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An Active Magnetic Bearing With High T_C Superconducting Coils and Ferromagnetic Cores

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AN ACTIVE MAGNETIC BEARING WITH HIGH T_c SUPER-CONDUCTING COILS AND FERROMAGNETIC CORES

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ABSTRACT

A proof-of-feasibility demonstration showed that high-T_c superconductor (HTS) coils can be used in a high-load, active magnetic bearing in LN_2. A homopolar radial bearing with commercially wound HTS (Bi 2223) bias and control coils produced over 890 N (200 lb) radial load capacity (measured nonrotating) and supported a shaft to 14000 rpm. The goal was to show that HTS coils can operate stably with ferromagnetic cores in a feedback controlled system at a current density similar to that for Cu in LN_2.

The bias coil, wound with nontwisted, multifilament HTS conductor, dissipated negligible power for its direct current. The control coils, wound with monofilament HTS sheathed in Ag, dissipated negligible power for direct current. AC losses increased rapidly with frequency and quadratically with AC amplitude. Above about 2 Hz, the effective resistance of the control coils exceeds that of the silver which is in electrical parallel with the oxide superconductor. These results show that twisted multifilament conductor is not needed for stable levitation but may be desired to reduce control power for sizable dynamic loads.

INTRODUCTION AND BACKGROUND

It is now possible to purchase HTS coils that carry 1000 A turns in LN_2, produce a few hundred gauss and are as small as copper coils operating in the same conditions. These are roughly the requirements for coils in active magnetic bearings. There are concerns about feasibility which center around the poor physical strength of the ceramic superconductors, their poor J_c at LN_2 temperature, and the prospect of high dynamic losses in HTS control coils that must carry currents with frequency components of several hundred hertz. These concerns have previously confined HTS magnetic bearing development to passive types.

Two distinct motivations for using superconducting coils in magnetic bearings instead of normal coils are to save power and to reduce coil cross section. At LN_2 temperature at this time only the Bi 2223 material can carry enough current in a small coil (limited by the self-field of the coil) to compete with normal conductors.

Under a NASA Lewis Research Center grant to the University of Wisconsin,[1] a substantial increase of load capacity was predicted if HTS windings are used in magnetic bearings. Three approaches were studied analytically. In the first ferromagnetic cores were retained, but high current density was assumed, yielding high load capacity by driving the cores into saturation. The second approach was to abandon the stator cores and use only stator coils. The third approach used HTS coils on both stator and rotor. The second and third approaches will lead to higher loads when HTS conductors can tolerate higher stress and higher self field in the coils. At present it is feasible to use only the first approach, which does not require high stress or high field strength in the coils.

PHYSICAL DESCRIPTION OF MAGNETIC BEARING

The bearing is a homopolar radial bearing with a separate bias coil. Successful operation of the bias coil, which carries only direct current, was expected and would save the majority of the power consumed in a normal bearing. Successful operation of the control coils, which must carry a combination of DC and AC to produce steady and dynamic forces, was less assured. There was concern about the ability of the HTS composite to carry rapidly changing currents.

A drawing of the bearing is shown in Fig. 1. The overall bearing size is 18 cm O.D., 11.2 cm long with a 7.57 cm diameter journal. The bias coil encircles the ferromagnetic shaft. Flux passes through the shaft, through four air gaps to the poles of one stator, to the exterior flux tube to the other stator and through that stator's air gaps to the rotor. We used only four control coils to reduce expense, installing them on one stator and leaving the other stator poles empty. We compromised the design of the other bearing parts to accommodate externally-wound, circular coils. The rotor and stator laminations are 2V Permendur.

THE HIGH-T_C COILS

Bias Coil

The bias coil in a homopolar radial magnetic bearing produces a steady (DC) magnetic field in the air gaps. The gap between the journal and stator is 0.5 mm. Since there are two gaps in series in the magnetic circuit, about 1000 A-turns are required to produce 1 T in the gaps, allowing for leakage and fringing.

