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**STUDY OF MAGNETIC BEARINGS
WITH HIGH TEMPERATURE
SUPERCONDUCTORS**

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PHASE III REPORT
December 1991

p-17

Contract NAG3-1041
for

NASA-LEWIS RESEARCH CENTER
CLEVELAND, OHIO 44135

by

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(NASA-CR-192229) STUDY OF MAGNETIC
BEARINGS WITH HIGH TEMPERATURE
SUPERCONDUCTORS, PHASE 3
(Wisconsin Univ.) 17 p

N93-19378

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Phase III
Magnetic Bearings with High- T_c Superconductor
December 1991

SUMMARY

This report covers three areas related to the actively controlled radial magnetic bearing concepts discussed in the 1990 annual report. These areas are:

- 1 - Modification to the ac loss calculations of the 1990 report
- 2 - A continuous charging mechanism to compensate rotor current drop due to ac losses
- 3 - Design of a proof of principle experiment simulating the proposed bearing concept.

Chapter 1 is a summary of the final design described in detail in the 1990 report.

Chapter 2 is a reexamination of the ac loss calculations. In the 1990 report, the losses due to stator ac fields were used as a load on the rotor stored energy. This is not correct because the stator ac field losses in the rotor winding come from stator power supplies resulting in practically no rotor current decay.

Chapter 3 is a discussion of a circuit that continuously charges the rotor coils through inductive coupling between rotor and stator.

Chapter 4 is a description of a future experiment to test the proposed concept (proof of principle experiment - POPE). A radial bearing system would be constructed and tested at liquid helium temperature. The test would demonstrate the feasibility of the design concept, the stability of stator and rotor coils, the ac losses due to ac fields and vibrations, the stator power supply requirements, the rotor current degradation time, and the bearing pressure as functions of currents.

I. RADIAL ACTIVE SUPERCONDUCTING BEARING CONCEPT

A conventional radial active bearing system consists of an iron sleeve in the rotor to be actively controlled by iron core electromagnets that produce corrective attraction forces. The maximum obtainable pressure is limited by the saturation magnetization of the iron to about 200 N cm^{-2} . In a recent publication, we disclosed the new configuration shown in Fig.1. The bearing rotor distance L is filled with a number of solenoid sets covering a distance of $2 h_t$ with alternate current directions in adjacent solenoids. These solenoids are in series; they either carry current in a persistent mode (no power supplies) or are inductively charged (as will be shown later) to compensate for ac losses in the rotor windings. The number of solenoid sets N_s , can be one or more placed next to each other covering the axial distance L (Figure 1 shows only one set). Note that $N_s = L/2h_t$. The stator has 4 saddle coils for each set of rotor solenoids. The advantages of the configuration are:

1. Both the rotor and the stator have superconductive windings for maximum attraction or repulsion.
2. The two opposite saddle coils produce simultaneous attraction and repulsion forces thus doubling the correction force. This is not possible if the rotor is a magnetic material since the force is attraction only.

Low and high temperature superconductor wires can be used. The requirement is that the dc rotor winding current density be $20 - 40 \text{ kA/cm}^2$ at 5 tesla dc field in addition to the 0.5 - 1 tesla ac field. Here we cover: 1.) the affect of ac losses in rotor solenoids on the degradation of their own persistent current; 2.) an inductively charging circuit for rotor coils to compensate for ac losses, and 3.) a proof of principle experiment.

