Research and Development of Magnetic Bearing Flywheels for Attitude Control of Spacecraft

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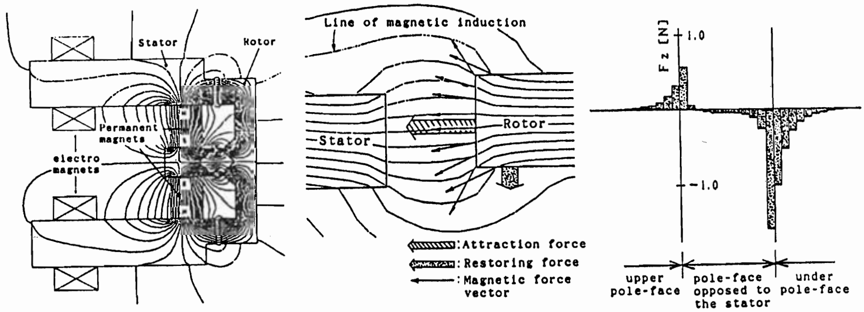
Summary

Magnetic bearings for space and industrial applications have undergone considerable development in laboratories and industries. Since 1978, several types of magnetic bearings have been manufactured and tested in National Aerospace Laboratory (NAL), concentrating on the development of the magnetic bearings utilizing permanent magnets and their applications for space. Two degree-of-freedom (DOF) radially controlled magnetic bearings is a candidate of practical use as attitude control actuator of spacecraft. In order to evaluate the characteristics of this type magnetic bearings, on-orbit experiments under zero g condition were performed, i.e. magnetic bearing flywheel developed by NAL was launched by H-I rocket TF#1 into a 1500 km circular orbit on summer of 1986 and several experiments were carried out successfully. This paper summarizes the activities of NAL for research and development of magnetic bearings.

1. Passively stabilized stiffness

Utilization of permanent magnets in the magnetic bearings not only provides the 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 coil by balancing the constant external force (e.g. gravitational force) with the unbalance force produced by permanent magnets. For practical uses of this type bearings, it should be pointed out that the procurements of a stable high speed rotation, sufficiently large stiffness and oscillation damping about passively stabilized axes are particularly important.

The passive stiffness is produced by the sum of restoring force acting on the magnetic pole pieces. Fig.1(a) shows the magnetic flux distribution chart calculated by finite element method(FEM). The magnetic fluxes generated by the permanent magnets pass through all magnetic pole pieces and concentrated on the central pieces. A specially magnified detail drawing of a central piece is shown in Fig.1(b). 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 electro magnets which is not shown in this figure and the restoring force supports the rotor mass passively. The force distribution on the magnetic pole-face is shown in Fig.1(c). The restoring force is highly centered on an extreme edge of magnetic pole pieces. As a result of this calculation, the passive stiffness becomes large with the increasement of the edge of magnetic pole pieces.



(a)Magnetic flux (b)Magnetic force (c)Restoring force

Fig.1 Magnetic force produced by permanent magnets.

The vibration damping in the passively stabilized axis is produced consequently as eddy current losses caused by the relative movements of stator and rotor in the magnetic fields. Under ordinary circumstances, the value of damping ratio will take an order of 0.05, which is strongly dependent on the magnetic parameters such as materials of magnetic poles, magnetic flux density, levitating position and so forth.

2. Configurations of magnetic bearings

2.1 One DOF active magnetic bearing

One DOF active magnetic bearing has the most simplest construction and the highest reliability because of the minimum

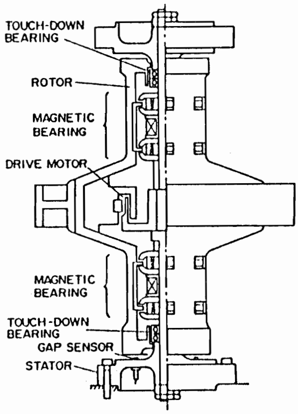


Fig.2 One DOF MBMW.

