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# Satellite Flywheels with Magnetic Bearings and Passive Radial Centering

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**Satellite reaction and momentum flywheels have been developed with magnetic suspension of the rotor. The magnetic bearings passively provide the radial centering of the rotor and utilize a single servoloop for its axial position control. Among several advantages, this concept does not limit the rotation speed at the level of the bearings; fiber composite rotors, accepting high stresses, have been adapted to maximize the profit of high rotation speed and to open the possibility of kinetic energy storage. Several models were successfully qualified in functional and environmental testing.**

## Introduction

WITH the trend in application satellites toward three-axis-stabilized configurations with longer mission durations, the reliability requirements on the momentum and reaction flywheels used for attitude control purposes are becoming more and more demanding. In particular, the bearings must be capable of high-speed continuous operation in adverse lubrication conditions for periods as long as ten years, during which time their frictional properties are required to remain virtually unchanged. These requirements cannot be fulfilled by conventional bearings, without considerable risk of degradation occurring after comparatively short times. Consequently, an increasing interest has arisen in contactless magnetic suspension bearings as a more reliable means of support.

The main advantages of magnetic bearings in satellite flywheel applications may be summarized as follows: 1) elimination of the life limiting wear and fatigue processes of conventional bearings; 2) reduced mass—it is possible to replace two or more conventional wheels by one magnetically suspended rotor wheel, with no single-point failure, the redundancy being implemented in the active part only; 3) improved performances concerning friction and stiction torques which are reduced by an order of magnitude with elimination of the temperature effect; consequently, the friction power is reduced; 4) higher speeds, allowing a significant improvement in the momentum-to-mass ratio of the wheels; 5) higher reliability of the "one active axis" magnetic bearings compared to other types of magnetic suspension and bearings.

The purpose of this paper is to describe the basic constructional features and overall performance characteristics of some of this equipment and establish that magnetic flywheel technology is now sufficiently mature to be considered for flight purposes.

## Magnetic Bearings and Associated Subsystems Description

The dominant and most important feature of all magnetic bearing flywheels described herein is the essentially passive nature of the magnetic suspension systems employed. Passive magnetic suspension based on maximal action of permanent magnets, is used in preference to alternative methods based on electronically controlled electromagnets, in view of the primary objective to maximize reliability. The passive suspension configuration adopted employs permanent magnets operating in the attraction mode for radial centering of the flywheel hub, and a single servo-driven electromagnet actuator for axial position control.

In this way, four of the six degrees of freedom of the suspended rotor are constrained passively, and only one actively. The sixth degree of freedom is the desired rotational motion of the wheel which, of course, requires no constraint from the suspension point of view. The realization of the various subystems involved are described separately.

### Passive Permanent Magnet Radial Bearings

Radial centering of the rotor is effected by means of two permanent magnet radial bearings, the dimensions, geometry, and design of which are chosen according to the specific requirements of each wheel. One possible configuration is shown in Fig. 1. Each bearing comprises four radially magnetized samarium cobalt rings of segmented construction, fitted with soft iron pole sleeves on their inner and outer curved surfaces. Oppositely magnetized rings are attached to the flywheel rotor and stator, respectively. The concentrated axial fields set up in the gaps between adjacent pole ring end faces give rise to appreciable radial centering forces for quite small radial displacements of the rotor with respect to the stator.

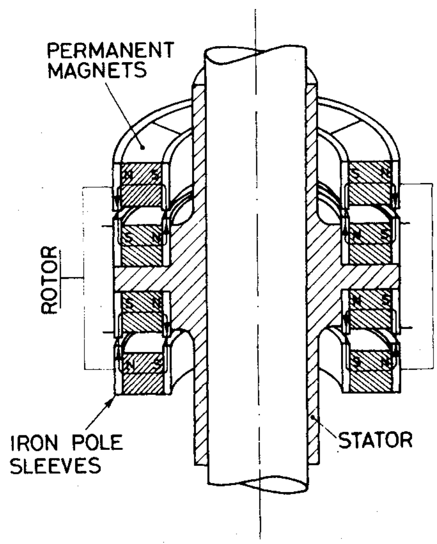


**Fig. 1 Radial bearing.**

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Radial stiffnesses in the order of $1.5\text{-}5\times10^5$ N/m per bearing are easily achieved for quite small bearing dimensions, while ratios of radial stabilizing/axial destabilizing stiffness in the order 0.5-0.25 are typical.

