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MAGNETIC BEARINGS FOR INSTRUMENTS IN THE SPACE ENVIRONMENT

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INTRODUCTION

Magnetic bearings, capable of supporting substantial loads with no physical contact in any axis, have been developed for space applications. This document focuses on recent efforts to achieve a design configuration compatible with state-of-the-art torque motors and with existing drive systems currently implemented with conventional ball bearings. The latter objective is an important step in achieving acceptance into flight programs in which only evolutionary development steps are permitted in order to maintain high confidence levels of success, rather than seeking maximum performance by too-rapid introduction of novel concepts.

PRIOR DEVELOPMENTS

During the past decade, magnetic bearings have emerged from the laboratory and have been incorporated into a number of engineering models, some of which were sufficiently engineered to be called flight prototypes, and were, in fact, subjected to environmental testing to demonstrate their ability to be considered for flight application.

To review briefly some of the advances that have been made in magnetic bearings one might start with the motorized pure electromagnetic bearing developed by Cambridge Thermionic Corporation in 1969. This unit had substantial load-carrying (7 kg) and speed (1200rad/s) capability, was servoed axially and had a rather large continuous power requirement (40W). Subsequent work at Goddard Space Flight Center introduced permanent magnets into the suspension system in such a way that loads no longer had to be carried through the structure from one end of the assembly to the other, and which supplied the steady-state magnetic flux without expenditure of power* (Reference 1). The power situation was further improved by the introduction of the "VZP" (virtually zero power) controller (Reference 2) by J. Lyman of Cambion, Incorporated which controls the suspension to a position in which all of the steady-state loads are carried by the permanent magnets.

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*Studer, P.A.: Magnetic Bearings for Spacecraft. TMX-66111, January 1972 (Available from National Technical Information Service, Springfield, Virginia 22161).

With the advent of a new permanent-magnet material ($SmCo_5$) the weight efficiency of magnet bearings rose substantially. These were employed by the General Electric Company, (Binghamton, New York) in the development of a radially-servoed $\approx 100 N \cdot m \cdot s$ momentum wheel in early 1973. Except for a case design and packaging of the electronics this machine represented a flight-qualifiable design.* Similar progress has been made in Europe by Aerospatiale for Comsat Laboratories (Reference 3), Teldix as reported by R. Sindlinger,** and in this country by Sperry Flight Systems.***

By early 1975, a radically new magnetically suspended flywheel configuration had been developed by Ball Brothers Research Corporation with Cambion, Incorporated supplying the magnetic suspension system. The device is noteworthy in this context since it represents a geometric configuration feasible only with magnetic suspension. In this case, a thin ring was supported at three points near the periphery with no spokes or axle. Axial and radial servo control was applied at each of three locations (Reference 4).

RECENT DEVELOPMENTS

In the early days of magnetic suspension development much discussion centered around the relative merits of axial versus radially servoed suspensions. Typically, greater stiffness (of the order of ten times) and load capacity are available in the servoed direction relative to the passive direction. Both types of systems have been successfully built; however, axially servoed systems requiring only one control loop obviously have the virtue of simplicity and an edge in rotational loss characteristics due to the inherent symmetry possible with this geometry. The simplicity is not merely of academic interest, since the goal of high reliability which occurs primarily from the elimination of physical contact and hence "wearout" phenomena, is still directly dependent on the failure rate of each servo channel. In the case of multiple servo loops the probability of success decreases progressively as each essential servo loop is added to the system.

This question, rather than being resolved, became considerably more complex as development progressed. As more application-oriented design was undertaken, the considerations of torsional stiffness assumed greater importance; for example, when overhung loads must be supported. Further, for a variety of reasons, designs employing not just one or four servo channels but two, three, five, and even six servo channels have been found best suited for particular design requirements. It is the author's opinion that no one "optimum" system exists except in the context of specific application criteria.

*Veillette, Leo J.: Design of a Momentum Wheel with Magnetic Bearings. 8th Aerospace Mechanisms Symposium. TM X-2934, October 1973, pp. 131-143. (Available from National Technical Information Service, Springfield, Virginia 22161.)

**Wehde, H. P. and R. S. Sindlinger: Magnetic Bearings for High-Speed Rotors. 2nd International Workshop on Rare Earth Cobalt Permanent Magnets and Their Applications. University of Dayton, June 1976, pp. 317-329.

