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MAGNETIC BEARINGS - FIFTY YEARS OF PROGRESS

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SUMMARY

Magnetic bearings are just beginning to be flown in spacecraft systems, but their development spans more than 50 years. The promise of completely non-contacting, unlubricated rotating systems operating at speeds substantially beyond the range of conventional bearings, and with no wear and virtually no vibration, has provided the incentive to develop magnetic bearing technology for many diverse applications. The idea is seductive indeed!

Earnshaw theorized in 1842 that stable magnetic suspension is not possible in all three spatial directions unless the magnetic field is actively controlled. Since that time, researchers have attempted to successfully support spinning rotors in a stable manner. Development of magnetic suspension systems over the past fifty years has included progress on both passive (permanent magnet) and active (electromagnet) systems. The improvements in bearing load capacity, stiffness and damping characteristics are traced in this report. The trends in rotor size, rotational kinetic energy and improvements in active control system capabilities are also reviewed. Implications of superconductivity on suspension system design and performance are discussed.

INTRODUCTION

The idea of magnetic suspension is not a new one. Man has long dreamed of magnetic levitation of spinning rotors as a means to the elimination of mechanical wear and the achievement of indefinite life to rotating machinery. Magazine covers in years past have depicted the day when high speed trains would smoothly criss-cross this country with absolutely no contact with the track beneath; levitation and propulsion would be provided by a magnetic field generated by electromagnets contained in the track bed. The energy shortages in the 1970's gave researchers new incentive to usher in a solar age when large photovoltaic arrays would collect the sun's energy for storage in large flywheels supported by frictionless magnetic bearings to provide near perfect conservation of energy for later use. Recent progress in the last few years in the field of superconductivity seems to herald the day when all of these dreams will come to fruition.

However, practical commercial applications of magnetic suspension have flourished for over ten years now without the use of superconducting materials. Rotating equipment ranging from high-speed, lightweight momentum wheels for satellites and electrospindles for precise positioning of cutting tools used in manufacturing industries to large turbomachinery including steam turbines, compressors and pumps have been successfully developed and operated with magnetic bearing systems. The successful development of this technology spans more than fifty years of effort fraught with many ingenious ideas that were doomed to ultimate failure. Not until the development of semiconductor and integrated circuit technologies was success of these same ideas possible.

The attractiveness of magnetic bearings for spacecraft applications is apparent. The elimination of lubrication requirements means that spinning rotor systems can run at speeds only limited by material strength considerations with minimal power losses and vibration. For precision pointing systems, the elimination of lubrication means that these systems can operate with no lubricant debris generation resulting in very low runout errors and drag torque. For both types of systems, non-contacting suspension eliminates mechanical wear and provides a good interface between the rotor and stator for thermal management purposes, especially in cryogenic applications. Exceptional reliability of the magnetic bearing systems promises that these systems may operate for many years in space applications without a failure.

SUSPENSION TYPES

In 1842 Earnshaw published the fundamental theorem (ref. 1) that governs all forms of magnetic suspension. Now bearing his name, this theorem essentially asserts that a body may not be stably supported in a magnetic field in all three spatial directions without dynamic control or diamagnetic effects; at least one axis of instability (negative stiffness) must exist. Except for some minor peculiarities, this theorem has not been disproved despite more than a century of experimentation and testing of different suspension arrangements. These various arrangements can be classified into three groups: diamagnetic (passive), permanent magnetic (passive), electromagnetic (active).

The early work was in passive suspensions of permanent magnetic and diamagnetic types due to their inherent simplicity. These types are termed passive since no control of the magnetic field is provided; mechanical restraint in at least one direction is required. Permanent magnet suspensions may be either attractive or repulsive depending on the magnet arrangement, but the early researchers soon discovered that no real success could be achieved without at least one axis of active control or physical restraint.

Diamagnetism is the effect created by a material with a relative permeability with respect to a vacuum of less than one which results in an opposing magnetic field being induced by a magnetomotive force (mmf) source. A diamagnetic body is repelled in a magnetic field and can thus be passively suspended. Under normal temperature conditions, known diamagnetic materials such as bismuth and antimony exhibit too weak an effect for other than very lightweight suspension systems.

The recent strides in superconductivity have promoted new interest in this type of magnetic suspension since a strong diamagnetic effect can be induced in a superconductor by virtue of the currents which arise to oppose introduction of a magnetic field (Meissner effect). This is the same effect which gives rise to conventional eddy currents except that superconductivity promotes currents which are sufficiently strong to counter induced mmf without additional excitation. The only physical limitation to application of this type of suspension is the critical value of magnetic field strength which disrupts superconductivity thus limiting the repelling forces.

The four types of electromagnetic suspensions as presently conceived are ac resonant, eddy-current, simple attractive, and simple repulsive. The ac resonant suspension provides attractive mode suspension of a ferromagnetic object by employing electromagnets tuned such that increasing air gap shifts the inductance of the electromagnetic circuit towards resonance with the excitation frequency thereby increasing coil current and restoring force. This suspension type provides intrinsic rotor position feedback but little or no damping.

The eddy-current suspension provides repulsive mode suspension of a non-magnetic, electrically conducting object by diamagnetic effects induced by ac electromagnets. Supporting forces are developed by inducing currents in the suspended body. Thus, high power consumption and heating of the body results. This type of suspension differs from the diamagnetic suspension discussed earlier in that external excitation is required to produce currents strong enough to counter the induced mmf.

In a simple attractive or repulsive suspension electromagnets are driven in response to discretely sensed feedback of the position, velocity, or acceleration of a ferromagnetic suspended object. The simple attractive or repulsive suspension requires active feedback control on one or more axis. Thus, a general system with five independent degrees of freedom (figure 1) will require five feedback control loops.

Despite this complexity, the advantage of active control on an axis is that gain and phase lead of the control loop can provide variable stiffness and damping characteristics for the rotor support, thus allowing influence of rotor dynamics. These considerations have favored the simple attractive or repulsive mode suspensions. Virtually all practical applications of electro-magnetic suspensions have been of either the simple attractive or repulsive modes. Successful applications of ac resonant and eddy-current suspensions have been, for the most part, limited to the laboratory.

Early researchers found all four types of electromagnetic suspension to require large power inputs and bulky structure to support the loads carried by the electromagnets. The large power input losses to the electromagnets arise from joule, hysteresis, and eddy currents. Since eddy currents and hysteresis losses are more significant in an ac systems, dc systems have certain inherent advantages when applied in the simple attractive or repulsive suspension. Furthermore, ac systems impose a higher drag on the suspended body compared to dc systems.

