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Dynamic characteristics of the rotor in a magnetically suspended control moment gyroscope with active magnetic bearing and passive magnetic bearing

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ABSTRACT

For a magnetically suspended control moment gyroscope, stiffness and damping of magnetic bearing will influence modal frequency of a rotor. In this paper the relationship between modal frequency and stiffness and damping has been investigated. The mathematic calculation model of axial passive magnetic bearing (PMB) stiffness is developed. And PID control based on internal model control is introduced into control of radial active magnetic bearing (AMB), considering the radial coupling of axial PMB, a mathematic calculation model of stiffness and damping of radial AMB is established. According to modal analysis, the relationship between modal frequency and modal shapes is achieved. Radial vibration frequency is mainly influenced by stiffness of radial AMB; however, when stiffness increases, radial vibration will disappear and a high frequency bending modal will appear. Stiffness of axial PMB mainly affects the axial vibration mode, which will turn into high-order bending modal. Axial PMB causes bigger influence on torsion modal of the rotor.

1. Introduction

Because a magnetically suspended control moment gyroscope (MSCMG) owns advantages on low loss, non-friction, and tiny vibration, etc. [1], it is regarded as one of the ideal executors to realize high precision attitude control of a spacecraft [2] through changing the angular momentum direction of the high-speed rotor [3,4]. However, compared with the ordinary machine bearing, the shortage of starting mechanical characteristics of magnetic bearing is evident; simultaneously, the harmonic vibration and random vibration are relevant to the frequency and equivalent stress of the rotor [5]. Some researchers had focused on the structure optimization and dynamic characteristic of the magnetically suspended rotor to improve its mechanical characteristics. Han adopted a sequential quadratic programming method to optimize the mass and stiffness of the rotor, and introduced a finite element method (FEM) into analyzing theoretically the structure modal of magnetically suspended flywheel [6]. Based on the transfer matrix method, Wan made some researches on the critical speed and stability of the slim rotor suspended by the magnetic bearing [7]. But there is lack of research on the relationship between the parameters of magnetic bearing and rotor modals.

In this paper, through investigating on dynamic characteristics of the flat rotor suspended by radial AMB and axial PMB, calculation methods for stiffness and damping of magnetic bearing are proposed; moreover, the relationship between rotor modals and parameters of magnetic bearings is achieved by applying the FEM for the dynamic characteristics of the rotor. This paper has been organized as follows. In Section 2, the mathematic analysis for the rotor in MSCMG has been introduced through calculating the stiffness of axial PMB and stiffness and damping of radial AMB. The relationship between the modal frequency and stiffness and damping has been investigated in Section 3.

2. Mathematic analyses for the rotor in MSCMG with radial AMB and axial PMB

2.1. Structure of the rotor in MSCMG with radial AMB and axial PMB

The structure of the MSCMG with AMB and PMB is shown in Fig. 1; the rotor system consists of wheel body, rotor of upper axial PMB, rotor of lower axial PMB, rotor of radial AMB, inner rotor and external rotor of the motor which are fixed on wheel body by the thread ring; the rotor system generates gyroscopic moment when

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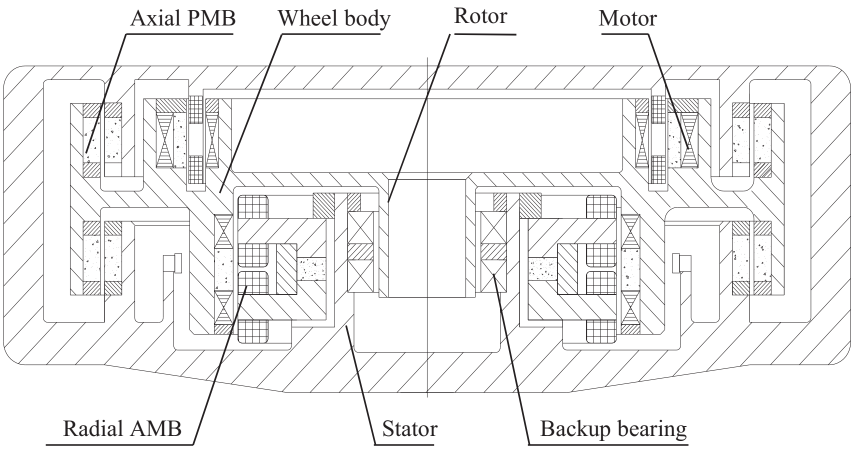