Table 1 Specifications of one DOF active MBMW (joint development between NAL and MELCO)

items		measured values
Axial stiffness	Ka[N/m]	1.78×10^{6}
Radial stiffness	Kr[N/m]	2.12×10^{5}
Orthogonal stiffness	Kθ[Nm/rad]	4.62×10^{2}
Dimension	[mm]	φ260 ×400
Rotor weight	[kg]	6.55
Moment of inertia	[kg·m²]	
Iz(rotation axis)		3.28×10^{-2}
Ix=Iy		3.83×10^{-2}
Angular momentum (at 10,000 rpm)	[Nms]	34

electronic circuit. Fig.2 shows a laboratory model of One DOF active magnetic bearing momentum wheel jointly developed by NAL and Mitsubishi Electric Corporation (MELCO). The purpose of this development is to investigate the rotational characteristics of this type magnetic bearings with two radial and two conical passively stabilized axes. Table 1 shows the specifications of this model. From the solution of the rotor dynamics equations, the natural frequency of the cylindrical mode is 28 Hz. On passing through this rotation speed, the vibration amplitude was 0.47 mm p-p , which could be decreased by balancing the mass unbalance of the rotor more precisely. After the passage of this natural frequency, this cylindrical mode occurred again at the rotation speed over 41.8 Hz. It is well known that the energy dissipation in the rotating body would cause the instability at a high speed rotation. From the results of this instability analysis [1] , the damping ratio of the cylindrical mode becomes as follows :

$$\zeta_{cy} = \zeta_{ocy} + \zeta_{icy}\,(1-w/w_{ncy}) \qquad (1)$$

where ζ_{ocy} and ζ_{icy} are the damping ratios of stator part and rotating part, w is rotaion speed and w_{ncy} is natural frequency of the cylindrical mode, respectively. From the measurements of ζ_{cy} at several rotation speeds, ζ_{cy} decreased linearly in inverse proportion to the rotaion speed and became zero at 41.8 Hz (Fig.3). From Eq.(1) and the experimental data shown in Fig.3, ζ_{ocy} and ζ_{icy} were estimated as 0.0016 and 0.0034, respectively.

In order to avoid this instability, special attention should be paid to design the damping mechanism of passively stabilized axes. In our laboratory model, this problem was solved by introducing the anisotropic radial stiffness [2] and stable rotation more than 10,000 rpm was obtained as a result.

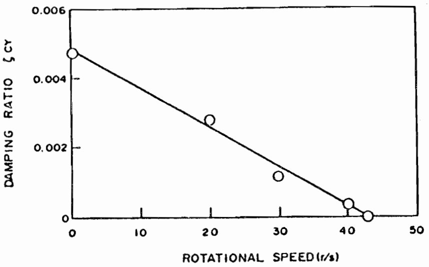


Fig.3
Relation between damping ratio of cylindrical oscillation and rotational speed for isotropic radial stiffness.

2.2 Two DOF active magnetic bearing

Two DOF active magnetic bearing has a relatively simple arrangement and easy construction. The most preferable feature of this type is its virtually flat-shaped form, which enables achieving a high moment of inertial/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, the author and others have studied and manufactured by way of trial several types of two DOF magnetic bearings [3,4] and found that they have a high potential for space applications such as reaction wheel.

Fig.4 shows a flat shaped reaction wheel jointly developed by NAL and Toshiba Corporation (TOSHIBA). The design goals of this model were 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 have

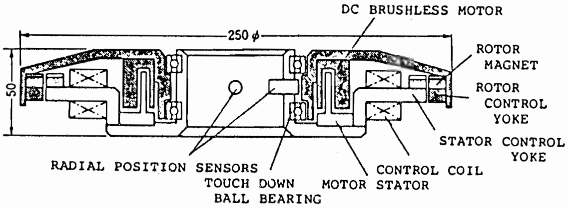


Fig.4 Flat shaped reaction wheel (joint development between NAL and TOSHIBA).

Table 2 Specifications of two DOF active MBRW

items		measured values
Axial stiffness	Ka[N/m]	3.2×10^{5}
Radial stiffness	Kr[N/m]	7.6×10^{5}
Orthogonal stiffness	Kθ[Nm/rad]	1.5×10^{3}
Dimension	[mm]	ϕ250×50
Rotor weight	[kg]	2.4
Angular momentum (at 3,000 rpm)	[Nms]	7.5

brought about high moment/mass ratio and high stiffness of the magnetic bearings. The values of stiffness were measured dynamically by modal analysis using the impulse hammering test, the results of which are shown in Table 2. The damping ratios were also measured and their values are over 0.3 for radial directions and over 0.01 for axial direction and the axes about radial directions.