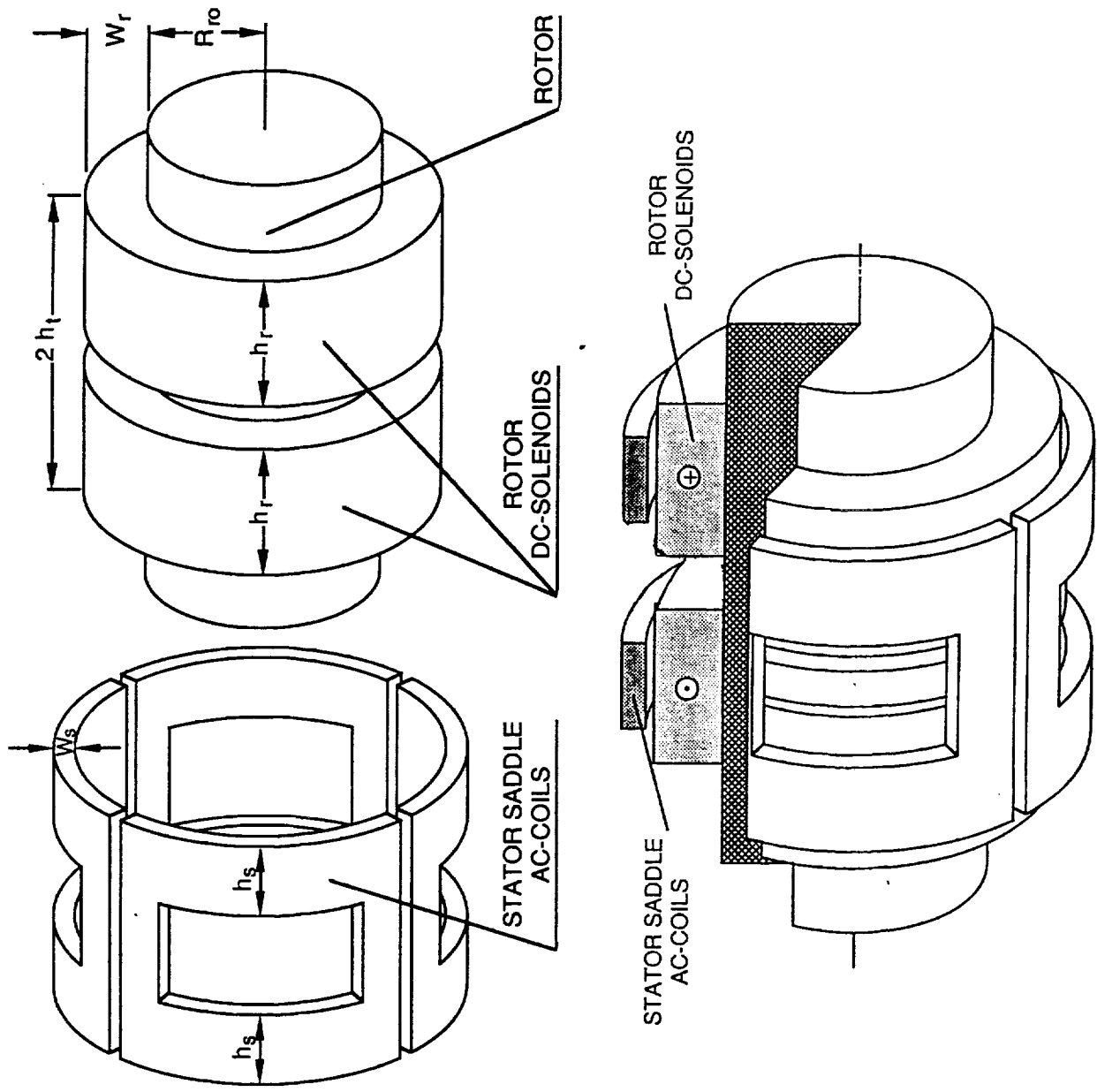


Figure 1 Actively Controlled Radial Bearing Concept Showing One Set of Rotor/Stator Coils

II. ROTOR CURRENT DEGRADATION from AC LOSS

LTS multifilamentary wires with greatly reduced losses have been produced commercially in lengths of several tens of kilometers by GEC ALSTHOM (France) and IGC (USA). Their ac losses consist of two parts: part one is due to magnetic hysteresis in the superconducting material which is proportional to the filament diameter (BEAN model) and the second part is from eddy currents in the matrix which are proportional to the square of the twist pitch divided by the matrix electrical resistivity.

The hysteretic loss decreases with filament diameter. If spacing between filaments is comparable to the coherence length of the matrix metal, then the filaments become coupled. From an electromagnetic point of view, coupled filaments behave like one large filament, with high losses and poor electromagnetic stability (proximity effect). If the spacing between filaments is larger than a smaller filament diameter leads to a smaller volume fraction of superconductor, and a smaller overall critical current density. In Fig.2 the CuNi to SC ratio is 1.48 for filament diam. $d_f > 200$ nm. For $d_f < 200$ nm the ratio is increased to maintain a 125 nm minimum distance between filaments. The CuNi to SC ratio at $d_f = 100$ nm is 4.58. The critical current densities in NbTi are: J_c (2 tesla) = 5×10^9 A m⁻², J_c (4 tesla) = 3.745×10^9 A m⁻², J_c (6 tesla) = 2.296×10^9 A m⁻² and J_c (8 tesla) = 0.84×10^9 A m⁻². As shown in Fig.2, it is difficult to obtain high overall current densities with very small filaments, especially at high magnetic fields. This makes it difficult to get high overall current densities in active superconducting bearings for filament sizes less than 400 nm.

When proximity effects are avoided, hysteretic losses of ultrafine filaments in low fields are lower than expected from the simple proportionality of diameter because of reversible flux motion.²

In order to lower the eddy current coupling losses, a 30% Ni coppernickel matrix is used. The twist pitch is five times the strand diameter. A shorter twist pitch is more difficult to manufacture and greatly reduces the critical current density. For a 0.1 mm strand, the

coupling loss is much smaller than the hysteresis loss for frequencies up to 1 kHz.

