Design, Analysis and Simulation of a Triaxial Spacecraft Attitude Control Testbed Based on Magnetic Bearing

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Abstract: Because of its technological significance, spacecraft attitude control testbed, have been widely used for the Earth-based testing of the spacecraft attitude systems. Traditionally, the spacecraft attitude control testbed is based on spherical air bearing, in this paper, a new kind of triaxial attitude control testbed (TACT) based on magnetic bearing is designed. The structure of the TACT is introduced, including it working principle. This paper especially described the hemispherical magnetic bearing applied in the TACT, designed a new kind of hemispherical magnetic bearing, and analyzed the distribution of the magnetic field in the bearing. In this paper, the magnetic force of the magnetic bearing is obtained by electromechanical-energy-conversion principles, the analytical equation of the mathematical model of the TACT is deduced, which make the feasibility of this design is verified.

Keywords: Magnetic Bearing, Triaxial Attitude Control Testbed, Spacecraft Attitude Control, Earth-Based Physical Simulation, Simulator

Introduction

Launching a spacecraft is a high-cast, high-profit, and high-risk venture. One way to mitigate much of this risk is to demonstrate the system by enough earth-based testing[1]. The triaxial spacecraft attitude control testbed is a kind of Simulator, which replicate a tiny gravity and low torque space-like dynamics environment on the ground, it mainly used for the Semi-physical Earth-based simulation or Full-physical simulation of the spacecraft attitude dynamics and control system[2].

Traditionally, triaxial spacecraft attitude control testbed usually based on the air bearing[3], but air bearing rotational system have their limitations, air bearings propelled by thin film of compressed air, interference torque caused by the glutinousness and the eddy of the compressed air will cause bad influence to the simulate. And, because of complex pneumatic circuit and precise surface of sphere, the manufacturing cost is too much; At work, it need a continuous gas supply, the system is cumbersome and expensive, and operate inconvenient. In this paper, a new kind of triaxial spacecraft attitude control testbed based on magnetic bearing, which allows unrestricted motion in yaw and $\pm 45°$ in roll and pitch angles. It have high performance index, simple structure, low cost, controllable and eco friendly. It is very suitable for the simulation of spacecraft attitude dynamics and control system, and the researching of spacecraft dynamics and control.

Design of the TACT

The essential principle of the triaxial spacecraft attitude control testbed is based on the physical implementation of a 3D pendulum[4]. The 3D pendulum and the load mounted above is suspend by spherical magnetic bearing, which support a 0-g condition and very low friction similar with the space environment, and the testbed have three degrees of rotational freedom, offer a financially viable option for Earth-based testing of advanced spacecraft dynamics and control components.

Particularly, this triaxial spacecraft attitude control testbed is consists of rotational platform system and pedestal system. (see Fig.1. and Fig.2.) The rotational platform system contains mounting plate, avionics, and barycenter control system, which is consist of XYZ balance weight, balance arm, pressure pickup and barycenter regulator. The mounting plate is a thick stainless aluminium alloy platform, which components can be mounted above. The avionics which include sensors, wireless devices and the spacecraft processors mounted under the plate. The hemispherical rotor of the magnetic bearing is mounted to the lower of the rotational platform, that make all the rotational platform system floating, and have three degrees of rotational motion. Fig. 2. shows the three dimensional view.

