Integral Design and Analysis of Passive Magnetic Bearing and Active Radial Magnetic Bearing for Agile Satellite Application

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In this paper, the design and development of a magnetic bearing system which consists of passive magnetic axial/tilting bearing and active two-axial radial magnetic bearing (RMB) used in magnetically suspended wheel (MSW) or magnetically suspended control moment gyroscope (MSCMG) for agile satellite application is presented. The passive axial/tilting magnetic bearing supplies an axial position stiffness to stabilize the rotor in the axial direction and a tilting stiffness to restrain the rotor when subjected to gyroscopic torque. The active two-axis radial magnetic bearing with bias permanent magnet stabilizes the rotor on the axes perpendicular to the rotation axis. Considering the complex distribution of flux density the system performance cannot be accurately analyzed by the conventional magnetic circuit method because of the high coupling between force and moment produced by the axial magnetic axial/tilting bearing and RMB. To analyze the coupling problem of the force, moment, position stiffness, and tilting stiffness between the passive magnetic axial/tilting bearing and RMB, an integral design and analysis method based on three-dimensional finite-element method is presented. An example is given and analysis results prove that the high coupling occurs on the radial direction and the light occurs on the axial and tilting directions orthogonal to the spin axis. Then the linearized model is given in this paper.

Index Terms—**Magnetically suspended control moment gyroscope, passive magnetic bearing, radial magnetic bearing, three-dimensional (3-D) finite-element method (FEM).**

I. Introduction

THE three-axis-stabilized spacecraft is equipped with reaction or momentum wheels for its attitude control [1]. And its precision and life is affected by the bearing supporting wheel rotor. The angular contact ball bearings are applied in conventional ball bearing wheel, and it cannot absorb the centrifugal force caused by imbalance of the wheel rotor. Therefore, the ball-bearing wheel can become one of the most harmful disturbance sources for the spacecraft attitude control, and the lubrication remains the principal factor restricting life [2], [3]. For ball-bearing wheel working under zero speed, there will be a torque spike. To avoid some of these problems, wheels supported by magnetic bearings have become a subject with intense development. Compared with traditional ball bearings, no contact and lubrication are the remarkable features of the magnetic bearings which can solve the problems of long life and high precision for momentum or reaction wheel through the active vibration suppression methods for disturbance suppression. The advanced magnetic bearing wheel has been flight-proven on the SPOT satellite [4]. The magnetic bearings as the key parts can be classified into three types, that is, active, passive, and hybrid magnetic bearings. Some passive magnetic bearings (PMB) [5]–[8] and different passive magnetic levitation devices [9], [10] have been described. Although these devices operate quite well, they are complex and bulky and therefore not suitable in satellite applications. On the contrary, active magnetic bearing (AMB) has better control ability and high stiffness, whereas it suffers from high power loss due to the biased current. Therefore, more attention is being paid to permanent magnet biased hybrid magnetic bearing (HMB) [11]–[13] which combines the merits of PMB and AMB. As for HMB, the permanent magnet generates bias flux to support the main supporting force. Consequently, the control current can be considerably reduced to acquire lower power loss. The HMB can only control two radial translational degrees of freedom (DOFs). Commonly, two radial magnetic bearings and axial magnetic bearings are required for controlling the five degrees of freedom of magnetically suspended system [11]. An integrated hybrid magnetic bearing (HMB) which can control four degrees of freedom is introduced [14]. One HMB and an axial magnetic bearing are also required for controlling the five degrees of freedom. This design results in a relatively large axial dimension and higher momentum-to-mass ratios, so they are also bulky and therefore not suitable in satellite applications.

The magnetically suspended wheel (MSW) of magnetically suspended control moment gyroscope (MSCMG) will suffer gyroscopic torque when the satellite attitude is regulated, especially for the agile satellite. The gyroscopic torque is the major factor that influences the stability of magnetic bearing system [15]; therefore the MSW is requested to restrain the rotor when subjected to gyroscopic torque. In order to solve this problem, an axial hybrid magnetic bearing with 3-DOFs used in MSW is presented [16], [17], and its reliability is reduced due to a complex structure and control system. To restrain the rotor from the gyroscopic torque the active control mode and current are requested, whereas the power loss will be increased correspondingly. The same as [18], a method of gimbals' angular rate feed-forward control for run-out depression in MSCMG is presented to improve the stability of MSW and moment-output performance of the MSCMG [12]. To improve the stability, the control current and accurate dynamic model is essential.

On the other hand, for MSW with radial and axial magnetic bearings the distribution of flux density is very complex, and the

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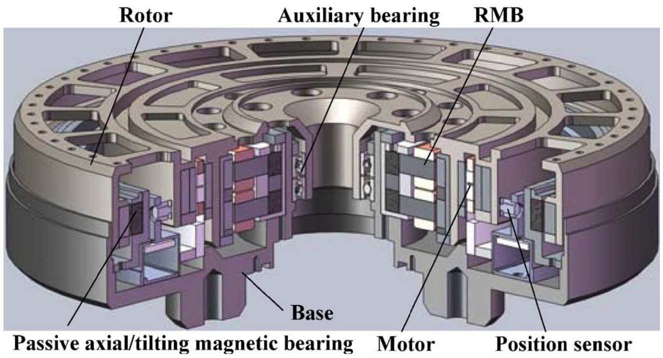


Fig. 1. Configuration of the magnetically suspended flywheel.

produced magnetic force and moment will be affected by each other. By magnetic circuit method the combination performance is very difficult to evaluate. And the traditional method is to design the radial and axial magnetic bearings respectively.