The commercially-produced circular bias coil (electrical size: 8.3 cm I.D., 11.8 cm O.D. and 1.36 cm long) was layer-wound on an aluminum coil form. A single length of multifilament conductor (19 filaments in a 0.2 mm by 2.5 mm Ag tape) was reacted before winding on the coil form. The silver-to-superconductor ratio is about 3. The 244 turn coil has a critical current (1 mV/cm criterion) of 3.9 A. The coil could be operated at 4.7 A with less than 20 mV potential drop. Without a ferromagnetic core the coil produces a calculated maximum axial magnetic induction of ~400 G at its inner bore. The voltage across the coil vs. steady current through the coil is shown in Fig. 2. The voltage was measured with voltage taps attached to the superconducting composite tape inside the current leads. The measured steady power

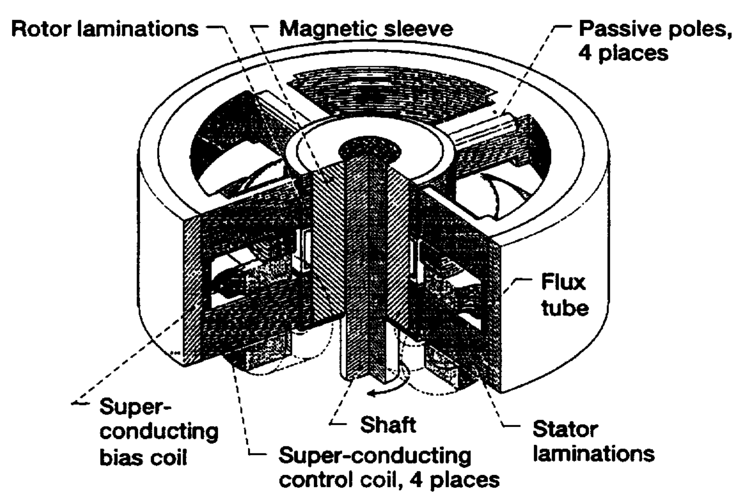

Figure 1.—Active magnetic bearing with high temperature superconductor bias and control coils.

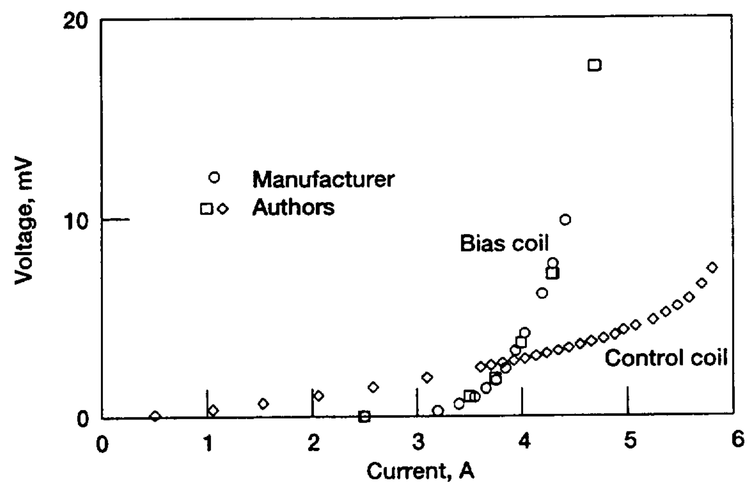

Figure 2.—Voltage across bias and control coils as functions of steady current in LN_2.

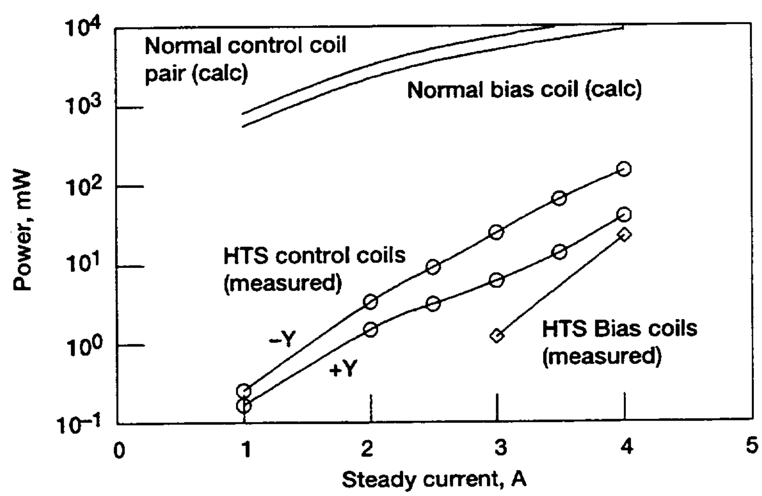

Figure 3.—Comparison of power consumption of HTS coils with normal coils (based on Ag cross sections in coils).

dissipated in the coil vs. current is shown in Fig. 3. This measurement was made in the bearing (with ferromagnetic cores). Also shown is the power that would be required if only the Ag matrix were present, to give a rough idea of the power saved by using the HTS composite.

