar hollow cylinder magnet contained in the stator. A piece of high temperature superconductor in the shape of an annular disk is inserted into the gap between these magnets for stabilization. The bottom set of magnets also consists of a hollow cylinder magnet embedded in the bottom stainless steel cap on the rotor, but is repelled by a solid cylinder magnet contained in the stator. While a piece of high temperature superconductor is inserted into the gap between magnets, an additional magnet attached to the case containing the superconductor occupies the volume of the hollow of the rotor magnet, to enhance the stabilizing prowess of the superconductor by decreasing the instability of the repelling magnets. This additional magnet also contributes to about one-sixth of the entire load on both bearings. Stability is further insured with a 4 in. ring magnet attached to the bottom of the flywheel, situated above a set of 12 superconductor pucks arranged in a ring and attached to the stator. Fig. 3 is a schematic representation of the magnet and superconductor placements.

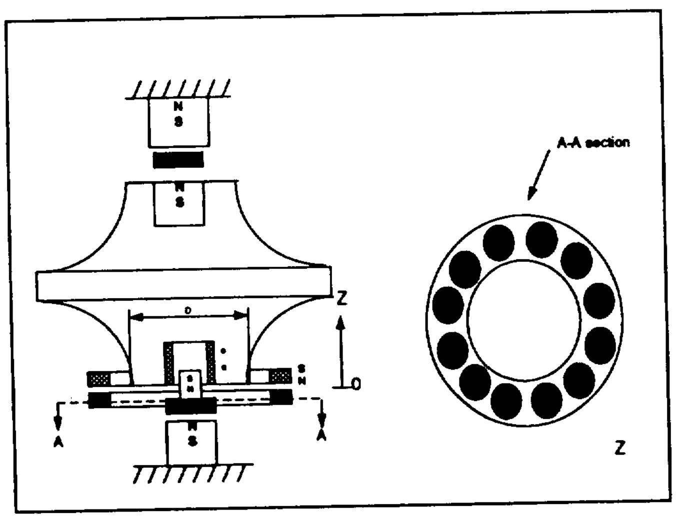

Fig. 3 Schematic representation of magnet and superconductor placements.

The above is the description of the barebone essentials of the storage system. To make it useful, it has to be efficiently interfaced with the outside world. Chief amongst the required accessories is a motor/generator with which to interconvert electrical and mechanical energies as energy is stored into or taken out from the system. A retractable non-contact magnetic clutch working with eddy currents is used as the link to transmit mechanical energy to and fro between the motor/generator and the rotating flywheel. Two chamfers, one near the top and one near the bottom of the flywheel, equipped with stepper motors to change their vertical positions, are used for positioning the flywheel vertically at the optimal height with respect to the magnets in the stators. Together with mechanical backup bearings placed on the top and the bottom of the flywheel, these two chamfers are also intended for use in arresting the motion of the flywheel in an emergency. The entire system is enclosed under a bell jar in vacuum, except for the superconductors which, naturally, have to be continuously immersed in liquid nitrogen. Thus, the superconductors are contained in vacuum-tight cavities made of stainless steel and supplied with cryogen through a plumbing system that includes a pump for liquid nitrogen and is open to the atmosphere. Considering that the superconductors have to be very close (< 5 mm.) to the rotating magnets on the flywheel in vacuum, the design and fabrication of these cold stages could present a formidable challenge. Fig. 4 is a drawing of the assembled device.

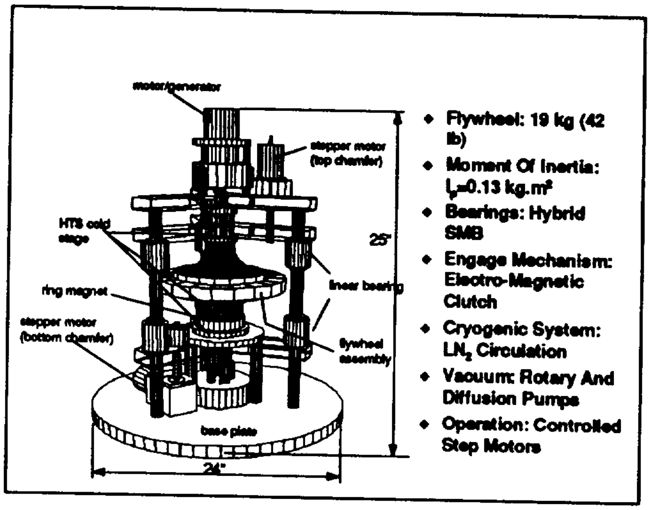

Fig. 4 Three dimensional drawing of our prototype kinetic energy storage system as assembled.