In order to promote the practical use of magnetic bearings for space, research flight model (REM) of magnetic bearing flywheel was manufactured [5] and launched into orbit to obtain several technical data of magnetic bearings operated under zero g condition. 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 characteristics of passively stabilized axis
(4) comparison of the ground tested data with the space experimental results, especially related to the levitation characteristics.

RFM of two DOF active magnetic bearing flywheel was manufactured by MELCO by the contract of NAL. Cross sectional view is shown in Fig.5. 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 rotor, a flywheel to

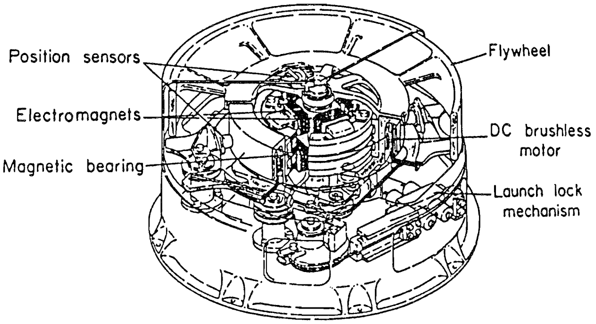


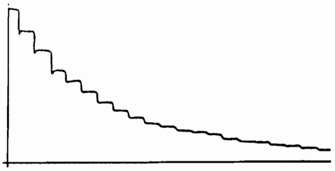
Fig.5 Magnetic bearing flywheel for space experiment (developed by NAL).

Table 3 Spicifications of two DOF active MBFW

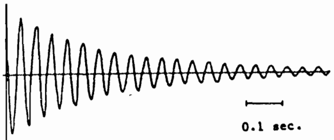
items	measured values
Axial stiffness [N/m]	8.3×10^4
Radial control force[N/A]	4.8×10
Dimension [mm]	270(dia.)×127 (machine body) 200×252×151 (electronics)
Weight [kg]	7.23 (machine body) 5.10 (electronics)
Rotation speed [rpm]	1,000 (only for this exp.)
Power consumption [W]	3(suspension), 7(at 1000rpm)

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. Additional four position sensors are mounted on the bottom base of the stator to detect the axial displacement of rotor by adding the four output signals and to measure the rotor's tilting motions about 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. Several environmental tests were performed before system integration. Random vibration level for each direction is about 14.5 g rms and the temperature range is -20 - +50 °C. Dimensions and specifications are shown in Table 3. In order to measure several features of magnetic bearings, this RFM was not designed in conformity to the purpose of the direct application for spacecraft from the view point of dimension and weight because of the additional sensors and coils for experiments.

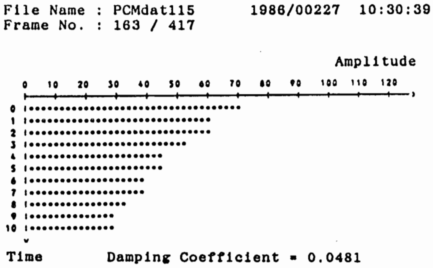
On the early morning of August 13th, 1986, MAgnetic Bearing flywheel Experimental System (MABES) was launched by H-1 rocket test flight number 1 (2nd stage) into a 1500km nearly circular orbit. MABES was given a pet name "JINDAI" after launch. The total system of JINDAI were already shown at the previous paper [6]. The experiment's duration time was three days and the termination of this experiment was brought about the current consumption of the onboad Ni-Cd batteries. Planned experiments were perfectly performed. After about two hours from launch, 136 MHz VHF telemetry data were transmitted from JINDAI and the first experiment has begun according to the command signal of the ground control center ; the launch lock release was successfully functioned, which was proved by the evaluation of position sensors' output signals. Secondary, magnetic levitation was confirmed after the corresponding command transmission and various telemetry data which indicate the operating conditions of magnetic bearings were recorded on the magnetic tape and converted simultaniously into the physical quantities for quick-look monitoring. The rotation speed of the flywheel was limitted to 1,000 rpm because of the minimization the amount of energy to be used. Fig.6 shows the damping characteristics of the tilting oscillation of the rotor about x-axis perpendicular to the rotation axis caused by the command signal. For application of magnetic bearings with passively stabilized stiffness, it should be focused our attention on the damping characteristics under different circumstances such as zero g condition. Fig.6(a) denotes the output signal of peak hold circuit while (b) is the original analogue value. Under the limitations of the telemetry transmitting capacity, the original analogue signals were sampled every 30 ms and digitized. Example telemetry data are shown in (c). From these data, oscillation period and its damping ratio were calculated. Fig.7 shows the levitation characteristics compared of the ground tested data with the space experimental results. The relative positions of actively controlled x- and y-axis were not different each other as inevitable results. On the other hand, z-axis position has displaced in the axial direction by 0.22 mm which corresponds to the rotor mass. The results of the tilting motion experiment are shown in Fig.7(c). A group of data obtained on the ground are