***Sabnis, Ajit: Magnetically Suspended Reaction Wheels. 2nd International Workshop on Rare Earth Cobalt Permanent Magnets and Their Applications. University of Dayton, June 1976, p. 133, abstract only.

The work described in this report restricts itself to a two–servoed axis design, although some of the design features, specifically pole shaping, are felt to be more universally applicable.

The concept for what emerged as a "pancake" geometry stemmed from consideration of the axially servoed bearings characteristic. That is, that high aspect ratios (bearing separation distance to diameter) are required to improve stability and torsional stiffness. Similarly, if the diameter of a radially active bearing is increased and its axial length minimized, it becomes more stable and can, in fact, handle overhung loads without need for a second bearing on the same axis. Since the load–carrying capability of a magnetic bearing is fundamentally limited to the force per unit area related to saturation of the magnetic materials employed, it is important to provide sufficient area in the working gaps. In this case, the need for short axial length is offset by the increase in diameter, whereas in the axial bearing greater center distances do not result in larger pole–face area.

The geometry of these bearings is more compatible than that of axial magnetic bearings with the large–diameter, short–axial–length geometry of torque motors which are highly weight efficient and are finding widespread usage in high–performance equipment.

At the outset there were two bearing configurations given consideration; the simplest (figure 1) was a sandwich of a permanent magnet between two permeable bars at 90° to earth other with arcuate pole pieces at both ends of each bar. The bars were canted toward the centerline bringing all four pole faces into a common plane and only a single planar ring was required on the rotor. Coils wound around the bars could be energized with either polarity giving the completed assembly the ability to produce bilateral forces in either of two axes, which when

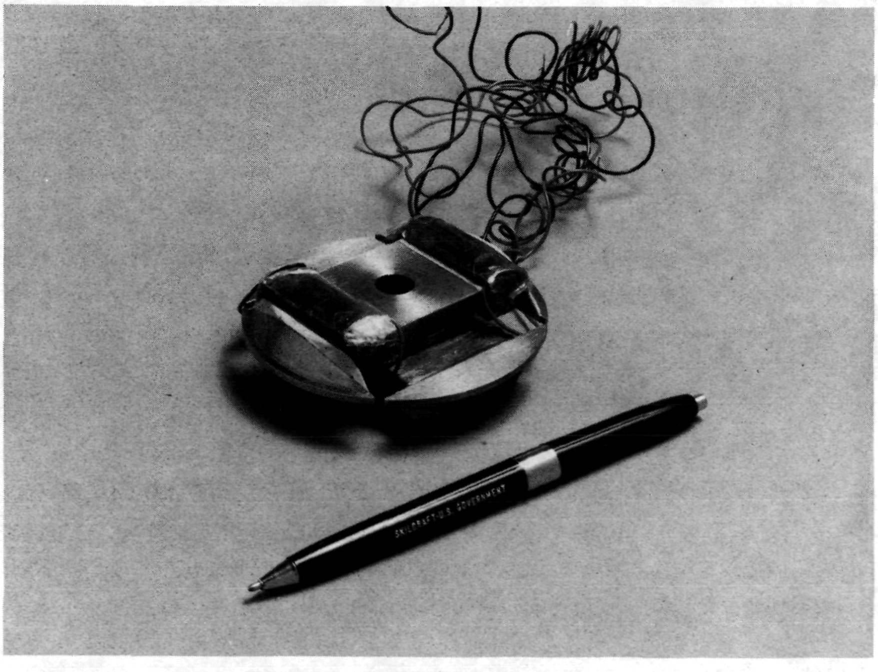

Figure 1. Planar 2-axis bearing

properly servoed, maintained the ring concentric with the stator. Axial loads are supported completely by the magnetic flux passing from the stator to ring and back to an adjacent sector. The device is simple, magnetically efficient, and exhibits the maximum diameter–to–length ratio possible. It has an inherent weakness, however, that the flux path in the rotating ring flows in two directions from each pole face; consequently magnetic losses with rotation are unavoidable. While lamination or the use of ferrites can minimize the viscous drag components, this configuration (K_1) is not a good choice for high speeds.