Repulsive mode suspension offers several advantages as compared to active mode suspension: the foundation can carry the vertical load instead of the machine frame; the mode is inherently stable since the repulsive force increases as the gap decreases, and less power is required. Nevertheless, despite the inherent instability of the attractive mode (force increases as gap decreases), it is more important commercially since higher bearing loads can be achieved, the magnetic leakage flux is less, and better stiffness and damping characteristics can be obtained.

DESIGN EVOLUTION

The realization of true contact free suspension of a rotor has been achieved in the last four decades with radially passive/axially active, radially active/axially passive, or active control on all axes. The first known successful work in magnetic bearings was performed by J.W. Beams at the University of Virginia. In 1937 his team successfully suspended a small spinning rotor up to 60,000 rpm using a radially passive/axially active arrangement, figure 2. Later work culminated in the achievement of the world's rotational speed record, 2.7 x 10^7 rpm, a record that still stands today. This early work was performed by servoing only one axis of the rotor in a simple proportional feedback loop in which the rotor's position was measured with a light beam. Comparison of the feedback signal with a reference input produced a control signal proportional to the signal difference to null the output (ref. 2). F. T. Backers (ref. 3) later employed permanent magnets in the radial direction to provide the first known successful hybrid arrangement of active and passive suspension elements in the late 1950's.

The complexity of actively controlling five axes for a typical two bearing rotor system was prohibitive for these early efforts. Furthermore, these early systems suffered from poor stiffness and damping characteristics: two physical parameters required for application to practical rotating systems. Poor availability of suitable power amplifiers for providing sufficient current for driving the electromagnets made these early achievements spectacular. All of the early work with these active and hybrid systems, including that of Beams, was performed using vacuum tube and magnetic amplifiers. The invention of the transistor in the Bell Laboratories in the early 1950's ushered in the present era of rapid advancement in magnetic bearing technology predominated by active and hybrid suspension arrangements.

Most of the important work in magnetic bearings in the sixties and early seventies was performed for spacecraft and satellite applications. Much of the current success in magnetic bearing technology is directly traceable to this effort despite the fact that actual use in space of this technology did not occur until 1983. This effort was largely centered around attitude control system development. Typically, these systems are comprised of (1) low speed reaction wheels, one for each axis; (2) two control moment gyros, each of which is capable of controlling two axes; or (3) momentum wheels capable of passive gyroscopic torques in two axes and active control in a third axis. Magnetic bearings were sought for these applications to resolve the lubrication design problems, power losses, and limited reliability that plagued the applications of conventional bearings.

The Cambridge Thermionic Corporation was the first to develop magnetic suspensions for these aerospace applications after scrapping their earlier work with ac resonance systems in favor of active systems. An eighteen month development effort culminated in 1970 with the delivery to NASA's Goddard Space Flight Center (GSFC) of two magnetically suspended motorized rotors of this type. These rotors weighed 3 kg and ran at speeds up to 12,000 rpm (ref. 4). However successful the demonstration of the technology feasibility, optimism was dampened by the fact that 3 kilograms of weight and 40 watts of power were being used to replace a conventional bearing weighing one thousandth as much and using very little power.

The development of hybrid designs employing permanent magnets and electromagnets for spacecraft applications was initiated at the same time with the introduction of the first designs by Studer at GSFC in 1970. These early hybrid suspensions were developed to reduce the power requirement by employing permanent magnets to supply the steady state magnetic flux for suspension with electromagnetic modulation of the flux in a common air gap. Furthermore, these designs served to reduce the weight requirement by reducing the amount of iron in the magnetic circuit and the required load capacity of the external structure used to support the electromagnet coils. In addition, the parallel PM (permanent magnet) and EM (electromagnet) circuits aided in linearizing the bearing force with control current.

Subsequent effort by Lyman at the Cambridge Thermionic Corporation resulted in the development of the "VZP (virtually zero power) Controller" for a hybrid suspension arrangement (ref. 5). This controller positioned the rotor at its force center rather than its geometric center of the working air gap. This feature forced the permanent magnets to carry the steady-state loads thus further reducing power and weight.

In the early 1970's other concerns, including Sperry Flight Systems and General Electric were also active in the development of flight prototype magnetic bearing systems for spacecraft and satellite applications. Figure 3 is a momentum wheel design derived from this effort. Designs that typify the development of the technology during this time period are illustrated in figures 4 through 6. Figure 7 is the result of a more recent design effort for a two degree of freedom system (ref. 6).

A noteworthy design in the development of magnetic suspension occurred in early 1975 when a unique satellite momentum wheel (ref. 7) appeared that represented a geometric configuration possible only with magnetic suspension, figure 8. A combination of permanent magnets and electromagnets were used to support the flywheel from three points near the periphery with no spokes or axle. Axial and radial servo control was provided at each of the three locations. This design marked the realization of one more important advantage available to rotating equipment with the use of magnetic bearings.

These early design concepts were successful in demonstrating the applicability of magnetic bearing technology to reaction and momentum satellite wheels. However, application to larger wheels or rotor systems operating above critical speeds was not feasible due to the inability to influence rotor dynamics because of limited stiffness and damping values.

On the other hand, as these researchers noted, the alternative, radially active suspension, requires high control bandwidth, with possible noise and structural interaction problems, and the added complexity of speed-dependent compensation to accommodate phasing and gyroscopic effects (ref. 8). These considerations delayed the start of large scale hardware development of the first totally active suspension until the late 1960's although a French company, Hispano-Suiza, filed a patent that used electromagnetic bearings and inductive rotor position sensors in 1957.

While all of this activity in application of magnetic bearings for satellite momentum and reaction wheels was taking place, efforts to apply magnetic bearings to other earthbound and space flight hardware including various sensors and energy storage flywheel systems was being pursued. A 1979 GSFC energy storage demonstration unit is shown in figure 9. This promising work continues (refs. 9 and 10). Another notable development was a magnetically suspended helium circulator for a spacecraft thermal control subsystem (ref. 11).

Comsat Laboratories decided to make a major commitment to magnetic **bearing** technology based on some of their own work with Cambion and the successful developments at GSFC. International competition brought support from both the German and French governments. In France, the exploratory work on spacecraft applications by Societe Europeenne de Propulsion (SEP) starting in 1969 culminated in 1976 with the formation of Societe de Mecanique Magnetique (S2M) in a joint effort with SKF to develop and market totally active systems internationally.

The first known commercial application of this technology appeared at an Italian exhibit of thread spinning machinery in 1975. By the next year, S2M had completed its first application of industrial equipment. In parallel efforts, development work on aerospace applications continued with the first use in space of active magnetic bearings coming in November 1983 with the launch of the Space Shuttle with the European Spacelab on board. Spacelab was equipped with a vacuum pump suspended on active magnetic bearings. The first known use of magnetic bearings in attitude control system flight hardware was in the SPOT satellite launched by an ARIANE booster on February 21, 1986 (ref 6).

