THE IMPACT OF RARE EARTH COBALT PERMANENT MAGNETS ON ELECTROMECHANICAL DEVICE DESIGN

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ABSTRACT

The discovery of rare earth cobalt magnets has introduced a new class of permanent magnets with energy products several times greater than heretofore available. The prospects for performance improvements and the miniaturization of electromagnetic devices are great.

This paper discusses specific motor designs which employ this revolutionary material with special emphasis on its unique properties and magnetic field geometry. Magnetic field geometry is an important design consideration since the material derives its high energy product from extremely high coercive force whereas flux density is the parameter which affects the motor torque equation directly. New magnetic circuit designs are therefore needed to capitalize on the potential benefits of this material in conventional torque motors. The advantages of this material in the design of ironless armature motors and linear actuators are more obvious. In addition to performance improvements and power savings, higher reliability devices are attainable.

Both the mechanism and systems engineer should be aware of the new performance levels which are currently becoming available as a result of the rare earth cobalt magnets.

INTRODUCTION

The rapid advance of electronics has stolen most of the headlines in recent years with regard to miniaturization. It is less well recognized that an exponential improvement in permanent magnet materials has also been underway. Most large systems are composed of both control electronics and a variety of electromechanical devices. In spite of all the advances in microcircuitry, in the end the desired function generally involves some physical motion or work to be done.

Of the large variety of electromechanical devices which are utilized in spacecraft and instruments, many employ permanent magnets. The design and utilization of these devices are a fertile field for significant performance improvements as well as weight and power savings if early attention is paid to the design and specification of mechanisms making full use of these new materials.

The designer of electromagnetic devices has seen the continued improvements in the energy products of permanent magnet materials available. During the 50's new alnico alloys appeared regularly year after year with an even more rapid rise with the development of directional cooling techniques in the presence of a magnetic field. For a few years this rapid progress seemed to have leveled off until the dramatic discovery of rare earth cobalt alloys and the commercial introduction of $SmCo_5$ and more recently Sm_2Co_{17} (Fig. 1).

