2-AXIS ACTIVELY CONTROLLED MAGNETIC BEARINGS

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SUMMARY

Microsatellites are characterized as better, faster, cheaper spacecraft, and their effective utilization is actively studied by universities, national institutes and private companies. Owing to technology innovations, small and lightweight on-board components are fabricated with high mission performances. For example, 3-axis attitude control is required for 50kg-class microsatellites. In order to satisfy such demands,weight, mass and power consumption of each sensor and actuator are strictly limited. The National Aerospace Laboratory (NAL) has been developing magnetic bearings for attitude control actuators such as reaction and momentum wheels. Several types of magnetic bearings have been manufactured and evaluated and resulted in the advantage of 2-axis magnetic bearings with a potential miniaturization. In this paper, the development histories of 2-axis magnetic bearings in NAL and recent small magnetic bearing reaction wheels for microsatellite attitude control actuators are described. The design goal is a small size magnetic bearing reaction wheel, which has the characteristics of approximately 1.5kg weight, 100mm diameter and 0.2Nms angular momentum at 6,000 rpm.

INTRODUCTION

Magnetic bearings are now practically used in fields of industry such as turbo-molecular pumps to obtain ultra high vacuum and precise positioning mechanisms applied for semi-conductor manufacturing systems. Several types of magnetic bearings for space applications have been researched and developed by NAL (refs. 1 and 2). 2-axis actively controlled magnetic bearings have the characteristics of simple construction, low power consumption and adequate dimensions for a flywheel system. These features have potential applications for practical use of magnetic bearing reaction wheels as attitude control actuators of spacecraft. In 1986, the research model of a 2-axis actively controlled magnetic bearing flywheel developed by NAL was launched and on-orbit experiments were done to evaluate the fundamental magnetic bearing system such as the launch lock mechanisms, levitation, rotation and damping characteristics.

In recent years, small satellite utilization is actively increasing, especially 50kg-class microsatellites which are focused on low cost performance by the researchers of institutes and universities. They proposed various missions, which required high performance attitude control systems such as 3-axis attitude stabilization adopted in large satellite systems (ref. 3). Since microsatellite bus systems are limited by volume and weight, then the actuator is also required to have small size and light-weight performances.

This paper describes the development of a small-size magnetic bearing reaction wheel for the application to small and microsatellites attitude actuator. They have potential characteristics of miniaturization of onboard components with high rotational speed and low vibration.

PIGGYBACK MICROSATELLITES

Many small and microsatellites have been launched as piggyback payloads in conjunction with the larger primary satellite. Large launchers such as H-II, Ariane IV and V, Delta-II etc. have sometimes provided mass margins in excess of the primary payloads. Piggyback satellites can be included making effective use of this mass margin, often providing very cost effective launching into orbit.

Since 1990, the SPWS (Small Payload Workshop) was organized as a non-government working group for the study of active utilization of piggyback satellites in the fields of technology demonstration, communication and earth observations. The activities of the SPWS has mainly focused on the mission proposals of small and microsatellites, information exchange among national institutes, universities and private companies in the world.

In 1995, the SPWS summarized and analyzed 61 proposed mission ideas. The proposed missions are divided into 4 categories, which are technology experiments, observations, communications and biological experiments. More than 50% are concentrated on science and technology missions such as in-orbit verifications of satellite bus system, components, materials like semi-conductors, robotics, tethers and another technological items. Missions related to the Earth and astronomical observations and survey of debris distributions take second place, about 30% of the total. Some demands for satellite attitude control systems are also requested. The almost microsatellites, launched in the past, have adopted gravity gradient attitude stabilization or slow tumbling (forced spinning or no active attitude control) because of the limited budget and requested attitude accuracy. The results of the questionnaires, on the contrary, show that more than 50% of missions require 3-axis attitude stabilization in order to meet future extensive demands such as high