In the last eleven years the trend in commercial applications has been to higher speeds and larger rotors as the availability of transistors capable of switching larger dc currents at higher frequencies has evolved. The rotational kinetic energy which magnetic bearings have been capable of supporting in commercial applications has increased from 10^3 to 10^7 N-m in these few years. Analog systems employing the classical proportional-integral-derivative (PID) control loop have been behind the success of these systems. The range in key system performance and size parameters is listed in Table 1.

Despite the success of some of these systems, attention has recently turned to digital control because of the developments in this field. Analog has been viewed as suffering from noise and drift problems and the inability to reconfigure components for changing system operating conditions. Since 1980 several digital controllers have been designed and built for laboratory studies. However, a case may be made that stable suspension of many of the cited commercial applications would not be possible with present digital technology because of data rate problems.

THE PID ANALOG CONTROLLER

Typical analog controllers consist of a chain of linear or operational amplifiers providing the signal conditioning and phase lead necessary for stable suspension of the rotor. A block diagram representation of the controller is presented in figure 10. Stability problems for a system can become quite complex when dealing with multiple shaft resonances, gyroscopic effects, rotor induced whirl due to rotor internal dumping, and the inherent negative stiffness of the bearing (attractive mode). For a hybrid design using permanent magnets, the magnetic break frequency above which the electrical gain falls off must be reckoned with (ref. 8).

The rotor dynamic performance and stability of the many commercial magnetic bearing applications is attributable, in a large way, to the capability in the PID controller to adjust bearing stiffness and damping parameters over a large range. The integral action of the controller is responsible for the elimination of system drift required to achieve high rotor positioning accuracies. While many systems have been built and tested, the classic PID controller continues to provide superior stiffness and damping characteristics. Static stiffness values up to 10^{10}N/m (ref. 12) have been achieved, thus surpassing that of conventional bearings. More typically, dynamic values in the range of 10^6 to 10^7N/m are obtained. Of course, the upper limit on achievable stiffness values is determined by system stability considerations; simple gain increases to achieve higher stiffness would otherwise be straightforward. Achievable damping values are significantly better than conventional bearings, and typically are optimized to provide maximum damping when crossing critical speeds by providing positive phase lead as described below.

The stiffness characteristics of conventional mechanical bearing systems including rotor mass have been approximated in the Bode plot form for a rigid rotor and a flexible rotor in figures 11 and 12 ,respectively. The phase advance, not shown, is minimal for conventional bearing systems.

In contrast, the stiffness and damping characteristics of active magnetic bearing systems, figures 13 and 14, exhibit the classical PID attributes: the proportional effort providing a positive spring-like stiffness, the integral effect providing high stiffness values at low frequencies to preclude drift, and the derivative effect providing damping by control loop phase lead. As described in ref. 13, position sensor information from a pair of radial bearings can be processed to readily control the two rigid body modes of the rotor.

Notice in figure 14 how the phase lead can be controlled to cover a large frequency band providing positive damping at multiple resonant frequencies. However, it is generally ill advised to provide positive phase lead at the frequency of the first bending mode by opening up the bandwidth due to noise considerations which may saturate the power amplifiers. A preferred method is to provide the ideal 90° phase lead in a very narrow frequency band in the region of the critical speed, Figure 15. This is accomplished through an inner control loop that resolves the rotor position sensor information to a rotating coordinate system.

This same rotating coordinate system is also used to provide rotor "automatic balancing", the feature which allows the rotor to seek its inertial axis within the stator air gap. A conventional rotor system constrains the rotor to its geometric axis thus resulting in the transmission of unbalance forces to the stator. The rotating reference system allows the bearing stiffness to be cancelled at the rotational frequency, Figure 16. The opposite of this feature is "peak of gain" which drives the electronic gain to a maximum value in a narrow frequency range, thus providing excellent rotational accuracy for pointing systems.

Other analog techniques for achieving some of these same results are just developing. The "rotating force control" (ref. 14) method provides stable magnetic suspension and the automatic balance feature through the use of velocity and accleration observers which avoids analog differentiation. Reported stiffness and damping values are not as high as those attainable with the classical PID controller.

SUPERCONDUCTIVITY IMPLICATIONS OF MAGNETIC BEARING DEVELOPMENT

Future improvements in magnetic bearing system performance may be tied closely to breakthroughs in superconducting materials. Recent progress (ref. 15) in this research has led to the discovery of a class of rare earth oxides with transition temperatures above $90^{o}K$. Cooling may now be achieved with relatively inexpensive liquid nitrogen at $77^{o}K$ instead of liquid helium at $4.2^{o}K$. This development represents a four fold increase in the transition temperature for superconductivity in the past year and heralds the advent of practical, cost effective superconducting devices.

This recent progress has been achieved with type II superconductors. The Abrikosov theory of type II superconductors (ref. 16) shows that for certain materials a magnetic field exceeding a lower critical field would penetrate the superconductor in a regular array of flux tubes each confined by a vortex of current. For other materials, the Meissner effect of ordinary, type I superconductors prevails whereby all flux is excluded. The condition of superconductivity exists only within parameters defining critical temperature, current density and magnetic field intensity.

The relevancy of superconductivity to magnetic bearings is at least twofold: electromagnet and control system design. Sensor technology is a possible third area where superconductivity may play a role in future improvements.

The application of these new materials in the design of the electromagnet coils used for magnetic suspension is obvious. Bearings of increased load capacity and reduced weight can be achieved by utilizing superconducting coils without any iron core. Presently available bearings operate with a magnetic field of about 1 tesla at room temperature. One present type II superconductor, $PbMo_6S_8$, has an upper critical field of up to 55 tesla at $4.2^{o}K$. Since the force producing capability and stored energy of a magnetic bearing varies directly with the square of the magnetic field, superconducting bearing power of over a thousand times that of a normally conducting device should be possible in future magnetic bearing systems.

The high critical current density possible in a superconductor (on the order of 10^8 A/m^2) and the lack of any requirement for field shaping iron combine to promise a compact, light bearing system for future spacecraft applications.

Current limitations governing the use of these materials in bearing systems include the quenching problem, high Lorentz forces, poor ductility, and high cooling requirements. Operation without an iron core requires that other means be provided for a structure to support the Lorentz force of the magnetic field. The

Lorentz forces become manifested as varying conductor stresses which store large amounts of mechanical energy. Small fractions of this energy are dissipated in the rapidly varying field needed to provide dynamic control of a spinning rotor. Since most conductors have very small enthalpies of solids at cryogenic temperatures, this energy dissipation can cause a "quench" or local transition to the normal conducting state. Current design provisions to prevent this occurence include dividing the superconductor into many fine filaments and embedding them in a copper matrix. In this manner, electromagnetic disturbances associated with the magnetic field gradient in the conductor itself are minimized while providing an adequate heat sink. Poor ductility properties are being resolved by continuing improvements in fabrication techniques.

