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THE ROLE OF SUPERCONDUCTIVITY IN MAGNETIC BEARINGS FOR HIGH-LOAD APPLICATIONS*

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SUMMARY

Slewing of large payloads will require control torque and angular momentum storage capacities that are large in comparison to the capabilities of available control moment gyros (CMGs). SatCon Technology Corporation is currently designing a CMG which may be employed as a slew actuator for large spacecraft or other payloads. The slew actuator employs a novel type of magnetic bearing which may be used in high load applications. The magnetic bearing is also used to fully gimbal the suspended rotor of the slew actuator.

The use of magnetic bearings in angular momentum exchange actuators has the primary advantage that physical contact between the rotor and stator is eliminated. This leads to greatly extended life, increased reliability, and reduced vibrations. Several actuators operating on magnetic bearings have been demonstrated in previous research efforts. These were sized for use in small satellites. For conventional magnetic bearings, which employ magnetic cores, high torsional loading may require that the magnetic structure be excessively massive.

This paper discusses an alternative magnetic bearing design which employs a superconducting coil and eliminates conventional magnetic structures. The baseline approach is to replace the field coil of a conventional magnetic bearing with the superconducting coil.

INTRODUCTION

This paper discusses a novel approach to the design of magnetic bearings in which a superconducting coil is employed in order to eliminate conventional magnetic cores and permanent magnets. The design was motivated by recent progress in superconducting materials and by the requirements for an advanced control moment gyro (CMG) type of slew actuator which is currently under development at SatCon Technology Corporation. The slew actuator is intended for use with large spacecraft.

In order to present the superconducting magnetic bearing, a chronological description of the design process is presented. First, the application and specifications for the slew actuator are derived. Next, a brief discussion of the operating principles for a CMG is presented. A discussion of recent advances in superconducting

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materials, particularly "high-temperature" superconductors is used to motivate the decision to apply this technology to a high-performance magnetic bearing. A baseline superconducting magnetic bearing design is presented. Finally, the performance of the magnetic bearing is compared to that of more conventional approaches. These results show that substantial improvements in mass and power consumption are obtainable through the use of superconducting technology.

SLEWING MANEUVERS FOR SPACECRAFT

Many civilian and military space missions require that the angular orientation (attitude) of a spacecraft be controlled over large angles. The purpose of a slew maneuver is to reorient a spacecraft (with moment of inertia I) through an angle (θ) in a time period (T). This section analyzes a typical slewing maneuver in order to provide specifications for the design of the slew actuator.

Bang-bang Slew Profile

One approach for accomplishing a slew maneuver is to apply a constant torque on the spacecraft for half of the maneuver time. During this acceleration period, the spacecraft will gain angular momentum. An equal but opposite torque is then applied in order to decelerate the spacecraft. Angle, angular momentum and torque profiles for this type of slew profile are shown in Figure 1.

Torque Shaping

The above analysis assumes that the spacecraft is a rigid body. In applications where this assumption is not valid, a smoother torque profile is typically employed to reduce vibrations (ref. 1). Possible torque profiles include sine-wave, double versine (1 - cosine), and sine-wave cubed. The primary effect of torque shaping on the requirements for the slew actuator is an increase in the peak control torque which is required for a given slew maneuver. During the early stages of the slew actuator design program, nine torque shapes were identified and analyzed. For the purposes of the present discussion, an eight percent increase in the peak control torque requirement will be used to account for the effect of torque shaping.

Slew Actuator Requirements

Table 1 presents the parameters (spacecraft moment of inertia, slew angle, and slew time) which define the slew. The table also presents the requirements (control torque and angular momentum storage capacity) for the slew actuator.