(a) peak hold data



(b) Oscillation about X-axis



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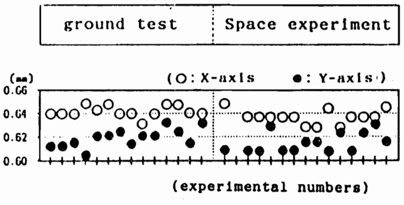
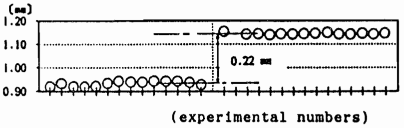
Damping Coefficient = 0.0481

(c) Example data of space experiment

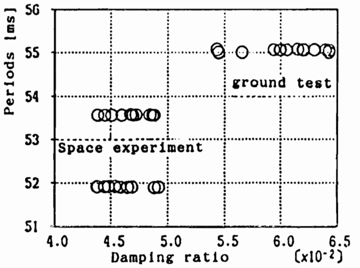
Fig.6 Damping characteristics about X-axis oscillation.



(a) Outputs of X- and Y-axis position sensors



(b) Outputs of Z-axis position sensor



(C) Oscillation characteristics of the flywheel about the X-axis perpendicular to the rotation axis

Fig.7 Levitation characteristics (Comparison of the ground tested data with the space experimental results).

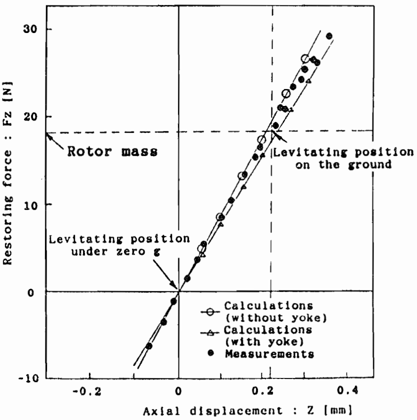
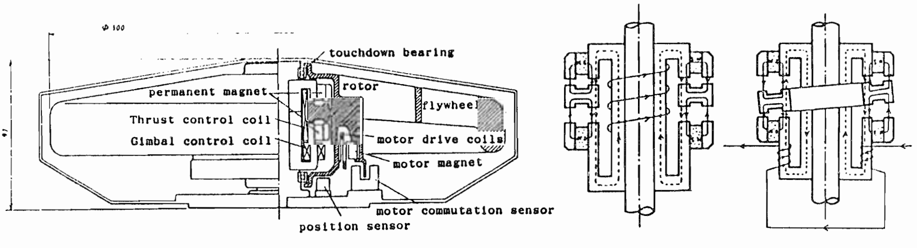


Fig.8 Fz and z relation.

plotted on the upper right of the figure, on the contrary, space experimental data are plotted on the lower left. The oscillation periods under zero g condition become smaller than that of the ground data, which express the increase of stiffness about x-axis. As the increse of the stiffness is closely related to the increase of the axial stiffness, the experimental result can be explained by the fact that the axial stiffness has the maximum value at null position. The seperation of space experimental data (51.9 ms and 53.6 ms) is inexplicable matter at present. The damping ratios under different environment are seperated clearly. It was proved that the oscillation damping ratio of passively stabilized axis became smaller than the measurement's data on the ground. That phenomenon can be explained in physics as follows ; the magnetic fields around the magnetic pole pieces are different under different relative position of stator and rotor. The magnetic flux distribution will effect the damping characteristics which are closely depend on the eddy current losses. The magnitude of the difference was about 20 %. Fig.8 shows the relationship between the axial displacement of rotor and the restoring force. Close agreement between measurement on the ground and calculated values was obtained. Z-axis displacement shown in Fig.7(b) is coincide with the results shown in Fig.8.

