X-721-72-56
PREPRINT

NASA TM X-66111

MAGNETIC BEARINGS FOR SPACECRAFT

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(NASA-TM-X-66111)  MAGNETIC BEARINGS FOR          N73-12499
SPACECRAFT  P.A. Studer (NASA)  Jan. 1972
10 p                              CSCL 13I
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JANUARY 1972

GSFC

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

11 pp

X-721-72-56

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Philip A. Studer
Mechanical Division

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GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland

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ABSTRACT

Magnetic bearings have been successfully applied to motorized rotor systems in the multi-kilogram range, at speeds up to 1200 radians per second. These engineering models also indicated the need for continued development in specific areas to make them feasible for spacecraft applications.

Significant power reductions have recently been attained. A unique magnetic circuit, combining permanent magnets with electromagnetic control, has a bidirectional forcing capability with improved current sensitivity.

The multi-dimensional nature of contact-free rotor support is discussed. Stable continuous radial suspension is provided by a rotationally symmetric permanent magnet circuit. Two bearings, on a common shaft, counteract the normal instability perpendicular to the rotational axis. The axial direction is servoed to prevent contact.

A new bearing technology and a new field of application for magnetics is foreseen.

CONTENTS

ILLUSTRATIONS

MAGNETIC BEARINGS FOR SPACECRAFT

INTRODUCTION

Magnetic bearings, capable of supporting substantial loads with no physical contact in any axis, are being developed to fill a definite need in the space program. They potentially remove the dependency of bearing life on rotational rate, typical of conventional ball bearings. In addition, they have a natural compatibility with vacuum operation, power sources, and control systems. They do not require ultraprecise machining tolerances or clearances and therefore are not extremely sensitive to thermal or structural distortion.

Our efforts have focused on magnets operating in the attractive mode, capable of supporting rotors in the multi-kilogram range; operation in a one "g" field and the ability to withstand external disturbances is required. Complete contact-free support makes their design a six dimensional problem or five dimensional if the motor drive and control on the desired axis of rotation are considered separately. Active servo control in at least one axis is required to achieve stable support.

EARLY DEVELOPMENT

An eighteen month development effort by the Cambridge Thermionic Corporation resulted in the delivery to GSFC of two magnetically suspended motorized rotors of the type shown in Figure 1. These engineering models demonstrated the feasibility of this approach and met all the fundamental requirements of our specification. The system utilizes two electromagnets, one at each end of the rotor with half of the magnetic circuit stationary, and the other half rotating. The rotor is held centered on the desired axis of rotation passively since this is the position of minimum reluctance for the cylindrical electromagnets. The electromagnets are proportionally controlled to equalize the air gaps axially. A photo-optical signal provides a signal proportional to the rotor axial displacement and an air core coil, in the field of a permanent magnet, provides a signal proportional to axial velocity; together, these allow a stable centering force to overcome the normal instability in the axial direction and keep the rotor freely supported. In the torsional direction (perpendicular to the desired axis of rotation) the passive radial centering forces also act to prevent cocking motions of the rotor. An electronically commutated dc motor provides torque and speed control about the axis of rotation. The motor construction employs an ironless armature which does not contribute destabilizing forces to the bearing load. A cutaway drawing, Figure 2, illustrates many of the details of construction. The radial support, as was mentioned, is passive and is simply due to the force between two cylindrical sections tending to keep aligned and concentric. This effect is enhanced by additional grooves machined into the pole faces; increasing the number of rings significantly improves the radial stiffness.