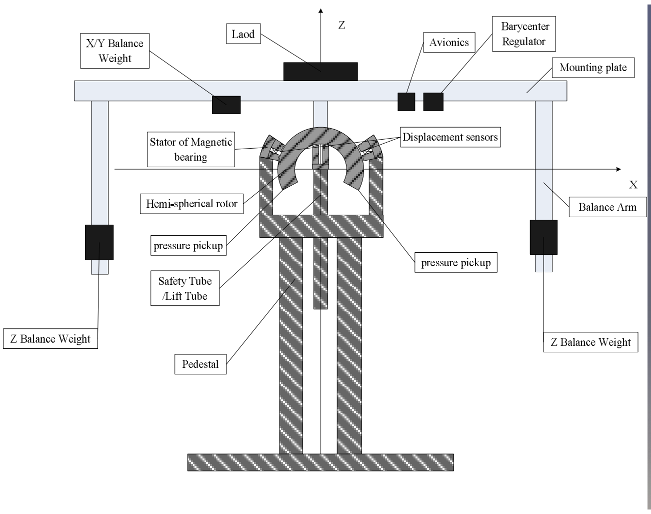


Fig.1. Structure of the TACT

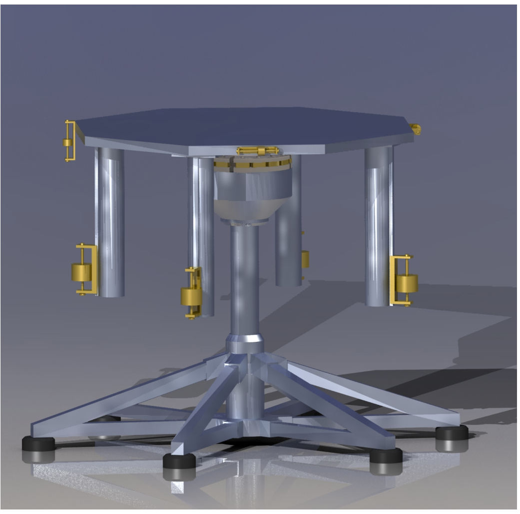


Fig.2. The 3-D view of the TACT

The pedestal system is consists of the magnetic bearing system and the pedestal. As an active magnetic bearing system, it contains the hemi-spherical rotor, transducer， controller, power amplifier and the stator with a spherical interface (schematic diagram of its structure is shown in Fig. 3.) . The rotor is a sphere cup made of material of high permeability. The stator is composed of four poles, two for the x-z direction, and two for the y-z direction. In each pole, electromagnetic coils is fixed in the stiffness stator magnet assemblies, which generate magnetic flux, that radially through the air gaps equally. The position sensor is fixed in the air gap, it obtains the position of the rotor, and control the air gap constant. The pedestal is a holder made of aluminium alloy.(see Fig.2.)

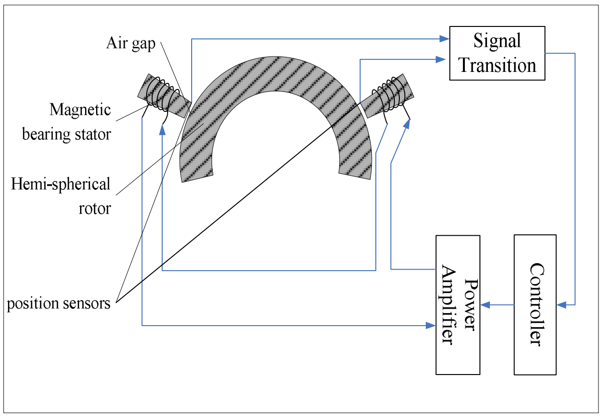


Fig.3. Schematic diagram of the magnetic bearing

Principle of The TACT

A. Sphere Magnetic Bearing

Fig. 3. shows the sphere magnetic bearing used in the triaxial spacecraft attitude control testbed. At work, the stator provides the bias flux, when the hemi-spherical rotor placed in by the lift tube, the magnetic force will be obtained, and make the platform floating. The displacement sensors get the signal of the rotor's position, control the current in electromagnetic coils to supply the control flux, kept the air gap constant.

In alalyzing the TACT controlled dispersedly, with the assumption of neglecting magnetic circuit resistance, leakage effects, and the variance of the effective cross section area of the air gap, the magnetic force for X,Y,Z direction can be expressed as

$$F_x = 2\sqrt{2}dr\mu_0 N^2\cos\theta[(\frac{i_{x0}+i_x}{\delta + x\cos\theta})^2 - (\frac{i_{x0}-i_x}{\delta - x\cos\theta})^2]$$

$$F_y = 2\sqrt{2}dr\mu_0 N^2\cos\theta[(\frac{i_{y0}+i_y}{\delta + y\cos\theta})^2 - (\frac{i_{y0}-i_y}{\delta - y\cos\theta})^2]$$

$$F_z = 8\sqrt{2}dr\mu_0 N^2\sin\theta[(\frac{i_{x0}+i_z}{\delta + z\sin\theta})^2 + (\frac{i_{y0}+i_z}{\delta + z\sin\theta})^2] - G$$

d is the thickness of the stator core, r is the radius of the hemi-sphere, μ_0 is the vacuum magnetic conductance, N is the number of winding turns, θ is the gradient of the stator, i_{x0} i_{y0} is the bias current, i_x i_y i_z is the dynamic control current, δ is the nominal air gap, x y z is the dynamic displacement of the rotor.

The linearization of the Eq. can obtained as follow:

$$F_x = K_x \cdot x + K_{i_x} \cdot i_x$$

Follow: $K_x = \frac{8\sqrt{2}dr\mu_0 N^2 i_{x0}\cos\theta}{\delta^2}, K_{i_x} = -\frac{8\sqrt{2}dr\mu_0 N^2 i_{x0}^2\cos^2\theta}{\delta^3}$

So strategy of PID control can be used.

