11. A REVIEW OF THE TECHNOLOGY OF NONCONTACTING SYSTEMS

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INTRODUCTION

Advanced components are the fundamental building blocks of advanced systems and spacecraft. Non-contacting elements, including magnetic bearings, brushless and ironless armature motors, rotary transformers and encoders, are discussed. Most of the information presented in this paper has been generated from a continuing program of component development at the Goddard Space Flight Center. The aim of this paper is to identify some of the important design features and provide a perspective on the state of development reached to date.

BRUSHLESS DC MOTORS

Electronic commutation techniques avoiding the problems of sliding electrical contacts in vacuum were developed and flown in the early sixties. Unfortunately, they are still not "catalog items" by any American manufacturer. Their usage in the space program, however, has found gradual acceptance; for example, the latest ITOS weather satellite has seven of various types used in the attitude control system, tape recorders, and in radiometer scanners.

A brushless dc motor consists of a rotor position sensor, commutation circuitry, stationary armature, and a permanent magnet rotor. As a "black box", it is an electrical to mechanical transducer. The developed torque is directly proportional to the armature current, independent of speed. Operated open loop, a linearly decreasing torque with speed characteristic is obtained as illustrated in Figure I.

Operation anywhere within the cross-hatched region is permissible with servo control, requiring only a controller capable of holding the current proportional to the desired error signal. Note that this region is bounded by the terminal voltage (supply voltage less commutator drop - typically 2 volts) at zero speed and decreases linearly as the generated voltage increases with speed. The actual output torque is always less than the developed torque due to the motor's own drag torques, magnetic hysteresis and eddy current losses. While these losses generally represent a small power loss, they must be considered by the servo designer. Operation in both directions is easily obtained simply by changing the switching sequence 180°, a simple digital logic function. Full four quadrant operation is obtainable by providing an alternate path for the generated voltage with diodes, since the motor functions with equal effectiveness as a generator.

Typical of the current state of the art is a tape recorder motor (Figure 2) under development at GSFC. A 2.54 cm (1") high, 5.08 cm (2") diameter package contains integrated circuit hall sensor-amplifier, rotor position sensor, a pancake style torque motor, and a high accuracy optical encoder for precision speed control. The commutation electronics (Figure 3) are modular hybrid integrated circuit packages consisting of a position decoder, amplifier and direction decoder, and a three phase power switching bridge.

The brushless motor represents the most efficient drive component, providing a readily controlled output which can be free of any known wear-out phenomena other than the bearings themselves. One of the early models which was placed on life test in 1963 ran for six and three quarter years at 3000 rpm in a thermal vacuum until the bearings wore out (Reference 1).

Today, any dc motor characteristic obtainable with conventional (brush-type) commutation can be obtained with electronic (brushless) commutation. We are currently working on motors from .03 Nm (4 oz-in.) to 140 Nm (100 lb-ft.).

IRONLESS ARMATURE TORQUE MOTOR

The Ironless Armature Torque Motor was developed to provide a drive element with improved servo characteristics. Both performance and efficiency can be improved by motors using this design concept (Reference 2).

It is, in fact, one of the oldest motor construction techniques which was employed before it was learned that conductors placed in slots perform as effectively as if they were actually in the air gap itself. It is, however, currently in vogue for high performance servo motors for fast response systems since the armature windings can have very low inertia. This latter capability was not a factor in our decision since, when it is electronically commutated, the armature is the stationary element and the permanent magnet field assembly rotates.