The alternate design (figure 2) is also of "sandwich" construction with lapped cruciform plates terminated with four arcuate pole faces on each side of a disk of samarium cobalt. Individual control coils are wound on each of the cruciform arms providing radial flux control in two axes. A ferrous ring, of "C"-shaped cross section, is the rotating element carrying nominally uniform radial flux from the upper plates axially to the lower plate where it again passes radially back to the stator. Because all of the arcuate pole faces in a plane are of the same magnetic polarity, there is little change of flux and consequently no inherent loss mechanism due to rotation. Some lack of uniformity around the arc and small discontinuities between the pole tips are responsible for the losses actually incurred in practice. Here again the construction is simple; the cruciform parts were lap-jointed to allow the control coils to be wound directly on the arms prior to assembly. All stator parts are held together and fastened to the structure with a single central bolt. The measured performance parameters for this bearing assembly (K_2) are shown in figure 3.

The measured characteristics were uniformly lower than the design predcitions by almost a factor of two. This was confirmed by gap-flux measurements which indicated 0.27 tesla,

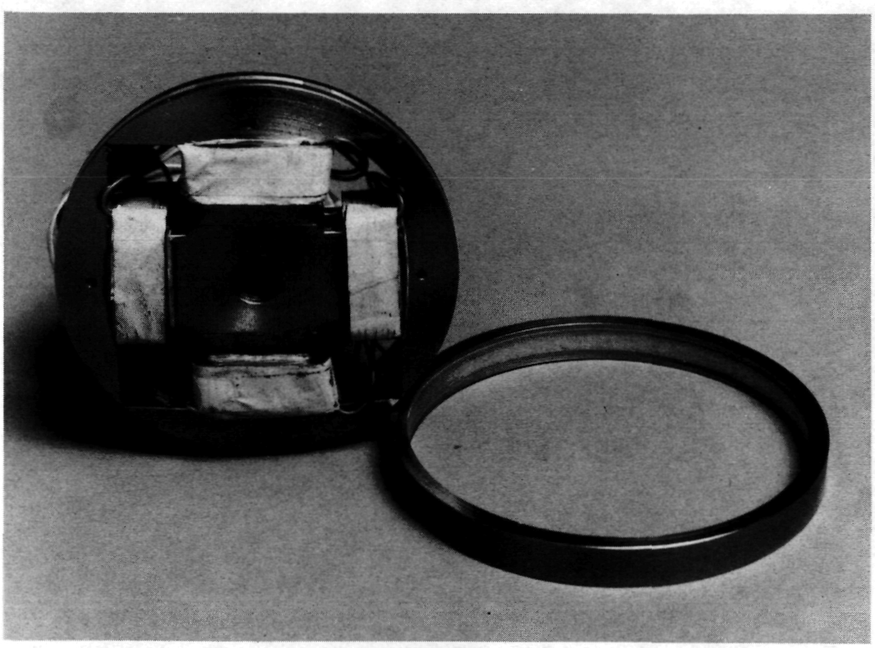

Figure 2. Baseline 2-axis bearing

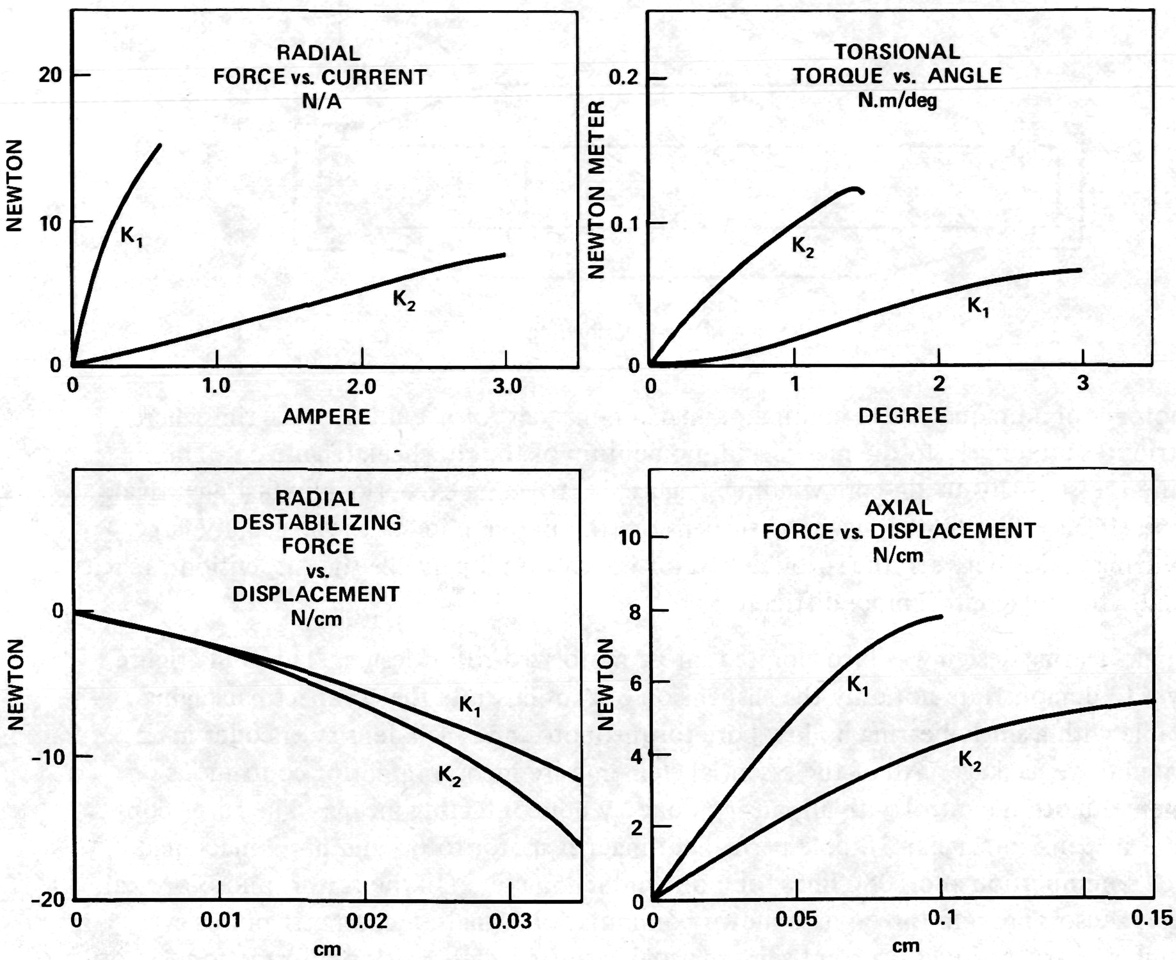

Figure 3. Bearing characteristics - baseline designs

only 70 percent of the desired value. The reason for this is the large surface area of the arcuate poles separated by only the thickness of the permanent magnet, 0.64 cm.

The stator assembly is 7.6 cm in diameter with an aspect ratio (diameter to length) of about 10:1. This was intended to provide a good balance between torsional and axial stiffness. In addition, a unique feature was employed in the pole-face shaping in order to avoid a soft centering characteristic near the null