Control Coils

The control coils in a homopolar magnetic bearing with a separate bias coil must each provide about half the number of ampere-turns (500 A-t) as the bias coil (1000 A-t). This allows the two control coils on an axis to double the field of one pole (in the absence of core saturation) and to reduce the field of the opposite pole to zero. This gives the maximum net radial force toward the double-strength pole. The control coil must carry a combination of DC and AC currents to support steady loads (such as shaft weight) and dynamic loads (such as those due to shaft unbalance). We over-designed the control coils with 1000 A-t to allow heteropolar operation, if desired.

The four commercially-produced circular control coils were 3.6 cm I.D., 6.2 cm O.D. and 2.0 cm long. They were layer-wound from a single length of Ag tape (tape cross section 0.11 mm by 4.7 mm) with a monofilament HTS core and reacted after winding. The epoxy-impregnated coils fit over the laminated stator poles without any coil form to conserve space and to avoid eddy currents. Each coil has between 230 and 232 turns, and the critical currents (1 mV/cm criterion) varied from 5.1 A to 5.6 A.

The voltage across one control coil as a function of steady current is shown in Fig. 2. The voltage was measured with taps on the Ag tape leads. The voltage increase at low currents comes partly from those leads, but it increases faster than linearly. The nonlinear part may be due to segments of superconductor with reduced critical currents, which force current into the Ag. The coil reached 5.8 A with under 8 mV potential drop.

The measured power dissipated at LN_2 temperature in two of the control coils is shown in Fig. 3, as well as the power calculated for the pair if only the Ag were present. Note the ordinate log scale. The HTS power is seen to be two to three orders of magnitude lower for steady current, which would be required in control coils to support steady loads such as the weight of a horizontal shaft.

AC LOSS MEASUREMENTS ON CONTROL COILS

Control coil power dissipation was measured for single frequencies, with and without superimposed direct current, and with and without ferromagnetic cores. The average power P_{av} was obtained from the product of the instantaneous current I and the voltage V, sampled at up to 12.8 kHz and averaged over a time T much larger than the period of the AC frequency f

$$P_{av} = (1/T) \int_{o}^{T} V(t) \quad I(t) \quad dt \tag{1}$$

where T >> 1/f and $I = I_o \sin(2 \text{ pft}) + I_{offset}$. When there is no DC offset current, we calculate an effective resistance R_{eff} by

$$R_{eff} = 2P_{av} / I_o^2. \tag{2}$$

We compare this effective resistance below to the calculated resistance of the Ag matrix at LN_2 temperature. That resistance is based on the measured room temperature resistance and the resistivity ratio, 5.97, for Ag at LN_2 temperature.

Air Core AC Losses

The average power dissipated in one of the control coils with no ferromagnetic core as a function of frequency with no DC offset current for several current amplitudes I_o was meas-ured. The effective resistance, calculated from the data by using Eqs. (1) and (2), is shown in Fig. 4. In the range of this data the effective resistance is roughly independent of AC amplitude. The figure also shows the resistance of the Ag matrix of the conductor for comparison. The resistance of the HTS composite surpasses the Ag resistance above about 100 Hz. The coils would have less resistance above that frequency if the oxide were not present. This result may be due to hindered flux penetration into the composite tape, predicted by a Bean-type model.[2] The currents and fields cannot freely penetrate the entire cross section of the tape, but must enter from surfaces as the current and field increase. Hence at high enough frequency, induced supercurrents prevent parts of the Ag from carrying transport current, increasing the apparent resistance.