What then were the reasons for selecting this motor construction technique? Actually, there are several:

1. Reduction of magnetic drag torques
2. No slot effect, or cogging
3. Fast electrical response
4. Absence of destabilizing forces in the motor air gap

All four of these are of value to the servo designer interested in optimized performance. The elimination of hysteresis and eddy current losses in the normally laminated armature has an obvious benefit in terms of motor efficiency, since these generally account for 50% of the motor losses at the peak of the efficiency curve. There are numerous applications, predominantly in direct drive systems with constant speed requirements, in which the motor losses represent the bulk of the steady state torque requirement. A more significant aspect is that magnetic hysteresis torques represent the greatest nonlinearity in direct drive systems which are free of gearing backlash. Hysteresis torque can become one of the limiting factors in accurate pointing systems, introducing a deadband at the servo null position. Figure 4 illustrates the wider dynamic range provided by the ironless armature motor. It is evident that the uniform slopes of the conventional motor show that the choice of a larger motor to increase the torque margin and reliability works contrary to the designer's effort to minimize static errors and losses. Only by a different design approach can an improvement in both aspects be obtained.

Figure 5 illustrates the construction of the ironless armature torque motor. There are no cogging torques since the windings are not placed in discrete slots. All torque ripple is not eliminated, however, since groups of conductors forming the three phase delta connected winding vary in effectiveness as the commutation proceeds. One objective of this development, a trapezoidal generated voltage waveform, was not achieved during this development and requires further work before a completely uniform (i.e., not position dependent) torque output is achieved.

The fast electrical response is due to the fact that the armature conductors are not surrounded with highly permeable iron but are cast into an epoxy cylinder projecting into magnetic gap. An order of magnitude lower inductance and a shorter time constant results, moves the electrical time constant in some cases outside the servo bandwidth, or at least reduces its impact on the servo compensation requirement.

There are no static destabilizing forces between the rotor and stator whereas in a conventional permanent magnet motor these represent a significant load on the bearings even in a zero "g" environment. As shuttle launched systems are developed and launch vibration isolation reduces the need for heavy bearing preloads, this aspect will assume still greater significance. In the case of magnetic bearing design, described elsewhere in this presentation, the rotor to stator forces could subtract substantially from the "payload".

The question arises easily that, if these benefits can be achieved, what is the penalty associated with this construction technique and why hasn't it been introduced sooner? The answer to the latter question is easily found if one looks at the permanent magnet assembly (stator) of a commercial moving coil servo motor. Those designed with Alnico magnets have a relatively huge magnet structure. The introduction of rare earth magnet alloys as the result of Air Force research has made the difference. Their tremendous coercive force makes it feasible to drive air gaps almost equal to the length of the magnet itself. A specific comparison to conventional brushless torque motors of similar diameter shows that approximately a two to one weight penalty is imposed by the choice of this design approach.

ROTARY TRANSFORMERS AND NON-CONTACTING ENCODERS

Another functional element required by some, although not all, rotating systems is a means to transfer power and signals to or from the rotating assembly. A non-contacting electromagnetic component well suited to perform this function is the rotary transformer. Matrix Research and Westinghouse Corporations have developed a signal and power transformer of this type as part of an advanced solar array drive system (Reference 3). The illustration (Figure 6) is indicative of the size and volume requirements for a device of this type. It also permits one to visualize the magnetic structure - basically two concentric cylinders - and the coil form. Obviously, the major difference between the rotary transformer and a static type is the necessity of air gaps to permit rotation of the primary with respect to the secondary. The adverse effect of this gap is minimized by the inherently tight coupling of concentric coils and by the superior form factor of circular coils which reduces the I^2R losses. The power transformer, which in this case provided the correct transformation as an inverter, was 99% efficient at the 500 watt level and weighed 1.2 kg (2.6 lb.). Both the signal and power sections were operated at 10 kilohertz with a radial air gap dimension of .01 cm (.004"). The size of the signal transformers was not minimized to electromagnetic requirements but controlled by mechanical considerations. Further effort could result in size reduction; however, substantial signal requirements can be multiplexed into the available channels.

Non-contacting optical and magnetic encoders are commercially available. We have generally used optical encoders because of their high resolution and low inertia and weight. A 2^{14} bit (16,384 line) incremental encoder was used with a 12 cm diameter torquer at 3 rpm and a 1,000 line encoder is being used in the 5 cm diameter motor package mentioned earlier.