Control system design will be impacted by advances in superconductivity that improve the overall energy density of magnetic bearings. Both analog as well as digital systems will be affected. The discovery of tunneling of particles between superconductors has led to ongoing development of tunnel junctions (e.g. Josephson juctions) for use in applications requiring high speed, low power signal processing. Present efforts are producing tunnel junctions with response rates in excess of 1THz (ref. 16). Development of other solid state superconducting devices will be used in amplifiers at presently unimaginable switching speeds to further enhance magnetic bearing load capacity and dynamic control capabilities.

Further potential applications of tunnel junctions are for use in advanced magnetic bearing sensor designs for both rotor position (displacement) and electromagnet coil flux. Today, rotor position accuracy of 10-6m total indicated runout has been achieved (ref. 12) using inductive position sensors on certain electrospindle applications. Currently projected spacecraft applications of spinning rotor systems require similar radial accuracies and certain pointing applications require angular positioning to within 5 microradians (ref. 17). Further improvements in these capabilities may be achieved by using SQUID (superconducting quantum interference devices) technology. Presently being developed for a host of applications from mapping of the magnetic field emanating from the human brain to the detection of submicroscopic motions of gravity wave detectors, these devices rely on superconducting Josephson junctions for operation. Non-contacting SQUID's may find their way into magnetic bearing sensor technology for precise rotor position and coil magnetic flux control.

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TABLE 1. CLASSIC PID CONTROLLER RANGE OF COMMERCIAL APPLICATIONS

Rotor mass	:	$3x10^{-2}$ - $7x10^{3}$ Kg
Rotational Speed	:	0 - $8x10^{5}$ rpm
Bearing Diameter	:	$1.5x10^{-2}$ - 1.2 m
Ambient Temperature	:	20 - 720 °K