A number of constructional variations are possible. One possibility with some important constructional advantages is to employ radially instead of axially stacked ring pairs. The latter configuration has been adopted in more recently developed wheels.

**Active Electromagnetic Axial Bearing**

The rotor radially centered by the magnetic rings has an unstable axial equilibrium position; if no external force is applied, this position corresponds to equal gaps between all stator and rotor centering rings. If an external axial force is applied (e.g., gravity for a vertical position of the axis of the wheel), there is another unstable equilibrium position in which the axial negative force compensates the applied force. In either of these two cases, the unstable equilibrium position is made stable by the operation of a servoloop controlling an axial actuator and which utilizes, as input signal, the emf produced in an electrodynamic sensor and proportional to the rotor axial rate, and as a feedback signal, a voltage proportional to the current in the axial actuator (Fig. 2).

The axial actuator is based on the following concept. A pair of series-connected, iron-clad coils attached to the stator modulates the field produced by a radially magnetized samarium cobalt permanent magnet ring attached to the rotor. The direction of the resulting force depends on the direction of current flow in the coils. Compared with a straightforward electromagnet without permanent magnet bias, this arrangement produces much larger axial forces per ampere turn and exhibits a nearly linear force vs current relationship in the useful part of the characteristics.

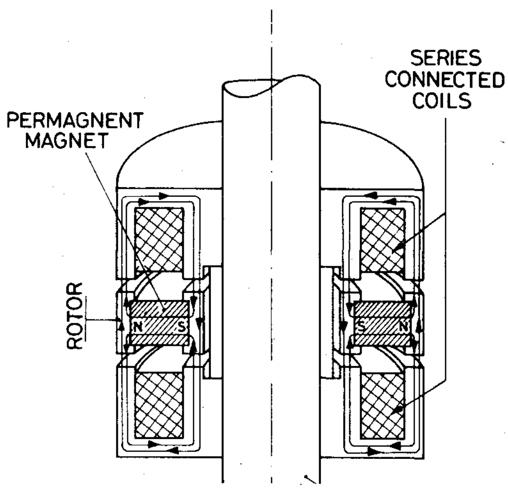


**Fig. 2 Axial bearing.**

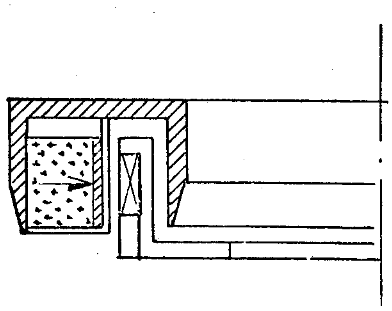

**Fig. 3 Axial rate sensor.**

The axial rate sensor is based on the following concept. A ring made of a samarium cobalt segment produces a field which moves axially with the rotor relatively to a coil fixed on the stator part. The magnetic field is confined to the coil by a soft iron magnetic envelope. The emf induced in the coil by the axial motion of the rotor is proportional to its axial rate (Fig. 3).

**Radial Dampers**

The passive radial magnetic bearings previously described may be likened to almost perfect lossless springs as far as their radial restoring characteristics are concerned. Together with the rotor mass, they form an undamped second-order vibratory system which is excited by unbalance forces during rotor spinup as well as precessional torques at normal operating speed. In order to prevent excessive amplitudes of rotor motion and the possibility of mechanical contact occurring between rotor and stator parts, radial damping of the rotor motion must be introduced. The radial damping devices employed in the momentum wheels are shown in Fig. 4. Each wheel contains two dampers, each damper being made up of four permanent magnet rings attached to the rotor and a copper disk attached to the stator. Radial motion of the magnet rings with respect to the copper disk induces eddy currents in the latter which interact with the permanent magnet field producing them to yield the required damping force. Rotational drag is small due to the azimuthal continuity of the fields. A variant appears on Fig. 4 with two magnet rings radially polarized. This type of damper was selected after extensive research involving a wide variety of alternative damping methods. Its chief advantages are its nonreliance on structural deformation for its operation and its easy possible adaptation at a combined active damper/vernier alignment device by substituting the copper disk with a system of coils, if particular applications require such a vernier gimballing effect.