The position encoder for motor commutation has a far lower resolution and we are currently using an integrated circuit hall effect sensor activated directly by fringing flux from the motor magnets. This device produces digital logic level outputs with lower power requirements than optical sensors used previously.

MAGNETIC BEARINGS

The elimination of sliding electrical contacts by electronic commutation and rotary transformers, and of sliding mechanical contact by direct drive rather than by use of gearing, can produce long lived systems. Nonetheless, full rotation systems are still not free of a lubrication requirement, nor do they have a life independent of speed, so long as they employ contacting bearings.

For these reasons, we started to look seriously at magnetic suspension as a means to provide the bearing function in a manner not influenced by the environment and with the potential of zero wear.

At that time (1968), considerable work had been done on instrument type suspensions with negligible load capacity, specifically for gyros (Reference 4), and on large gap systems where power and weight were no obstacle, specifically wind tunnel model support. We set out to develop flyable (Reference 5) systems of significant load capacity.

The latest results of this effort will be described in another paper at this conference.

I would like to recount some efforts of the past several years, starting with some of the fundamental characteristics and design problems associated with magnetic bearings, and indicate what progress has been made.

A fundamental aspect of magnetic suspension was proven mathematically by Earnshaw in 1837; simply stated, it is that "no combination of permanent magnets can provide a stable support in all directions". As a practical matter then, a servo (active) system is required for stability in a non-contacting system. The availability of adequate sensors and reliable electronics does not rule out magnetic bearings as a more reliable system. In fact, greater stiffness is generally obtained in the direction of characteristic instability. Early systems, such as that built by Cambridge Thermionic Corporation for GSFC in 1970 (Reference 6), used forty watts and weighed 5.5 kg (12 lbs.) because all of the magnetic flux was supplied by electromagnets (Figure 7). Several successful developments have been made since then, all involving permanent magnets to reduce the power required. At GSFC, a method to differentially modulate the flux in two opposing permanent magnet circuits was invented (Reference 7 & 8) and tested (Figures 8 & 9). At Cambion, a control technique to minimize the average power in the drive coils was also successful (Reference 9) and a prototype momentum wheel was delivered to COMSAT Corporation, which is currently pursuing further development in Europe.

A fundamental problem is weight, since the force per unit area is a function of the square of the flux density, and all of the materials capable of handling high flux densities are of the ferrous group. Fortunately, the development of Samarium Cobalt, a magnetic material of high coercive force by Air Force research has been forthcoming as mentioned previously. While not at all a lightweight material, it can result in shortening the length of the magnetic circuit by nearly a factor of ten. Consequently, a significant payload improvement has been made feasible. Whereas the early model had about 50% of its rotating weight composed of bearing material, the latest device has a payload to bearing weight ratio of better than 10:1 - the bearing assembly no longer overwhelms the rest of the assembly (Figure 10). An interesting new development occasioned by this same new magnet material is renewed interest in repulsive bearings, in contrast to those mentioned above, all of which have magnetic circuits working in the attractive mode.

An interesting model of a repulsive bearing, with pivots providing axial restraint, was demonstrated at the Naval Ordnance Laboratory in 1971. Hughes Aircraft has also investigated a system using ferrite magnets in repulsion, from which it predicts even more impressive characteristics when Samarium Cobalt is used.

Magnetic bearings, then, have been the subject of some fruitful development, such that they now allow the designer to consider rotating systems which no longer have a life measured in number of revolutions.

CONCLUDING REMARKS

Electromechanical devices are playing an increasingly broad role aboard spacecraft. The reliability of these devices cannot be allowed to fall as application requirements become more demanding and performance tolerances are reduced. Advanced control techniques, improved sensors, and narrower beam-width communication systems have increased the demands on systems performance to the point where fundamental device characteristics limit systems capability. We believe that the component developments which have been undertaken over the past several years will allow a new generation of electromechanical devices to meet future requirements with lifetimes limited only by the failure rates of the control electronics.