ENERGY PRODUCT OF COMMERCIALLY AVAILABLE MAGNET MATERIALS

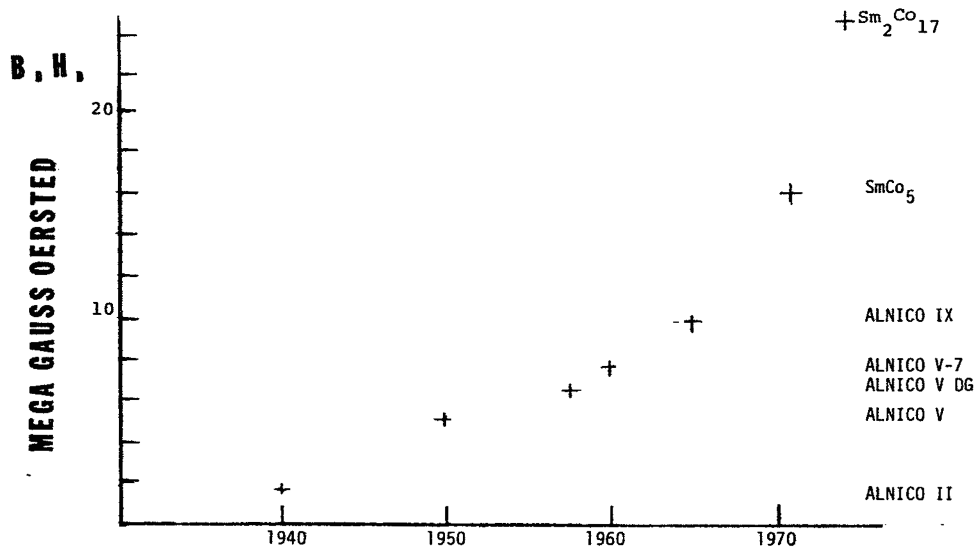


FIGURE 1

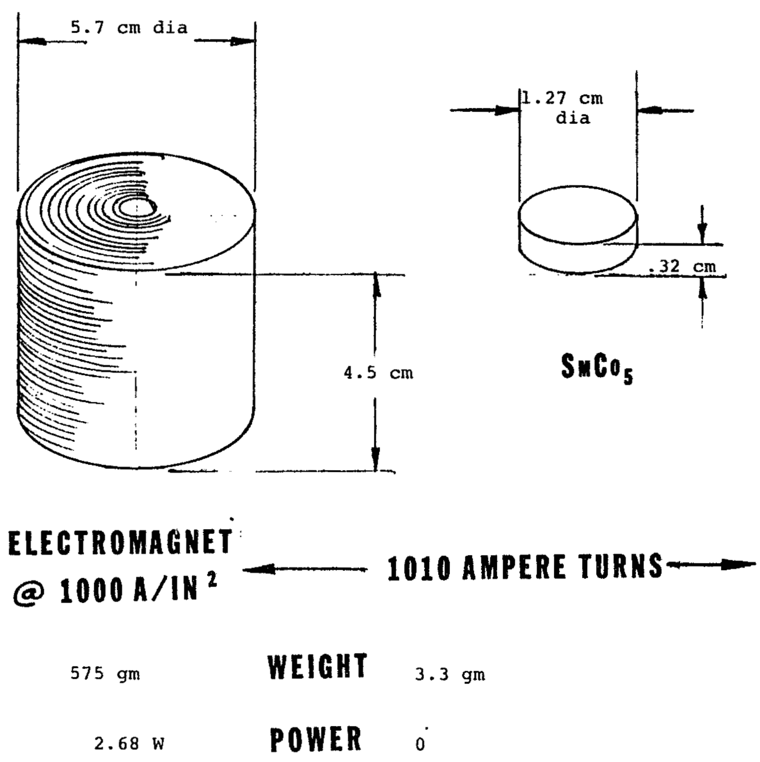


FIGURE 2

This exponential increase in permanent magnet characteristics has continued to broaden the range of applications to which electromagnetic devices can be effectively employed. Figure 2 shows the dramatic size and weight savings of modern rare earth magnets compared to an electromagnet.

Rare earth magnets are having a profound impact on the performance of electromechanical devices. Despite the obvious advantage of their higher energy product (β H max) usually expressed in millions of gauss oersteds a considerable amount of engineering is required to make effective use of their potential. The fundamental reason for this is that the improvement is in the coercive force rather than flux density.

Figure 3 shows the magnetic properties of the most commonly used alnico magnet materials and some of the rare earth materials. As can be seen, there is quite a difference in the magnetic characteristics. It is not possible to obtain improved motor performance by merely substituting rare earth magnets in place of alnico magnets. The motor must be designed to exploit the characteristics of the particular magnet material. If you consider the basic equation for the force or torque developed by a motor it is only the air gap flux density rather than the coercive force which has a direct effect on the performance. The challenge to the device designer then is to utilize this high coercive force most effectively to produce a more effective, higher performance, lighter weight, and/or more cost effective mechanism.