**Motor**

The motor is of the ironless, brushless dc type with electronic commutation. The construction is shown in Fig. 5. The rotating field structure consists of an iron ring fitted with a number of rare-earth permanent magnet poles. The stationary armature comprises several coils of multistrand insulated

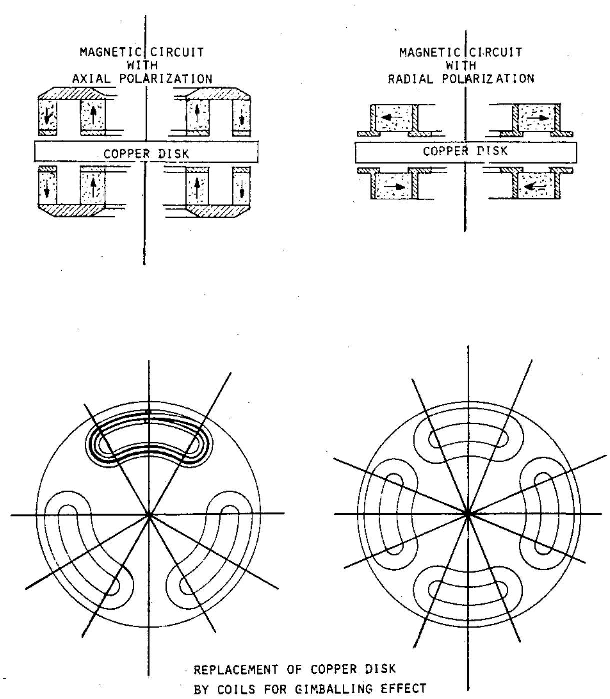


**Fig. 4 Damping/gimballing system.**

conductors encapsulated in an epoxy resin cylindrical support. The use of ferrous materials in the stator armature is specifically avoided in order that no radial decentering forces due to attraction between the armature and magnetic field parts are introduced. In momentum wheel, the motor is located at the flywheel hub, while in reaction wheels, location at the rim of the wheel has been found to be a more mass-effective solution.

According to each specific wheel design, the number of poles was, until now, between 12 and 24. It can be adapted for each case.

For the deceleration, the motor operates as a generator.

Several systems of commutation were developed and tested: 1) photodiodes/photo transistors commutation, 2) hall effect cells commutation, and 3) electromagnetic sensor commutation, which is now chosen for reliability reasons. A windowed sleeve on the rotor crosses the magnetic flux of stator ferrite coils fed with a high-frequency signal. The $Q$ factor of the coils is modified by the windowed sleeve, according to the angular position of the rotor in relation to the stator.

The resulting signals are utilized to open or close the gates controlling the current in the motor coils. Two types of windings were successively experimented with four and three circuits sequentially commuted. The useful torques were either 0.05 or 0.1 Nm. Much higher torques can be produced. The efficiency of the motor itself without the control electronics is $> 95\%$ at the maximum torques and nominal speed, higher for lower torques.

#### Touchdown Bearings

In order to avoid damage to the magnetic bearings in the event of a suspension failure at high wheel speeds or excessive slewing rates being applied, a touchdown bearing system consisting of a dual pair of deep-grove, dry-lubricated ball bearings is provided. These bearings act as both axial and radial excursion stops and only come into operation in case either axial or radial excursions become too great. The chosen configuration insures consistently smooth touchdown behavior, even at very high rotor speeds (tested up to 24,000 rpm).

#### Caging Mechanism

Magnetic bearing momentum wheel rotors must be caged during the satellite launch phase in order to sustain the very high levels of vibrations that exist during launch. Two types of caging mechanism have been developed: one version permits repeated decaging/recaging of the rotor for test purposes, after integration of the wheel on the satellite, the other is a simple one-shot device. Both versions include redundant pyrotechnic cable cutters for decaging in orbit.