ANGULAR MOMENTUM EXCHANGE ACTUATORS

One approach for controlling the attitude of a spacecraft is to apply equal and opposite torques to the craft and a flywheel. The net angular momentum of the flywheel and the spacecraft will remain constant. This type of device is referred to as an angular momentum exchange effector since any angular momentum which is gained (lost) by the spacecraft is lost (gained) by the flywheel. This type of actuation has several advantages over reaction control systems (thrusters). These include reduced maintenance and improved compatibility with optics. Thrusters operate by expelling a fluid which is stored, in tanks, on-board the spacecraft. These stores of fluid must be periodically replaced. Another advantage of angular momentum exchange effectors is that there are no effluents to disturb the on-board optics. The operating principles for the most common type of momentum exchange effector, the control moment gyro, are described below.

Control Moment Gyros (CMGs)

This type of actuator exchanges angular momentum by varying the angular orientation of a constant-speed flywheel through the use of gimbals. Figure 2 describes the acceleration phase of the slew maneuver in terms of applying a torque to a spacecraft over a fixed period of time. The torque is applied through the azimuth-axis torquer. The flywheel precesses about the elevation axis to conserve angular momentum.

Magnetic Gimballing

The use of a mechanical gimbal structure such as the one shown in Figure 2 is the conventional approach for CMG design. An alternative approach which consolidates the functions of conventional bearing and gimbal systems has been demonstrated. A large-angle magnetic suspension (LAMS) is a five-axes, actively-controlled magnetic bearing which is designed to accommodate a certain amount of angular motion about the lateral axes of the flywheel (ref. 2). An early study (ref. 3) indicated that the mass of conventional gimbal systems is approximately equal to that of the gimballed rotor. Later research (ref. 4) indicates that the mass of a LAMS can be made to be less than that of a gimbal system by a factor five (depending on the amount of angular freedom). The magnetic bearing which is described in this paper is an extension to this technology.

MOTIVATION FOR THE USE OF SUPERCONDUCTORS

The decision to employ superconductors in the design of the magnetic bearing for the slew actuator was motivated by recent progress in superconducting materials and by the drawbacks (power and mass) associated with meeting the control torque requirement for the slew actuator through the use of conventional technology. This section provides further discussion of these issues.

Recent Advances in Superconductors

Recent advances in superconducting materials have sparked new interest in a technology formerly restricted to sophisticated laboratory applications. In fact, the potential of these advances is so far reaching that numerous articles on the subject have recently appeared in the popular press (refs. 5, 6, and 7). The renewed interest in superconductivity is a result of the discovery of a new class of materials with significantly higher transition temperature (the temperature at which superconductivity occurs). Progress on this front has been so rapid that a better than four-fold increase in transition temperature has been achieved in the past year with a new record of 98 degrees Kelvin. This temperature allows cooling to be accomplished using inexpensive liquid-nitrogen as opposed to the exotic and expensive liquid-helium previously required, thus improving the economic feasibility of numerous applications. The new materials are a class of rare-earth ceramics and are thus very brittle and fragile. In addition, at the present time they are limited in operation to current density approximately one percent of that for conventional superconductors, or roughly equivalent to normal household wiring. However, the level of intensity of research world-wide is expected to overcome these obstacles and produce usable devices in a few short years.

Deficiency of Current Approaches

Based on the results of preliminary analyses, it became obvious that conventional approaches to the design of the magnetic bearing would be excessively massive and inefficient. Thus, it was decided to turn the design toward a magnetic bearing based on superconducting technology. This decision promised significant reductions in power and weight for the following reasons:

1) The current density in a superconductor can be extremely high (on the order of 10^8 A/m^2);

2) No field-shaping iron is required;

3) Higher flux density increases the force-producing capability of conventional coils.

DESCRIPTION OF THE MAGNETIC BEARING

A superconducting magnetic bearing is an advanced design for a magnetic bearing which may be used in a CMG to deliver large torques to a spacecraft without the need for an excessively massive magnetic core or the consumption of a large amount of power. The superconducting magnetic bearing, as its name suggests, employs a superconducting coil and thus eliminates all conventional magnetic structures in order to produce an energy-efficient, light-weight design. The following paragraphs describe the construction and operation of a superconducting magnetic bearing when it is used in a large CMG.