FIGURE 1. SUSPENSION PRINCIPLE

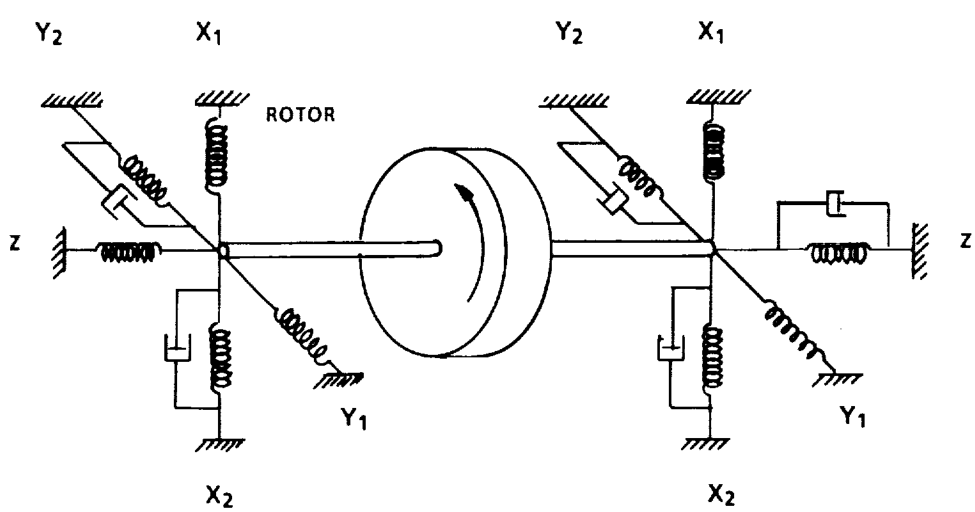


FIGURE 2. FIRST RECOGNIZED MAGNETIC SUSPENSION SYSTEM, BEAMS, CIRCA 1937

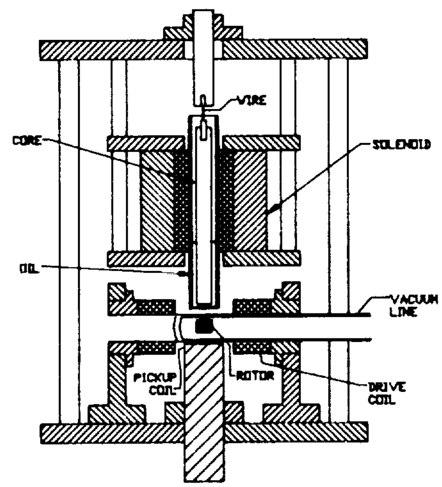


FIGURE 3. MAGNETICALLY SUSPENDED MOMENTUM WHEEL, 1973

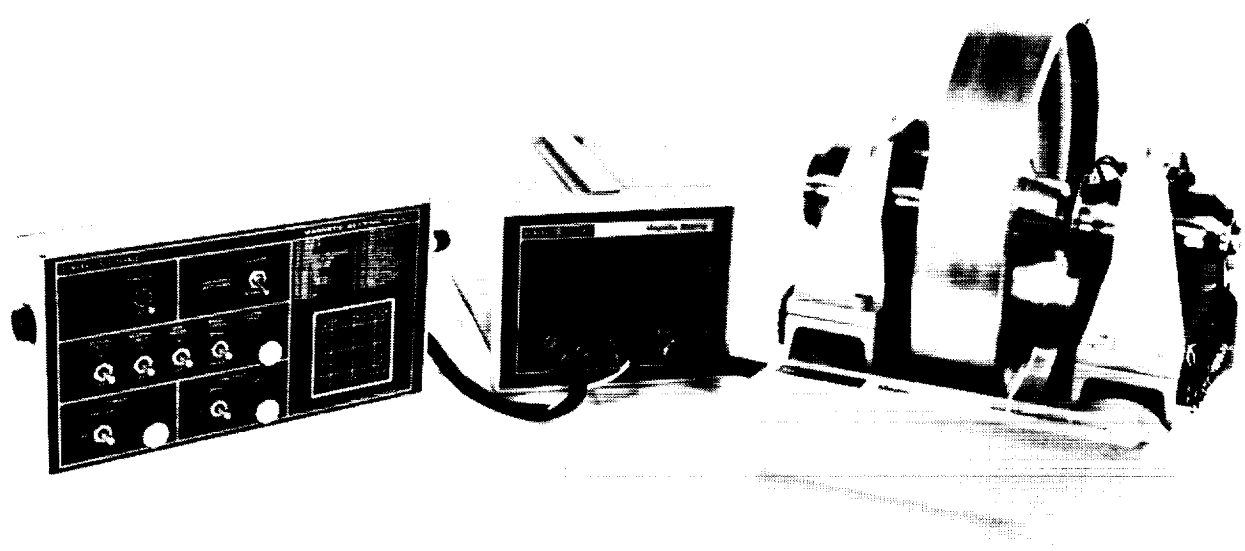


FIGURE 4. PM SUPPLEMENTED MAGNETIC BEARING

- PARALLEL PATH FOR CONTROL FLUX
- RELUCTANCE OF PM PATH CONSTANT FOR MOTION OF SUSPENDED ROTOR

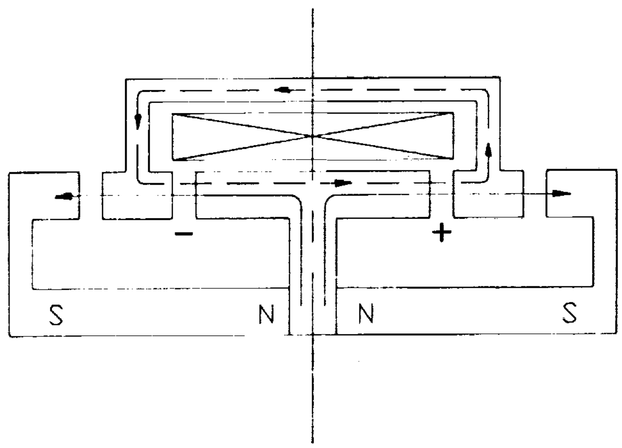
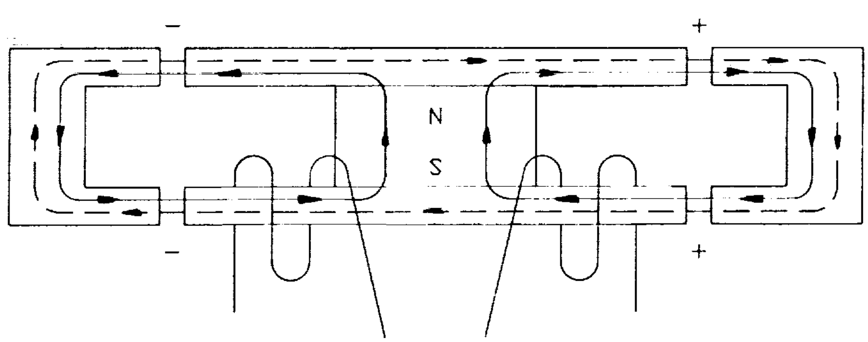


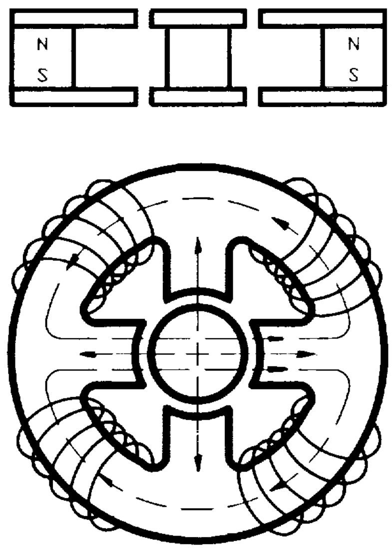
FIGURE 5. "PANCAKE" BEARING



- PARALLEL PATH FOR CONTROL FLUX.
- MINIMAL PM CIRCUIT RELUCTANCE CHANGE.
- PM AND CONTROL COILS ON STATOR.

U.S. Patent No. 4,000,929.