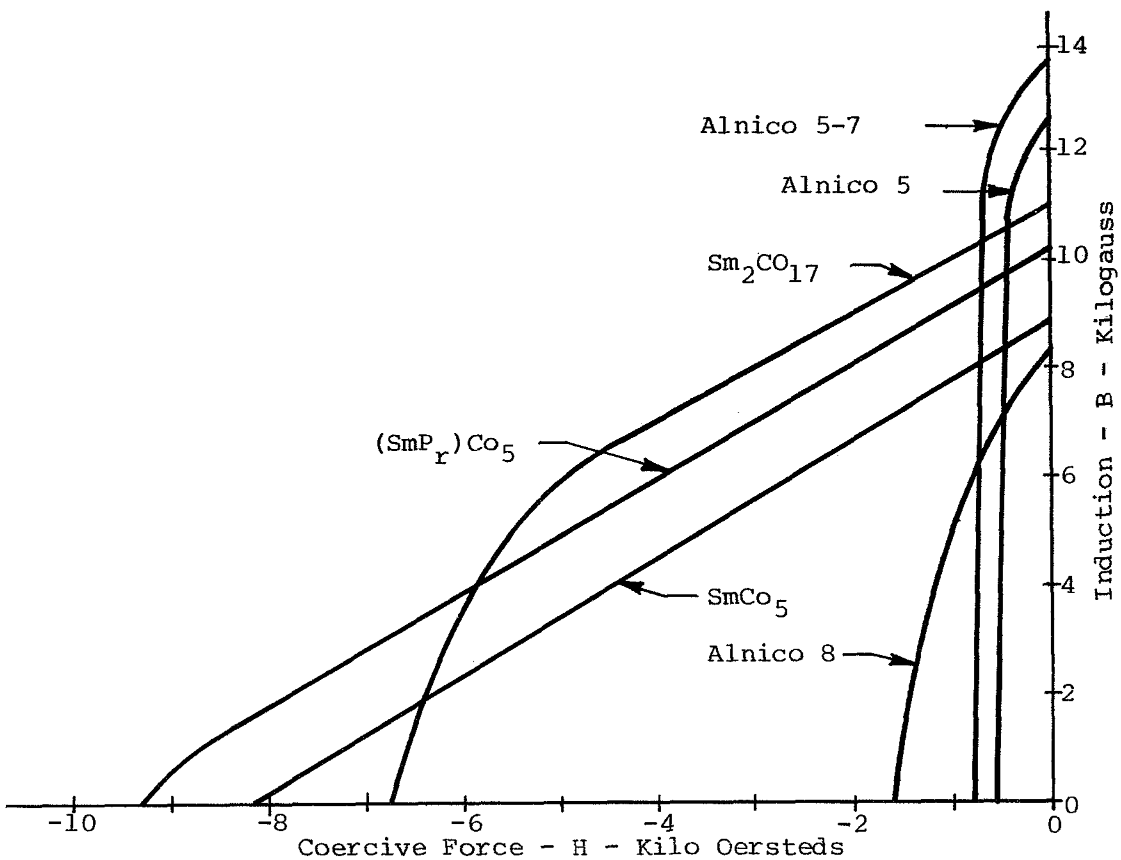


Figure 3 - Typical Magnetic Properties

DEVICES USING RARE EARTH MAGNETS

DC Torque Motors

A DC torque motor is an electromagnetic actuator which can be attached directly to the load. Most torque motors are provided as frameless units consisting of a wound rotor assembly, a permanent magnet stator assembly, and a brush ring assembly. They are usually thin in axial length compared with diameter, and have a relatively large bore through the rotor for direct mounting on the load shaft. A DC torque motor is designed to provide the highest torque practical for the size, weight and power available while providing smooth control in a high response system.

The key to improved DC torque motor performance is improved permanent magnet materials. Figures 4 and 5 depict the construction of motors with alnico magnets and with rare earth magnets. Alnico magnets need a large length-to-area ratio because of the low coercive force. For example, if the operating slope for an alnico 5-7 magnet were to fall below 18 cgsu, the magnetic flux would be reduced due to permanent demagnetization of the magnet. Therefore, much care must be taken in keepering the stator assembly during handling and assembly, and to insure that current spikes are controlled so as not to cause demagnetization.

The alnico torquers are constructed with two magnets feeding one pole piece in order to keep a large length-to-area ratio. Anywhere from one-third to one-half the total magnetic flux is lost as leakage flux. The stator assembly must be mounted in a non-magnetic housing to prevent the housing from shunting the magnetic flux.