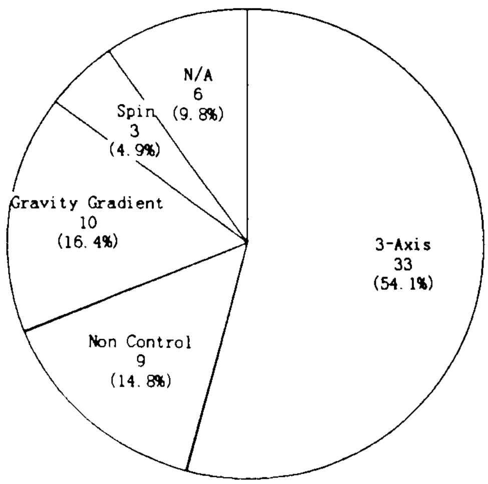


Fig. 1 Attitude Requirements for Microsat

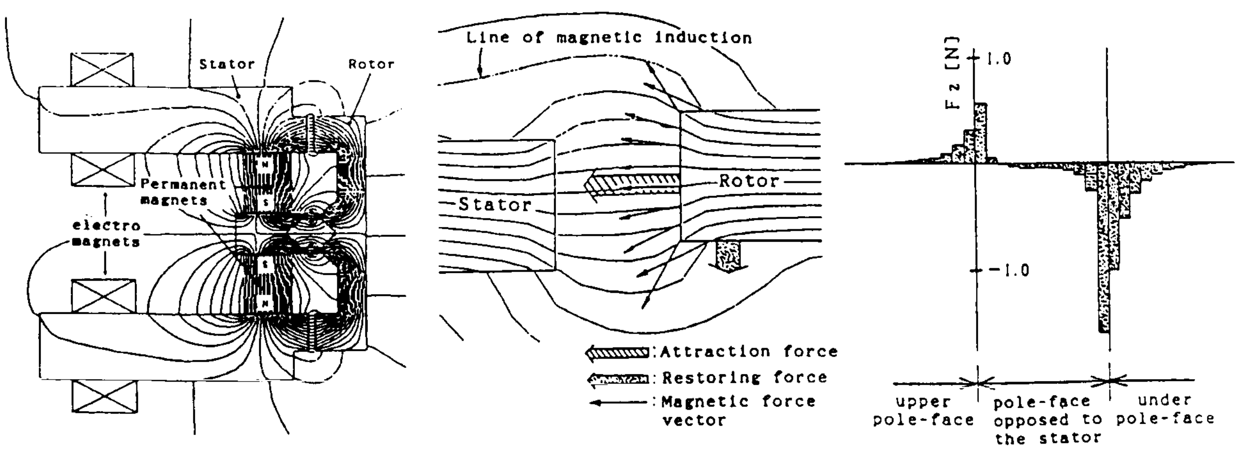
bit-rate data transmission, high accuracy pointing, fixing to the inertial frame, micro-gravity environment and so on. Low-cost, simplified 3-axis attitude control packages must be developed as soon as possible. Fig. 1 shows the required attitude control distribution. Small-sized reaction wheels or a momentum wheel with magnetic suspension will be candidates as actuators.

MAGNETIC BEARINGS WITH PERMANENT MAGNETS

Magnetic bearings used for suspending rotating bodies must constrain the five degree-of-freedom (DOF) motion of the body, leaving the motion about the rotational axis out of consideration, three DOF being assigned perpendicular to the rotation axis. Principally, each direction of motion may be actively controlled or passively stabilized with the help of permanent magnets, as long as at least one axis is actively controlled. Thus, various types of magnetic bearings have been proposed, ranging from an axial-active and radial-passive type (one axis active control) to a five DOF active control type.

Utilization of permanent magnets in the magnetic bearings not only provides passive stabilization but it also helps the control system to overcome the inherently nonlinear relationships between the electromagnetic quantities (e.g. coil current, gap flux density etc.) and the resultant forces by a technique called "flux density modulation". Another advantage of permanent magnet utilization is that it enables the "Virtually zero power" method capable of minimizing (or nulling) the power consumption in the control coils by balancing the constant external force (e.g. gravitational force) with the unbalance force produced by the permanent magnets.

The passive stiffness is produced by the sum of restoring forces acting on the magnetic pole pieces. Fig.2(a) shows the magnetic flux distribution chart calculated by finite element method (FEM). The magnetic fluxes generated by the permanet magnet pass through all magnetic pole pieces and are concentrated on the central pieces. A specially magnified detail drawing of the central pieces is



(a) Magnetic Flux Distribution (b) Force Vector (c) Force Distribution

Fig.2 Magnetic Attraction and Restoring Force Acting on the Pole Pieces shown in Fig. 2(b). The magnetic force vector of each corresponding magnetic flux is expressed by a straight line with an arrow head and the vector sum is decomposed into attraction force and restoring force. The attraction force is controlled by electromagnets which is shown in Fig.2(a) and the restoring force supports the rotor mass passively. The force distribution on the magnetic pole-face is shown in Fig. 2(c). The restoring force is highly concentrated on the extreme edge of the magnetic pole pieces. Then the restoring force is roughly proportional to the number of edges and the flux density.