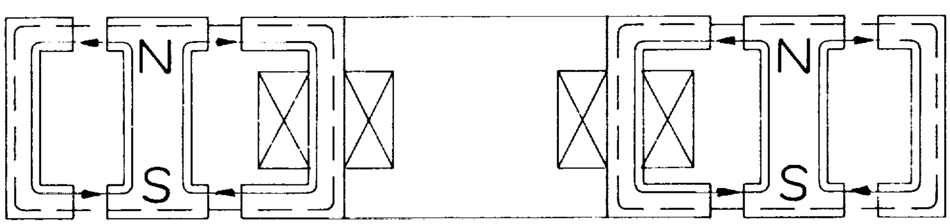
FIGURE 6. EXTERNAL STATOR BEARING



- PARALLEL PATH
- SMALL RELUCTANCE CHANGE
- STATIONARY WINDINGS AND PERMANENT MAGNETS

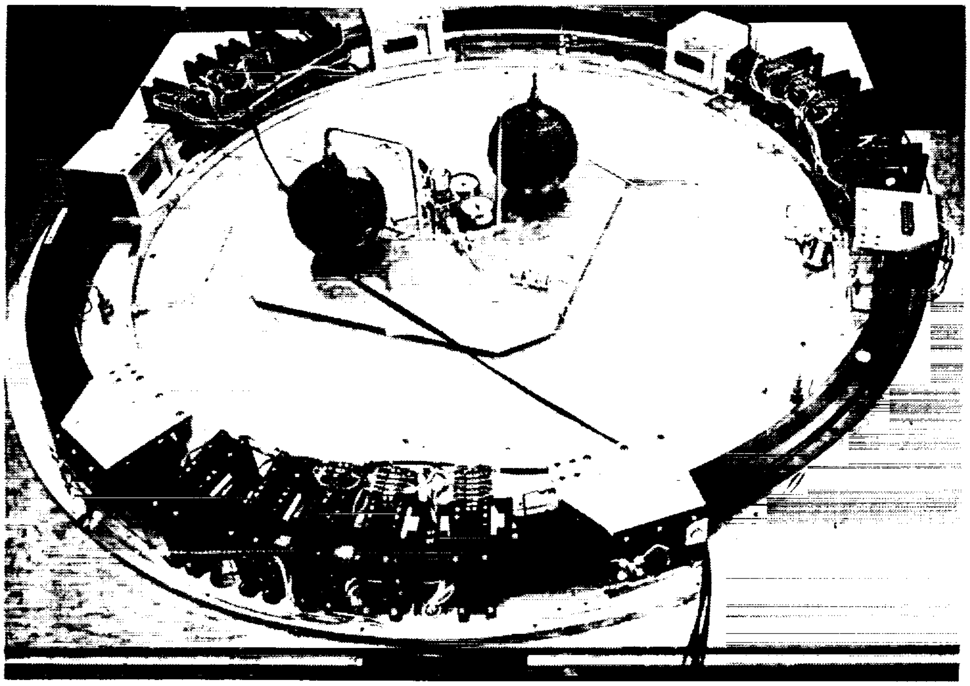
Patent No. 4,381,875

FIGURE 7. LOW COST 2DOF BEARING



- PARALLEL PATH
- MINIMAL RELUCTANCE CHANGE
- OUTER RING PROVIDES STABILITY FOR RADIAL AND AXIAL MOTION

FIGURE 8. ANNULAR MOMENTUM CONTROL DEVICE, 1977



The AMCD in Final Stages of Assembly

FIGURE 9. NASA ENERGY STORAGE DEMONSTRATION, 1979

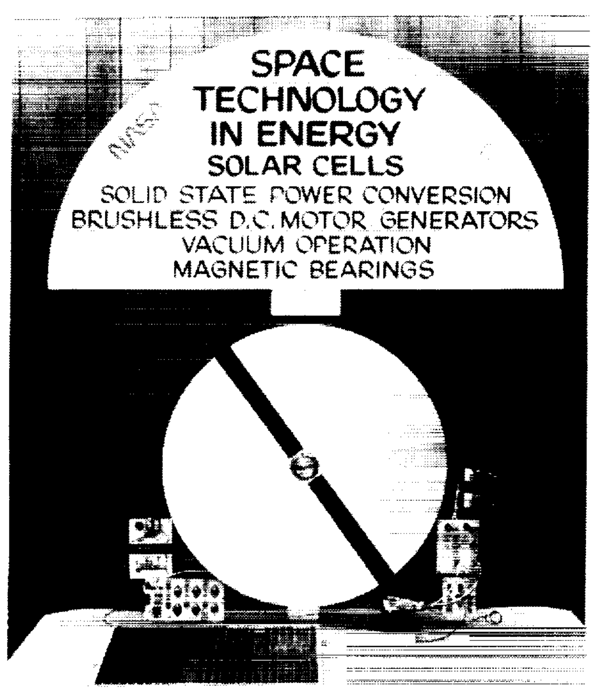


FIGURE 10. ACTIVE MAGNETIC BEARING CONTROL SYSTEM

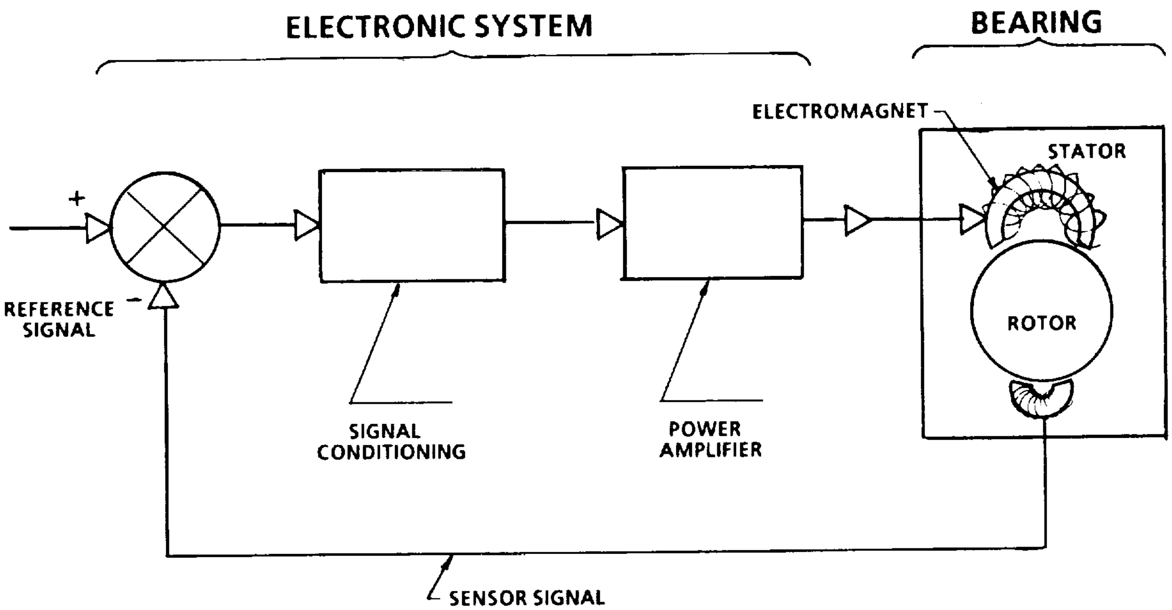
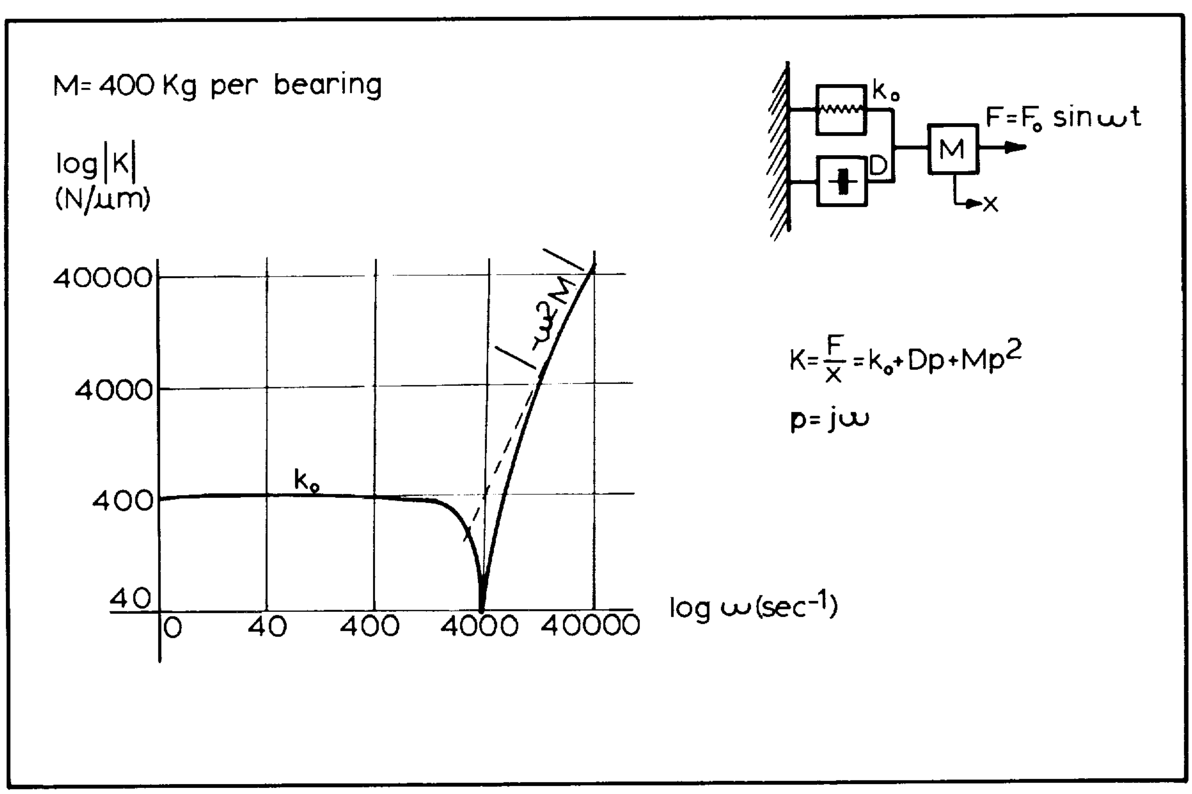