In this paper, the design and improve of a magnetic bearing system used in MSW for agile satellite application which consists of a passive axial/tilting magnetic bearing and an active 2-axis radial magnetic bearing (RMB) with biased permanent magnet is presented. The passive axial/tilting magnetic bearing can supply an axial position stiffness to stabilize the rotor in the axial direction and a tilting stiffness to restrain the rotor when subjected to gyroscopic torque. The RMB stabilizes the rotor in the plane perpendicular to the rotation axis. An integral design and analysis method based on 3-D finite-element method (FEM) using Ansoft Maxwell V13 is presented to analyze the coupling problem of the force, moment, position stiffness, and tilting stiffness between the passive axial/tilting magnetic bearing and RMB. In this paper an example together with its linearized model is given.

II. Analyzed Model and Operating Principle

Fig. 1 illustrates configuration of the MSW for satellite application, the magnetically suspended rotor is supported by a passive axial/tilting magnetic bearing and an active 2-axis radial magnetic bearing (RMB) with biased permanent magnet.

At wheel level, subassemblies of the MSW are the following:

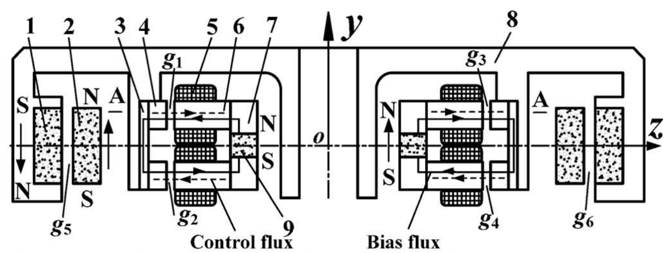
- **The RMB** stabilizes the rotor on the two axes orthogonal to the spin axis, with permanent magnets providing a steady-state bias flux for suspension and the electromagnets providing the necessary stability and control, which resulted in a lower power consumption bearing.
- **The passive axial/tilting magnetic bearing** exerts restoring forces on the rotor at axial translation and creates a tilting stiffness to restrain the rotor when subjected to gyroscopic torque. Its permanent magnet is attached to the rotor rim and thus makes a useful contribution to the rotating mass.
- **The position sensor**, using eddy current type position sensor, detects the radial position of the suspended rotor and provides the necessary error correction signals which are used for the stabilization of the rotor. The difference between the measured position and the desired position is converted in the control loop into a change of the current through the coils that generate the load-carrying capacity.
- **The motor**, for maintenance of the suspended rotor's angular rate, is a brushless ironless DC type in which phase commutation relies on digital Hall-effect sensors.
- **Auxiliary bearings**, using ball bearing, provide a safe landing of the rotor in the event of a failure occurring in the suspension electronic, or loss of power supply while rotating. They provide for radial support and axial support.

The configuration results in not only a lower power consumption bearing, but also in a lighter bearing because less iron is needed in the magnetic circuit. This design is developed to suppress the axial dimension of the MSW and higher momentum-to-mass ratios.

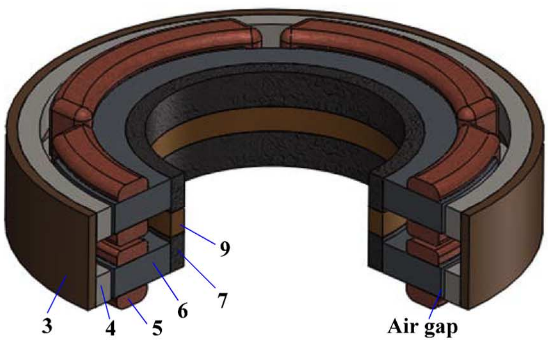
As shown in Fig. 2, the passive axial/tilting magnetic bearing is made up of magnet rings which are axially magnetized and locate at the circumference of the rotor and stator. Both magnets are magnetized in the opposite direction throughout the bulk and are inherently unstable in radial direction. Definitively the main advantage is their potential to miniaturization, high stiffness and high cost-effectiveness with no additional energy input and no computing power.

Fig. 2 shows the construct of the RMB, which consists of rotor and stator. The rotor consists of two soft magnetic axisymmetric pieces and axisymmetric return magnetic ring (made in soft magnetic material). The stator consists of two soft magnetic pieces each of which has four equally spaced electromagnet poles and four coils distributed at intervals of 90 degrees around the stator iron, one axially magnetized permanent magnet ring, and two axisymmetric return magnetic rings. The two magnetic poles with opposite magnetization allow control forces on the axis perpendicular to the spin axis and taking into account the linearization effect respectively which is beneficial for the position control. The permanent magnet (PM) supplies radial "bias" flux to the rotor iron across the air gaps in opposite directions. The control flux is produced by the control coils which allow adding or subtracting flux to the air gaps according to the current direction, and then the restoring force will be produced to stabilize the rotor on the two axes orthogonal to the spin axis due to disturbed force in relation to the rotor position. The bias magnetic field is generated by the stator permanent magnet of RMB whose flux flows across the stator return ring, the stator iron, the air gaps, the rotor iron, the rotor return ring, as shown the solid arrow lines in Fig. 2(i). The electromagnetic field is generated by the currents in stator coils according to the control system. For example, the magnetic flux produced by z -axis pole coils will flow across the z-axis stator iron, the z-axis pole air gap, the rotor iron, and return to the z-axis stator iron, with little magnetic flux flowing across the z-axis stator iron, the x-axis pole air gap, the x-axis stator iron, and returning to the z-axis stator iron, as shown the dotted arrow lines in Fig. 2(ii). In this structure, the bias magnetic flux is almost independent of the adjusting electromagnetic flux, which is more beneficial to enhance the stiffness and to load capacity of the RMB.