position. The latter is typical of flat pole-face bearing designs and is due to the nonlinear magnet force/displacement relationship. It can be seen that a point on the face away from the centerline moves closer to the pole when the rotor ring tips about its center. The solution is simply to make the pole faces true spherical radii about the geometric center, (figure 4). In this case a straight angular cut slightly greater than the true radius was used. The measured values confirm this approach; the angular stiffness near the null is slightly greater than for large angles.

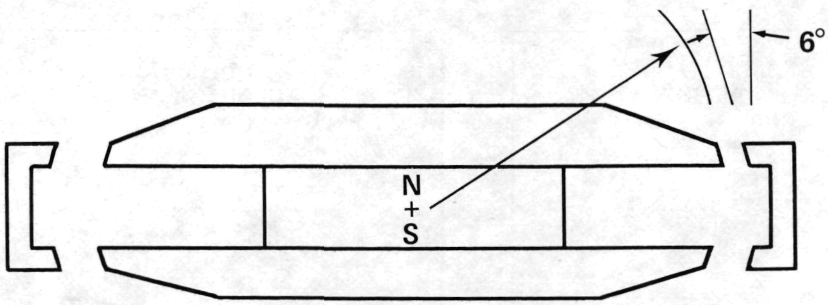

Figure 4. Pole-face shaping

The motor is of a unique design* with a permanent–magnet rotor built into the rim where it contributes effectively to the inertia and momentum of the flywheel, (figure 5). The armature is essentially an air–core winding, (figure 6) providing exceptionally fast electrical response. In its effect on the magnetic suspension, this design eliminates the usually large destabilizing forces between the rotor and stator which would penalize the suspension capacity and render bearing control more difficult.

The single-bearing design was incorporated into a motorized-rotor design. This unit (figure 7) serves to demonstrate not only the suspension but to illustrate the compact packaging achievable with a single-bearing hollow-bore torque motor and high-density encoder in an integrated drive package. All of the essential elements are incorporated for continuous or incremental motion control with all sensing done by noncontacting means. The rotor contains the suspension ring, an 18-pole permanent-magnet motor rotor, and has 9 machined slots for commutation and 1080 lines for a digital tachometer. On the stator, photo-optical reflective sensors provide three-phase motor commutation signals, tachometer pulses every 20 minutes of arc, and eddy current sensors provide rotor radial-position information to both sets of magnetic-bearing drive coils.