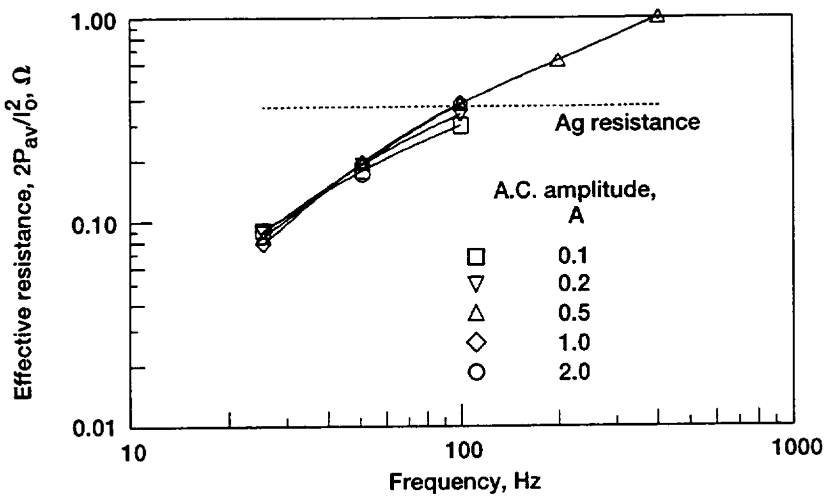

Figure 4.—Effective resistance of control coil as a function of frequency for several values of AC amplitude with no DC offset. No ferromagnetic core.

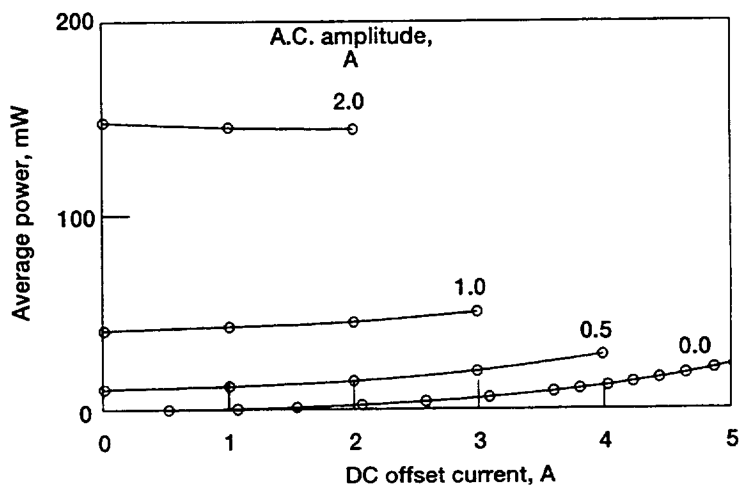

Figure 5.—Average control coil power as a function of DC offset at 25 Hz for four values of AC amplitude. No ferromagnetic core.

This problem may be reduced by twisted multifilamentary conductor, which is well developed for low temperature superconductors but was beyond the HTS art when these coils were made.

The effect of DC offset current added to AC is shown in Fig. 5. There the frequency is fixed at 25 hz and data for AC amplitude values of 0.0, 0.5, 1 and 2 A are shown. At this frequency the effect of DC offset is relatively minor and appears to be mainly due to the increase in resistance seen without any superimposed AC component. The measured power actually decreased with DC offset for an AC amplitude of 2 A. This might be due to the DC offset reducing the ability of the composite conductor to support shielding currents, allowing a greater portion of the Ag to carry transport current.

AC Losses with Ferromagnetic Core

The effective resistance of all of the control coils was measured in the magnetic bearing for pure frequencies. The results are shown in Fig. 6 with filled symbols and solid lines. There are substantial differences between coils, which is not surprising at this stage of HTS conductor and coil technology. All AC results before Fig. 6 were for the –X coil, one of the lowest loss coils. The +X coil stands out as significantly worse than the others at high frequencies. The increase in resistance occurs at much lower frequencies than it did without ferromagnetic cores. With cores the resistance surpasses the Ag resistance below 2 Hz rather than between 60 and 100 Hz. This is apparently related to the much greater change of flux through the coils.

The behavior of the resistance in the two cases with respect to frequency is remarkably similar with a simple change of frequency scale. Figure 6 shows (in open symbols and dotted lines) the effective resistance of the four coils from air-core tests with the frequencies divided arbitrarily by 50 (a number selected to best superimpose the two sets of data). With this rescaling there is considerable correspondence between the results for the same coil, with and without cores. Inductance measurements were made on the coils between 1 and 10 Hz in the superconducting state with and without the ferromagnetic cores. Those measurements yielded 75 and 2.2 mH, respectively. The ratio of these values is 34, a number of the same order of magnitude as the value of 50 used above to rescale the air-core frequency data. These results suggest that the losses can be largely linked to the rate of flux change through the coils. It is therefore hoped that twisted, multifilamentary conductor will substantially reduce the losses, making their onset occur at higher frequency and limiting their maximum values to approximately what would occur in the Ag.