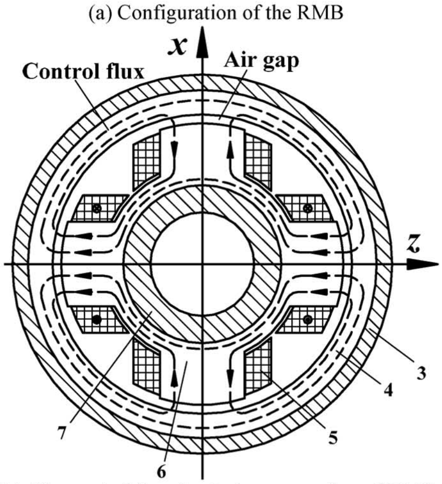
Fig. 3 describes the operating principle of the magnetic bearing system through one radial axis perpendicular to the rotation axis, such as z-axis. If a disturbance force acts on the rotor and displaces it from the central position along z-axis



(i) Representative cross section of the magnetic bearing system



(a) Configuration of the RMB



(a) The control flux for A-A cross section of RMB

(ii) Configuration of the RMB and its control flux for A-A cross section

Fig. 2. Representative cross section of the magnetic bearing system and the RMB. 1. Rotor permanent magnet of axial/tilting magnetic bearing. 2. Stator permanent magnet of axial/tilting magnetic bearing. 3. Rotor return ring of RMB. 4. Rotor iron of RMB. 5. Electromagnetic coil. 6. Stator iron of RMB. 7. Stator return ring of RMB. 8. Rotor. 9. Stator permanent magnet of RMB. g_5 and g_6: outer air gaps. g_1, g_2, g_3, g_4: inner air gaps. (i) Representative cross section of the magnetic bearing system. (a) Configuration of the RMB. (a) The control flux for A-A cross section of RMB. (ii) Configuration of the RMB and its control flux for A-A cross section.

direction, it will have a displacement by δz from its center. At this time, the left air gaps, g_1 and g_2, is smaller while the right air gaps, g_3 and g_4, gets larger. The position sensor will detect the offset of z direction and transmits it to the control system, and then the control system adjusts the z direction stator coils current to change forces of the magnetic bearing. The magnitude of the control current is determined by a control loop with feedback of the radial rotor position, measured by the eddy current type position sensor. At this time, the control flux in right air gaps of the RMB, g_3 and g_4, will be added to the bias flux and subtracted in the left air gaps, g_1 and g_2. Then a restoring force will be produced on the rotor in the negative

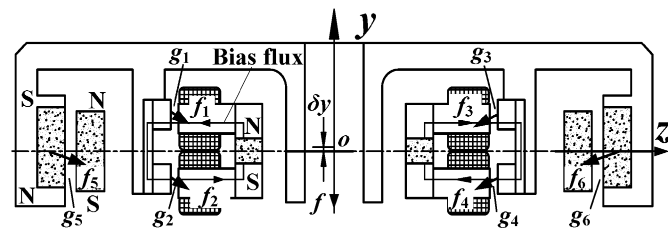


Fig. 3. The force produced by the RMB and PMB in y-axis direction.

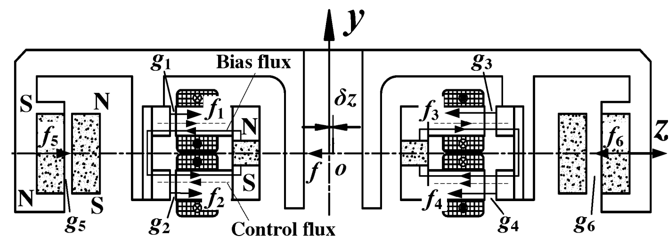


Fig. 4. The force produced by the RMB and the PMB in z-axis direction.

direction of z-axis, while an opposite force will be produced by the passive magnetic bearing (PMB). The opposite force produced by the PMB will affect the performance of the RMB, thus it must be calculated in the design of the RMB. The stabilizing force is produced by the RMB in the z-axis direction.

Fig. 4 describes the operating principle of the magnetic bearing system when the rotor has a displacement by δy from its center with disturbance force in positive direction of y-axis. Since the radial air gaps from g_1-g_6 do not change, the rotor still locates at radial center, and no control current is needed to produce the control flux. The force produced by the PMB and RMB is shown in Fig. 4. The net restoring force, f, in negative direction of z-axis is produced. The stabilizing force is almost produced by the PMB in the y-axis direction.