The effect of dc transport current on hysteresis losses due to external ac fields on very fine filaments is not repeated here. Previous work on large filaments shows a slight increase in ac losses for large β [see Eq. 8.25 of "Superconducting Magnets" by Martin Wilson, Oxford Science Publications - 1983]. For simplicity, we neglect the effect of dc transport currents on hysteresis losses.

The rotor solenoids in the bearings in Fig.1 are connected in series. There is no flux linkage between the stator and rotor coils when exactly centered. In Fig.3 the top and bottom saddle coils produce simultaneous repulsion and attraction forces due to the small flux linkage for off-center radial positions. This flux is very small compared to the self flux of each rotor solenoid and produces only small changes in rotor persistent currents. These small changes average to zero over a few cycles. The ac loss that the rotor experiences comes mostly from ac changes in the stator field. Losses due to small changes in the rotor current are insignificant. The ac heat generation in the rotor winding due to the stator ac fields is a load on the stator power supply and will not degrade the rotor persistent current. The ac loss due to the small changes in rotor currents may slowly degrade the rotor current. We do not have an easy mechanism to calculate this effect exactly, but we know it is very small. Later we introduce the concept of a flux pump that can inductively charge the rotor coils and compensate for current degradation.

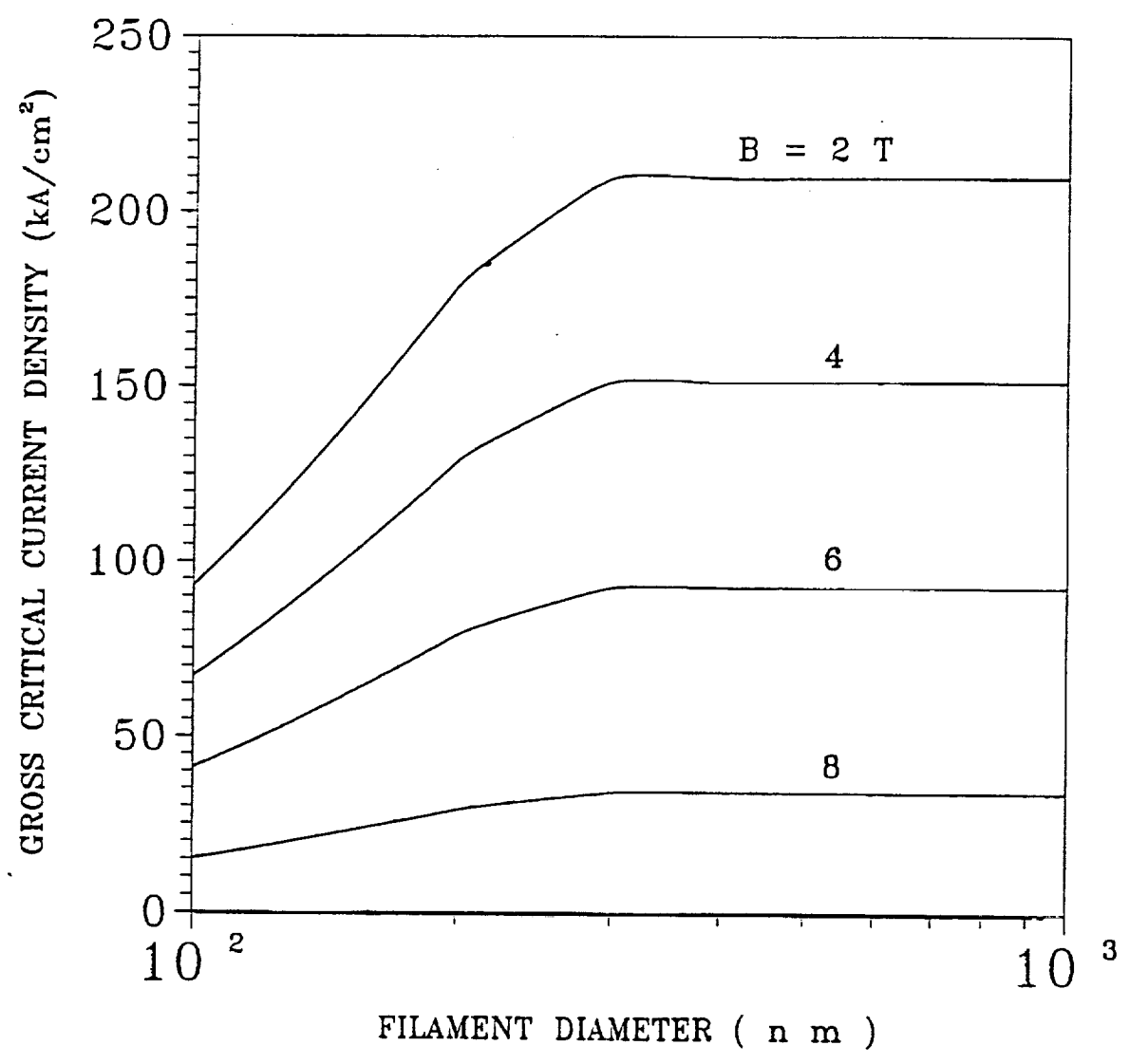


Figure 2. Overall current density J vs. filament diameter d_f