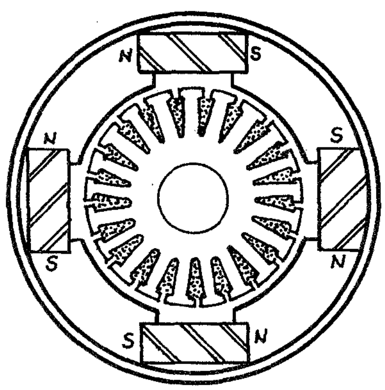


Figure 4

Alnico Magnet Construction

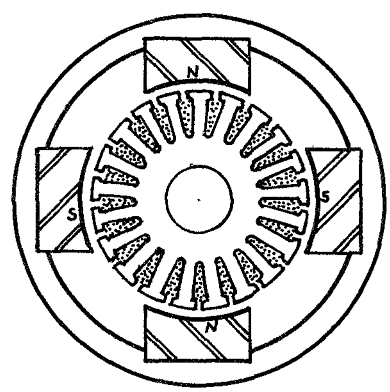


Figure 5

Rare Earth Magnet Construction

The rare earth magnets have less induction but a much larger coercive force than the Alnico magnets. Therefore, a much smaller length-to-area ratio is possible, allowing the construction shown in Figure 5. With this configuration, the housing can be either magnetic or non-magnetic without affecting performance. Only about 10% of the magnetic flux is lost as leakage flux. Since the permeability of the rare earth materials is very close to that of air, the inductance of the motor is reduced, resulting in lower electrical time constant. Because of the large coercive force a rare earth magnet torquer cannot be demagnetized as the result of overcurrent conditions. Keepering is not required for handling.

The advantages of DC torque motors having rare earth magnets are:

1. Greater peak torque capability.
2. In most cases less power required for a given torque.
3. No keepering required.
4. Overcurrent will not demagnetize.
5. Less electrical time constant.
6. Fewer stray magnetic fields.
7. Larger air gaps are possible, making rotor-to-stator concentricity less critical.

Inland torquer QT-1207 with $SmCo_5$ magnets was designed to be a direct replacement for a similar size unit which has Alnico 5-7 magnets. The characteristics of the two motors are compared in Table I. Pulse currents were applied to the new design to avoid overheating at the large values of current, and the output torque measured with a torque transducer. At 0.282 Nm (40 oz.in) peak torque (double the peak torque rating), the torque sensitivity was reduced by only 11%. No demagnetization resulted from the high current pulses.

TABLE I

CHARACTERISTICS	T-1218A	QT-1207A	UNITS
Magnet material	Alnico V-7	$SmCo_5$ (18 MGO_e)	---
Peak torque rating	106	141	mNm
Power input at 106 mNm	63	46	watts
Motor constant	13.4	15.6	mNm/$\sqrt{\text{watts}}$
Static friction	3.5	4.9	mNm
Motor weight	65	65	g
Torque sensitivity	84.7	98.9	mNm/A
DC resistance	40.0	40.0	ohms
Inductance	12	7.9	mH

Table II compares the performance of three Inland torque motors; one with alnico 8 magnets, one with $SmCo_5$ magnets (18 MGO_e), and one with $(SmP_r)Co_5$ magnets (26 MGO_e). The $SmCo_5$ unit develops 29% more torque than the alnico unit and the $(SmP_r)Co_5$ unit 48% more.

TABLE II

CHARACTERISTICS	T-2405A	QT-2402A	QT-2403A
Magnet material	Alnico 8	$SmCo_5$ (18 MGO_e)	$(SmP_r)Co_5$ (26 MGO_e)
Peak torque rating Nm	3.39	4.38	5.01
Power input, stalled watts	285	261	261
Motor constant $Nm/\sqrt{watt}$	0.20	0.27	0.31
Static friction Nm	0.07	0.11	0.11
Torque sensitivity Nm/A	0.339	0.438	0.501
DC resistance ohms	2.85	2.61	2.61
Inductance mH	5.0	2.7	2.7

Ironless Armature Torque Motors

One type of motor of particular interest to the aerospace mechanism and instrument designer is the ironless armature motor. The advantage of this type of motor is the complete elimination of breakway friction caused by hysteresis and cogging due to the interaction of discrete poles and slots in the usual motor lamination. For certain applications such as position control servo loops, these non-linear effects can result in a fundamental limitation on achievable precision. Ironless armature motor construction eliminates all hysteresis, cogging, and static forces between rotor and stator. This is accomplished by combining all of the "iron" structure with the permanent magnet assembly and inserting the armature conductors into the air gap. These motors also have an order of magnitude lower armature inductance since the motor windings are essentially an air-core within the air gap. Of necessity, large coercive force is required to produce high flux densities in an air gap large enough to accommodate many conductors of adequate current carrying capability. Prior to the advent of rare earth magnets, the use of this type of motor was generally restricted to high performance servos with stationary magnet assemblies where the weight of the magnet assembly was not critical (Fig. 6).