The effect of DC offset current on AC power dissipation was measured at 1 Hz for AC amplitudes of 0.5, 1 and 2 A for two of the coils in the bearing. The results are shown in Fig. 7. At the lowest amplitude there is not much increase in power dissipation below 3 A offset current. For the higher amplitudes the dissipation first falls with offset current, perhaps because of a suppression of shielding supercurrents. As the sum of offset plus AC amplitude approaches within an ampere or so of the critical current, the dissipation begins to increase.

Control Coil Power Dissipation with Rotating Shaft

The average power dissipated in the control coils during bearing operation was meas-ured at various constant speeds of the rotor, with the rotor in its best balance condition and with 6.8 g-cm of unbalance. The shaft rotating frequency ranged from 0 to 160 Hz during the measurements. The results are shown in Fig. 8. The +X coil is again generally the worst. The –Y coil, as previously, is next worst. The Y axis generally had less stability margin than the X.

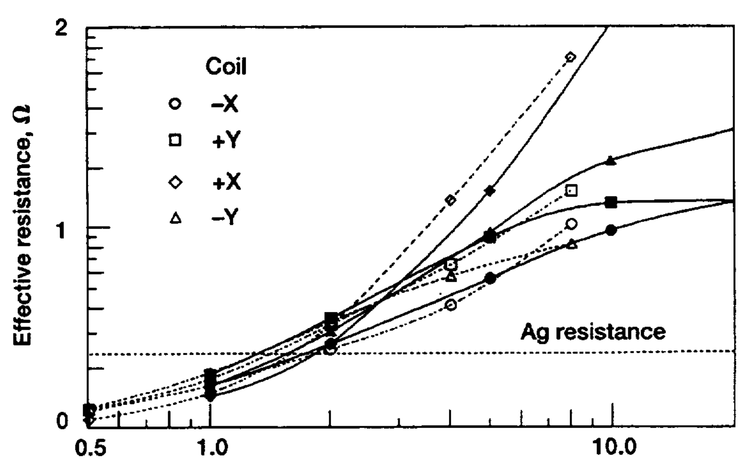

Figure 6.—Effective resistance of control coils vs. frequency with ferromagnetic cores (filled symbols) and vs. frequency divided by 50 for coils without cores (open symbols). AC amplitude is 0.5 A.

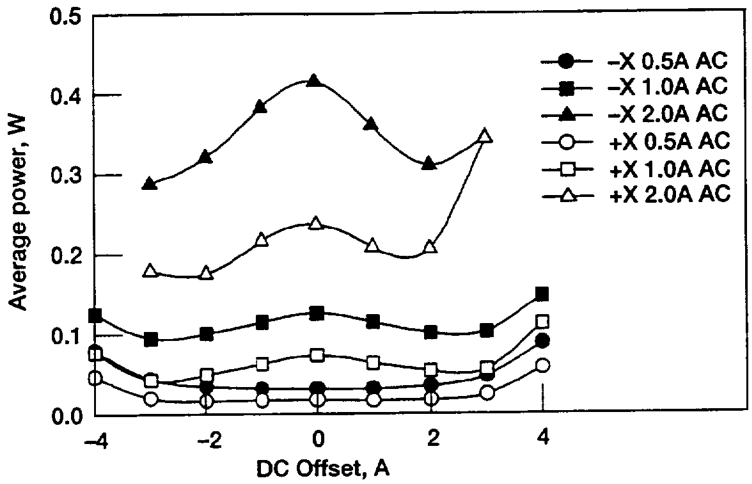

Figure 7.—X axis HTS control coil power dissipation vs. DC offset at 1 Hz with ferromagnetic cores.

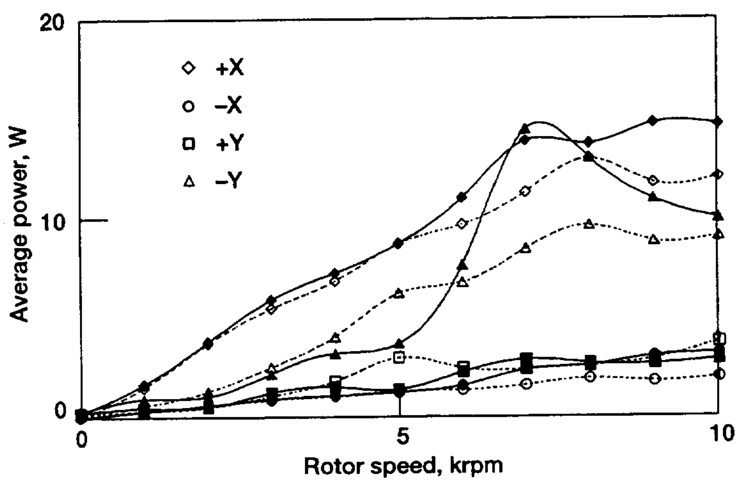

Figure 8.—Control coil power dissipation vs. rotor speed, balanced (open symbols and dotted lines) and with 6.8 g-cm unbalance (filled symbols and solid lines). Bias = 4 A.