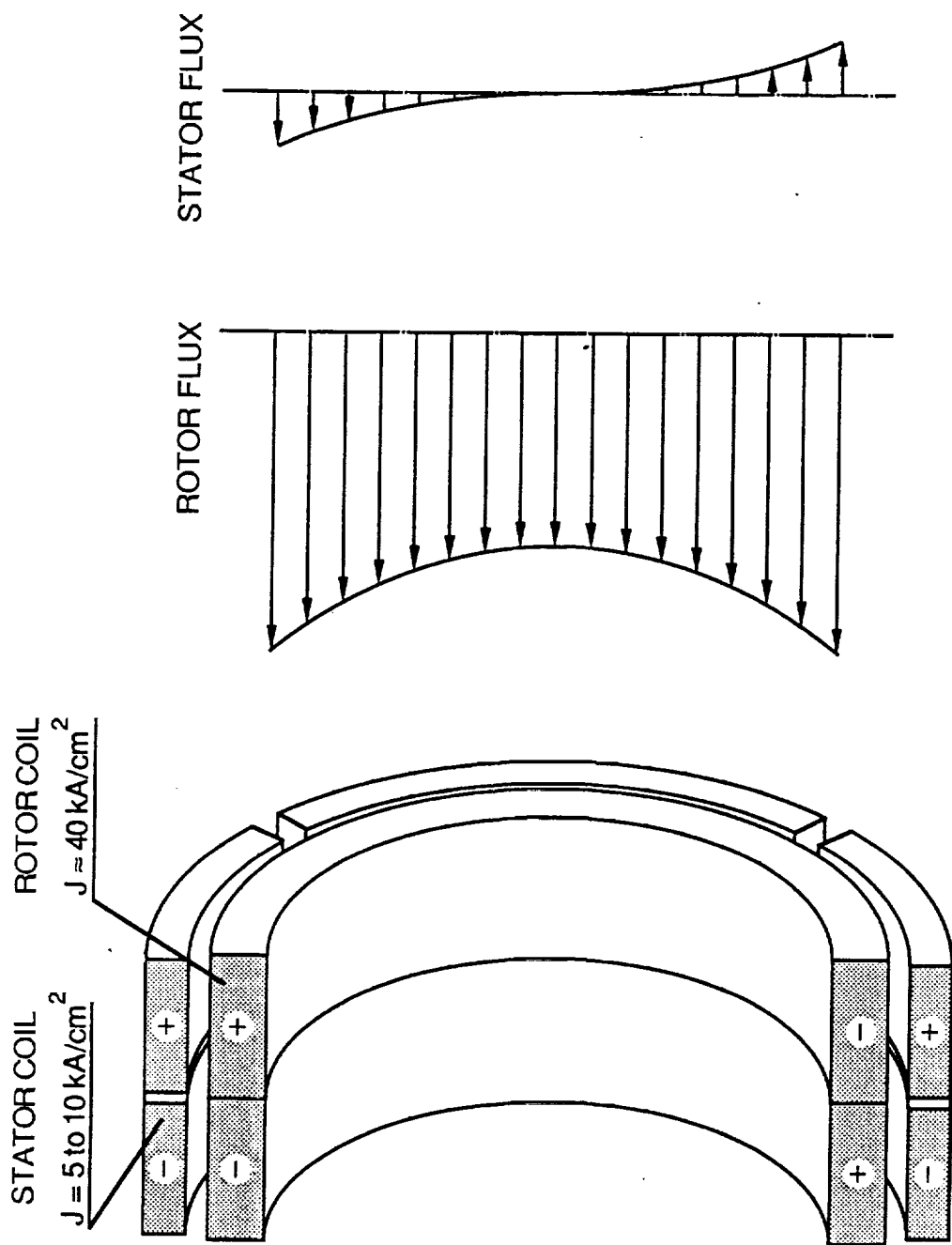


Figure 3. Stator/Rotor coils flux linkage

III. ROTOR SOLENOIDS CHARGING CIRCUIT

Figure 4 shows the proposed concept for charging and maintaining a constant current in the rotor solenoids. It is basically a brushless flux pump (a transformer) located in a low field region between two rotor solenoids. The transformer has two small concentric solenoids (the outer one is in the stator while the inner one is part of the rotor) that are not magnetically coupled to either the rotor or stator magnets. The primary winding is connected to a voltage source while the secondary winding is connected to the rotor solenoids as shown. The persistent switch in Fig.4 is closed while the secondary winding of the transformer is being charged to its peak current which is higher than the rotor current. At this point the field at the persistent switch location is high enough so that it is easy to open the switch with only a small temperature rise. When the switch, S, is opened the secondary solenoid is connected directly to the rotor solenoids and the currents equilibrate, thus increasing incrementally the rotor current and dissipating part of the energy transferred in the resistor R. The efficiency of this energy transfer is about 50%, but since it is very low power transfer due to the insignificant rotor current decay, the low efficiency is no problem. After the switch opens the secondary current drops to the rotor current value and the field at the switch location drops allowing the switch to recover to its superconducting state quickly and a new charging cycle can begin.