B. TACT

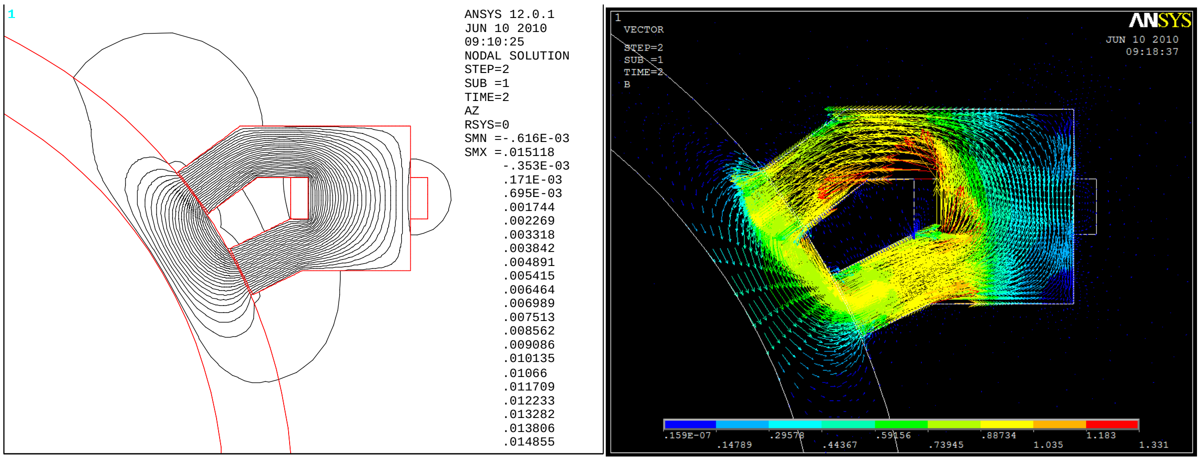
When use the TACT to do some simulation of the spacecraft attitude control, mount the spacecraft or the components above the platform, adjust the position of the XYZ three orthogonal balance weight to make the barycenter of the attitude platform system and the load coincided with its center of rotation (the spherical center of the hemi-spherical magnetic bearing) ,the attribute can simulates a zero or low gravity spacecraft environment with no friction. In this case, the equations of motion of the components and the platform are given by[5]

$$\begin{cases} J\dot{\omega} = J\omega \times \omega \\ \dot{R} = R\omega \end{cases}$$

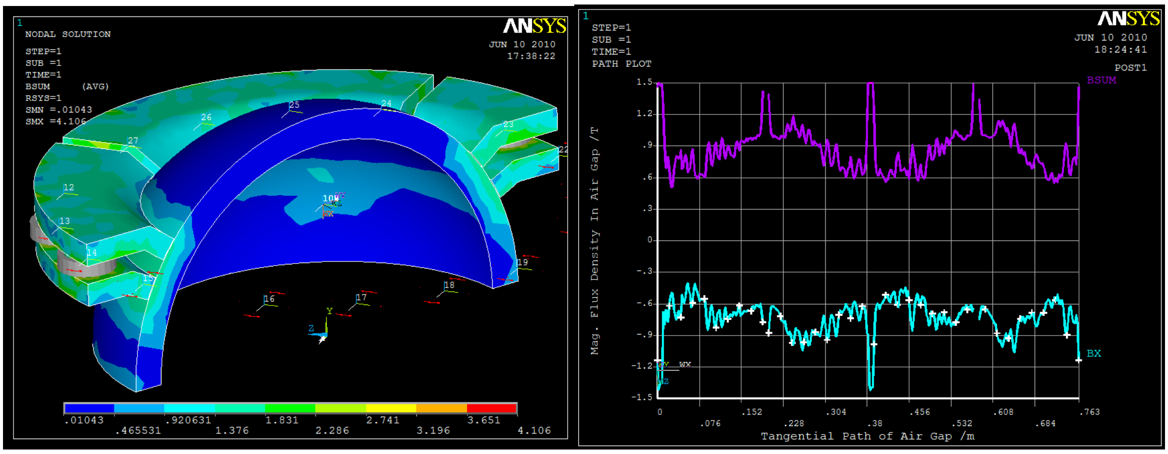
J is the inertia matrix of the platform system and the load, ω is the angular velocity of the it, R is the attitude of the platform system and the load in a inertia coordinate. These equations are the same with the global attitude dynamics of rigid spacecraft in a high altitude circular orbit.

Result of the Simulation of Sphere Magnetic Bearing Used in The TACT

This paper also analyzed the distribution of the magnetic field in the bearing, and get the magnetic force attribute of the magnetic bearing by ANSYS software. Fig.4. is the 2-D contour plot of the flux lines and the 2-D vector plot of the flux density.