Assuming that the rotor receives disturbed moment around x-axis orthogonal to the spin axis, the rotor will rotate counterclockwise as shown in Fig. 5. The air gaps g_2 and g_3 will decrease, and g_1 and g_4 will increase. Then the force produced by the RMB will change accordingly without control current. Then the magnetic force produced by the four magnetic poles respectively due to the change of air gaps can be compared as follows:

$$f_1 + f_4 < f_2 + f_3. \tag{1}$$

Thus, the moment produced by force f_1 and f_4 is smaller than the moment produced by f_2 and f_3. And a counterclockwise moment T_1 whose direction is the same as the disturbed moment is produced. Also a restoring moment T_2 is produced by the PMB to stabilize the rotor. When the restoring moment T_2 is larger than the sum of the other moments, such as the disturbed moment and moment T_1 which produced by the permanent magnet of RMB, the net restoring moment T will be produced.

In the same way, similar results can be concluded when the rotor receives disturbed moment around z-axis.

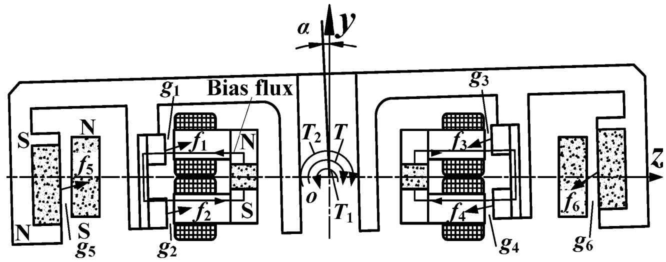


Fig. 5. The moment produced by the RMB and PMB around x-axis.

TABLE I
DESIGN PARAMETERS

Parameters	Value
Parameterization of RMB	
The area of the stator magnetic pole face, mm^2	262.1
The cross-section area of magnet ring, mm^2	999
The outer diameter of magnet ring, mm	59
The inner diameter of magnet ring, mm	47
The thickness of magnet ring, mm	5
Air gap, mm	0.8
The number of winding turns	150
Parameterization of axial/tilting passive magnetic bearing	
The outer diameter of the stator magnet, mm	185
The inner diameter of the stator magnet, mm	175
The thickness of the stator magnet, mm	10
The air gap between stator magnet and rotor magnet, mm	1
The outer diameter of the rotor magnet, mm	197
The inner diameter of the rotor magnet, mm	187
The thickness of the rotor magnet, mm	10

III. PERFORMANCE ANALYSIS OF THE SYSTEM

A. Design Parameters

The main parameters of the system are the maximum magnetic force, current stiffness, and position stiffness which affect the performance of the MSW. For agile satellite the effect of the satellite attitude move on the system stability, must be considered, and a high angular stiffness (referred to the tilting stiffness) is required. Whereas a high tilting stiffness which is used to solve the moving-gimbal effects is required in magnetically suspended control moment gyroscope [12] and decides the value of output moment. According to the above-mentioned requests, the force, moment, tilting stiffness and power, etc. are synthesized for the magnetic bearing system design. The design parameters of system are calculated according to the requirement of the MSW with angular momentum of 15 N·m· s (the rotor mass is 3.6 kg), the gyroscopic torque is created up to 10 N·m, and the strength of the material is also calculated. The example aims at the validation of integral design and analysis method based on 3-D finite-element method. And the design parameters are shown in Table I.

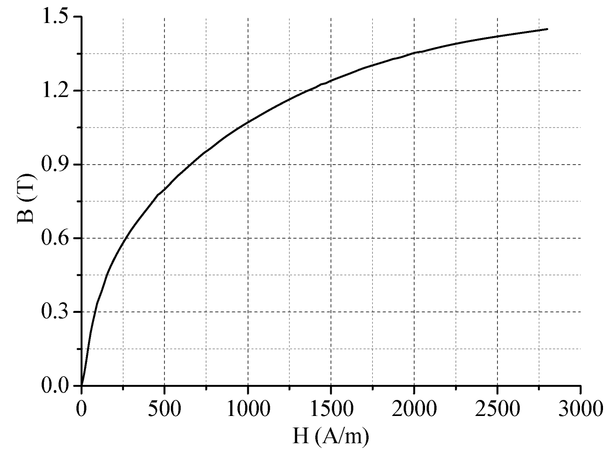


Fig. 6. B-H curve of soft magnetic material.

TABLE II
PARAMETERS FOR PERMANENT MAGNET

Parameters	Value
The residual flux density, Tesla	1.0503
The coercive field force, kA/m	796
The relative permeability	1.05

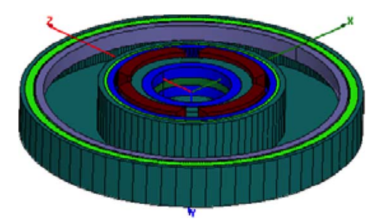


Fig. 7. 3-D finite-element model.

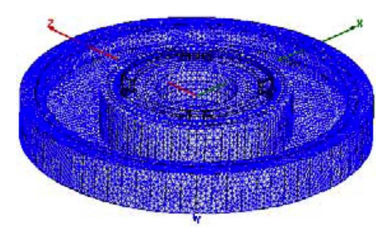


Fig. 8. 3-D finite-element mesh.

The core of the RMB stator and rotor is made in soft magnetic material the B-H curve of which is shown in Fig. 6.

The parameters for permanent magnet in this paper are shown in Table II.

The 3-D finite-element model using Ansoft Maxwell V13 is built and is shown in Fig. 7 except the air. And its mesh is shown as Fig. 8 the total number of which is 412 420.