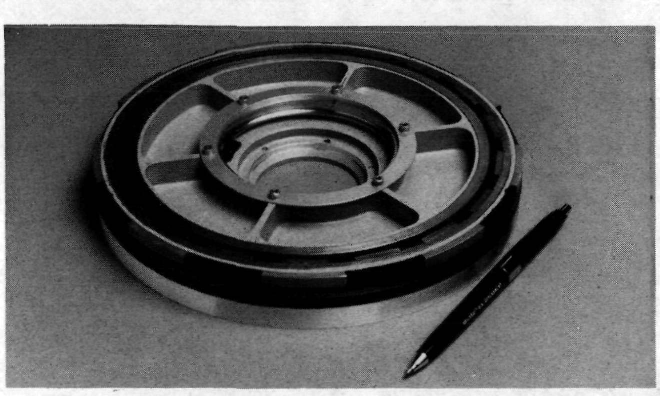

Figure 5. Rotor with rim-mounted motor rotor

*Studer, Philip A.: A New Type Torque Motor. 2nd International Workshop on Rare Earth Cobalt Permanent Magnets and Their Applications. University of Dayton, June 1976, pp. 274–283.

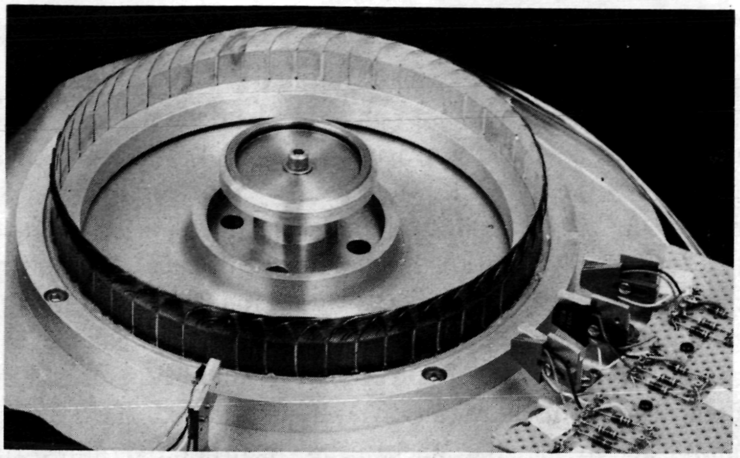

Figure 6. "Ironless" motor armature

Figure 7. Motorized rotor unit

SECOND GENERATION DESIGNS

The engineering model described in the previous section has been operated and tested over a period of several months. It was intended to provide a hardware demonstration of a small magnetically suspended reaction wheel for attitude control. As previously mentioned, the suspension forces fell short of the initial design objectives. The passive static support capability is just sufficient to support the rotor axially in a 1-g field. This is a practical necessity for testing but is not a functional operational requirement in space. More significantly, the torsional stiffness characteristic, while sufficiently linear and demonstrating the validity of the pole-shaping technique (Reference 5), was also less stiff than intended. Since low cross-axis stiffness could have a deleterious effect on spacecraft stability, especially when accompanied by light damping, several design variations were considered. Two of these concepts were implemented and tested by Mac Bar Mechanisms, Incorporated on test fixtures designed by H. Maclanski of that company. These fixtures are able to measure axial, radial, and torsional stiffness and rotational drag characteristics of these bearings. It is a tribute to the careful initial design of these measuring instruments, that sensitive measurements could be obtained on the most satisfactory new design which produces forces many times the original design objectives. The fixtures employ air bearings to make accurate measurements of small forces in the presence of much larger destabilizing forces in the perpendicular direction.

Several design variations were built to improve bearing characteristics. The first of these design changes involves no modification to the bearing stator elements. Replacing the solid iron "C"-shaped ring on the rotor is a pair of thin planar ferrous rings separated by a permanent-magnet ring. This ring is a special centrifugally cast magnet with samarium cobalt particles in an epoxy binder with fiber-glass reinforcement. The sample magnet was supplied by Cambridge Thermionic Corporation and is machinable, (figure 8).