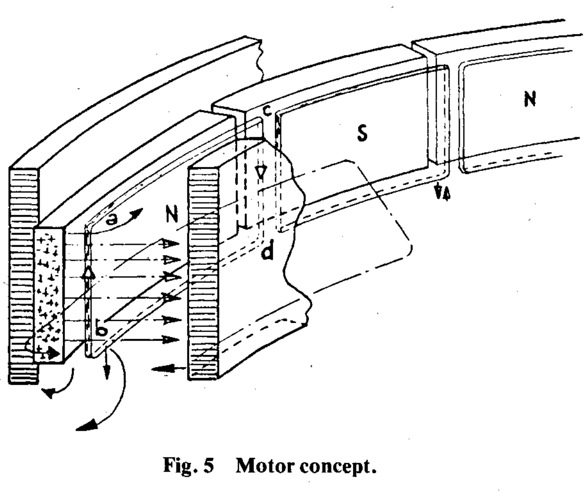


**Fig. 5 Motor concept.**

#### Rotor

The rotor configuration adopted consists of: 1) a central hub containing all the magnetic bearing parts, the touchdown bearings and, in the case of momentum wheels, the drive motor; 2) an outer rim giving the required moment of inertia and, in the case of reaction wheels, containing the magnetic circuit of the motor; and 3) a connection system between hub and rim.

The materials and the construction are chosen with a view to the centrifugal stresses set up and the need to maintain a high degree of balance in the presence of centrifugal and launch vibration loads.

Several solutions have been developed and tested; both metallic as well as filamentary composite material rotors have been fabricated.

#### Stator

The stator configuration adopted consists of: 1) a stiff, central shaft passing through the rotor hub and supporting all nonrotating parts of the magnetic bearings, motor, touchdown bearings, etc.; 2) a base-plate fixed to the lower end of the central shaft providing a mounting surface for the electronics and an attachment interface to the satellite (overhung construction); and 3) stiff lightweight framework or housing around the whole wheel, giving radial support to the upper end of the shaft during the launch vibration phase.

#### Electronics

The electronics provide several functions, for the axial servoloop operation (Fig. 6) and for the motor commutation: 1) the necessary transfer function between the axial rate signal and the current in the biased electromagnet actuator, taking into account the current feedback circuit: 2) the liftoff signals for initial operation when the circuit is being switched on; 3) the monitoring of the servoloop operation by the survey of the axial actuator current in order to switch on a redundant channel and to send a signal to the telemetry in case of abnormal operation of the servoloop; and 4) the commutation of the motor coils.

Three technologies were successively utilized for the electronics: 1) The first models were based on the utilization of integrated circuit operational amplifiers. It was a simple solution, but it involved the utilization of +15 V and −15 V for the integrated circuits. 2) After the successful operation of the first medium-speed (8000 rpm) and high-speed (24,000 rpm) models, the electronics were redesigned in discrete components. In this configuration, it was possible to operate the electronics of the axial servoloop, exclusively, with one power supply voltage (+28 or +50 V). In the case of momentary lack of power supply, the motor operating as a generator is able to feed the electronics of the axial servoloop. For 50 Nms, the electronics can be fed for 90 min, during which the speed decreases from 8000 to 4000 rpm without touchdown. 3) On the basis of the discrete components electronics, hybrid thick-film circuits were developed to reduce the electronics mass (1.4 kg in cordwood technology, 0.6 kg in hybrid thick-film technology).

In the cordwood (or other conventional technologies), the electronics package is outside of the wheel with interconnecting plug. The hybrid circuits are fixed inside the wheel on the lower flange with direct interconnection. Wheel drive electronics were developed; it allows control of the torque as well as the speed.