B. Analysis Results

The magnetic force produced by the permanent magnet of the PMB and RMB is zero when the rotor locates centrally, but it can be affected by the control current. Fig. 9 shows the magnetic force variations with the control current by FEM, the control currents in the x axis (or z axis) coils change from -0.75

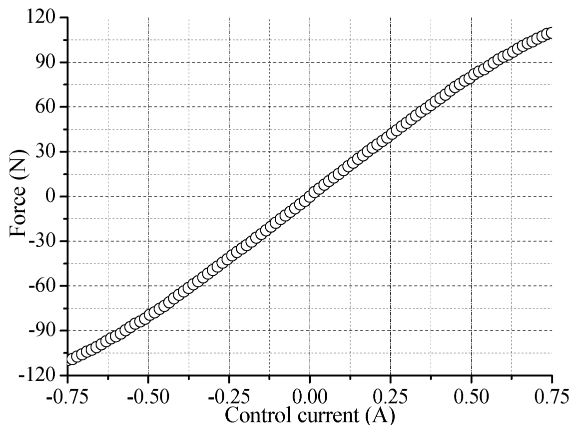


Fig. 9. Calculated bearing force versus control current.

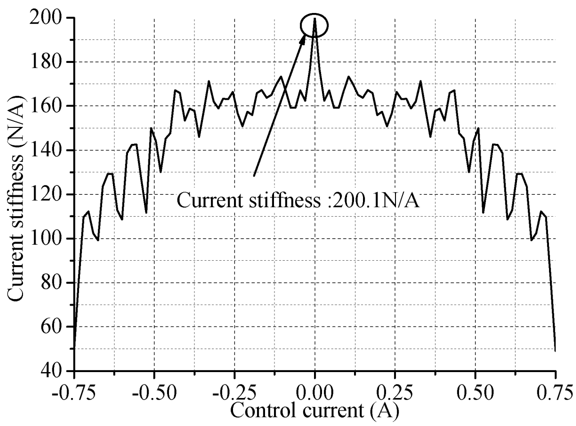


Fig. 10. Calculated current stiffness by FEM.

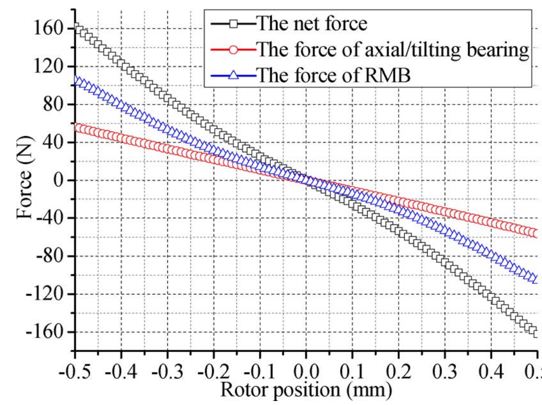


Fig. 11. Calculated force versus rotor position without control current (x/z-axis).

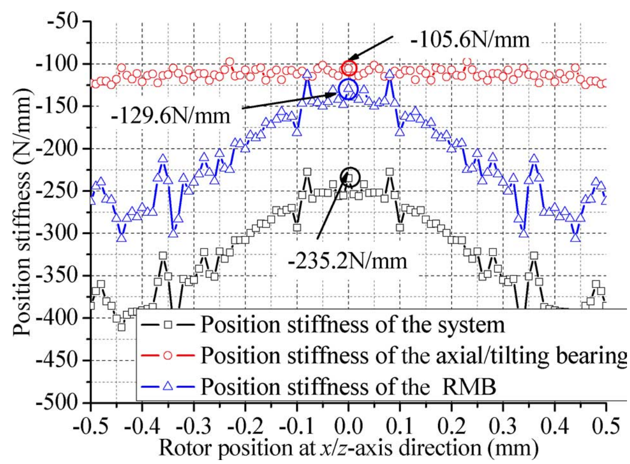


Fig. 12. Calculated position stiffness (x/z-axis).

A to 0.75 A, and the current step is 0.015 A, then the corresponding net force will be produced. The current stiffness calculated through the first derivative of the curve in Fig. 9 is given in Fig. 10 and is 200.1 N/A when the rotor locates its central position.

The curves that calculated net force versus rotor position, calculated force produced by the PMB, and force produced by the RMB without control current in direction of x-axis or z-axis are shown in Fig. 11. The net force is affected by both the RMB and the PMB. It is obvious that the magnetic force produced by the PMB is near-linear, whereas the force produced by the RMB is nonlinear, and is near-linear dependency to the small values of rotor position. The nonlinear relationship of the net force is affected by the RMB. Since the permanent magnet of the PMB is axially magnetized. This can be further proved by the curves of the position stiffness in x-axis or z-axis direction shown in Fig. 12. And the position stiffness turns out to be negative which is a major drawback since much effort for the position controller is necessary to overcome it, and also the achievable control quality will be limited.

In the rotor center, the position stiffness of the system is -235.2 N/mm in direction of x/z-axis while the position stiffness of the PMB is -105.6 N/mm which accounts for 44.9% of the system position stiffness. And to overcome it control current is required.

Similarly, the curves of calculated net force versus rotor position, calculated force produced by the PMB, and force produced by the RMB without control current in direction of y-axis are shown in Fig. 13. The force produced by the RMB is small enough to ignore the rotor position variation in y-axis; therefore the net force is determined by the force which produced by the PMB. The net force is near-linear to the small values of rotor position.