Fg.4. 2-D flux lines and the vector plot of the flux density



Fg.5. Contour plot of the flux density and the graph plot of the flux density in the air gap

Fig.5 is the 3-D contour plot of the Mag. flux density in the TACT and the graph plot of the flux density in the air gap. The magnetic bearing force output is shown in Table1, when the air gap is 0.4mm, and the MMF is 600 ampere-turns, and the rotor displacement is 0. In this case, the TACT's carrying capacity is 529Kg, that is a perfect performance.

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                          SUMMARY OF FORCES BY VIRTUAL WORK
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  UNITS OF FORCE:          ( N )

  COMPONENT           FORCE-X            FORCE-Y            FORCE-Z

  ROTOR               -0.28511E+02       0.69810E+01        0.52902E+04
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Tab.1. The mag. force of the rotor obtain by the ANSYS software

The magnetic bearing force output versus input control MMF is plotted in Fig.6. when air gap is 0.3mm, 0.4mm,0.5mm. And the Fig.7 shows the mag. force vs the air gap when the MMF is 600A-Turns.

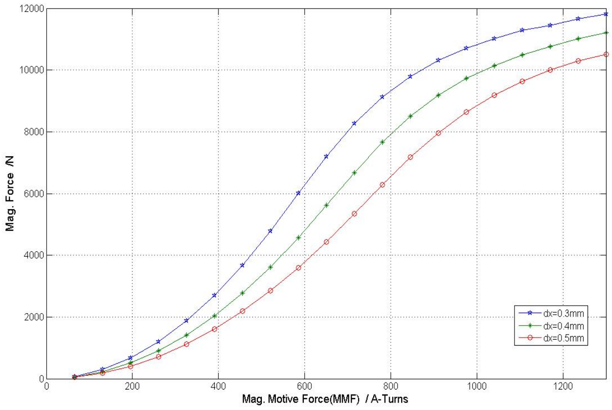

Fig.6. The mag. force vs MMF

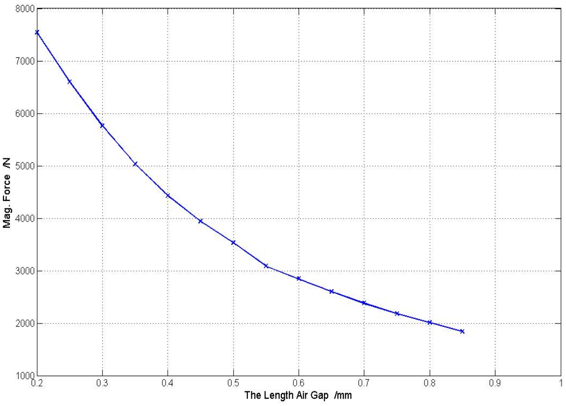

Fig.7. The mag. force vs air gap

The two fgures show that in this design the actuator could produce a load of 10000N(1000Kg), and an ambient condition the degree of linearity of the force vs MMF and the force vs air gap is very good. As the air gap's increasing the degree of the force vs MMF will be better, and as the MMF's increasing the degree of the force vs MMF will be worse, that is because of the magnetic saturation of the stator.

Conclusions

In this paper, a TACT based on magnetic bearing is designed, which provide the basis for Earth-based testing of the spacecraft attitude dynamics and control systems. And a new kind of suspending system for the TACT is designed, which have high performance index, simple structure, low cost and controllable. The magnetic attribute of the new magnetic bearing is analyzed, the load capacity of the TACT is obtained, it shows the magnetic bearing based TACT have a perfect performance, and make the feasibility of this design is verified.

References

[1] Lu Xingju. Design Analysis of Spacecraft Attitude Control Table [D],National Univ of Defense Tech.2005.11

[2] Xu Jian, Bao Gang, Yang QinJun, Li Jun. Design and Development of a 5-DOF Air-Bearing Spacecraft Simulator. International Asia Conference on Informatics in Control, Automation and Robotics.2009:126-130.

[3] Schwartz Jana L, Peck Mason A, Hall Christopher D, Historical Review of Spacecraft Simulators[J]. Advances in the Astronautical Sciences, vol. 114, 2003: 405-423.

[4] J. Shen, A.K. Sanyal, N.A. Chaturvedi, D. S. Bernstein, N. H. McClamroch, Dynamics and Control of a 3D Pendulum. Proceedings of the 43rd IEEE Conference on Decision & Control, Bahamas, December, 2004: 323-328.

[5] Mario A. Santillo, Nalin A. Chaturvedi, N. Harris McClamroch, Dennis S. Bernstein. 3D Pendulum Experimental Setup for Earth-based Testing of the Attitude Dynamics of an Orbiting Spacecraft. Proceedings of the 2007 American Control Conference. New York, July 2007:2479-2484.