Overall Slew Actuator Design

Figure 3 is a partially cut-away view which shows the rotating components (superconducting coil and flywheel) and cryogenic housing of a two-degree-of-freedom CMG which employs a superconducting magnetic bearing. The superconducting coil is a solenoid which operates in persistent-current mode (without an electrical input). The current in the solenoid persists because of the lack of resistance in the superconducting material. The spherical case which surrounds the rotating components also serves as the cryostat for the superconducting solenoid.

Flywheel. A high-strength graphite/epoxy composite flywheel is attached to the solenoid to provide angular momentum storage capacity. This material is currently being used for advanced energy storage flywheels for space power applications (ref. 8). The outer diameter of the flywheel is machined to a spherical shape. This allows the flywheel to be completely gimballed without contact with the case.

Spin Motor. Figure 4 shows one phase of the multi-phase stator (armature) of an axial-field electric machine in the center (bore) of the solenoid and illustrates the operation of this device as a motor. Radial currents (I) in the stator interact with the axial flux density (B) produced by the solenoid to apply torques about the spin axis (SA) of the flywheel. Torque is applied to the rotating components of the CMG until the rotor reaches its operating speed. Drag losses will be sufficiently small that the motor need not operate continuously in order to maintain the nearly constant rotational speed required of a CMG.

Magnetic Bearing Loading

This section discusses the mechanisms which are used to apply forces and torques to the flywheel of the slew actuator. The design employs a total of twelve (12) normal (non-superconducting) coils in conjunction with the superconducting solenoid in order to apply forces and torques.

Radial Forces. Figure 5 shows two coils which are attached to the outer surface of the case of the superconducting CMG. The interaction of the magnetic field (B) produced by the solenoid and the current (I) in each differential section (dV) of the coil produces a differential force (df). The net force (f) produced by the two coils is perpendicular to the spin axis of the flywheel (shown as being along the x axis). Two additional sets of concentric coils are shown in Figure 6. The y-axis coils operate in the same manner as the x-axis coils in order to produce forces along the y-axis. The third set of coils is used to provide radial forces when the spin axis has a large angular displacement from the z-axis.

Axial Forces. Figure 7 shows six additional control coils. These coils are used to apply either axial forces or torques about the lateral axes. In the discussion which follows, the spin axis of the flywheel is assumed to coincide with the z-axis.

Figure 8 shows the interaction of the current (I) in the axial-force coil and the magnetic field (B) produced by the superconducting solenoid. Each differential segment (dV) of the coil has applied a differential force (df) to the rotor. The net result of this interaction is a force (f) which acts along the z-axis as is shown in Figure 8.

Torques. The coils shown in Figure 7 which are not coaxial with the spin axis of the flywheel are used to apply torques to the flywheel. Figure 9 illustrates the torquing mechanism. Assuming that the spin axis is along the z-axis, the magnetic field (**B**), produced by the superconducting solenoid is nearly parallel to the z-axis and constant. The torque (τ) results from the interaction of the dipole moment (μ) produced by the current (I) in the normal coil and the magnetic field.

PERFORMANCE OF THE MAGNETIC BEARING

Although the design of the superconducting magnetic bearing is not yet finalized, some preliminary estimates of the mass and power consumption of the magnetic bearing as a torquer are available. Table 2 presents these performance characteristics and compares them to the comparable characteristics for other types of CMG torquers. The performance of a conventional gimbal torquer (ref. 9), a conventional magnetic bearing (ref. 10), and a LAMS (ref. 4) are scaled from previous designs. The increased mass and power consumption of the other types of torquers result from the mass of the backiron required to shape the magnetic fields and from the power dissipated in copper coils. It should be noted that this table compares only the mass and power consumption of these torque-producing mechanisms and is not intended to show detailed system-level trade-offs.