#### Axial Servoloop

In a first interpretation, it can be considered impossible to stabilize the system in a defined reference position without any signal correlated to a position reference. In fact, it has to be observed that the axial magnetic force is dependent on the rotor position. In the stationary state, this force is exactly compensated by the force produced by the actuator—a measurement of which is directly provided by the current in

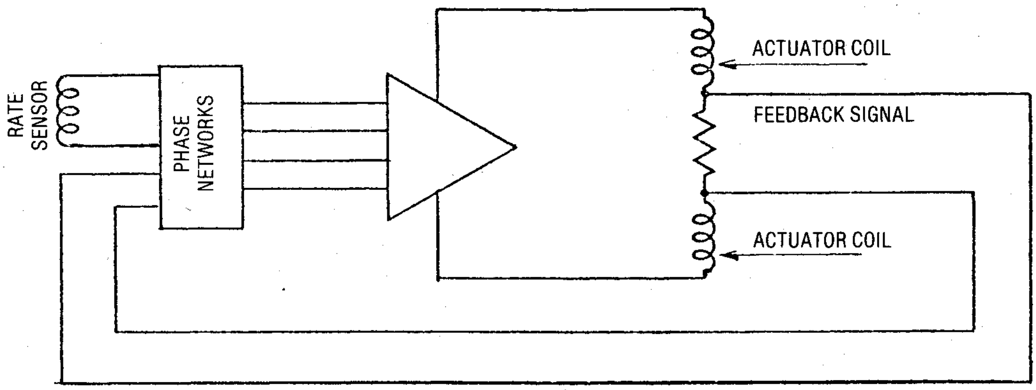


Fig. 6 Axial servoloop principle.

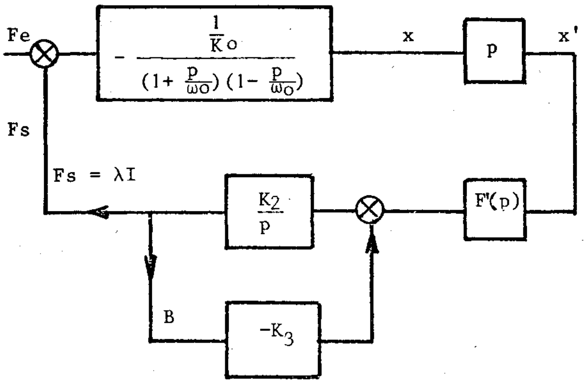


Fig. 7 Servoloop block-diagram.

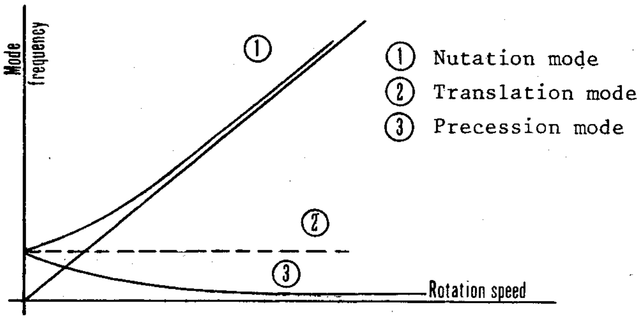


Fig. 8 Oscillation modes.

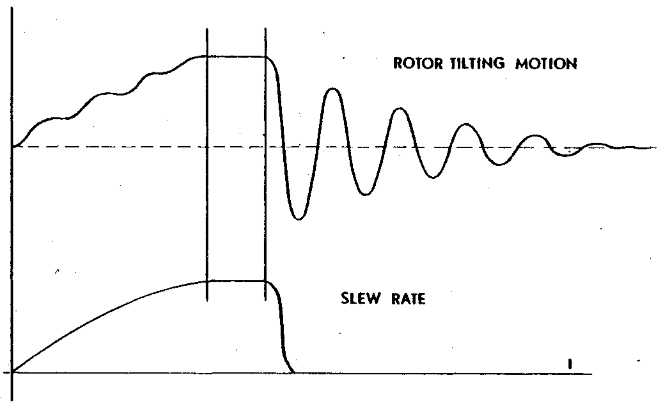


Fig. 9 Damping of dynamic modes.

the coil. Moreover, this remains nearly true as long as the acceleration remains sufficiently small in order that the inertia effects can be neglected compared to the magnetic force. That occurs within the low-frequency bandwidth in relation to $\omega_o/2\,\Pi$. For higher frequencies, the position information can be correctly provided by the speed signal integration. The appropriate data processing is made by the electronics control logic of Fig. 7 which shows the realization of the unstable root (loop B). It should be mentioned that it includes a feedback in intensity (or force), which, in fact, represents the previously indicated long-term position measurement.