We may hope that the losses measured for the better coils represent upper bounds for what will be possible for monofilament conductor as its technology improves. Twisted multifilamentary conductor should provide substantial reduction from that level.

MAGNETIC BEARING OPERATING RESULTS

The LN_2 test rig has been described previously.[3,4] The shaft is vertical, supported near the top by a conventional ball bearing pair operating at room temperature. The magnetic bearing near the lower end of the shaft can be submerged in LN_2.

The bearing was operated to the maximum speed of the rig, 14,000 rpm, both at room temperature at 2A bias and at LN_2 temperature at various bias currents up to 4A. For stable operation it was

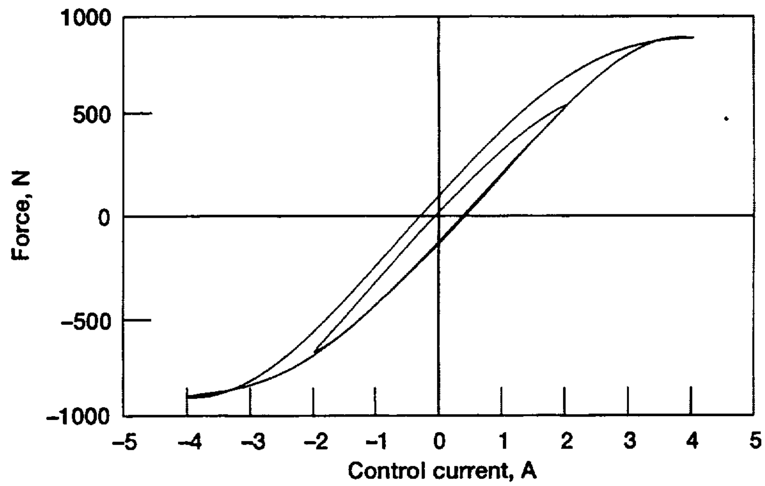

Figure 9.—X axis force as a function of control current at 4 A bias. Liquid nitrogen temperature.

necessary to use values of damping several times as high as required for other bearings we have run of similar size. At this time we do not know if this was due to the superconducting coils, the uncontrolled stator poles, or some other cause.

A maximum load capacity of 890 N (200 lb) was produced by the bearing, as shown in Fig. 9. An approximately linear load range extends (during load increase) to about 556 to 668 N (125 to 150 lb). The figure shows complete force hysteresis loops (each taken over a 5 sec period) for maximum control currents of ±4 and ±2 A. The higher current carries the force to a saturation level. The hysteresis is probably due to the Co-Fe core material rather than to superconducting effects. Loads were measured with the shaft nonrotating with a load fixture with small load cells.

With approximately 3 cm increase in bearing length, control coils could be added to the empty stator, increasing the maximum load capacity to 1780 N (400 lb).

CONCLUDING REMARKS

We have shown that an active high-load HTS magnetic bearing can be operated at LN_2 temperature with several performance measures approaching those possible with conventional windings. Comparable current density and hence coil size were obtained. For a lower temperature application (e.g., in LH_2) the coils could be substantially smaller, subject to stress limitations, of course. Power to supply the bias field was reduced essentially to zero, the same advantage provided by permanent magnet biasing. Power dissipated in the control coils to support steady loads was reduced essentially to zero. The control coils support dynamic currents sufficiently well to permit stable levitation up to the top speed (14,000 rpm) of our rig. A.C. losses appear to be related to coil inductance, suggesting that a twisted multi-filamentary conductor could reduce the losses substantially.

We found that the power dissipated in the control coils above about 2 Hz exceeded that which would be dissipated in normal coils.

Critical currents of the HTS conductors are improving and smaller coils are already possible. The primary technical improvements needed for active bearings that retain ferromagnetic cores are noncircular coils and twisted, multifilamentary conductor.

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