RESULTS

A unique type of magnetic bearing has been presented. The bearing, when incorporated in a magnetically-gimballed CMG-type of slew actuator, produces an energy efficient, lightweight device. When compared to other types of torquers, the superconducting magnetic bearing produces superior performance in terms of mass and power consumption.

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TABLE 1. - SLEW PARAMETERS AND ACTUATOR REQUIREMENTS

Slew Angle (θ)	1 rad.
Slew Time (T)	4 sec.
Inertia (I)	100 $kNms^2$
Control Torque (τ)	27 kNm
Angular Momentum (H)	45 kNms

TABLE 2. - RELATIVE PERFORMANCE OF THE SUPERCONDUCTING MAGNETIC BEARING AS A TORQUER (27 kNm)

Torquer Mass (kg)	
Superconducting Magnetic Bearing	530
Conventional Gimbal Torquer	12,700
Conventional Magnetic Bearing	2,500
Large-angle Magnetic Suspension	5,300
Power Consumption (kW)	
Superconducting Magnetic Bearing	7
Conventional Gimbal Torquer	60
Conventional Magnetic Bearing	200
Large-angle Magnetic Suspension	12

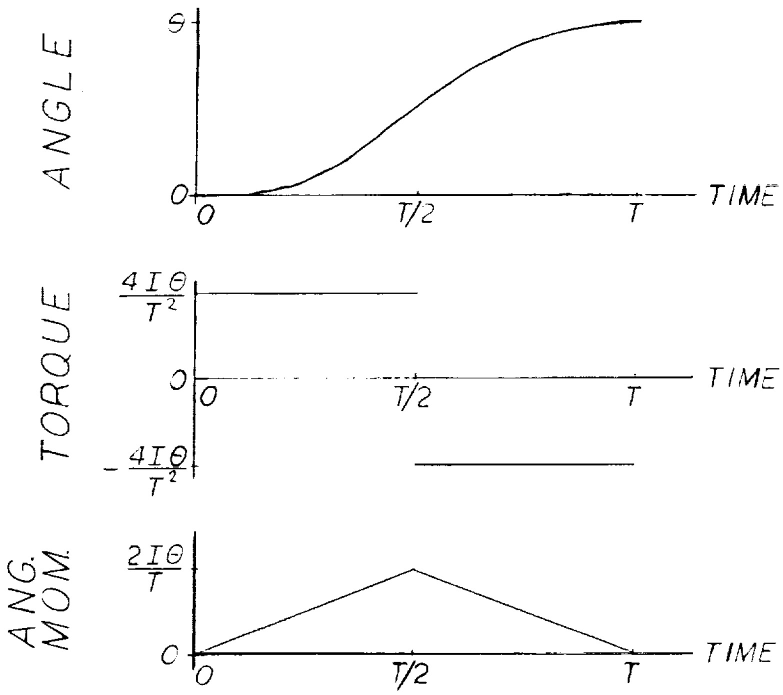

Figure 1.- Slew trajectories.