Fig. 1. Structure of the MSCMG with axial PMB and radial AMB.

it rotates at high speed. Stator alnicos of upper and lower axial PMBs and rotor alnicos of axial PMB are magnetized along the axial direction, but their magnetization directions are inverse. Every pair of alnicos form into close magnetic field, which not only reduce the external magnetic disturbance, but also ensure that rotor is suspended stably on the axial direction [10]. When the rotor moves upward, rotor of upper axial PMB will attract stator of upper axial PMB; stator of lower axial PMB will attract rotor of lower axial PMB separately, and then, recovery force generated by two pairs of alnicos will attract the rotor back to equilibrium point. Similarly, when the rotor moves downward, two pairs of alnicos will provide recovery force to the rotor, and keep the rotor stable. However, the axial PMB produces additional negative stiffness on the radial direction. When the rotor moves rightward in the horizontal direction, the left gap of alnico decreases, the attractive force between stator and rotor will increase rapidly. Meantime, on the right side, the attractive force will reduce rapidly because the right gap increases, so the rotor will be unstable on the radial direction. To ensure that the rotor is suspended stably on the radial direction, the radial AMB and displacement sensors are applied. Radial displacement sensor measures the radial location and feedbacks to control loop, which will modulate the current of radial AMB timely to control magnetic force between the stator and rotor of radial AMB based on location signal of rotor and control current signal. When the switch current with definite frequency is imported into the winding of hollow cup motor, the mutual action between switch magnetic field and the magnetic field of inner rotor will generate rotation moment, so the rotatory speed of rotor will be controlled. In order to make the rotor suspend and inhibit collision with other components when magnetic bearing invalidates, backup bearing is joined in the middle of rotor; moreover, reasonably designing the gap between the backup bearing and rotor, the collision and touch between the stator and other components of rotor can be avoided.

Axial PMB and radial AMB can make the rotor suspend stably; meantime, influences on rotor dynamics characteristics caused by stiffness and damping of magnetic bearing cannot be ignored; especially in this paper, axial PMB will produce negative stiffness along radial direction so that radial stiffness of radial AMB seriously reduces, as a result, the rotor dynamics characteristics will be affected.

2.2. *Force and the stiffness of axial PMB*

According to the structure of MSCMG with axial PMB and radial AMB as shown in Fig. 1, the axial suspension of rotor is realized by axial PMB as shown in Fig. 2. To ensure the calculation for the stiffness of axial PMB more clearly, PMB can be simplified into the structure as shown in Fig. 3; we only analyze one pair of magnetic poles. When stator and rotor move along axial direction, path$_m$ and path$_f$ are used to represent the practical distribution of magnetic field, where path$_m$ is the main magnetic flux between the stator and rotor when magnetic pole of stator coincides with magnetic pole of rotor. When magnetic pole of stator does not coincide with magnetic pole of rotor, path$_f$ is the fringing magnetic flux. Assuming gap g_f of fringing magnetic flux is proportional to the axial displacement, according to Fig. 4, g_f is

$$g_f = g_m + (g_{f0} - g_m)\frac{\Delta h}{h} \tag{1}$$

where g_m is the air gap when magnetic pole of stator coincides with magnetic pole of rotor, g_{f0} is the equivalent air gap of path$_f$ when magnetic pole of rotor and stator starts to coincide, and Δh is the relative drift between stator and rotor. According to

Fig. 2. Structure of axial PMB.

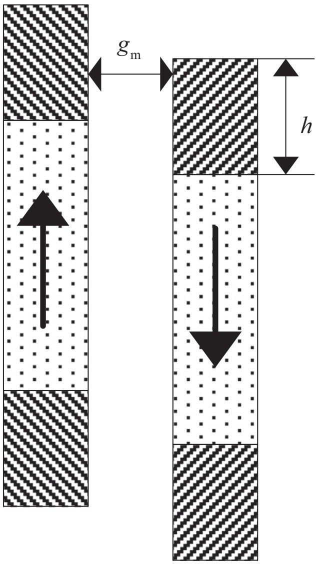

Fig. 3. Simplified axial PMB.

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