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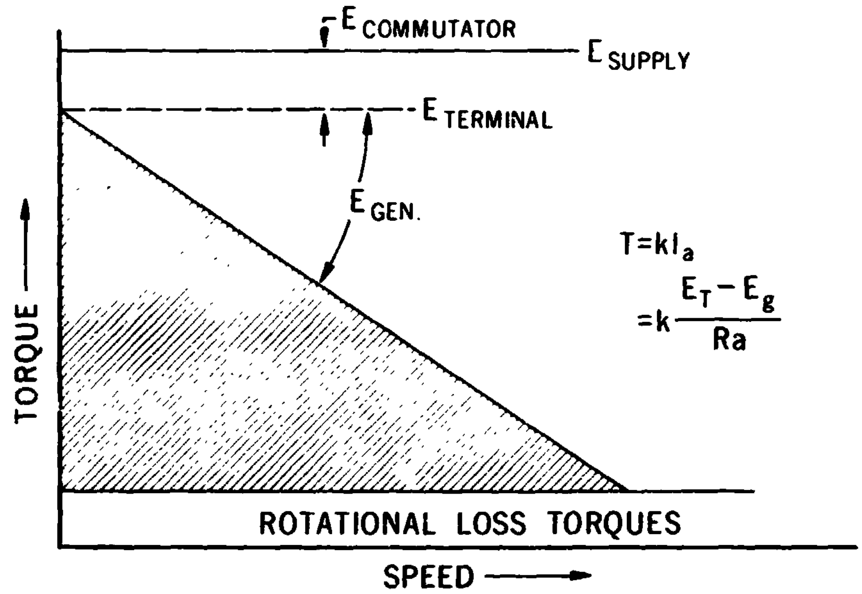

Figure 1.- DC motor torque/speed characteristics.

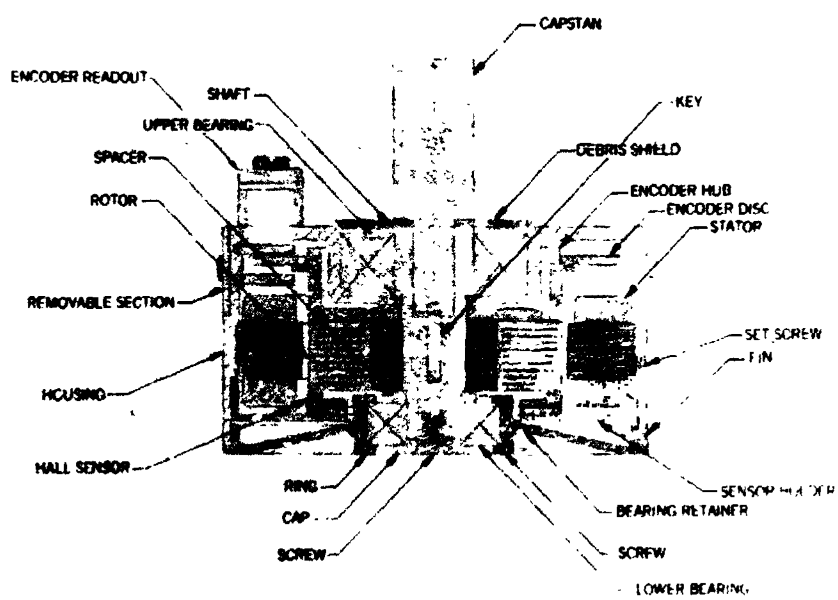

Figure 2.- Tape recorder motor.