FIGURE 11. CONVENTIONAL BEARING STIFFNESS CHARACTERISTIC--RIGID SHAFT



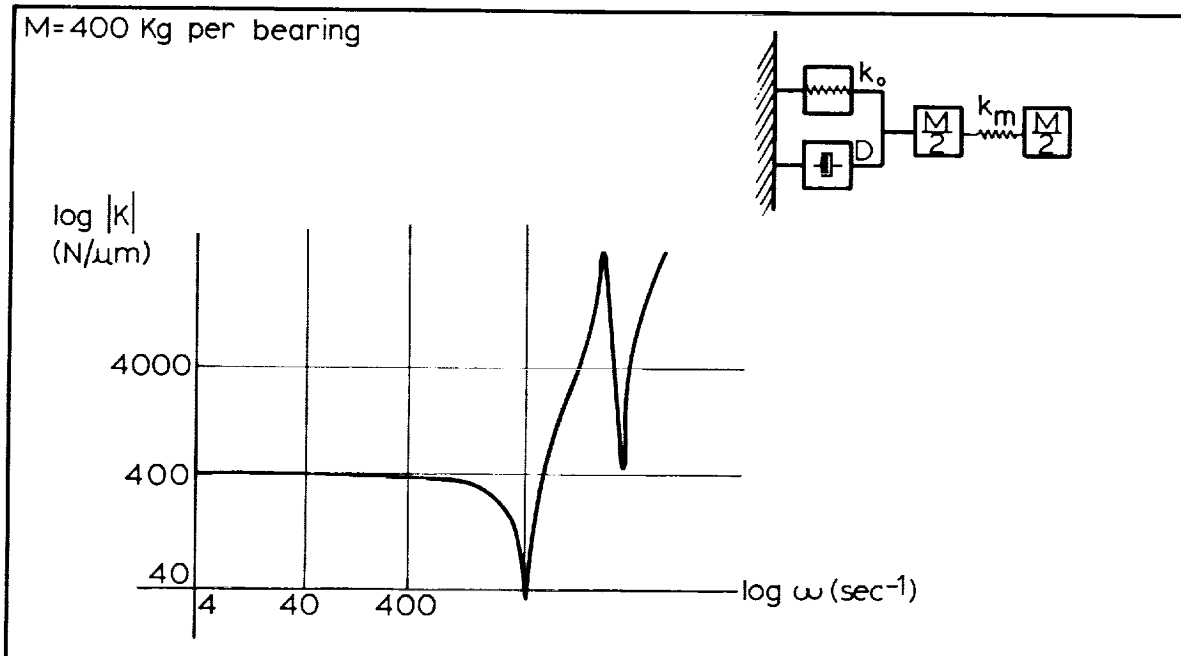


FIGURE 12
CONVENTIONAL BEARING STIFFNESS
CHARACTERISTIC-FLEXIBLE SHAFT

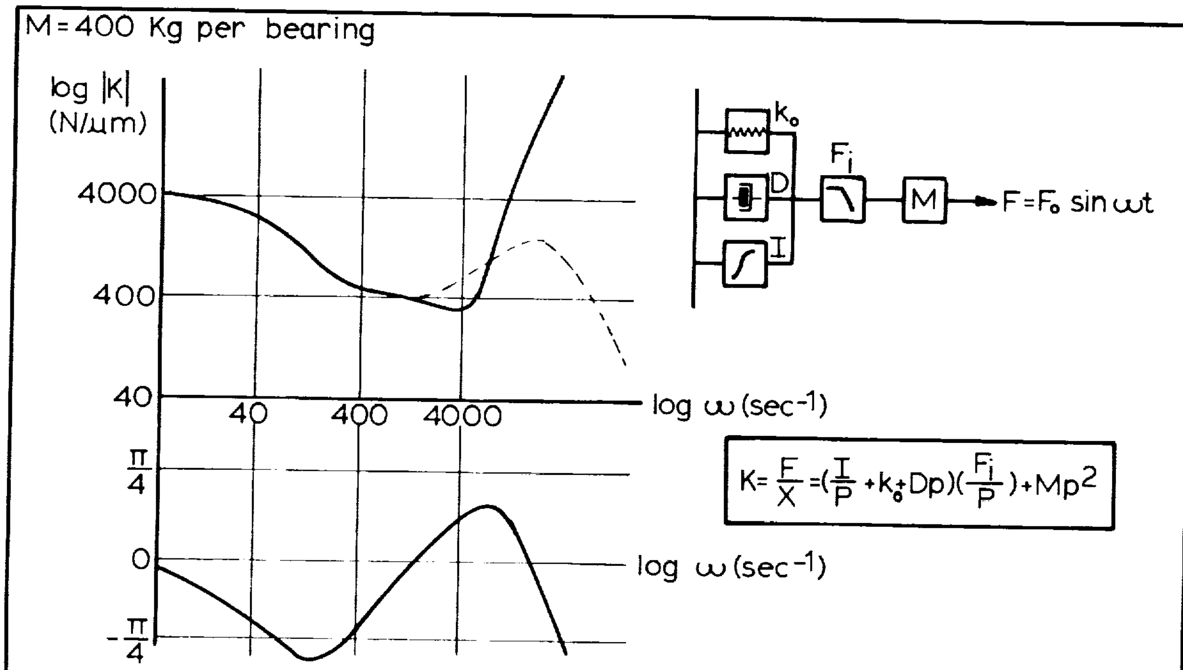


FIGURE 13
ACTIVE MAGNETIC BEARING STIFFNESS
CHARACTERISTIC-RIGID SHAFT