It can be further proved by the curves of the position stiffness in direction of y-axis shown in Fig. 14. In the rotor center, the position stiffness of the system, RMB and PMB is 223.88 N/mm, 16.81 N/mm, 207.08 N/mm respectively which all turn out to be positive, therefore no control current is required. The position stiffness of the RMB accounts for only 7.5% of the system position stiffness, therefore the total position stiffness is determined by the position stiffness of the PMB.

The curves of calculated moment which comprise the net moment, the moment produced by the PMB, the moment produced by the RMB versus angular position of rotor around x-axis or z-axis without control current are shown in Fig. 15. And the curves of the tilting stiffness are shown in Fig. 16. The moment produced by the RMB is small enough to ignore, therefore the net moment is determined by the moment produced by the PMB. In the rotor center, the tilting stiffness of the RMB, the axial/tilting bearing and the system is -24.79 N·m/rad,

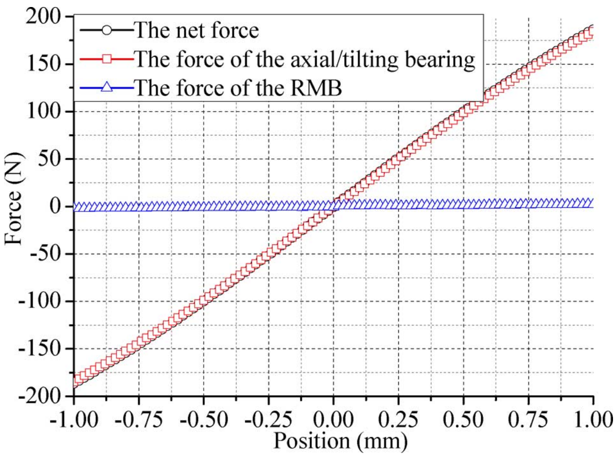


Fig. 13. Calculated force versus rotor position without control current (y-axis).

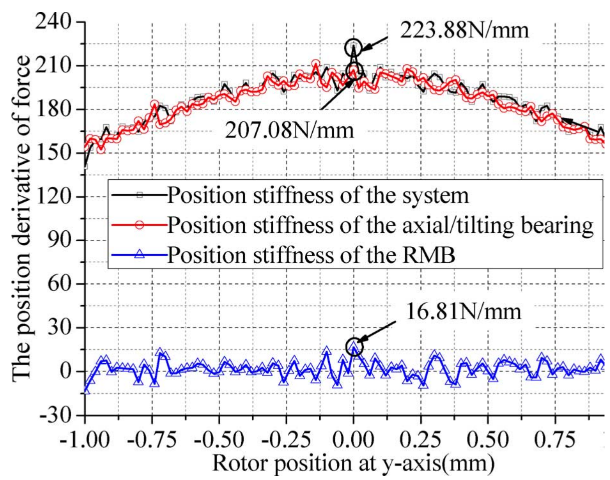


Fig. 14. Calculated position stiffness (y-axis).

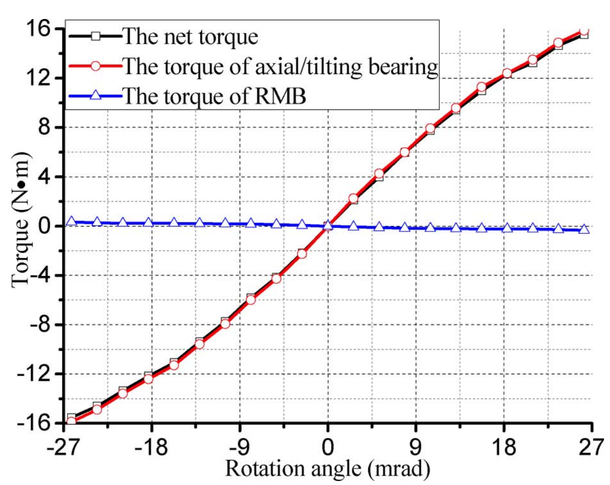


Fig. 15. Calculated moment versus the angular position of rotor.

861.18 N·m/rad, 819.94 N·m/rad respectively. The tilting stiffness of RMB is negative while that of PMB is positive. The tilting stiffness of the RMB accounts for 3% of the tilting stiffness of the system. And when the rotation angle about x-axis or z-axis is 1.5° the output moment of the system can reach 15.5 N·m.

Fig. 17 shows distributions of flux density vectors and the distributions of flux density vectors in y-z sectional area are shown

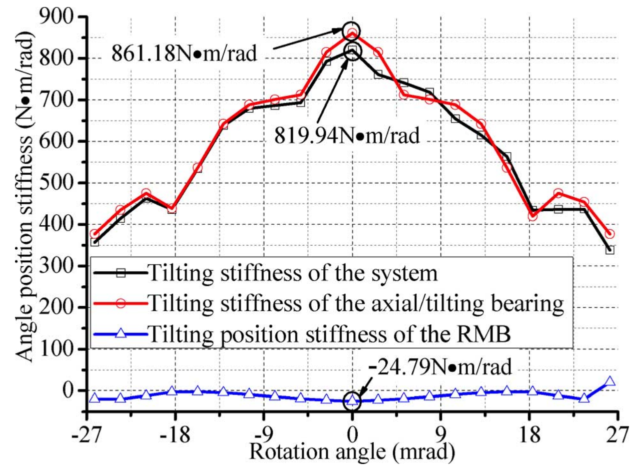


Fig. 16. Calculated tilting stiffness.