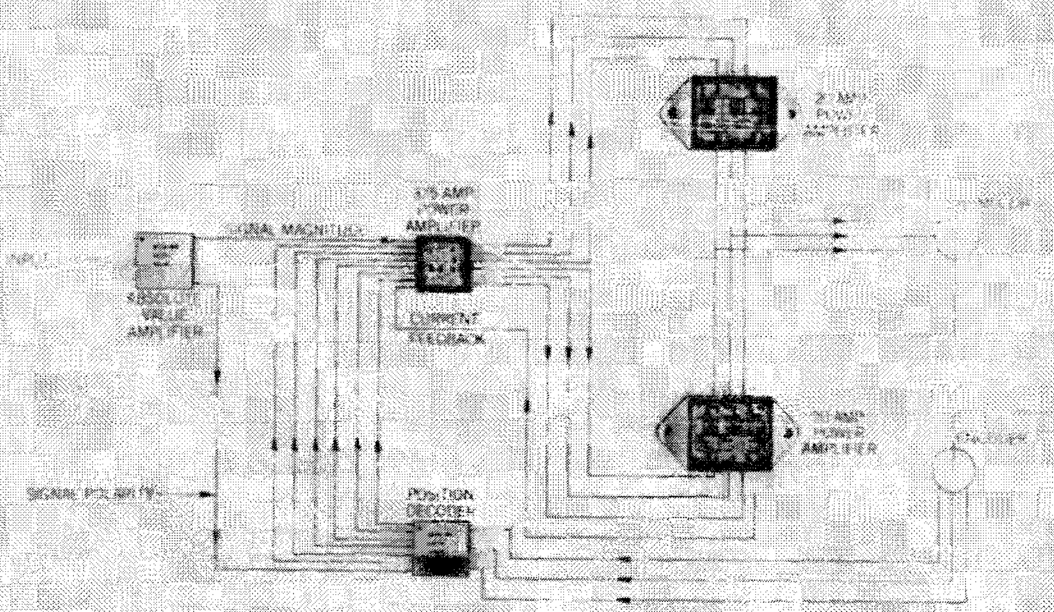

Figure 3.- Hybrid, integrated circuit commutator.

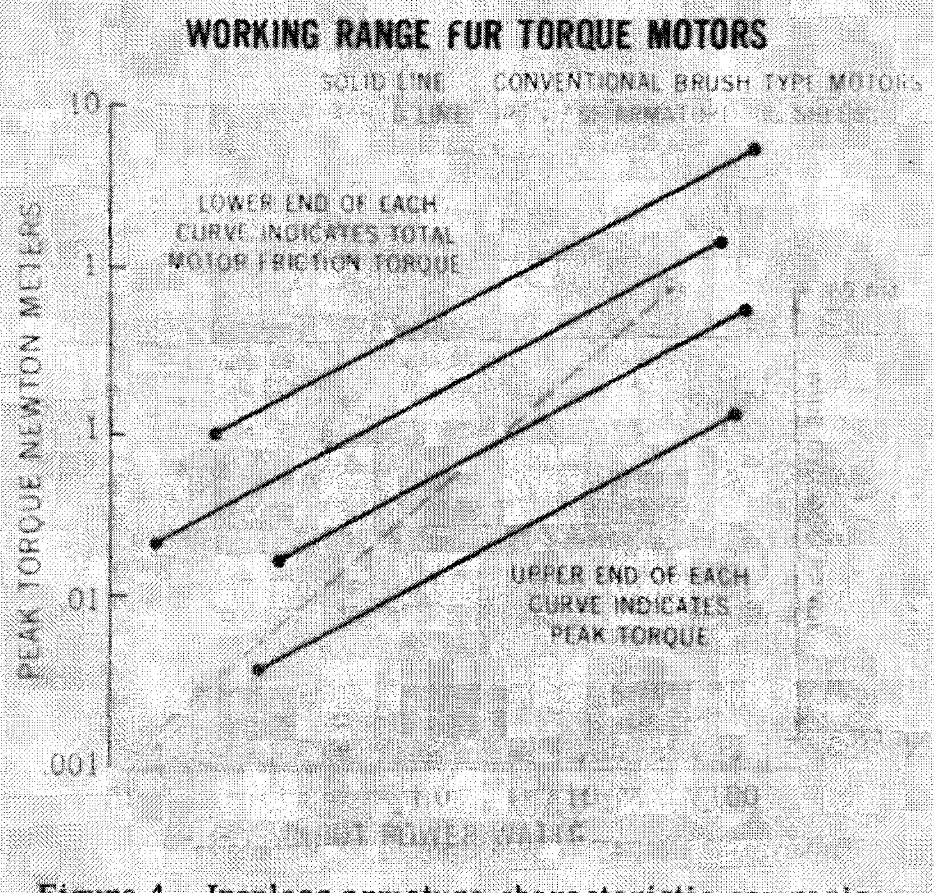

Figure 4.- Ironless armature characteristic comparison.