MAGNET ASSEMBLIES FOR AIR CORE ARMATURES

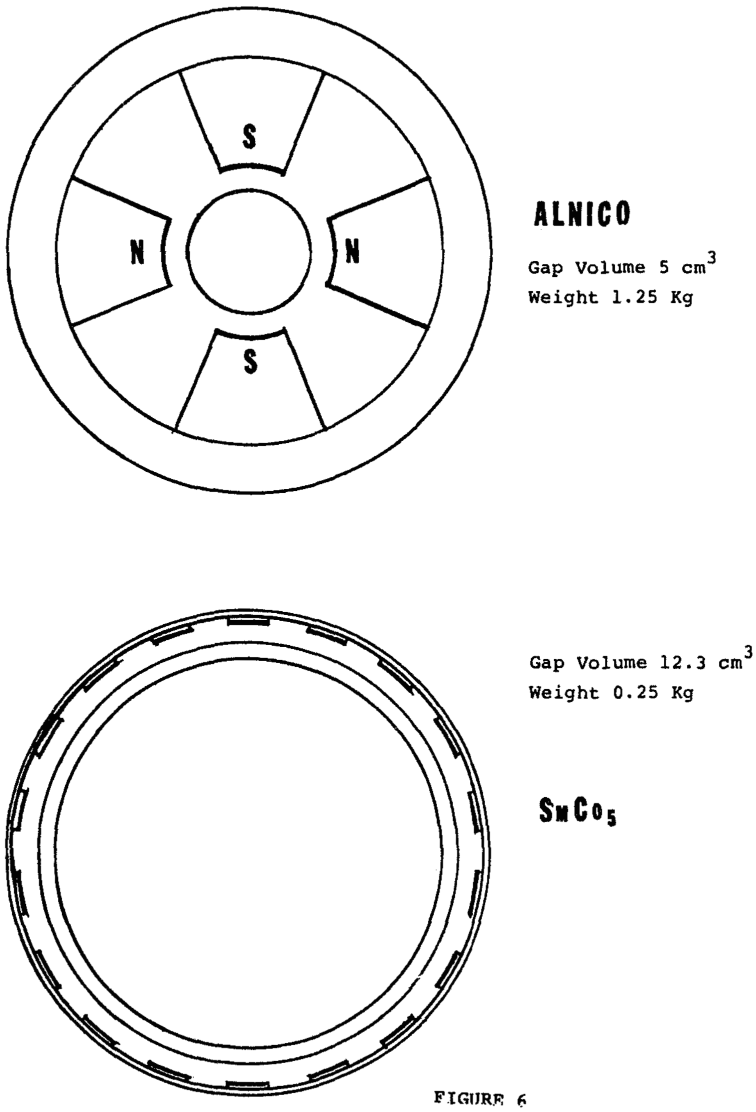


FIGURE 6

Samarium cobalt magnets however have made it feasible to drastically reduce the weight of the magnet assembly and to rotate the magnet assembly with only the windings stationary. The non-rotating mass of a typical ironless armature motor is only 20% of the total motor weight.

The most effective use of rare earth magnets in this case is to bring the face of the magnet directly to the air gap with the magnet itself forming the pole. These magnets can operate at their peak energy product (minimizing magnet volume) while supplying flux across an air gap nearly equal to their length in the direction of magnetization. This allows a large number of adequately sized conductors to be inserted in the gap achieving good power ratings.

In a reaction wheel the magnet assembly can be built into the wheel near the rim where its mass contributes to the necessary inertia leading to a very substantial weight reduction. In other applications the elimination of motor induced disturbances is even more important. With advances in sensors, especially with the advent of extremely narrow beam widths for communication links, the elimination of hysteresis and preferred position is vital. These motors have been applied successfully to fractional arc second pointing systems and are being applied to the Space Sextant. They have been used in conjunction with an optical encoder to develop a microprocessor based programmable stepper* with an order of magnitude greater resolution than realizable with mechanically defined steps. This machine retains the advantages of fast slew rates and servo damped behavior of a true torque motor. The servo designer at last has a system which behaves exactly as his linear analysis has predicted it should, even around null. A multi-axis and all-digital controller** has more recently been developed which is being integrated with ironless armature motors for the Spacebore Geodetic Ranging System. This will snap a laser beam from target to target on each orbital pass to detect earth fault motions. The ironless armature motor for this system is shown in Figure 7.