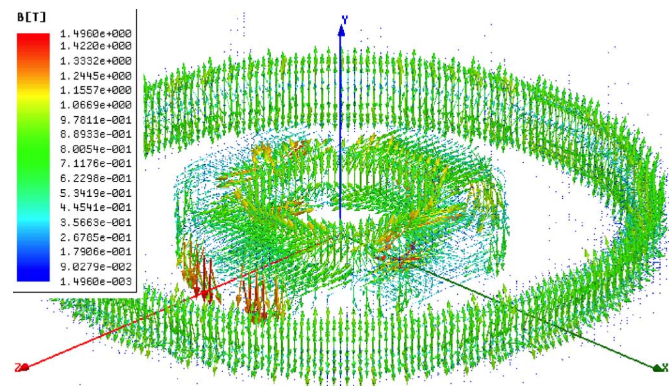


Fig. 17. Distributions of flux density vectors of the system in case that the rotor in its center position without control current.

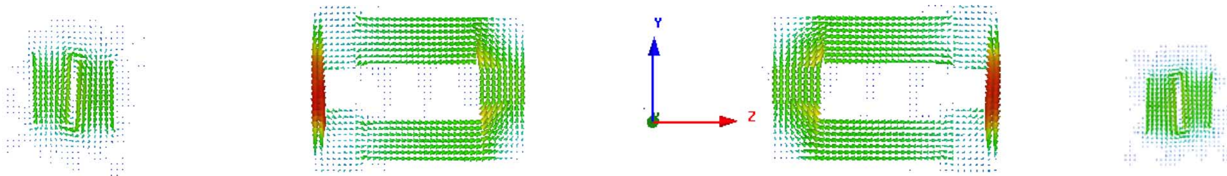
in Fig. 18 when there is no control current. The flux density in left air gap, g_5, is equal to the flux density in right air gap, g_6, for the PMB, and the flux density in left air gaps, g_1 and g_2, is equal to the flux density in the air gaps, g_3 and g_4, for the RMB. The magnetic force is only produced by the permanent magnets of the PMB and RMB, so net force is zero when the rotor locates its central position.

When the rotor has a displacement by 10 μm in z-axis direction and the control current is 0.5 A in coils as shown in Fig. 3, the control flux in right air gaps of the RMB, g_3 and g_4, will be added to the bias flux and subtracted in the left air gaps, g_1 and g_2. Then a restoring force will be produced on the rotor in the negative direction of z-axis. Fig. 19 shows the distributions of flux density vectors in y-z sectional area of the system.

The linearized system model through the 3-D FEM is given in (6).

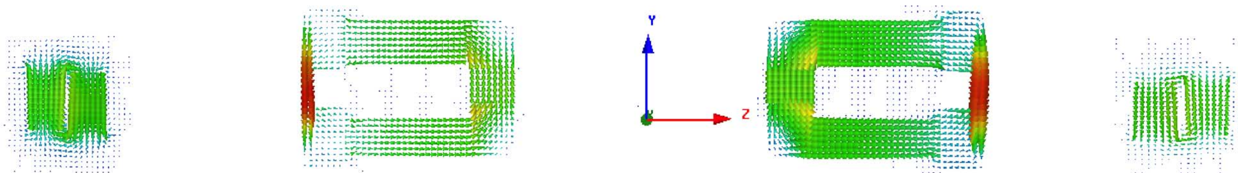
$$\begin{cases} f_x = k_{i_x} i_x + k_x x = 200.1 i_x - 235.2 \times 10^3 x \\ f_z = k_{i_z} i_z + k_z z = 200.1 i_x - 235.2 \times 10^3 z \\ f_y = k_y y = 223.88 \times 10^3 y \\ T_x = k_\alpha \alpha = 819.94 \alpha \\ T_z = k_\beta \beta = 819.94 \beta \end{cases} \tag{2}$$

where k_{ix} and k_x is the current and position stiffness of the system in x-axis respectively, similarly, k_{iz} and k_z is in the z-axis, k_y is in the y-axis, k_α is the tilting stiffness around x-axis



(Flux density vectors of PMB) (Flux density vectors of RMB) (Flux density vectors of RMB) (Flux density vectors of PMB)

Fig. 18. Distributions of flux density vectors in y-z cross section when the rotor locates its central position and there is no control current.



(Flux density vectors of PMB) (Flux density vectors of RMB) (Flux density vectors of RMB) (Flux density vectors of PMB)

Fig. 19. Distributions of flux density vectors in y-z cross section when the rotor has a displacement by 10 μm in z-axis direction and the control current is 0.5 A.

and k_β around y-axis. The model is based on the system with PMB and RMB for agile satellite application during the integral design and analysis. It shall be noted that the rotor can be controlled by this integral magnetic bearing system in five degrees of freedom. The position stiffness of the model is 223.88×10^3 N/mm in y-axis, the tilting stiffness is 819.94 N·m/rad around x-axis and z-axis when the rotor locates its center position. It's near exact when the rotor position changes from -25 μm to 25 μm and the rotation angle of rotor position changes from $-0.3°$ to $0.3°$ around x-axis or z-axis. The current stiffness and position stiffness are 200.1 N/A and -235.2×10^3 N/mm respectively when the rotor locates its center position. It's also near exact when the control current changes from -0.4 A to 0.4 A. The dynamic model is nearly exact when the rotor locates near its center position and can be used to analyze the system stability and design controller which is used to eliminate the negative position stiffness. The design parameters, such as the permanent magnet, control current, and the coils, etc. will all affect the performance of the system. The sensitivity of the model with respect to the design parameters will be introduced in the future.