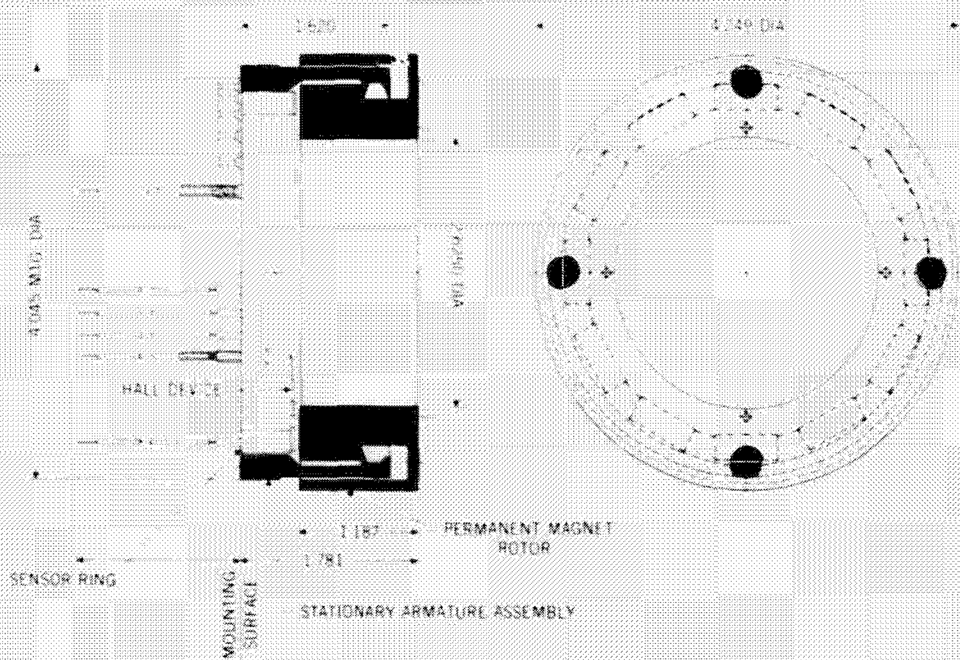

Figure 5.- Ironless armature, cross section.

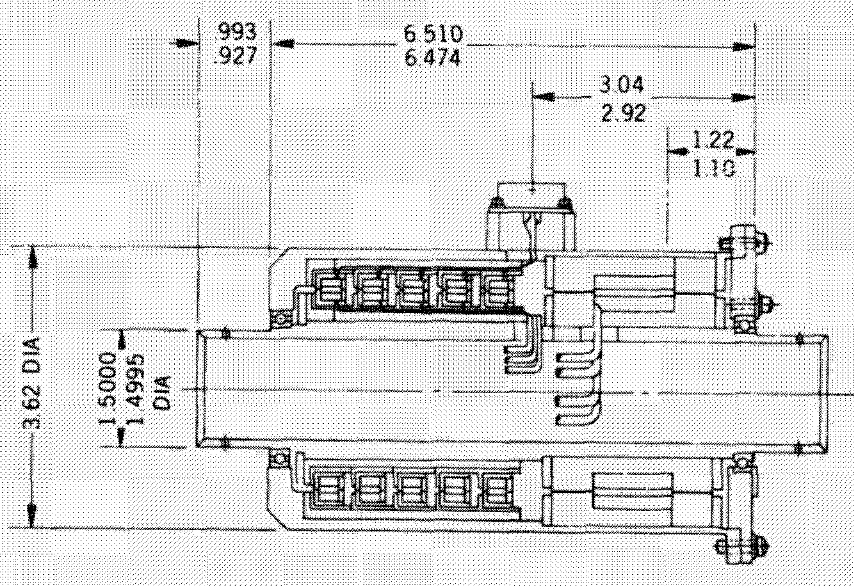

Figure 6.- Rotary transformer, cross section.