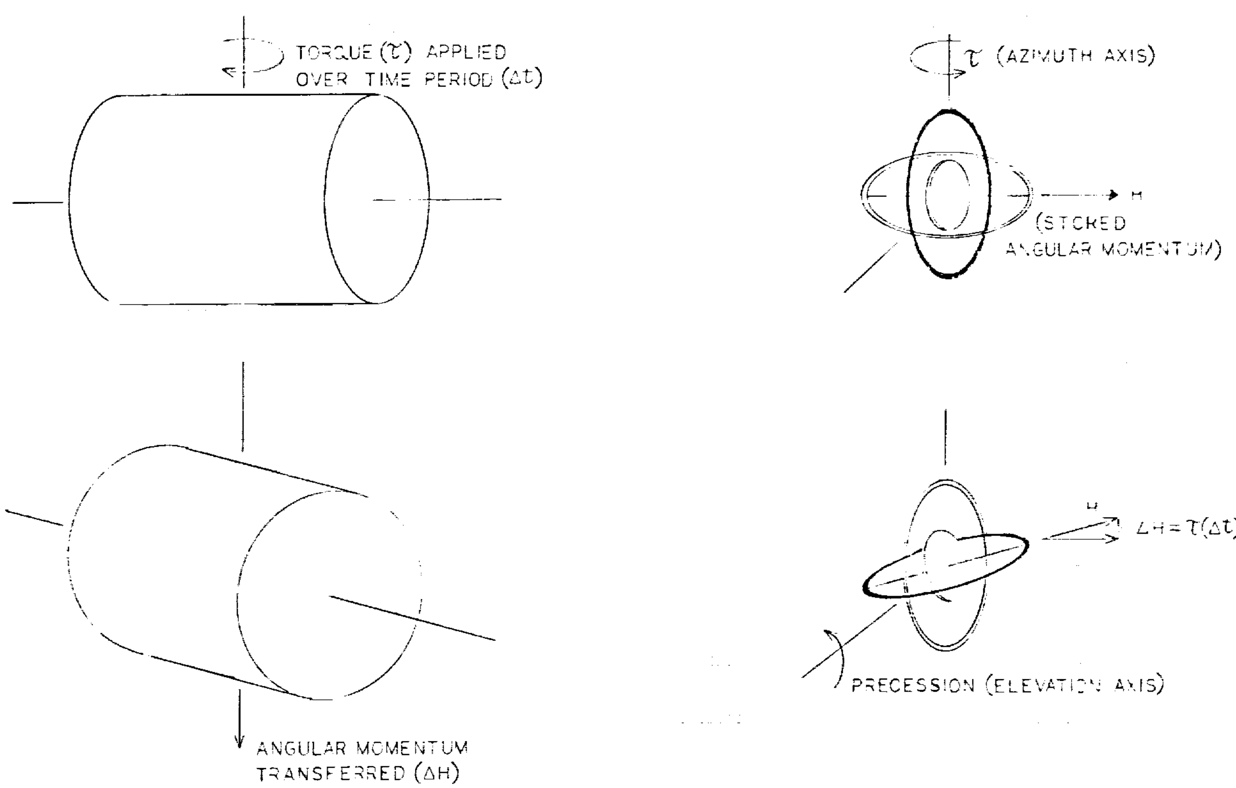

Figure 2.- CMG operating principle.

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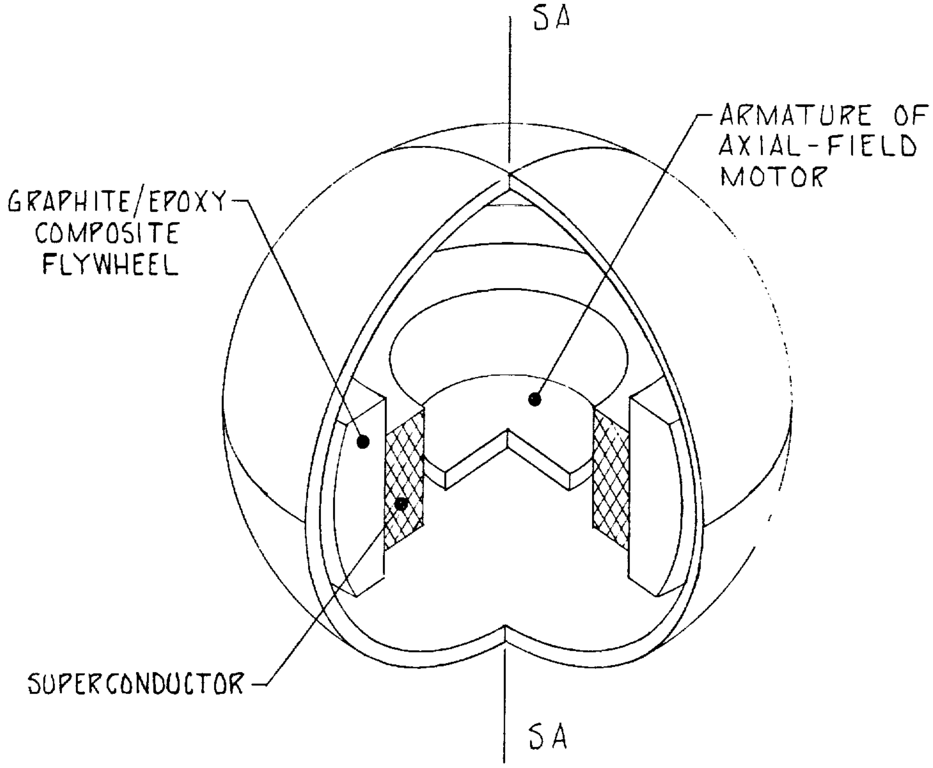