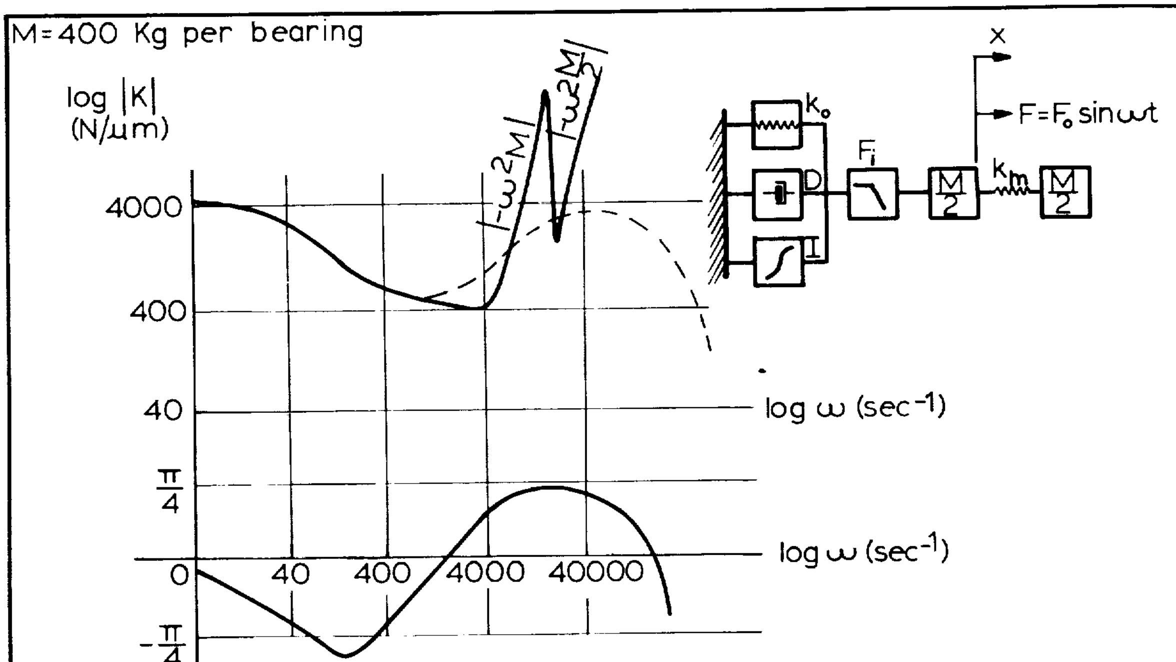


FIGURE 14
ACTIVE MAGNETIC BEARING STIFFNESS CHARACTERISTIC-FLEXIBLE SHAFT

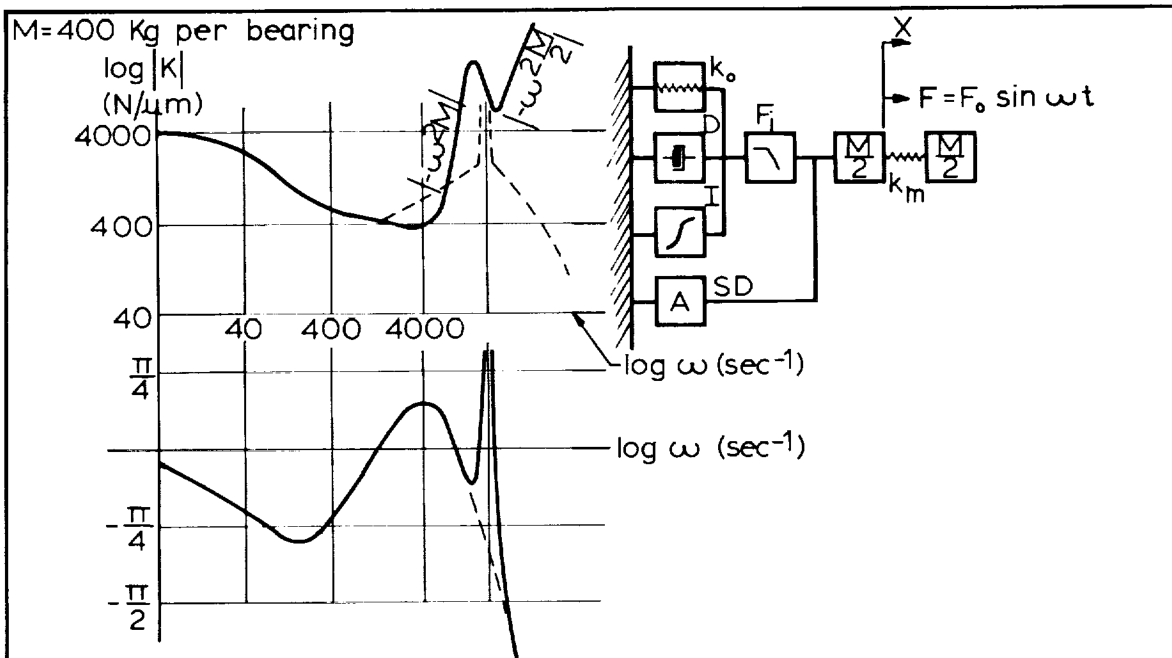


FIGURE 15
SYNCHRONOUS DAMPING CONTROL CHARACTERISTIC

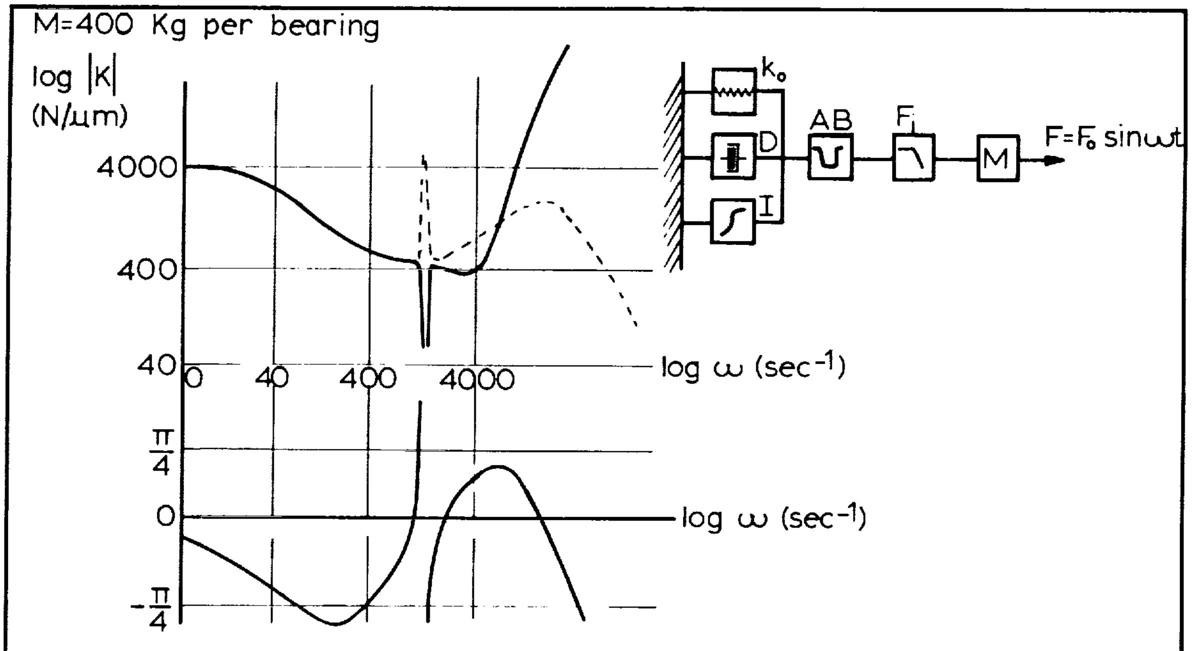


FIGURE 16
AUTOMATIC BALANCING CHARACTERISTIC