The charging circuit in Fig.5-a consists of the voltage source V_s , the transformer (L_p , L_s and $M^2 = k^2 L_s L_p$), and the switch S. The resistor R across the switch S is used to control the current transfer time between the transformer secondary and the rotor solenoids.

The sequence of charging is as follows:

- 1- A voltage pulse in the form of half sine wave is supplied to the primary over time interval t_1 ,

$$V_s = V_0 \sin \omega t.$$

- 2- While S is closed, the secondary current I_s increases to I_{sm} and

$$I_{sm} = \frac{MV_0}{L_{se}L_p\omega} (1 - \cos\omega t_1) + I_{si} \quad ,$$

where I_{si} is the initial current in the secondary at $t = 0$.

- 3- The switch S opens and the current equilibrates between the two inductors L_{se} and L_R .
Using the magnetic flux conservation principle the rotor current increases over its initial current, I_{Ri} by an increment ΔI_R , where

$$\Delta I_R = \alpha (I_{sm} - I_{Ri}),$$

and

$$\alpha = \frac{L_{se}}{L_R + L_{se}}.$$

- 4- The switch S closes and the secondary current becomes J_{Rf} .

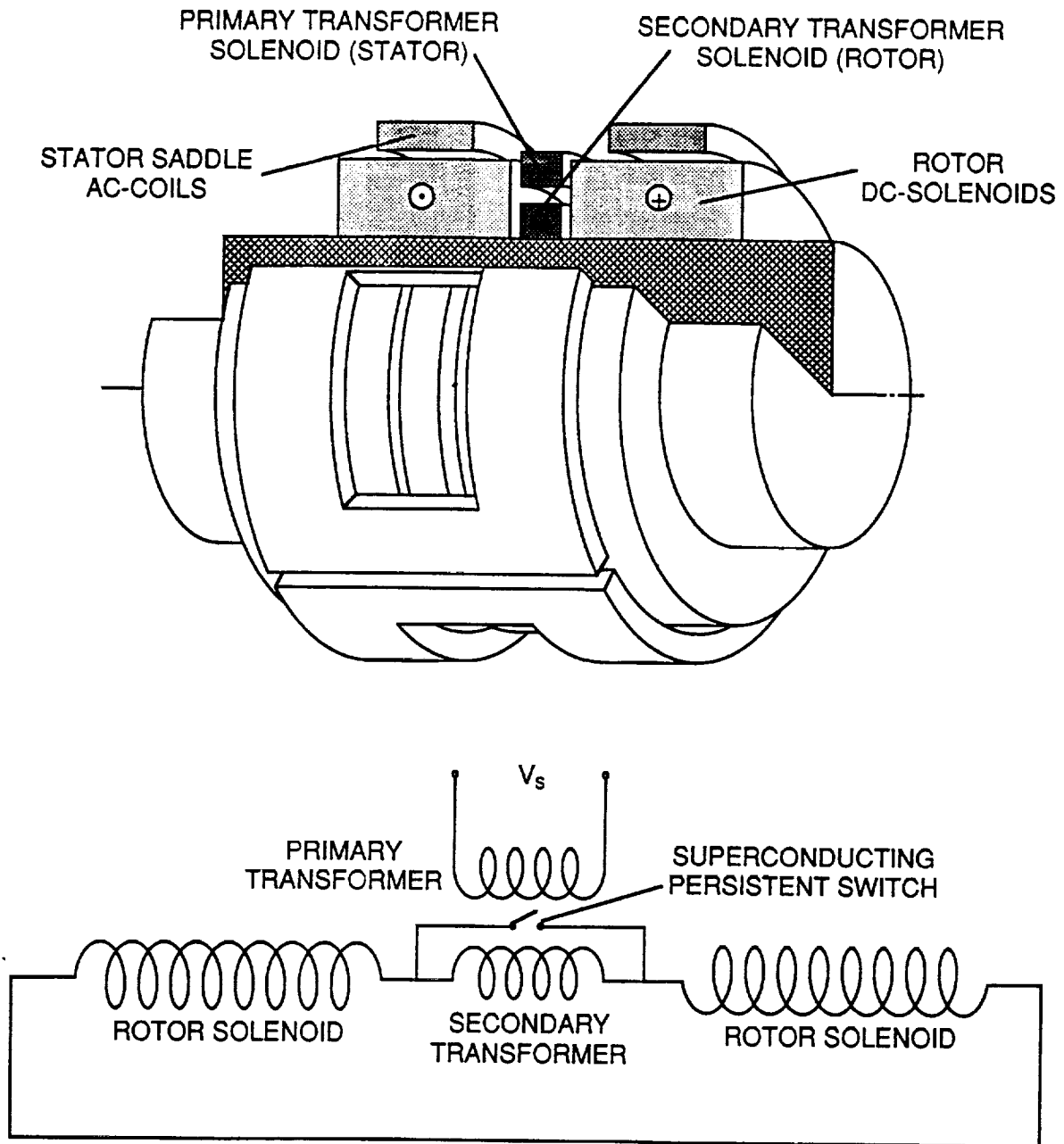


Figure 4. A brushless charging scheme for the rotor solenoids via transformer coupling from the stator primary solenoid to the rotor secondary solenoid that can be shorted with a persistent switch.

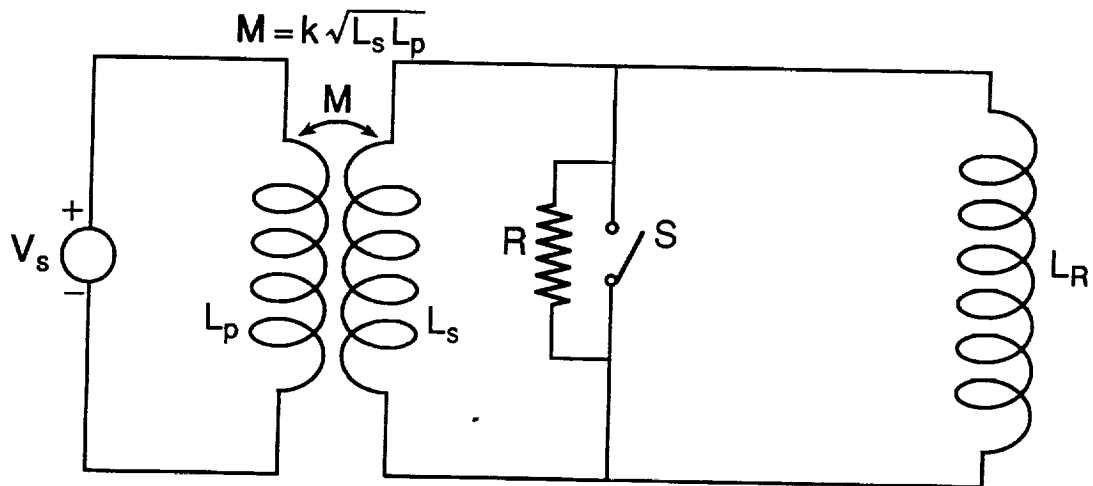