Figure 3.- Slew actuator.

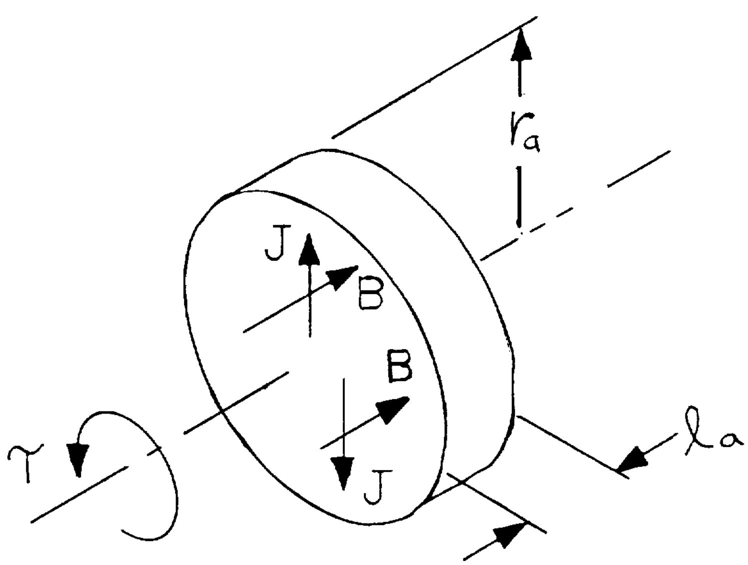

Figure 4.- Spin motor.

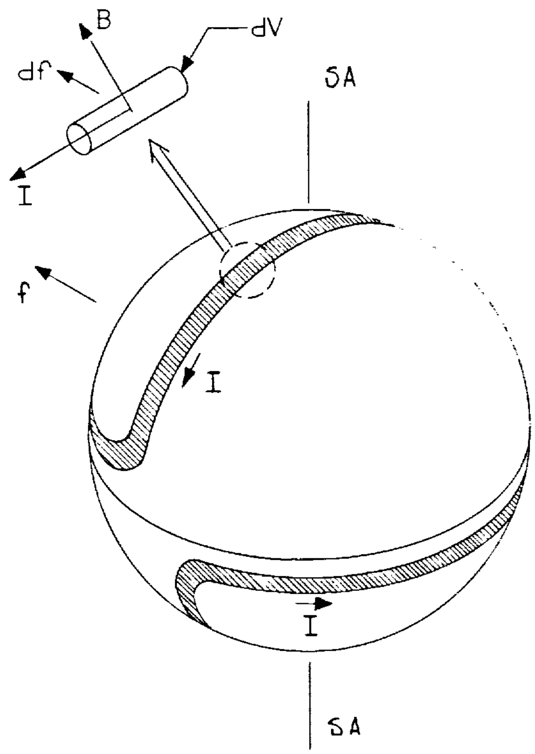

Figure 5.- Radial-force loading.