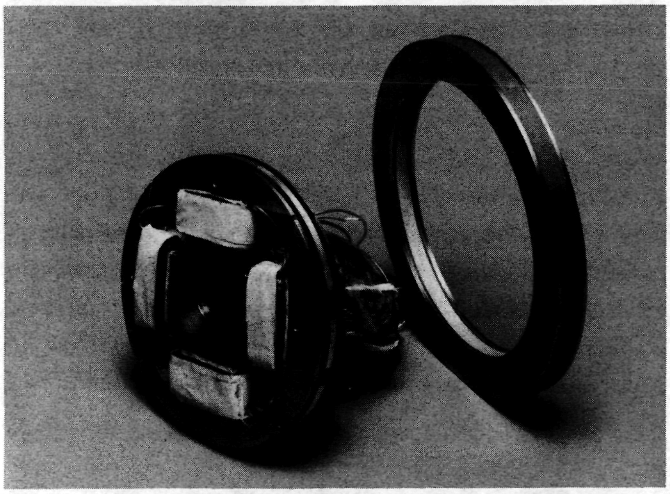

Figure 8. Bearing with permanent-magnet rotor ring

Figure 9 shows a significant increase in axial and torsional characteristics with only a small increase in radial destabilizing force. Note that the control characteristic suffers also, even though the steady-state permanent-magnet flux in the air gap is increased. This is because the control flux sees this ring as a much higher reluctance in the axial direction and consequently a larger percentage of flux returns to the stator through the sectors at right angles to the driving coil.

The second variation on the basic design is on the stator assembly. Instead of a single permanent magnet, individual 2.5-cm-diameter magnets are employed at each sector. The sectors 180° apart are no longer integral parts; instead they are each separated from one