The first step in the operation of this kinetic energy storage system is to identify the optimal position of the flywheel with respect to the stator magnets, and the position of the top and bottom stator magnets with respect to each other. This is done with partial information from the mapping of the magnetic fields from the magnet components and the measurement of forces and stiffnesses between the magnet and the superconductor components before assembly. Final adjustments are made after assembly and before closing the bell jar, by observing the motion of the flywheel as the chamfers holding them in position are pulled apart from each other. After the bell jar is closed and the system is pumped down to its ultimate low pressure, we circulate liquid nitrogen through the cold stages, and spin the flywheel up to speed. Then we release the chamfers to allow the flywheel to levitate after the superconductors have undergone transition to the superconducting state, which is gauged by a certain amount of time after we started the liquid nitrogen pump, a period of time obtained with experience. We also tried releasing the flywheel first, after the superconductors are cold enough, and then spinning the flywheel up to speed from rest in a levitated state. There seems to be little difference in the result.

Fig. 5 shows the spin down curves of our prototype kinetic energy storage system at two different pressures. Under a vacuum of 7×10^{-4} torr, we have been able to spin this flywheel up to a speed of 6000 RPM, storing an energy of 8 Whr. The initial rate of energy loss is about 5% per hour. The flywheel did not stop after 40 hours, at which time its speed has decreased to 240 RPM. The average rate of energy loss for this entire period is 2.5% per hour. With an improved vacuum of 10^{-5} torr, and

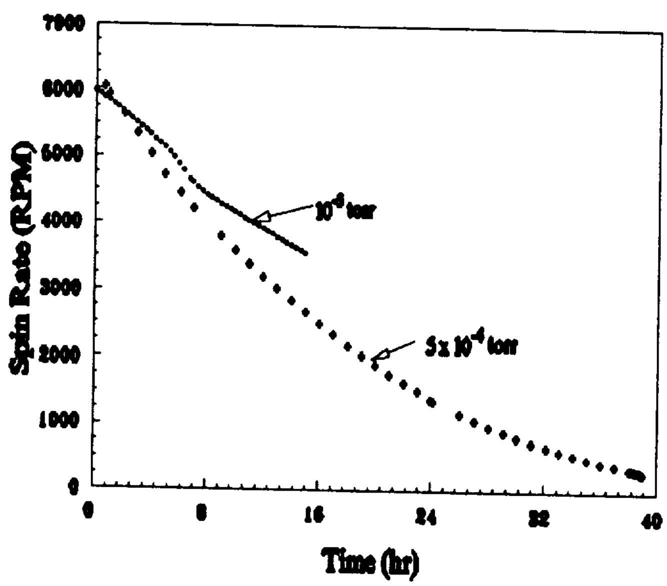

Fig. 5 Spin down curve of our prototype kinetic energy storage system under two different pressures.

starting at the same speed, the initial rate of energy loss reduced to about 4% per hour. The run was ended after 15 hours for non-technical reasons. The extrapolated time to stop would be 75 hours, with mean energy loss rate of less than 2% per hour.