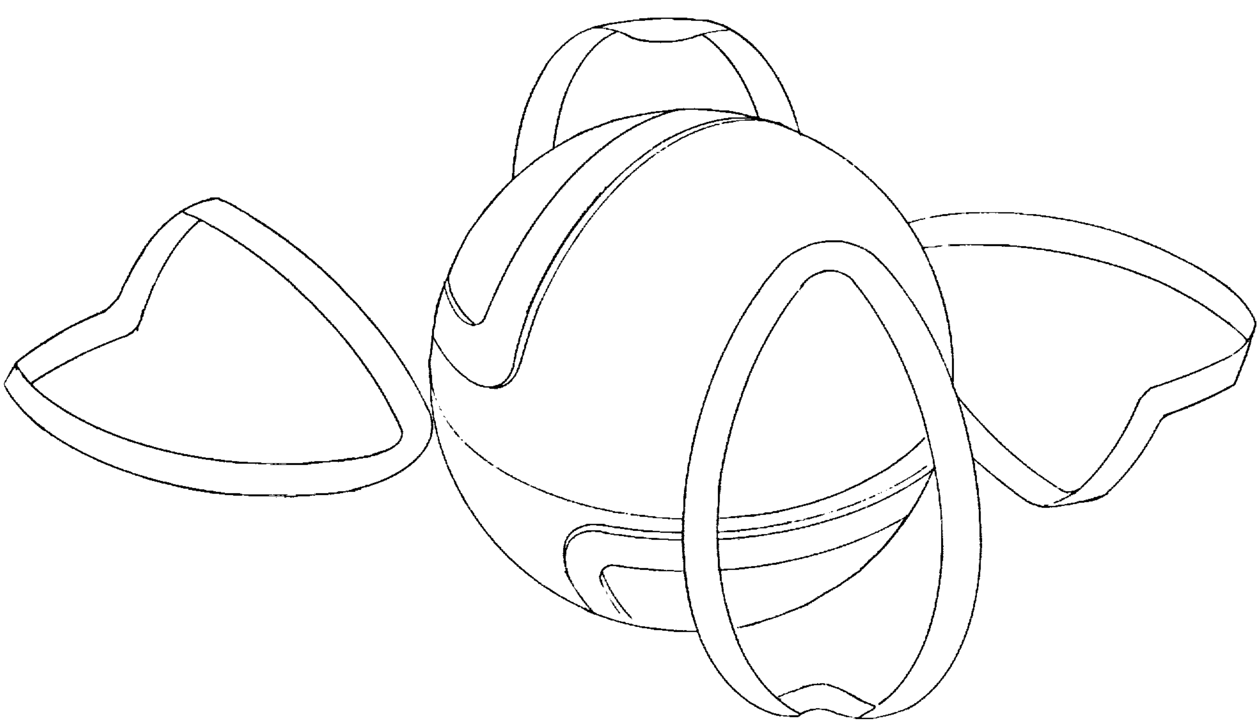

Figure 6.- Radial-force coils.