2-AXIS ACTIVELY CONTROLLED MAGNETIC BEARINGS

2-axis active magnetic bearings have a relatively simple arrangement and easy construction. The most preferable feature of this type is its virtually flat-shaped form, which enables the achievement of a high moment of inertia/mass ratio flywheel. From this point of view, it is possible to realize a high capacity angular momentum with minimum weight and manufacturing cost. Since 1980, NAL has studied and manufactured, by way of trial, several types of two DOF magnetic bearings and found that they have a high potential for applications such as a reaction wheel.

Fig.3 shows the principle of 2-axis actively controlled magnetic bearings developed by NAL. The magnetic forces act on the pole pieces on G1, G2 and G3, two of which (G1 and G3) are so-called magnetically modulated gaps where magnetic flux densities are modulated by radial electromagnets whereas G2 is a non-modulated gap. This non-modulated gap plays an important part where magnetic flux density is very high, therefore both axial and tilting stiffness can be made high. There are two ring-shaped permanent magnets on the stator side only. Eight electromagnet

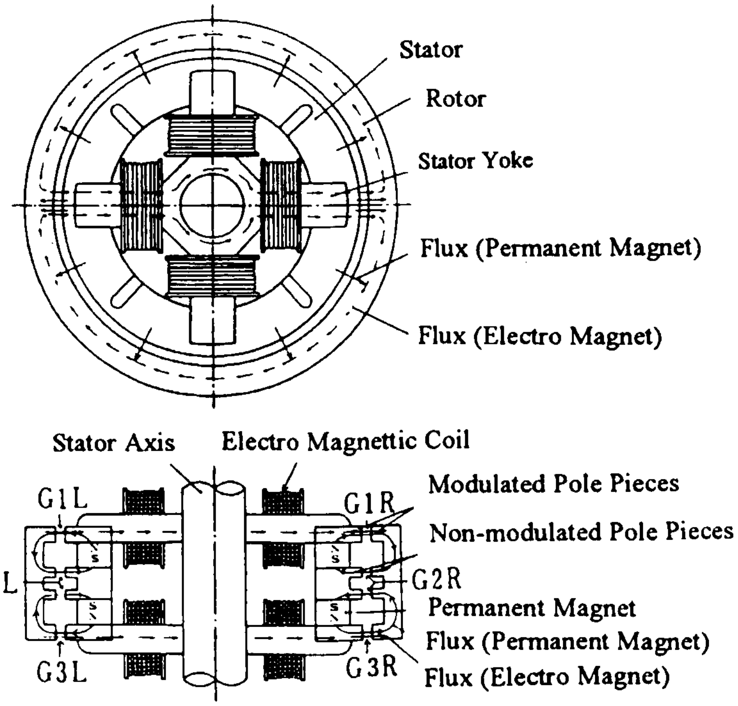


Fig.3 Cross Sectional View of 2-axis Actively Controlled Magnetic Bearings

coils are wound around both upper and lower cross-shaped stator yokes to modulate the two gaps (G1 and G3) for levitation. The arrow lines represent the magnetic flux flows generated by the permanent magnets. Two closed loops are generated and both lines commonly pass through the non-modulated gap G2. The dashed lines represent the flux flows generated by the electromagnets, which pass only G1 and G3 and modulate the biased flux generated by permanent magnets. Eddy current type gap sensors (which are not shown in the figure) detect the radial displacement for radial active control.

2-Axis Actively Controlled Magnetic Bearing Flywheel for Space Experiment

In order to evaluate the on-orbit characteristic of a 2-axis actively controlled magnetic bearing flywheel, the research flight model (RFM) was manufactured and launched into orbit in 1986. Experimental items are:

(1) manufacturing of a magnetic bearing flywheel for space flight model
(2) functional test of the launch lock mechanism
(3) measurements of the damping characteristic of the passively stabilized axis
(4) comparison of ground test data with space experimental results, especially
(5) levitation characteristics

A cross sectional view of the RFM is shown in Fig. 4. It was composed of axially magnetized samarium-cobalt permanent magnets, electromagnetic coils for x- and y-axis control, two pairs of eddy current type position sensors to detect the radial displacements of the rotor, a flywheel to accumulate an angular momentum, emergency ball bearings and launch lock mechanism which fasten the rotating part with elastic metal plates and 2 mm diameter twisted wire. An additional four position sensors are mounted on the bottom base of the stator to detect the axial displacement of the rotor by adding the four output signals to measure the rotor's tilting motions about the x- and y-axis by subtracting each pair of sensors. A pair of electromagnetic coils are additionally wound around stator yokes to excite a tilting oscillation for the purpose of damping characteristics measurement.