Figure 5-a Rotor charging circuit

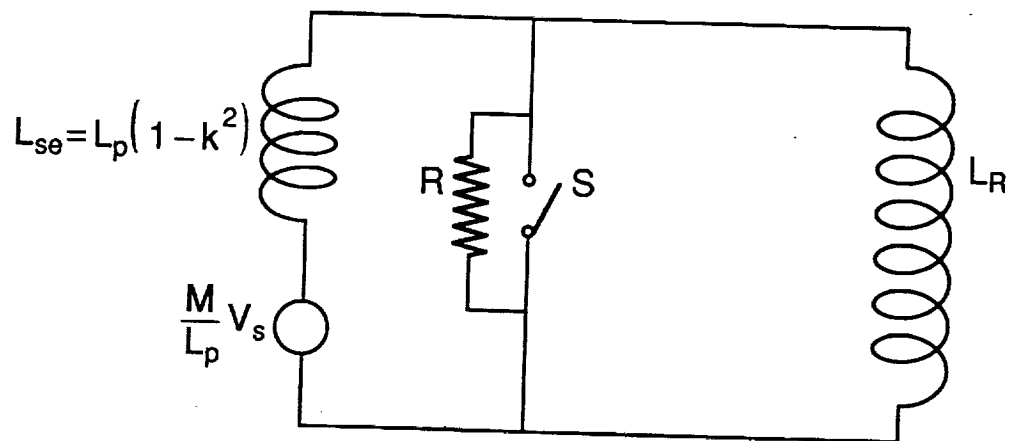


Figure 5-b equivalent rotor charging circuit

IV. PROOF OF PRINCIPLE EXPERIMENT

We propose a proof of principle experiment to demonstrate the feasibility of the active radial bearing concept. A radial bearing system as shown in Fig.6 will be constructed and tested at liquid helium temperature. Only 2 stator saddle coils (top and bottom) will be built. The coils are connected to a power supply with a control circuit. The solenoidal coil is complete and will be operated in a persistent mode. The rotor is supported by springs at both ends as shown. The stiffness of the springs is designed to be comparable to the stiffness of the bearing system. Displacement sensors are attached to the rotor to measure its displacement. Fig.7 shows the circuit diagram of the test model. An ac current at different frequencies is supplied to the stator coils by the power supply, generating simultaneous attraction and repulsion forces to the rotor and forcing rotor vibration to simulate actual vibrations due to high RPM rotation. The magnetic force is calculated for forced vibration from the rotor displacements, rotor mass and spring stiffness. One of the advantages of this simulation is that there is no need for a control system. The experiment will test the following:

- 1- the ability to operate rotor solenoids at high current density under dynamic vibrations and stator ac fields,
- 2- the bearing pressure as a function of stator currents,
- 3- the stator coil power requirement as a function of stator currents and frequency,
- 4- the ac losses in both stator and rotor magnets.
- 5- the maximum stator current as a function of frequency,
- 6- rotor current degradation(decay) due to vibrations and ac loss.

The university of Wisconsin is proposing to construct the POPE and would request that NASA might provide the sensors, power supplies and the required instrumentation. Our preliminary cost estimates for constructing and testing is about \$250,000. We plan to submit a formal proposal with more accurate cost estimates.

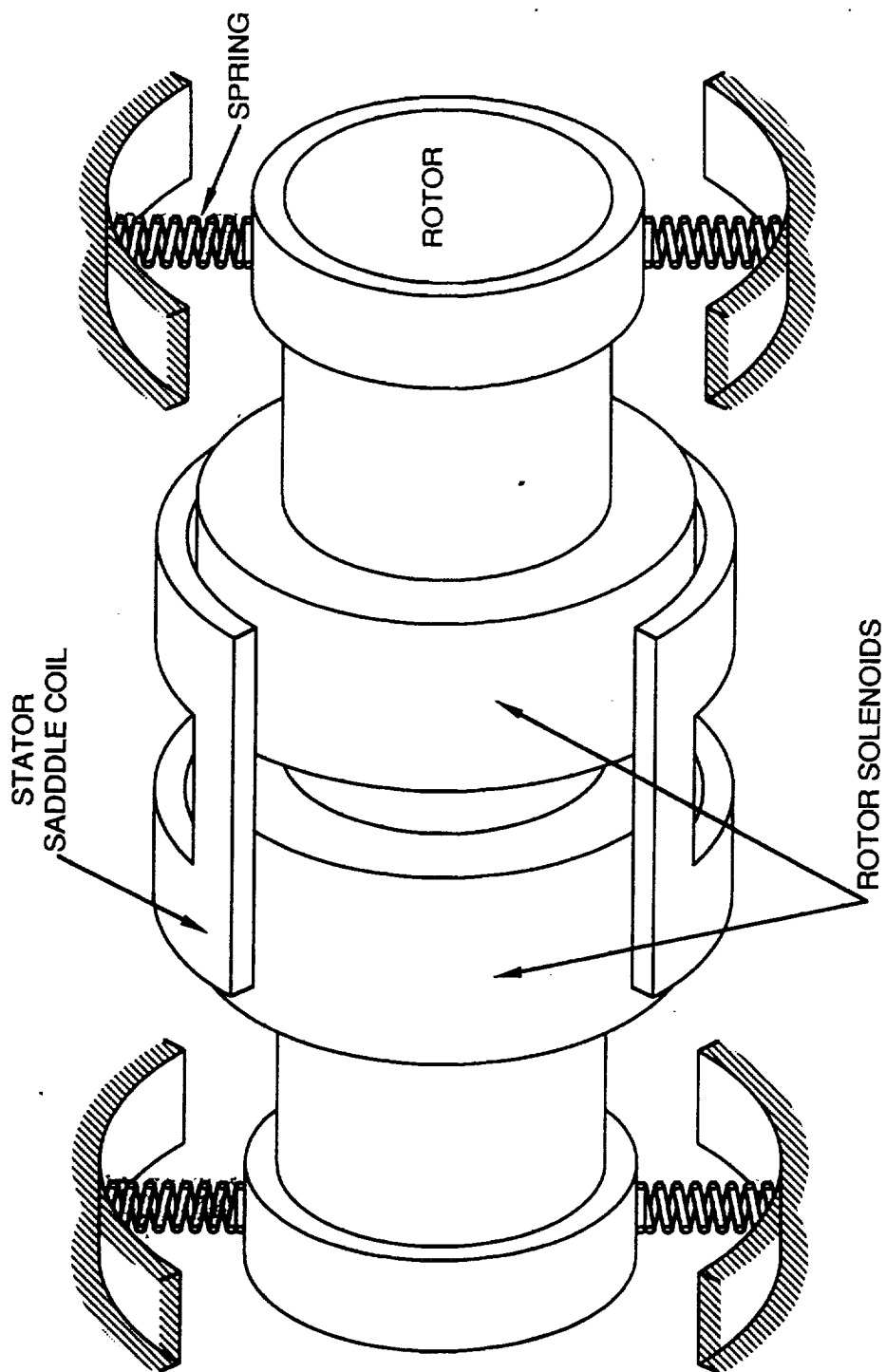
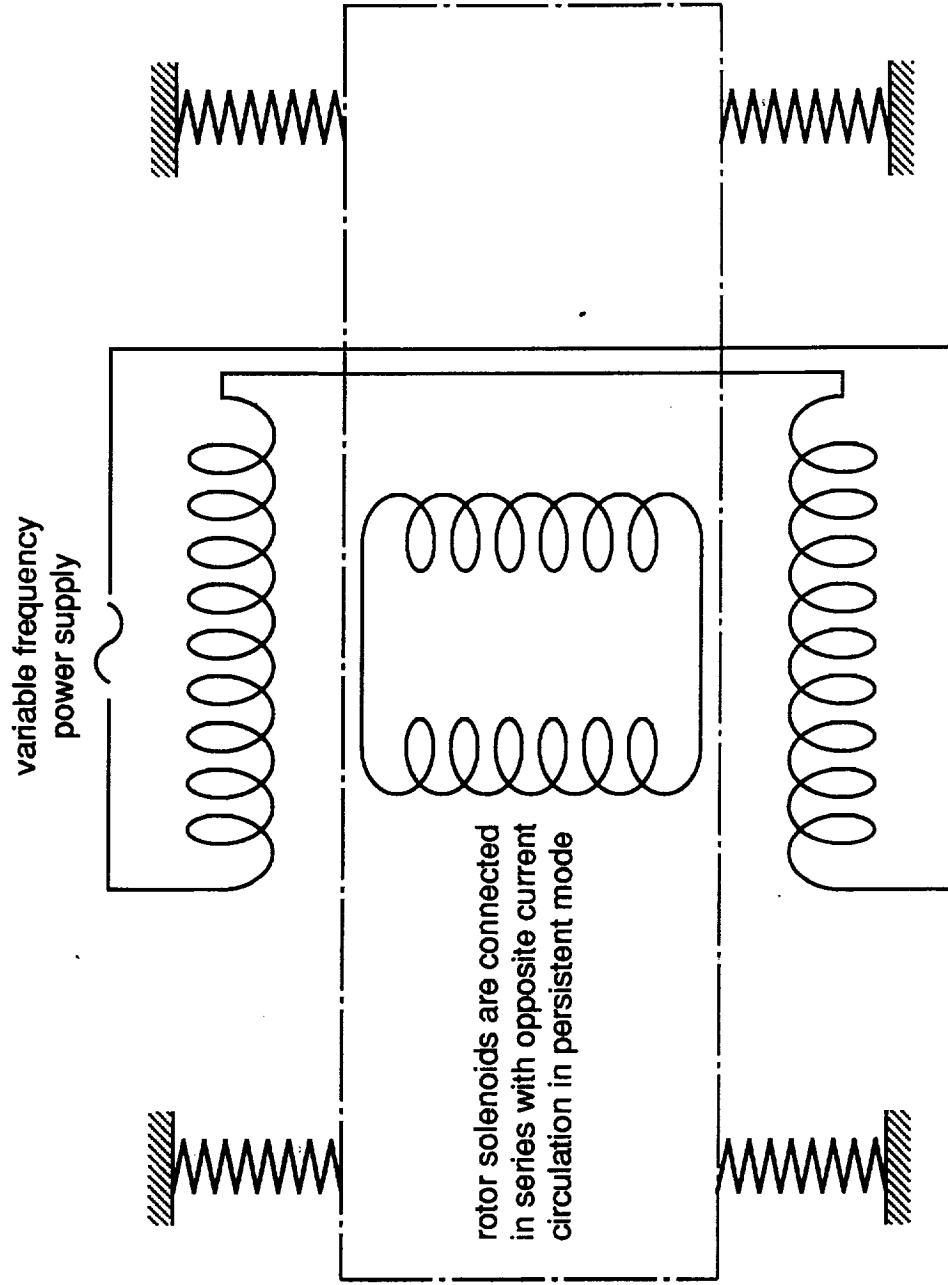


Figure 6. The proposed proof of principle experiment (POPE)



stator coils connected in series to produce simultaneous repulsion and attraction

Figure 7. Circuit Diagram of the POPE Model.

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ACKNOWLEDGEMENT

The work is supported by a grant from NASA-Lewis Research Center, Contract NAG3-1041 under Mr. Gerald Brown. The authors would like to thank Dr. J. L. Smith and Dr. M. A. Hilal for their useful discussion and suggestions regarding of ac loss calculations.