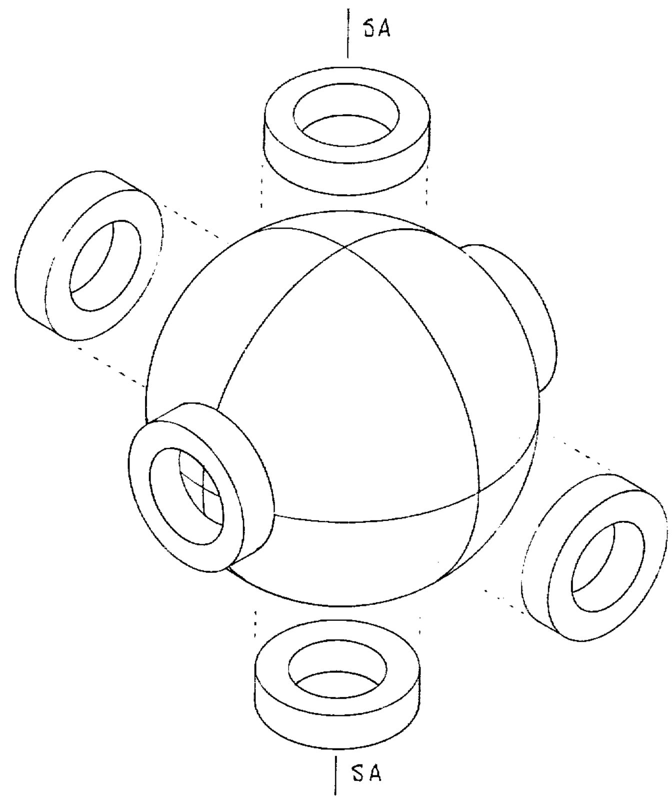

Figure 7.- Axial-force/torque coils.

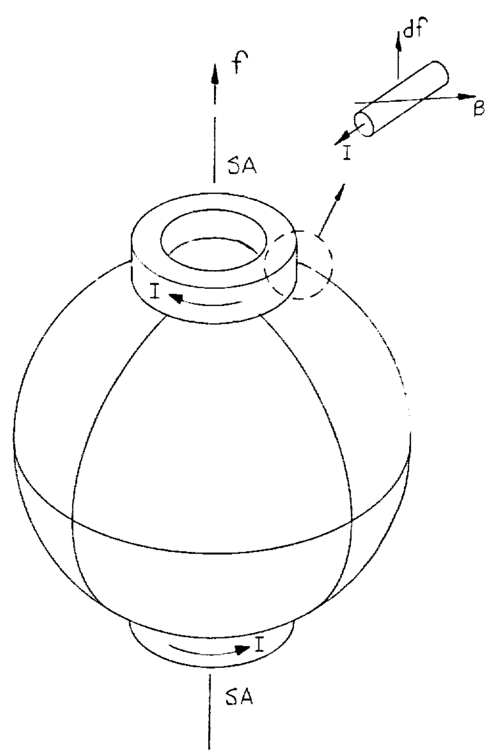

Figure 8.- Axial-force loading.

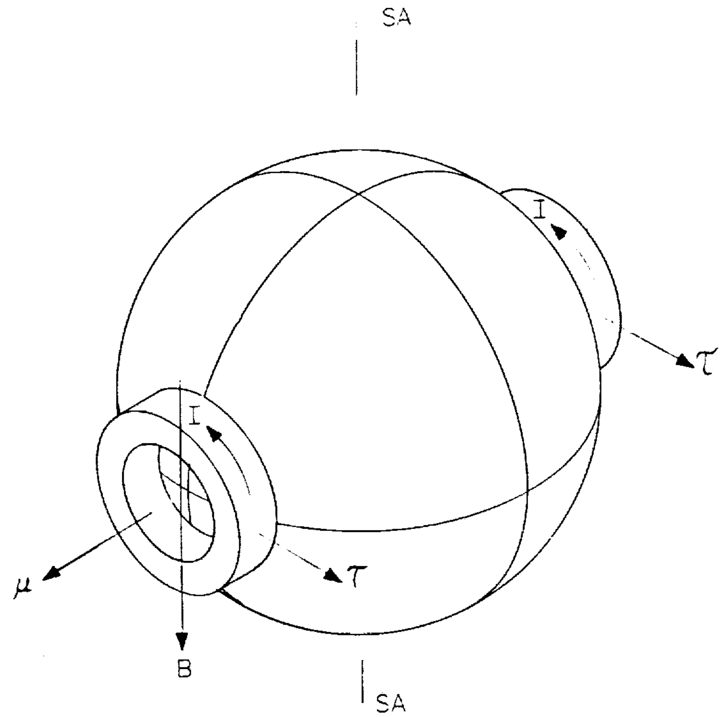

Figure 9.- Torque loading.