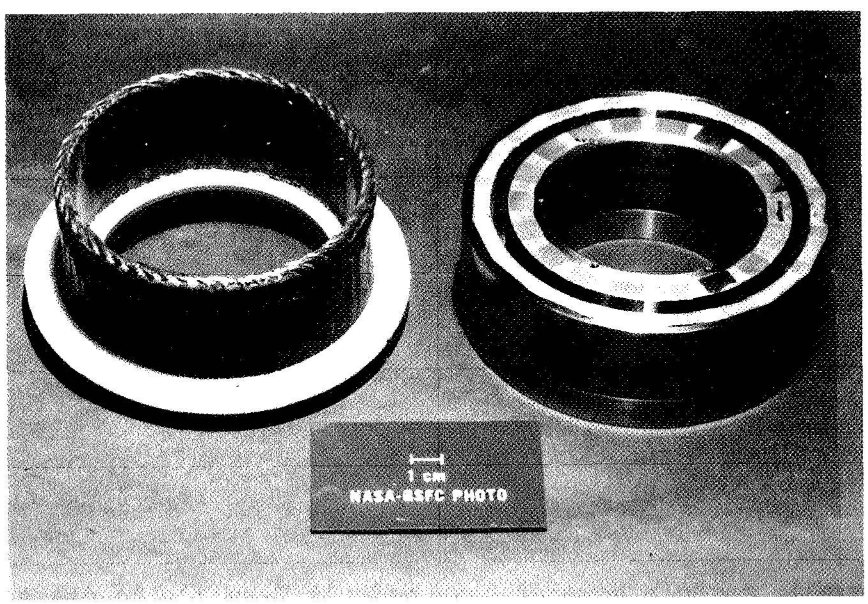


Figure 7 - Ironless Armature Motor

*Programmable Step Scan, NAS5-24048
**All Digital Controller, NAS5-24199

Linear DC Force Motor

A linear DC force motor developed recently at Inland is another example of the use of rare earth magnets. The magnet assembly is the moving member or slider. Therefore the size and weight of the magnets are important. Inland model FM-1901 develops a force of 245 newtons (55 lbs) with a slider weight of only 2.45 Kg (5.4 lbs).

The linear force motor consists of a stationary winding assembly and a slider. The windings are commutated through brushes which are attached to the slider.

The slider contains four $SmCo_5$ magnets, two on either side of the stator assembly. The two sets of magnets are mechanically connected together. The slider also has brushes for commutation and brushes to bring the input power from the stator to the slider.

The stator contains a lamination core, windings, commutator, and two power rails. The windings are arranged so that only the windings under the magnet assembly are energized.

This particular model was designed for a total travel of 429mm (16.9 in). The travel can be modified by changing the length of the stator assembly without affecting the motor performance. The performance parameters are shown in Table III.

TABLE III
LINEAR FORCE MOTOR (FM-1901)

PERFORMANCE CHARACTERISTICS		
Peak Force (Fp)		245 N (55 lbs)
Power Input at Peak Force @ 25°C		570 watts
No Load Speed @ Vp		226 cm/s (89 in/s)
Electrical Time Constant		4.6 ms
Static Friction		5.6 N (1.25 lb)
Ripple Force (average to peak)		4.5%
Theoretical Max. Acceleration		9936 cm/s^2 (326 ft/s^2)
WINDING PARAMETERS		
Voltage @ Fp		29.3 volts (Vp)
Force Sensitivity		12.6 N/A (2.82 lb/A)
DC Resistance @ 25°		1.5 $\pm$ 0.2 ohms
DIMENSIONS	STATOR (Winding Assembly)	SLIDER (Magnet Assembly)
Height	48.3 mm (1.90 in)	94.0 mm (3.70 in)
Width	98.3 mm (3.87 in)	118 mm (4.65 in)
Length	604 mm (23.8 in)	175 mm (6.90 in)
Travel		429 mm (16.9 in)
Weight	14.4 Kg (31.7 lbs)	2.45 Kg (5.40 lbs)

DC Tachometer

Rare earth magnets have also been utilized to good advantage in DC tachometers. Unlike the DC motor, a tachometer does not have to withstand large demagnetizing currents. The tach is normally connected to a high impedance load. The main objectives are to provide a high voltage sensitivity and to have a low ripple voltage.