OBSERVATION OF ROTORDYNAMICS DURING SPIN DOWN

For the purpose of load levelling for the utilities, an energy loss rate of around 0.1% per hour would be desirable. Hence, reducing energy dissipation is still our first priority. Comparing the spin down results at different pressures with theoretical estimates, we have come to the conclusion that the majority of the dissipation is not due to aerodynamic drag from the residual gas. Thus, further improvement of vacuum would not be very fruitful at this point, and we have to look into the other major suspected reason: magnetic losses, of which there are quite a few different mechanisms: (i) even with the flywheel perfectly centered and its rotation axis perfectly aligned, any slight off axisymmetry of the rotor magnets would induce eddy currents in the surrounding metal parts, notably the stainless steel cold stages, and magnetic hysteresis losses in the superconductors in these cold stages; (ii) even with perfectly axisymmetric rotor magnets, if the flywheel is rotating about an off-center or slightly tilted axis, the magnetic field as seen by the stator parts would still have an alternating component, with the same consequences as regards to loss; and (iii) similarly, the metallic parts on the rotor would experience a fluctuating magnetic field giving rise to energy loss if either the stator magnets or the magnetic field trapped inside the superconductors are non-axisymmetric, or again, the flywheel is not rotating about an axis at the geometric center, or about an axis aligned with the geometric axis. The same result would happen if all the magnetic components are perfect, but the inertial properties of the flywheel is off the mark, either due to static imbalance or dynamic imbalance.

The purpose of following the spin down process in more detail is to assess the relative importance of the above mechanisms of energy dissipation. We have accelerated the deceleration of the flywheel in the observation by keeping the non-contact magnetic clutch engaged, so that the experiment may be performed in a shorter time span. The observation is carried out by monitoring the position of the flywheel surface at five different points, from which the position and orientation of the flywheel may be reconstructed. The placement of these position sensors is illustrated in fig. 6. A sixth sensor, consisting of a laser with a photodiode, monitors the total rotation rate of the flywheel by a chopping technique.

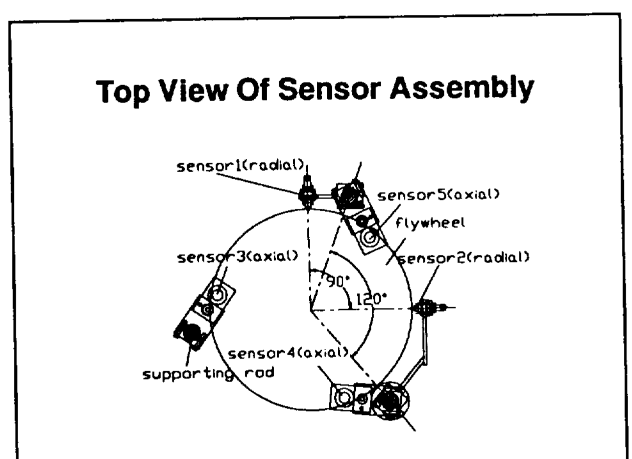

Fig. 6 Drawing for placement of position sensors.

RESULTS AND DISCUSSION

Let us start with the flywheel not rotating, but levitated. By comparing the readings of the position sensors after the flywheel is released into its levitated position and before, when it is clamped at an estimated optimum position, we found that the flywheel has tilted by about 0.2° and its center has shifted laterally by about 0.4 mm., not inconsiderable amounts, but still within the tolerance of our bearings because they were designed to operate with a large gap. The tilt and the displacement are in the same plane. A schematic drawing illustrating these deviations is shown in fig. 7. This result definitely indicates some sort of asymmetry in the system, but we cannot pinpoint its origin as yet.

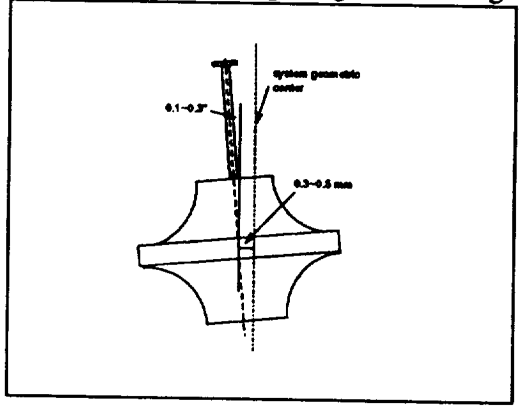

Fig. 7 Illustration of tilt and lateral shift of flywheel when levitated and stationary.