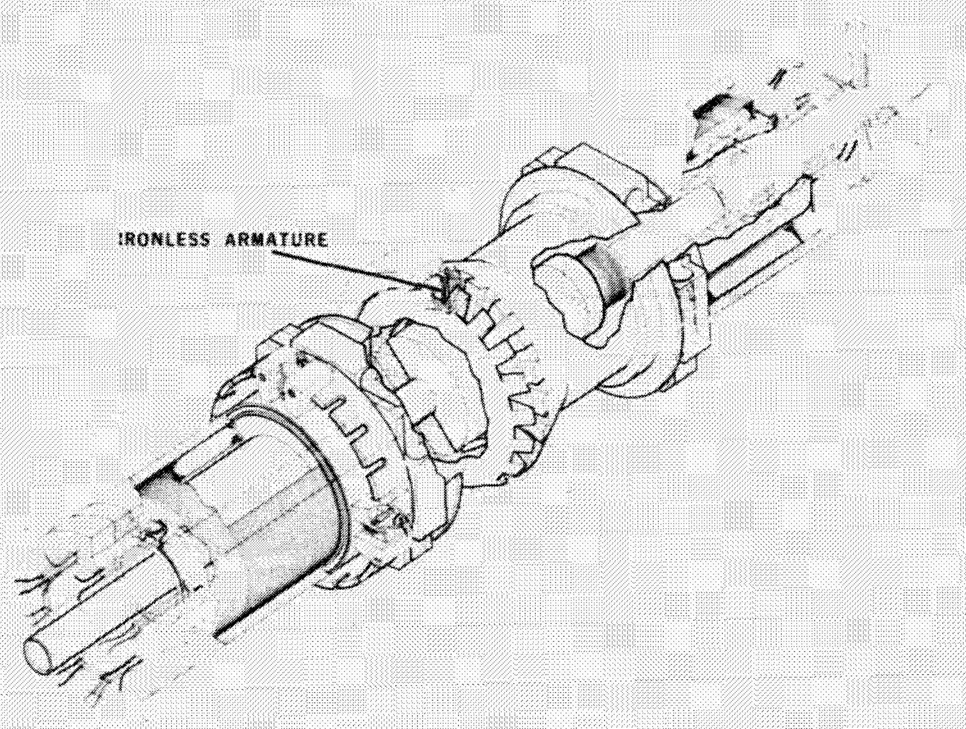

Figure 7.- Magnetically suspended motor.

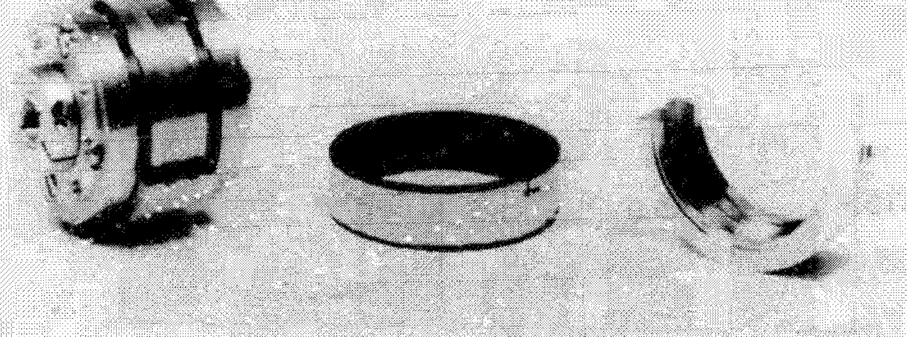

Figure 8.- GSFC magnetic bearing.