2.3 Three DOF active magnetic bearing

The gimballing capability is possible by adopting the magnetic bearings with more than three DOF active type. Three



(a)Cross sectional view (b)Axial control (c)Gimbal control

Fig.9 Control principle of three DOF MBMW.

DOF active magnetic gimballed momentum wheel was designed and is under developement by the cooperation with NAL and MELCO [7], which is shown in Fig.9. The stator is composed of four equivalent parts, each of those has a gimbal control coil, permanent magnets and an axial position sensor. The mechanism is much simpler than that of the five DOF active type. For the axial control, a thrust control coil wounded around the four stators is used. The axial position of the rotor is measured by four sensors and the control current modulates the flux densities in the four inner gaps by the same quantity as shown in Fig.9(b). For the gimbal control, two pairs of gimbal control coils are used. The gimbal deflection of the rotor is measured by subtracting a pair of axial position sensors and the control current yields two control forces with opposite directions ; upward force in the left quarter, downward force in the right quarter(Fig.9(c)).

2.4 Four DOF active magnetic bearing

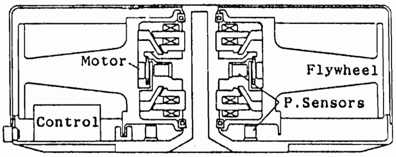
Four DOF active magnetic bearing has also a potential for high speed rotating machine. The basic construction of this type is similar to that of the two DOF active type and has a easy handling for assembly and disintegration. For the purpose of high speed rotation, a laboratory model of this type magnetic bearings was manufactured and some rotational tests were performed. Magnetic characteristics of this model are shown in Table 4.

Table 4 Specifications of four DOF active MB for high speed rotation (developed by NAL)

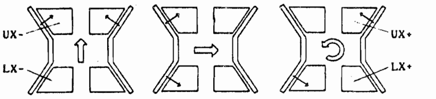
items		measured values
Axial stiffness	Ka[N/m]	2.46×10^5
Radial control force	[N/A]	$(4\sim5)\times10$(variable)
Dimension	[mm]	app. $\phi\,90\times150$
Rotor weight	[kg]	5.7
Rotation speed	[rpm]	32,000

2.5 Five DOF active magnetic bearing

Five DOF active magnetic bearing has also jointly developed by NAL and MELCO [8], which is different from other types in that no permanent magnets are used. In order to improve the mass property of this type magnetic bearings, axial electromagnetic coil was omitted, while two



(a)Cross sectional view



(b)Axial control (c)Radial control (d)Gimbal control

Fig.10 Five DOF MBMW.

pairs of upper and lower electromagnetic coils were installed in a conical shape for five axes active control as shown in Fig.-10. By activiating an equivalent pair of coils, axial, radial and gimbal control could be obtained. The characteristics of this model are shown in Table 5.

Table 5 Specifications of five DOF active MBMW (joint development between NAL and MELCO)

items		measured values
Orthogonal stiffness	K_θ[Nm/rad]	1.9×10^{2}
Dimension	[mm]	$\phi 314\times125$
Weight	[kg]	5.2(total) 2.6(rotor)
Angular momentum (at 10,000 rpm)	[Nms]	18
Moment of inertia	[kg·m^2]	
Iz(rotation axis)		1.7×10^{-2}
Ix=Iy		1.1×10^{-2}
Gimbal angle	[deg]	±0.5

3. Applications in space

Several types of magnetic bearings are described in this paper. These models are not necessarily manufactured for the purpose of the space use directly, but some of them would reach the stage of becoming practical uses in space. As a result of the space experiment in JINDAI, two DOF active magnetic bearings developed by NAL could be available as a reaction wheel for three-axis stabilized satellite. Five DOF active type jointly developed by NAL and MELCO could also be a candidate as a momentum wheel with gimballing capability.

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