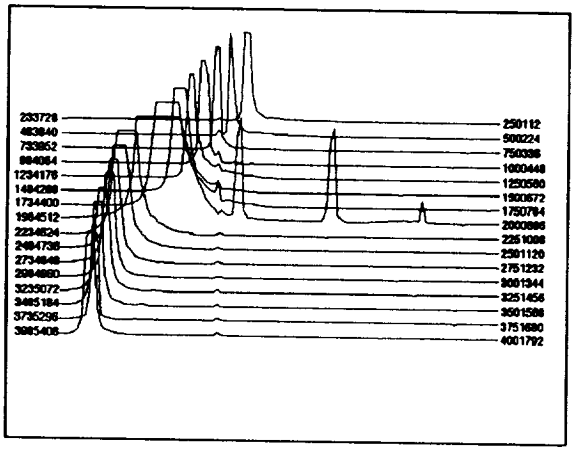

Fig. 8 Rotordynamic response of flywheel on spin down. The numbers are millsecond time markers.

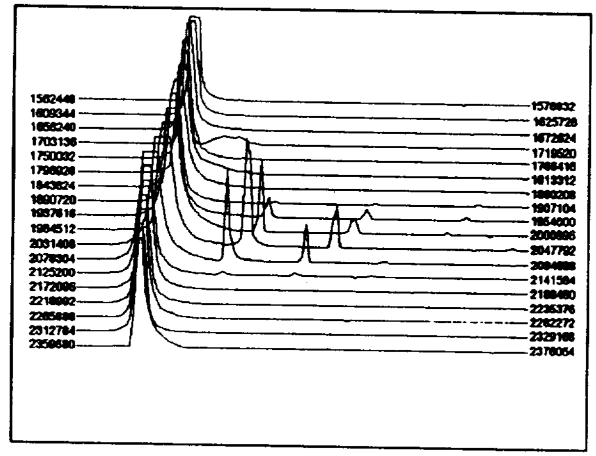

Fig. 9 Rotordynamic response of flywheel on spin down through the critical speed. The numbers are millsecond time markers.

On spinning up the flywheel, it goes through a critical speed regime as expected, and similarly on spin down. The rotordynamical response of the flywheel on spin down is shown in fig. 8. An expanded version in the transition region around the critical speed is shown in fig. 9.

Further examination of this region shows that this can be interpreted as several criticals closely clustered around 5 hz. Fig. 10 is a graph of the time evolution of the amplitude in the fundamental that is suggestive of this interpretation. This multiplicity is a result of multiple rigid body modes, with very similar stiffnesses. The value of 5 hz. agrees well with the value predicted from the spin whirl map, using the stiffness values measured before the magnets and superconductors were assembled. It also agrees with the simple formula

$$\omega^2 = k/M. \qquad (1)$$

The stiffnesses of the bearings can be estimated from this to be of the order of 30 N/mm. This value of the stiffnesses is rather low, and it does have its disadvantages. To some extent, these disadvantages are compensated for by gaps that can be large enough to accommodate the vibration amplitude when the flywheel goes through these criticals. These low stiffnesses also yield low critical speeds, which means that the flywheel can easily be boosted to operate in the supercritical regime, where the flywheel is self-centering and self-aligning. Measurements in this regime show that, as the rotational speed of the flywheel is increased, the vibration amplitudes of all the variables in this supercritical regime decrease as ω^{-2} with no offset for three of the sensors sensitive to tilt, and about 0.1 mm for the two sensors sensitive to lateral shift. Fig. 11 is a plot of the data which exhibits behavior according to this relationship.

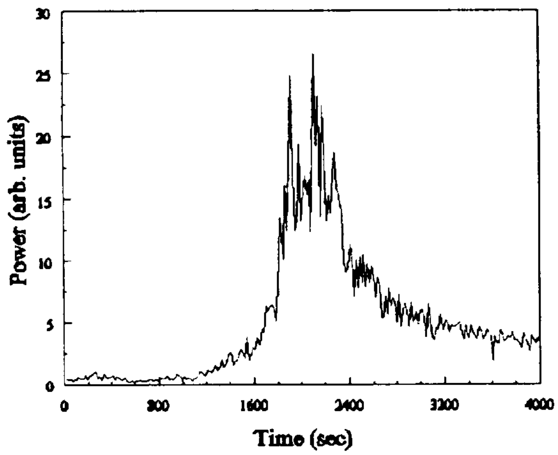

Fig. 10 Time evolution of the squared amplitude of vibration at the fundamental frequency of one of the position sensors.