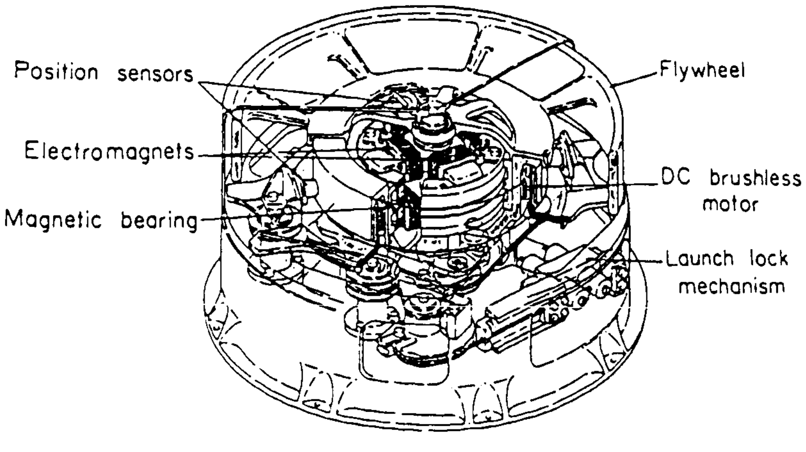


Fig.4 Cross-sectional View of Magnetic Bearing Flywheel for Space Experiment

Several environmental tests were performed before system integration. Random vibration level for each direction is about 14.5 Grms and the temperature range is –20 ~ +50℃. Dimensions and specifications are shown in Table 1. In order to measure several features of magnetic bearings, this RFM was not designed in conformity to the purpose of direct application for spacecraft from the view point of dimension and weight because of the additional sensors and coils for experiments. All on-orbit experiments were carried out successfully.

Table 1 Characteristics of Magnetic Bearing Flywheel for Space Experiment

items	measured values
Axial stiffness [N/m]	8.3×10^4
Radial control force [N/A]	4.8×10
Dimension [mm]	270 (dia.) × 127 (machine body) , 200 × 252 × 151(electronics)
Weight [kg]	7.23 (machine body) , 5.10 (electronics)
Rotation speed [rpm]	1,000 (only for this exp.)
Power consumption [W]	3 (suspension) , 7 (at 1,000 rpm)

Flat-shaped 2-axis Actively Controlled Magnetic Bearing Reaction Wheel

Fig.5 shows a flat shaped reaction wheel. The design goals of this model are to reduce weight, dimensions (especially height) and power consumption, and to increase angular momentum, bearing stiffness and reliability. The magnetic bearings were installed at the outside of the stator, then the mass concentration to the outer part of the wheel could be satisfied. This installation has brought about high moment/mass ratio and high stiffness of the magnetic bearings. The values of stiffness are measured dynamically by modal analysis using the impulse hammering test. The characteristics are shown in Table 2. The damping ratios are also measured and their values are over 0.3 for radial directions and over 0.01 for axial and around radial directions.