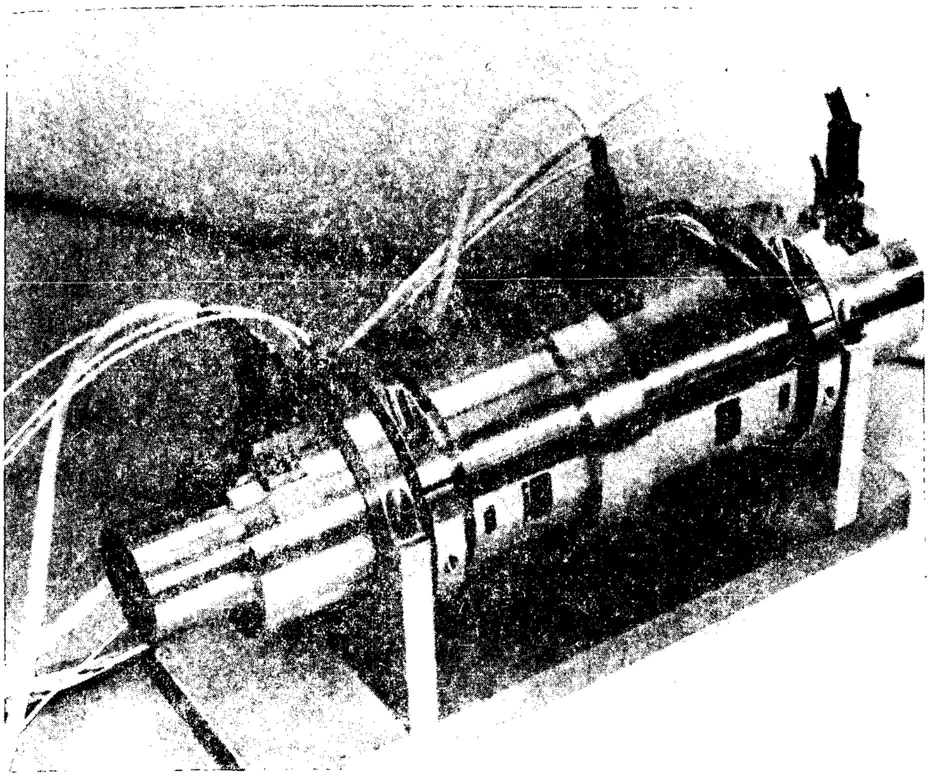

Figure 1. Photograph, Magnetically Suspended Motor Rotor

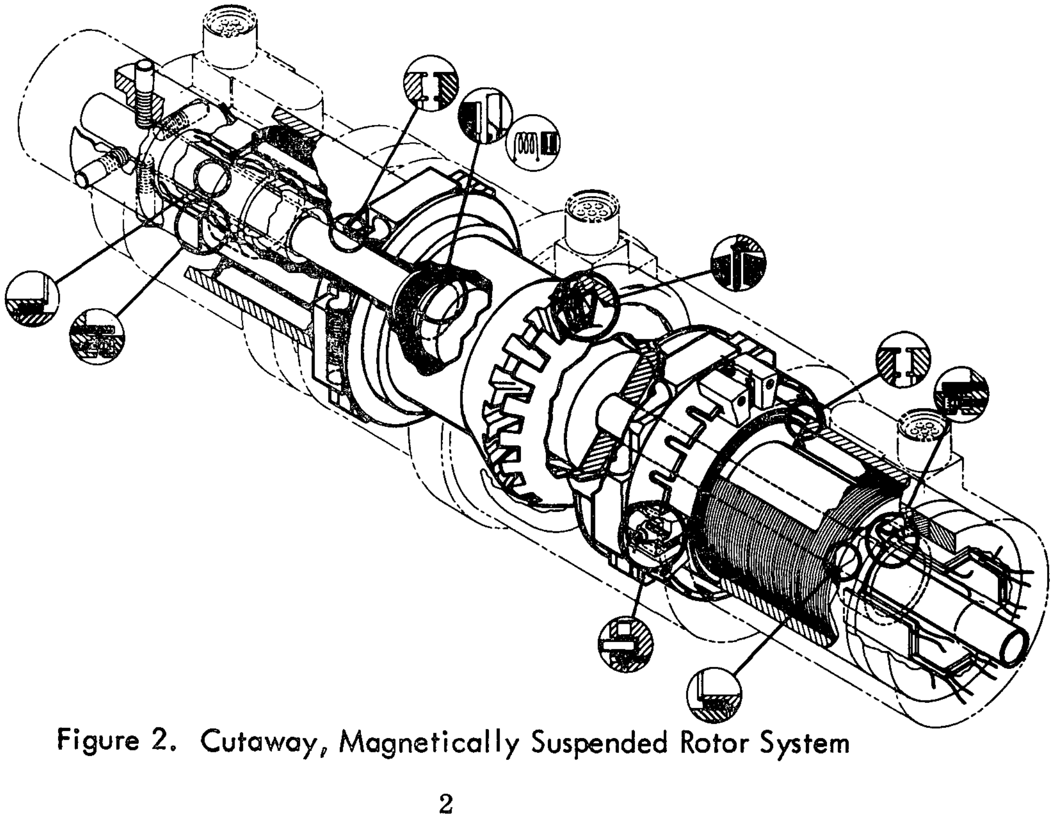

Figure 2. Cutaway, Magnetically Suspended Rotor System

The suspended weight of the rotor is three kilograms (6.5 lb) and it has been operated at speeds up to 1200 Radians per second ($\approx$ 12,000 RPM), the no load speed of the motor. The radial stiffness is in excess of 2 x 10^5 newtons/meter (1100 lb/in.) and the axial stiffness in the servoed direction is ten times as great. Ten "g" steady state acceleration can be readily handled axially. Frictional measurements were made by coast down tests in vacuum with 2.1 x 10^5 newton meters (.003 oz. in.) hysteresis torque and 2.0 x 10^{-6} newton meters per radian per second (.00003 oz. in/RPM) viscous torque being observed. No higher order effects were detected. These values are lower than a well lubricated ball bearing of equivalent load capacity. These values are approximately what were calculated from a consideration of the flux variation in the pole faces due to the eccentricity of rotation in a one "g" field. Somewhat surprising, was the fact that when operated vertically, the measured torques were not significantly lower. This is believed to be due to the torsional destabilizing forces which tend to displace the rotor from perfectly parallel orientation. This points out the nature of the problem; free suspension gives the rotor six degrees of freedom and the magnetic circuit design must be visualized in three dimensions.

Subsequent modifications to one of the units have been made by the contractor, approximately doubling the load capacity and stiffness. This involved greater cross-sectional area and more machined rings on the pole faces. These improvements have allowed rotors of higher inertia, weighing over 6 kilograms to be tested in order to gain further insight into the gyrodynamic effects. The contractor's report* has been approved for publication by NASA.

At that point in the program feelings swayed between optimism based on the realization of a mechanical device free from the predominant wear-out mechanism and pessimism based on the harsh fact that 3 kilograms (6.5 lb.) of weight and 40 watts of power were being used to replace a bearing weighing one thousandth as much and using no power.

RECENT DEVELOPMENTS

Both power and weight are vital constraints in flight applications. However, systems weight reduction is often possible if bearing performance allows operation at higher speeds. Therefore, during the past year we have directed our efforts toward power reduction.

The use of permanent magnets seemed to offer an opportunity for power reduction, since a high bias flux density was required to obtain sizable forces. A

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*Final Report, Contract NAS5-11585.

somewhat unique bearing design referred to as a permanent magnet supplemented bearing was evolved at GSFC, which will be described in some detail.

As mentioned previously, the magnetic circuit design for magnetic bearings is a multidimensional problem. In the bearing previously described, the radial centering force was achieved passively when both coils were energized. This force arises from concentric rings on the faces of the air gaps, which try to align themselves to minimize the circuit reluctance. In this design, a ring-shaped magnet was used with "soft" iron poles to form a toroidal shape with an open slot. A ring within this slot is self-centering in the radial direction. Passive support in the radial direction is continuous, due solely to the permanent magnet.