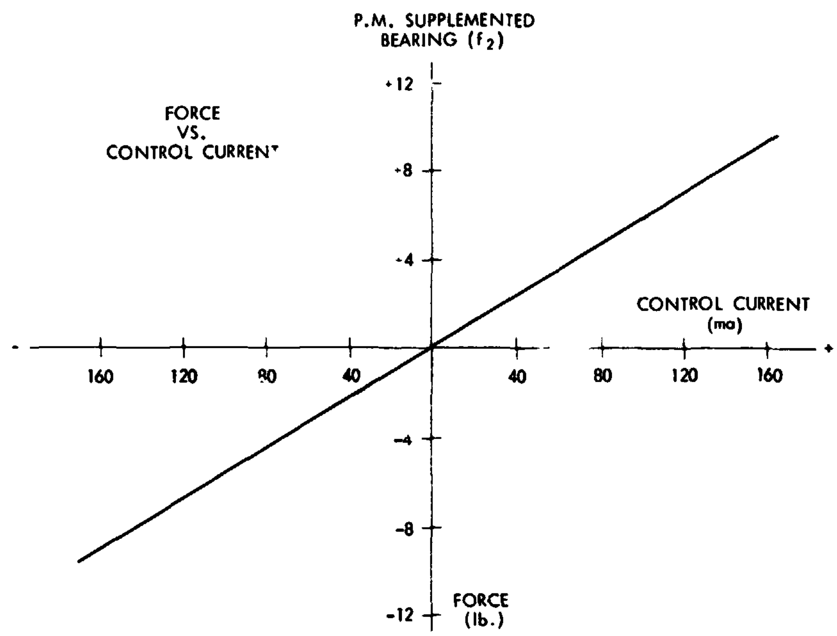

Figure 9.- Characteristics of GSFC magnetic bearing.

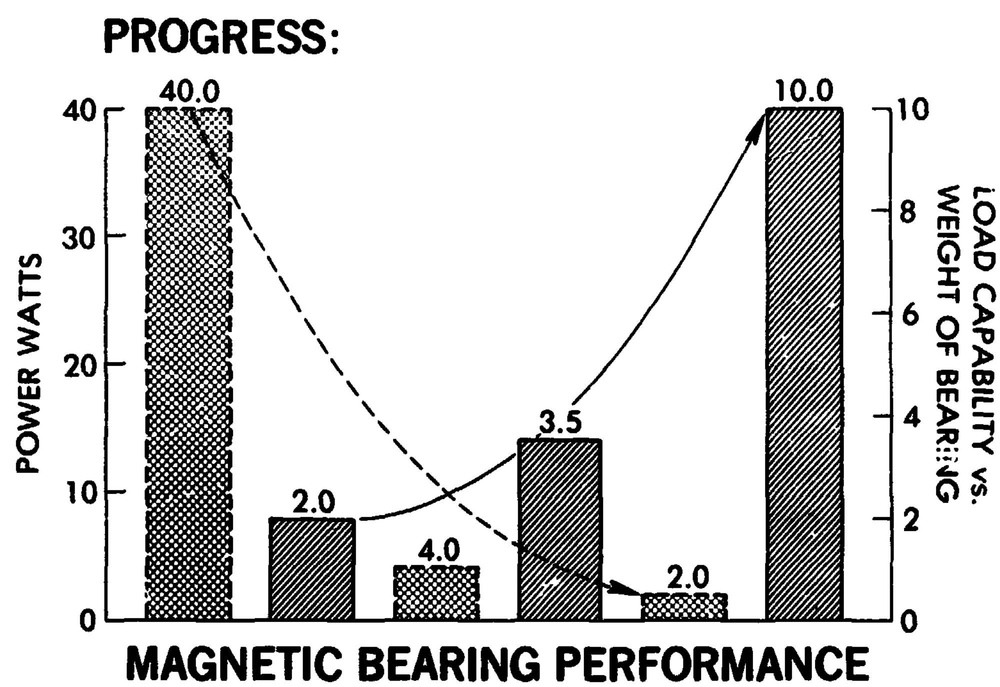

Figure 10.- Progress in magnetic bearings.