## Rotor Dynamics

The motion of the rotor toward the stator involves three oscillation modes: the translation mode (critical frequency of the radial magnetic suspension), the precession mode, and the nutation mode. Taking into account that the moment of inertia $C$ around the rotation axis is higher than the same parameters $A,B$ along the conventional orthogonal axes, the three modes evolution vs rotation speed are presented in Fig. 8, and the nutation frequency is never excited by the rotation ($C/A > 1$). The precession frequency appears mainly when the stator is submitted to a slew maneuver. The amplitude of the rotor tilting motion depends, for given parameters of the wheel, on the slew acceleration and slew rate. The curves of Fig. 9 give the tilting motion of the rotor for a slew rate of 0.05 rad/s, reached with an angular acceleration of 0.01 rad/s$^2$, and stopped with an angular acceleration of 0.15 rad/s$^2$ (experimental recordings).

A lot of effort was devoted in the last five years to the stability of the attitude control of a satellite equipped with a "soft suspension" momentum wheel.[1] They demonstrate that the damping between rotor and stator contributes to the damping of the nutation motion of the satellite. Nevertheless, it has to be pointed out that this is only true when the damping energy is dissipated on the stator. It is the reason why the copper disks of the dampers are on the stator.

## Main Characteristics of Satellite Flywheels

### Momentum Wheels

The characteristics of a high-speed momentum wheel, designed to operate up to 24,000 rpm, were described previously.[2] Until now the stability of the characteristics was verified on four models of the same type in long-term operation. There was a double interest in the work performed on the high-speed models: 1) to demonstrate the wide safety margins (axial servoloop stability, stresses, balancing stability), 2) to prepare the way to kinetic energy storage systems.

As far as the attitude control momentum wheels are concerned in the range of angular momentum up to 100 Nms, and for the medium speed type, the light alloy rotor appeared to be the convenient solution up to 12,000 rpm.[3]

The typical characteristics of a medium-speed momentum wheel are given in Table 1. The complete functional and environmental testing was performed successfully on two models. The cut view is given in Fig. 10.

**Reaction Wheels**

The concept presents the following aspects: 1) The radial stiffness is sufficient to produce a radial critical frequency of the rotor suspension higher than the maximum rotation speed of 50 rps, avoiding the necessity of a damping system. 2) The motor is of the same type as the momentum wheel, but it is in a peripheral position in order that the magnetic circuit mass contributes to the inertia. 3) The motor has to rotate clockwise as well as counterclockwise. This is obtained by two sets of angular position sensors.[3]

The typical characteristics are indicated in Table 2.

## Development of Kinetic Energy Storage Systems

The high-speed momentum wheel has demonstrated the feasibility of kinetic energy storage for a satellite which appears to be a well-adapted solution for long-life missions.

In that way, the association of two counter-rotating flywheels provides the energy storage at constant angular momentum along the mean axis of these wheels, provided the two wheel torques are equalized.[4] Two magnetic bearing rotation wheels are necessary to compensate for the residual angular momentum resulting from the storage wheel misalignment.[5] This concept, as well as the concept utilizing two or three pairs of wheels oriented along different axes, appears to be very promising.

With the present technology of composite materials, particularly high-stress carbon and polyamide fibers, and with the necessary safety margins for the stresses, an overall capacity of useful energy storage of 35 Wh/kg appears to be a realistic and very attractive value compatible with long-life satellites. The permanent improvement in the characteristics of fibers permits later evolution toward higher values.