IV. Conclusion

A novel magnetic bearing system which consists of PMB and RMB used in MSW or MSCMG for agile satellite application is presented. The PMB can supply an axial position stiffness to stabilize the rotor in the axial direction and a tilting stiffness to restrain the rotor from the disturbed moment. An integral design and analysis method based on 3-D FEM is presented to analyze the coupling problem of the force, moment, position stiffness and tilting stiffness between the PMB and RMB. An example is given and analysis results prove that when the rotation angle is 1.5° about x-axis or z-axis the output moment of the system can reach 15.5 N·m. Also the linearized model is presented in this paper.

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References

[1] D. A. Christopher and R. Beach, "Flywheel technology development program for aerospace applications," *IEEE Aerosp. Electron. Syst. Mag.*, vol. 13, no. 6, pp. 9–14, 1998.
[2] F. Congyu and L. Yingtang, "Nonlinear control law of satellites attitude at zero-speed of reaction wheels," (in Chinese) *Chin. Space Sci. Technol.*, vol. 10, no. 5, pp. 21–24, 2001.
[3] W. Feng, S.-J. Zhang, and X.-B. Cao, "Research and semi physical simulation for the compensation observer of wheel low speed friction," (in Chinese) *J. Syst. Sim.*, vol. 17, no. 3, pp. 613–616, 2005.
[4] W. Auer, "Ball bearing versus magnetic bearing reaction and momentum wheels as momentum actuators," in *AIAA Int. Meeting & Technical Display "Golbal Technology 2000"*, Baltimore, 1980, pp. 1–5, AIAA-80-0911.
[5] T. Azukizawa, S. Yamamoto, and N. Matsuo, "Feasibility study of a passive magnetic bearing using the ring shaped permanent magnets," *IEEE Trans. Magn.*, vol. 44, no. 11, pp. 4277–4280, Nov. 2008.
[6] P. Samanta and H. Hirani, "Magnetic bearing configurations: Theoretical and experimental studies," *IEEE Trans. Magn.*, vol. 44, no. 2, pp. 292–300, Feb. 2008.
[7] R. Ravaud, G. Lemarquand, and V. Lemarquand, "Force and stiffness of passive magnetic bearings using permanent magnets. Part 1: Axial magnetization," *IEEE Trans. Magn.*, vol. 45, no. 7, pp. 2996–3002, Jul. 2009.
[8] T. M. Brian *et al.*, "Permanent magnet bias, homopolar magnetic bearings for a 130 kW-hr composite flywheel," in *Ninth Int. Symp. Magnetic Bearings*, Lexington, KY, Aug. 2004, pp. 66–72.
[9] O. V. Tozoni, "New stable magnetodynamic suspension system," *IEEE Trans. Magn.*, vol. 35, no. 2, pp. 1047–1054, Mar. 1999.
[10] A. Musolino *et al.*, "A new passive maglev system based on eddy current stabilization," *IEEE Trans. Magn.*, vol. 45, no. 3, pp. 984–987, Mar. 2009.
[11] Y. Zhilichev, "Analysis of a magnetic bearing pair with a permanent magnet excitation," *IEEE Trans. Magn.*, vol. 36, no. 5, pp. 3690–3692, Sep. 2000.
[12] T. Wei and J. Fang, "Moving-gimbal effects and angular rate feedforward control in magnetically suspended rotor system of CMG," *J. Astronautics*, vol. 26, no. 1, pp. 19–23, 2005.
[13] X. Yanliang *et al.*, "Analysis of hybrid magnetic bearing with a permanent magnet in the rotor by FEM," *IEEE Trans. Magn.*, vol. 42, no. 4, pp. 1363–1366, Apr. 2006.
[14] H. Bangcheng, "Modeling and analysis of novel integrated radial hybrid magnetic bearing for magnetic bearing reaction wheel," *Chin. J. Mech. Eng.*, vol. 23, no. 5, pp. 1–8, 2010.
[15] C. Ehmann, T. Sielaff, and R. Nordmann, "Parison of active magnetic bearings with and without permanent magnet BIAS," in *Ninth Int. Symp. Magnetic Bearings*, Aug. 2004.

[16] F. Jiancheng, S. Jinji, L. Hu, and T. Jiqiang, "A novel 3-DOF axial hybrid magnetic bearing," *IEEE Trans. Magn.*, vol. 46, no. 12, pp. 4034–4045, Dec. 2010.
[17] H. Liu, J.-C. Fang, and G. Liu, "Research on the stability of magnetic bearing system in magnetically," *J. Astronautics*, vol. 30, no. 2, pp. 625–630, 2009.
[18] K. R. Rajagopal and K. K. Sivadasan, "Low-stiction magnetic bearing for satellite application," *J. Appl. Phys.*, vol. 91, no. 10, pp. 6994–6996, 2002.

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