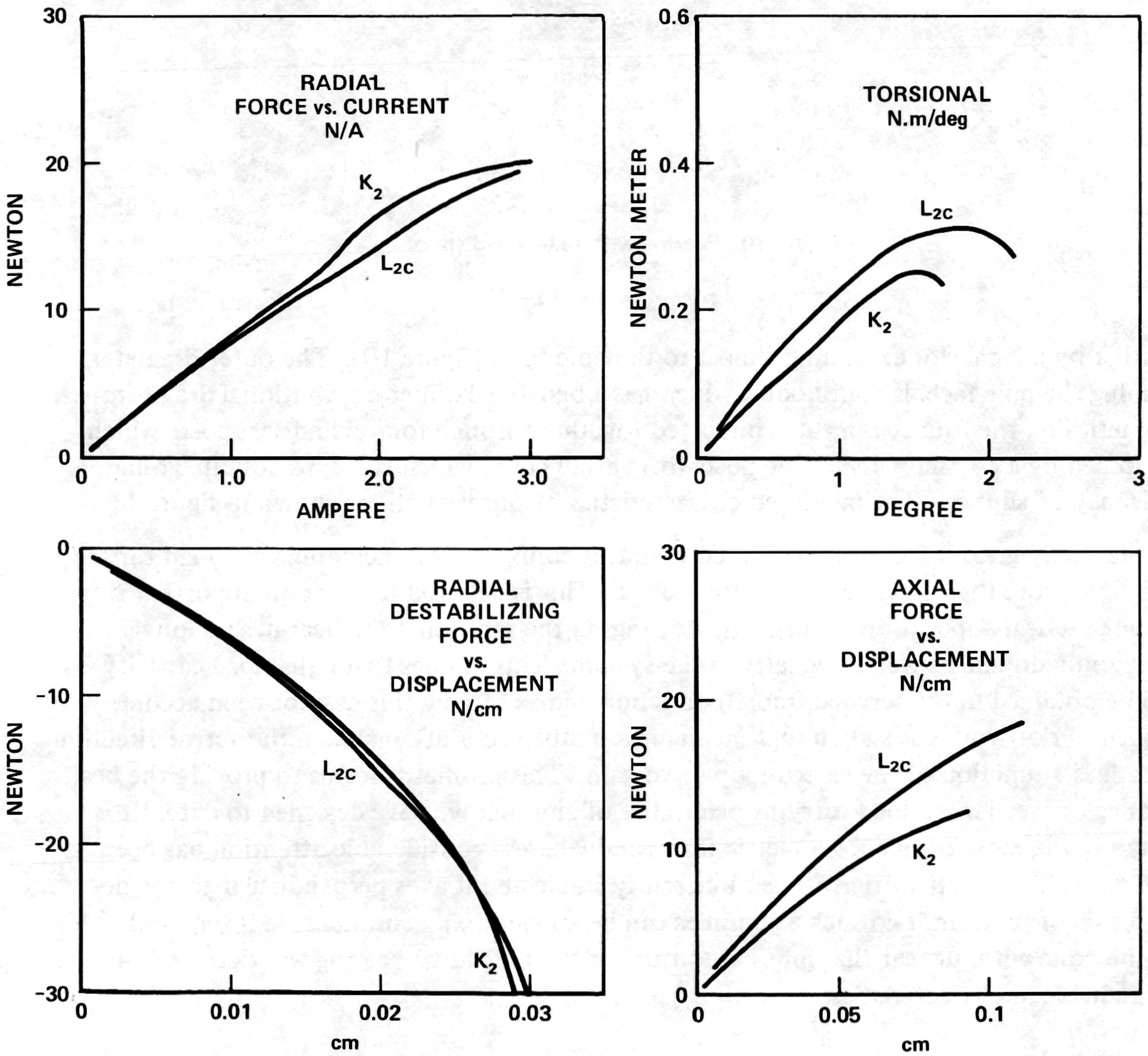

Figure 9. Bearing characteristics–with permanent-magnet rotor ring

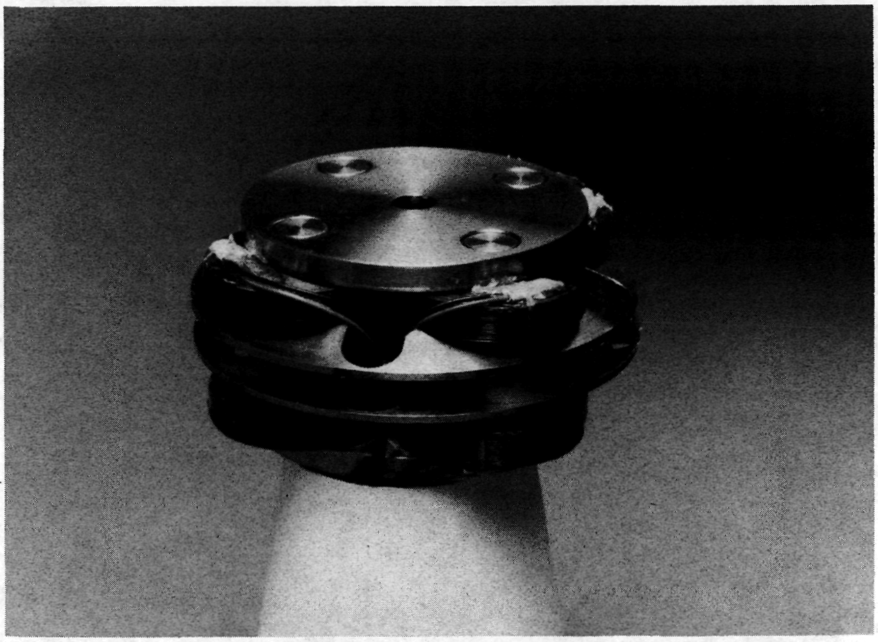

Figure 10. Bearing with redesigned stator

another by a 1-cm slot extending almost to the pole face, (figure 10). The outer diameter, forming the pole face, is continuous, which has a beneficial effect on rotational drag torques. Magnetically, the four sectors are connected together through four cylindrical posts which are joined by a common disk. The posts form arbors over which standard bobbin-wound coils may be slipped. The measured characteristics of this version are shown in figure 11.

Substantially greater forces are obtained with this configuration including axial load capacity of 8.6kg; more than 10 times the stator weight. This is believed to mark an important step in the practical application of magnetic bearings in the sense that the bearings no longer represent a dominant weight penalty in the system. This implies that equal load capacity will be obtained in the servoed (radial) direction and as of now this has not been accomplished. Prior work has shown that much greater stiffness is attainable in the active direction since it is a function of the closed-loop servo gain. This geometry seems to provide the best balance of mechanical load-carrying properties of any that we have designed to date. It is certainly the most compact geometric form; and whereas considerable attention has been paid to making it self-sufficient, i.e., inherently stable about axes perpendicular to the desired axis of rotation, two such assemblies can be applied to a common axle if required. This can be done without fear that internal torques of the individual bearing will detract from the net radial-load characteristics.