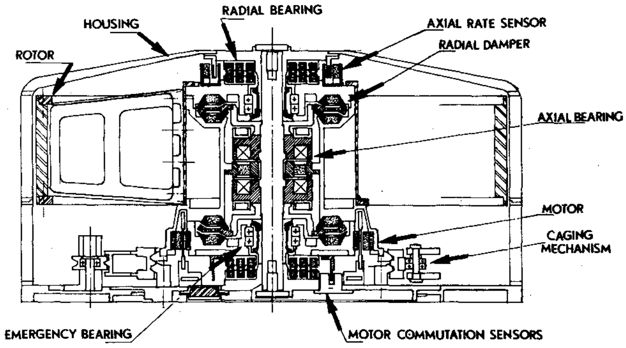


**Fig. 10 Magnetic bearing momentum wheel qualification model.**

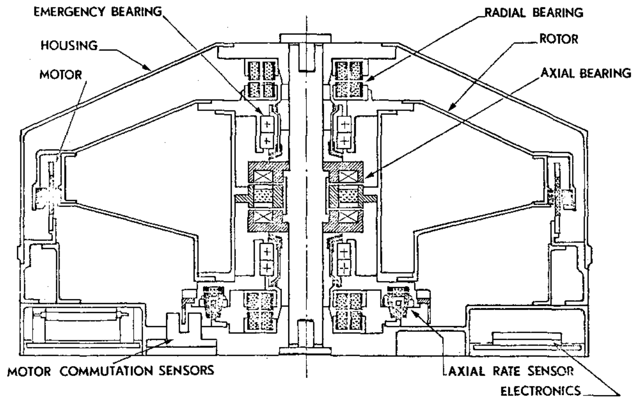


**Fig. 11 Reaction wheel.**

**Table 1 Attitude control momentum wheel characteristics (magnetic bearings, medium-speed type)**

| Parameters | Characteristics | Growth capabilities |
|---|---|---|
| Nominal angular momentum, Nms | 50 | 200 |
| Nominal speed, rpm | 7700 | 12,000 |
| Angular momentum and speed range control, % | −70- +70 | |
| Reaction torque, Nm | 0.1 | 0.3 |
| Slew rate, rad/s | 0.07 | 0.15 |
| Steady-state power, W | 10 | |
| Maximal power (0.1 Nm nominal speed), W | 105 | |
| Reliability (10 years) | 0.998 | |
| Dimensions: | | |
| Height, mm | 190 | |
| Diameter, mm | 350 | |
| Mass (including caging mechanism), kg: | | |
| Without electronics | 11.5 | |
| With redundant electronics-cordwood | 13.1 | |
| With redundant electronics-hybrid | 12.1 | |
| Temperature range, °C | −20- +50 | −30- +70 |

## Conclusion

The results obtained in the momentum wheel, as well as in the reaction wheel development, demonstrate the validity of the "one active axis" magnetic suspension for satellite flywheels and kinetic energy storage systems.

Altogether, this magnetic suspension adapted to satellite flywheels was tested in full operation conditions with four models in the 8500-12,000 rpm speed range, four other models up to 24,000 rpm, and one reaction wheel experimental model.

Among these models, two medium-speed and one high-speed model were tested in vibrations (locked by their caging mechanism), and in temperature, the flywheels being in full operation (one in the range −15- +55°C and two in the range −20- +50°C).

The electronics were tested in the −30- +70°C range. All of these tests were successful—they demonstrated the wide safety margins that exist in the concept and in the realization of the models described herein.

These results also demonstrate that this technology is now mature and ready for flight on application and scientific satellites.

**Table 2 Reaction wheel characteristics—magnetic bearings type**

| Angular momentum-Maximum speed | Diam., mm | Height, mm | Mass, kg | Stiction torque, Nm | Friction torque, Nm | Idling power, W | Max. power, W |
|---|---|---|---|---|---|---|---|
| 2 Nms-3000 rpm | 250 | 120 | 3.1 | $10^{-4}$ | $10^{-3}$ | 3.5 | 40 |
| 5 Nms-3000 rpm | 250 | 120 | 4.5 | $10^{-4}$ | $10^{-3}$ | 3.5 | 40 |
| 10 Nms-3000 rpm | 350 | 150 | 7 | $10^{-4}$ | $10^{-3}$ | 3.5 | 40 |

Common characteristics: reaction torque = 0.1 Nm; slew rate = 0.1 rad/s; 1 electronics channel (thick-film/hybrid).

## Acknowledgments

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