The ring, assumed centered in the gap of the permanent magnet, is unstable torsionally. That is, any rotational deviation from a plane parallel to the pole faces will cause an increasing torque away from equilibrium. Therefore, a pair of bearing elements, adequately spaced on a shaft, must be used. This, in itself, is standard practice with all bearings. However, the destabilizing torque must be considered since it operates against the radial centering forces and is nonlinear. This torque has a significant impact on the dynamic characteristics of a rotor, coning motions being a predominant natural mode. The torque sets the minimum gap dimension which is practical for a given L/D ratio or bearing separation versus diameter.

Around the desired axis of rotation, symmetry is maintained so that there are, in theory, no flux variations or torque losses. How well this is actually achieved depends on the machining accuracy, homogeneity of the material, and the magnitude of disturbing forces.

The fourth direction of motion, axial, is perhaps the most interesting. Refer again to the ring, positioned in the slot of a torus and subject to a high flux density field. The position of the ring (axially) does not change the total air gap area nor the net gap length; therefore, there is no change in the permeance of the permanent magnet circuit. Only fringing pattern changes give it a preferred axial position; therefore, it is not greatly unstable. On the other hand, the required control for axial loads is missing. Connecting two similar rings, each held in their own permanent magnet circuit, as illustrated in Figure 3, provides a useful way of introducing control forces. The particular advantage gained by the design shown is that a push-pull effect is achieved, but a magnetic connection linking the two circuits introduces a destabilizing force. Both positive and negative forces are produced, as a function of the polarity of the control current. A high current sensitivity (force per ampere) is achieved because the control flux is only a modulation superimposed on a high flux level. The more important power reduction is achieved by eliminating the bias power required to obtain sufficiently high flux levels for high force per unit area.