Since rare earth magnets have very low magnetic leakage, it is possible to reduce the flux in the commutation zone. The high coercive force of the magnets also helps reduce flux changes due to reluctance changes with rotation. This results in reduced ripple voltage.

Recently a tachometer with alnico magnets was redesigned with $SmCo_5$ magnets. As a result, we obtained a 25 percent increase in voltage sensitivity, ripple voltage was reduced by one third. Additionally it does not require keepers for assembly.

MAGNETIC BEARINGS

As early as 1970 GSFC introduced permanent magnets into magnetic bearings in order to minimize power consumption. This early attempt utilized a pair of cylindrical alnico magnets, each 4 cm in diameter and 2 cm in length. The advent of rare earth cobalt magnets has made magnetic bearings vastly more feasible for space applications on both a power and weight basis. For example, a recent magnetic bearing* used a single 3 cm diameter by .65 cm $SmCo_5$ magnet for 3 axis support. The use of permanent magnets in magnetic bearings permits the establishment of high flux densities in the air gap which in turn allows the ampere-turn requirement of the control windings to be greatly reduced. The curve in Fig. 8 shows the force per unit area produced plotted versus flux density. Since the force is a function of the square of the flux density, sizeable forces would require substantial ampere-turns from a pure electromagnet. The tradeoff between number of turns and high currents both lead to undesireable effects. A high number of turns leads to poor speed of response and compromises dynamic response while high currents result in power dissipation and thermal problems. Permanent magnets can be utilized to establish a high flux density which allows a smaller control signal to modulate the net force. A desireable by-product is that the force becomes a linear function of the control current.

A particularly effective way of using samarium cobalt is illustrated by the controllable permanent magnet biased electromagnet in Fig. 9. A set of these magnets at 3 points supported a 1.5 meter diameter momentum wheel jointly developed for the Goddard Space Flight Center and Langley Research Center in 1974. The volume of magnet material was only 2.6 cm^3 in each of these permanent magnet biased electromagnet modules. The angular positioning of the magnets afforded flux focusing and a low reluctance to control flux. With the magnet at a 30 degree angle, the flux density in the iron is twice that of the permanent magnet and its reluctance to control flux is only half of what it would otherwise have been.