This result implies that the center of gravity of this flywheel coincides with its geometrical center to within 0.1 mm., and its principal moments of inertia coincides with its geometrical axis to a precision better than 0.002^0. It also means that the tilt and the lateral shift of the flywheel in its levitated, but stationary state is due more to the deviations of the rotor magnet from perfect axisymmetry, with a minor contribution from mass eccentricity, which we suspect comes from the mounting of the large ring magnet at the bottom. From the systems operation point of view, it also means that we do not have to be overly concerned with the inertial balance of the flywheel. Should it still be desirable to enhance the stiffness of the bearings, use of ion implantation techniques to create damage and pinning centers has been shown to be able to change the critical current density by orders of magnitude.[10] A corresponding, but perhaps more moderate increase in the stiffness can be expected.

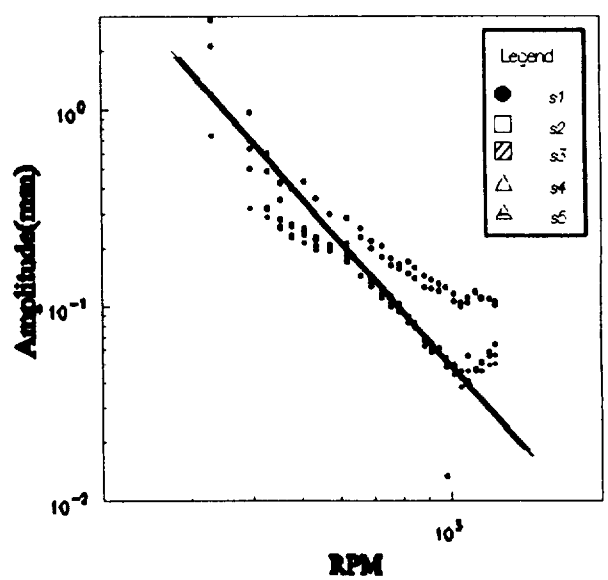

Fig. 11 Amplitude of oscillation measured at all the position sensors in the supercritical regime. The final upturn was observed to coincide with mechanical vibrations of the holding structure.

The effect of the vigorous oscillatory motion of the flywheel on the rate of energy loss is clearly evident in the spin down curve shown in fig. 12. With care, even the effect of minor resonances in the supporting mechanical structure, such as the pipes that carry liquid nitrogen, can be discerned. However, all these effects go away at high spins, and what we should focus attention on is the general and gradual increase in the rate of energy loss as spin is increased. If the energy loss is due to magnetic hysteresis in the superconductor, the spin down curve can be expected to be linear in time, whereas, if it is eddy current loss, the spin down curve would be exponential in time. Our curve is somewhat of a mix, and we are in the process of sorting this out in our next set of experiments with cold stages constructed out of electrically insulating material to eliminate eddy current loss.

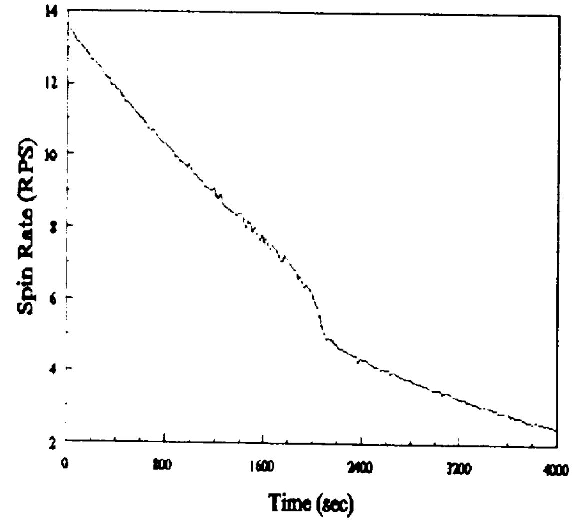

Fig. 12 Accelerated spin down curve for rotodynamic analysis of our prototype flywheel/bearing system. The sudden drop near the midpoint is where the system goes through its critical speed(s).