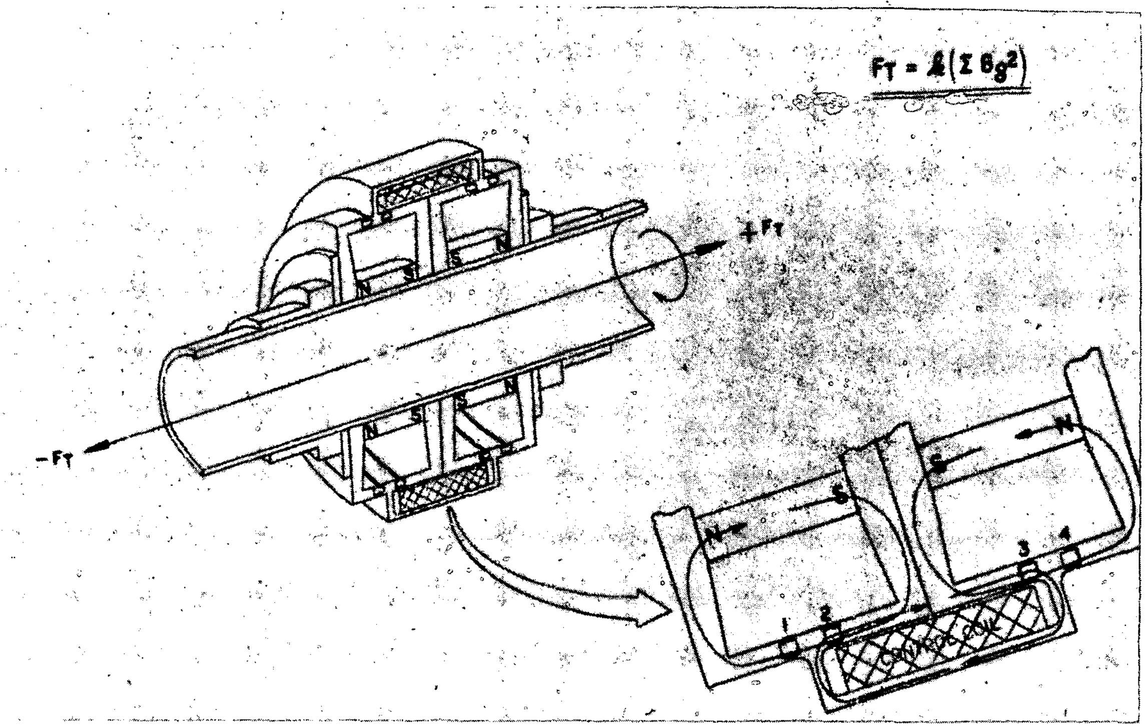

Figure 3. Cross Section, P. M. Supplemented Magnetic Bearing

The cross section of the toroidal magnetic bearing design shows the typical flux paths. Two independent permanent magnet circuits, oppositely polarized, are intersected by a parallel control path consisting only of "soft" iron. The control flux shares a common air gap with each of the PM circuits such that it adds to one and subtracts from the other. Reversing the current flow in the coil produces a similar effect and force in the opposite direction.

A bearing of this type has been built and tested. Its characteristics are given in the following table:

P. M. Supplemented Bearing

Outside Diameter	7.6 cm.	(3 in.)
Length	4.8 cm.	(1.9 in.)
Weight	.73 Kg.	(1.6 lb.)
Magnet (Two)	Alnico V	
Radial Load, Passive	44.5 Newton	(10 lb.)
Radial Stiffness, Passive	7×10^5 Newton/meter	(4000 lb/in)
Axial Load @ .2 Amp.	89 Newton	(20 lb.)
Axial Sensitivity	445 Newton/Amp.	(100 lb/Amp)

The photograph (Figure 4) illustrates a partially disassembled bearing to reveal the control coil and the cross section of the split "jacket" which normally surrounds it. Either this magnetic shunting element (jacket), or the permanent magnet assembly may rotate; the control coil being attached to the alternate (stationary) element.

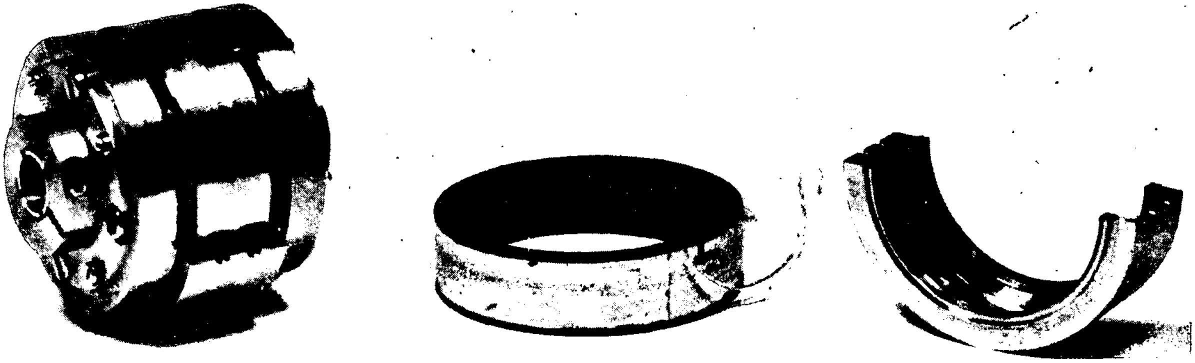

Figure 4. Photograph, P. M. Supplemented Magnetic Bearing

In this design, all of the gaps contribute to the radial support capability, only two to the axial forcing function; therefore, a better radial to axial load capacity is achieved. Additionally, the steady state axial forces are contained within the individual bearing elements, greatly reducing the structural problems and weight required to transfer them through the rotor and structure.

In conclusion, the development of magnetic bearings capable of handling substantial loads for space flight applications has progressed from demonstration of feasibility to the stage where the major factors inhibiting their application are being successfully attacked. It is believed that continuing development of these devices, incorporating advanced magnetic materials, further refinements of the magnetic circuitry, and analysis of their dynamic behavior will yield still better results. This can mean the opening up of a whole new area of bearing technology and a new field of application for magnetics. Potentially, it can be a boon to the rotating equipment designer by freeing some of the restrictions on operating speed. It promises an electromechanical device whose life is determined by the reliability of the electronics controlling it, rather than limited by mechanical considerations.

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