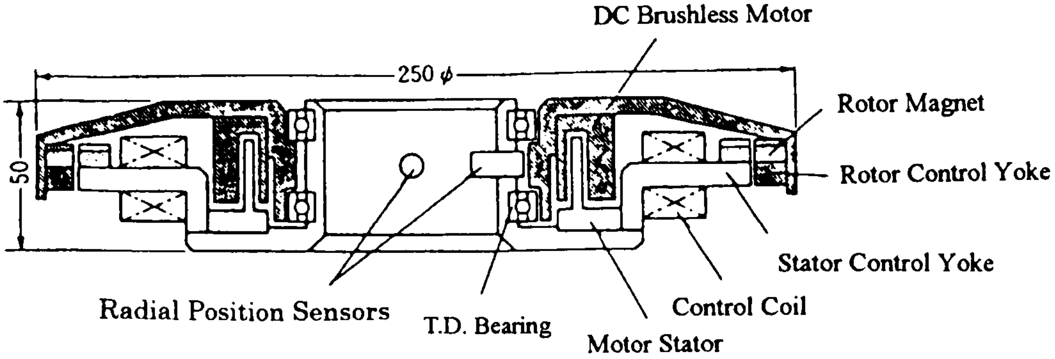


Fig.5 Flat-shaped Magnetic Bearing Reaction Wheel

Table 2 Characteristics of Flat-shaped Magnetic Bearing Reaction Wheel

items		measured values
Axial stiffness	Ka [N/m]	3.2×10^5
Radial stiffness	Kr [N/m]	7.6×10^5
Orthogonal stiffness	Ke [Nm/rad]	1.5×10^3
Dimension	[mm]	$\phi 250 \times 50$
Rotor weight	[kg]	2.4
Angular momentum (at 3,000 rpm)	[Nms]	7.5

SMALL MAGNETIC BEARING REACTION WHEEL FOR MICROSATELLITE ATTITUDE CONTROL

A small size magnetic bearing reaction wheel for the attitude control of microsatellites has been designed and is now being manufactured (ref. 4). The design baseline is similar to the reaction wheel described in the previous section (flat-shaped reaction wheel). The design parameters are shown in Table 3 and the sectional view of the construction is shown in Fig. 6. The required maximum angular momentum is 0.2 [Nms], where the rotation speed is at 6,000 [rpm].

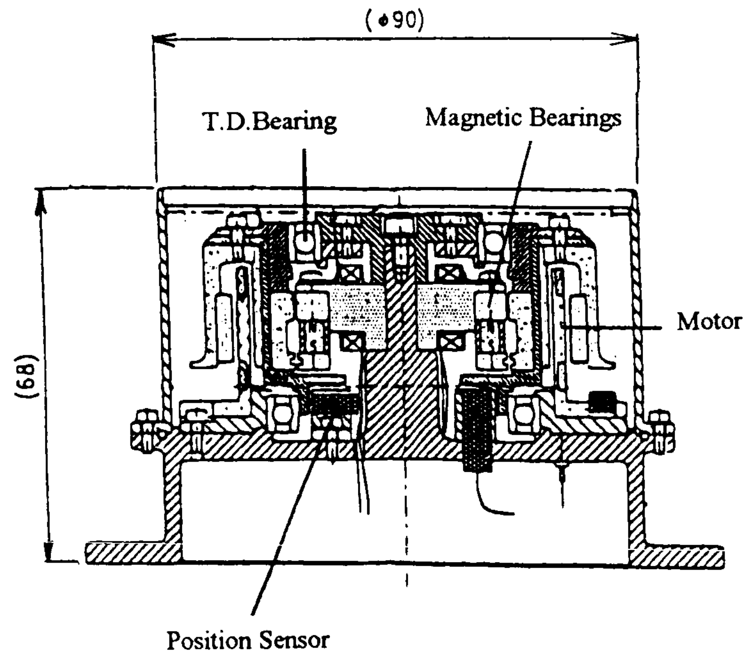


Fig.6 Small Magnetic Bearing Reaction Wheel

Table 3 Design Parameters of Small Magnetic Bearing Reaction Wheel

items	design values
Dimension	φ 90 × 70[mm]
Weight	1.5[Kg]
Angular momentum	0.2[Nms] (at 6,000rpm)
Torque	0.005[Nm]
Permanent magnet	R26H(SINETSU Rare Earth)
(for magnetic bearings)	
Maximum energy-product	210[KJ/m^3]
Dimension	outer diameter φ 37[mm] , insidc diameter φ 30[mm] height 6[mm]
Magnetic pole Dimension	outer diameter φ 50 × 14[mm]
Face width	5[mm] × 1(Modulating magnetic pole) 1[mm] × 2(non-modulating magnetic pole)
Magnetic flux density	
Modulating magnetic pole	0.41[T]
Non-modulating magnetic pole	0.68[T]

CONCLUDING REMARKS

Research and development activities of magnetic bearings, especially emphasizing a 2-axis actively controlled type developed by NAL are overviewed. For large satellites, magnetic bearing reaction wheels are already practically used and sufficient characteristics are demonstrated. In the past, microsatellites are usually passively stabilized by gravity gradient torque, as an example. According to the high-quality mission requirements for microsatellite attitude control system, 3-axis stabilization is necessary. NAL is now developing a small magnetic bearing reaction wheel for microsatellite application and will be actually used as attitude control actuators for piggyback microsatellites, under development in NAL, which will be launched within a few years.

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