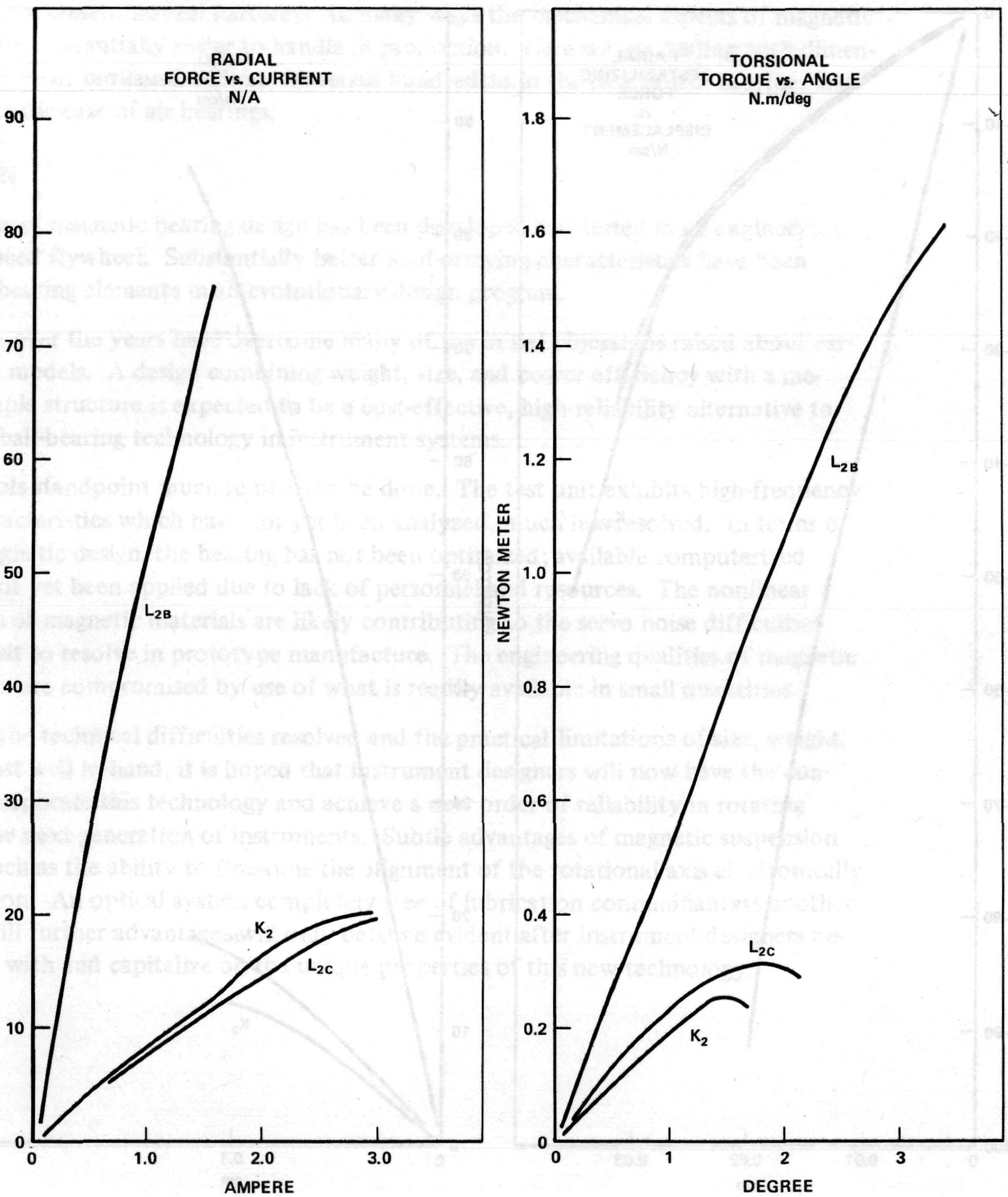

Figure 11. Bearing characteristics with new stator design (L_{2B})

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16. Abstract

This report documents a magnetic bearing development which has been successfully applied to support a 0.9 kg (2 lb) - 19 cm (7.5 in) - diameter rotor in 5 degrees of freedom, with fully controlled drive capability to ± 200 rad/s in the other axis. The construction details are described and illustrated.

Performance data on five design variations are presented which extend the load capacity to 8 kilograms at which point the bearing element on the rotor is less than one-half of 1 percent of the total load capacity.

The compact size, low power requirement, and ability to operate with no lubricant in a vacuum environment seem to indicate that magnetic bearings are now first-rate candidates for rotating instrument systems in the space environment.

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