Throughout the spin down process, from high spins to low spins, we have observed that the flywheel is off axis and off center, but is keeping the same face outwards. This is indicated by the observation that the chopping signal is always in synchronism with the fundamental in the signal from all the sensors. One explanation of this is that the rotor magnets are not precisely axisymmetric, with the result that it is favorable to have one side always facing outside. However, it is expected that this should switch in going through the critical region. A phase slip of 180°

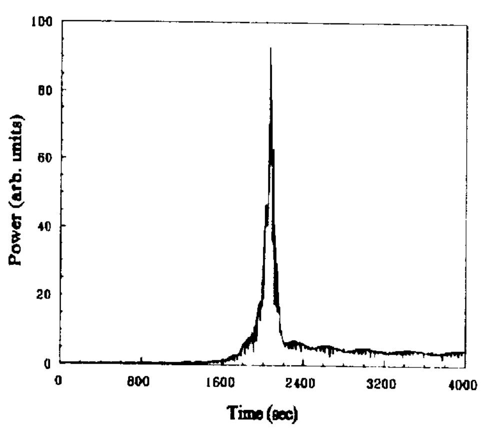

Fig. 13a Time evolution of the squared amplitude of vibrations of the tilt angle in the x-direction, defined arbitrarily to go through one of the three position sensors placed for tilt detection.

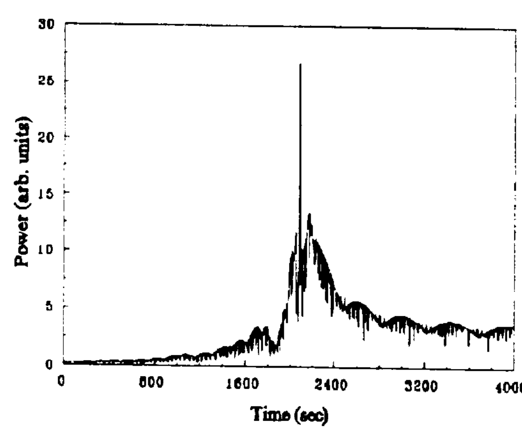

Fig. 13b Time evolution of the squared amplitude of vibrations of the tilt angle in the y-direction, perpendicular to the x-direction defined in fig. 13a.

during the transition could have been missed. The stator magnets are not exactly axisymmetric either, but perhaps deviate from axisymmetry to a smaller extent. The time evolution of the power spectrum of the tilt of the axis of the flywheel is slightly different for the two orthogonal directions, as shown in fig. 13 on the previous page.

FUTURE DEVELOPMENTS

The subsequent stages of development will see us pushing towards devices with higher and higher storage capacities. This will be achieved in two ways, increasing the maximum operating speed of the flywheel with a moderate increase in weight, or increasing the weight with a moderate increase in speed. It is estimated that machines with 1 kWhr to 10 kWhr can be reached in the next stage. This by no means represent a limitation for further growth.

Another issue is a materials issue. These high temperature superconductors show a promise of enhanced critical current density, and by implication stiffness, using ion implantation techniques to create an optimal amount of damage in the material which serves as pinning centers. This would certainly be a welcome development.

Finally, we should be focussing more attention on the overall problem of systems integration, such as designing a motor/generator that would couple into a low stiffness flywheel system effectively for energy storage and release. We are still in the process of designing a cold stage to enclose liquid nitrogen and high temperature superconductor in the vacuum chamber, without metallic parts. Reliability of the present operation procedure also needs improvement.

CONCLUSION

In conclusion, we would like to point out that kinetic energy storage system is a feasible application for hybrid superconductor magnet bearings, despite the objection of their low stiffnesses, which, in fact, offers some features that partially compensate for their disadvantage. Last, but not least, there is still some room for improvement of their stiffnesses.

ACKNOWLEDGEMENT

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