*NASA TM78048

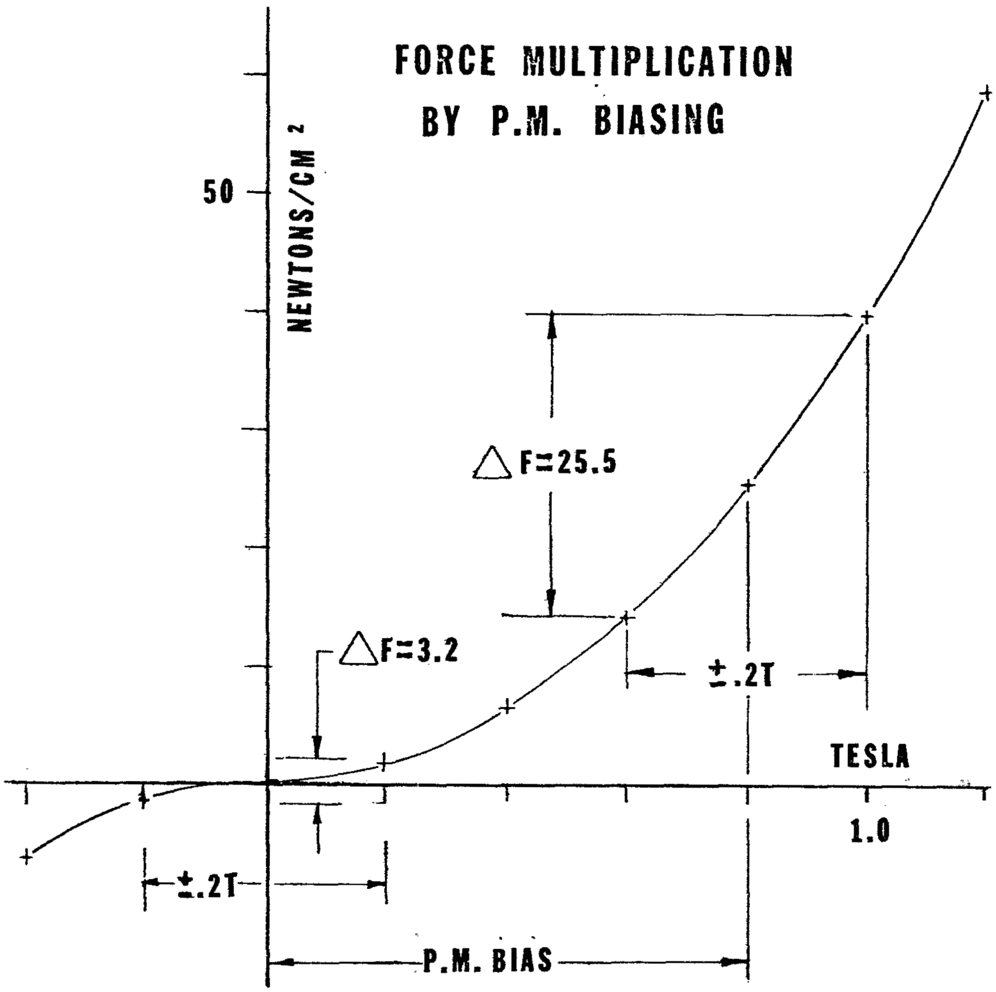
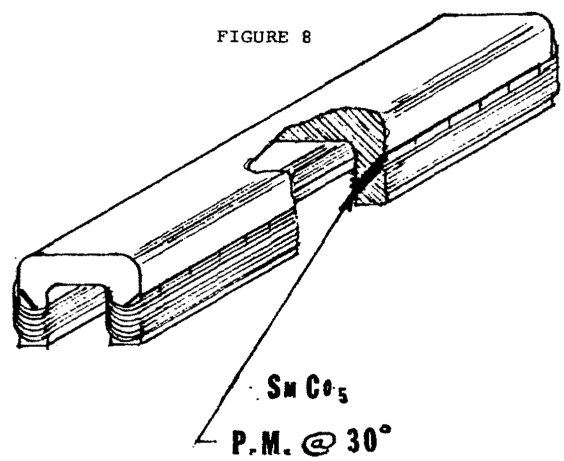


FIGURE 8



P.M. BIASED

ELECTROMAGNET MODULE

FIGURE 9

Magnetic bearings offer the spacecarft mechanism and instrument designer several new freedoms. Active electromechanical systems can be designed without life-limiting restrictions of lubrication in vacuum and without some of the speed limiting factors which restrict the power density of rotating devices. The suspension dynamics, including damping, can be electronically controlled. Only one magnetically suspended system is known to be operating in space. However, the European Space Agency is planning to introduce magnetically suspended wheels into communications satellites and NASA is developing a vernier pointing platform for Shuttle based instruments.

CONCLUSION

The order of magnitude improvement in permanent magnet energy products has spawned a whole new generation of electromechanical devices. These span the whole field from torque motors which are used routinely for countless applications to special purpose devices and even totally new mechanisms. The improvements are dramatic in terms of power and weight savings but even more significant in performance.

Aerospace instrument and systems engineers are likely to profit most from these new developments. Yet the automobile industry, also currently interested in shaving pounds, was well represented at the last R.E.-Cobalt magnet workshop. General Motors engineers showed that total costs could be reduced with the use of advanced and relatively expensive high energy magnets when the total system cost including power supply, structure, etc. was considered.

It is hoped that this paper will assist the mechanism designer to see some of the possibilities and challenges of designing with this new material by affording some insight into key aspects of some successful designs. As these developments become mature products a wider knowledge of their availability and characteristics is needed by instrument and spacecraft systems designers.

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