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EXPERIMENTAL RESEARCH ON A MOMENTUM WHEEL SUSPENDED BY ACTIVE MAGNETIC BEARINGS

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ABSTRACT

This paper describes a momentum wheel suspended by AMBs for spacecraft attitude control. Such wheel are low friction and a long lifetime, and high momentum storage can be achieved through high rotational speed. The rotor tend to have strong gyroscope coupling which must be considered in the control system design. To implement the control arithmetic, which include cross feedback based on PD controller, the RT-linux on Personal Computer is selected for experimental researching. Based on the analyzing and simulation, a composite fiber-reinforced high-speed wheel suspended by 5 DOF AMBs system is made, a special sensor is installed into housing by integrated with preamplifier. Some experiment results are given.

INTRODUCTION

Almost all spacecraft in orbit are equipped with momentum or reaction wheel serving as actuators in the attitude control system. The ball bearing wheel can be one of the most harmful disturbance sources for the spacecraft attitude stability due to residual unbalances; bearing imperfections etc. this disadvantage can be avoided by the use of magnetic bearing wheel. For this reason, a research project call AMB-wheel was started at Tsinghua University to develop a momentum wheel suspended by AMBs for attitude control system. The system consists of the following key components:

- A composite fiber-reinforced high-speed wheel
- 5 DOF AMBs to support the rotor
- A high-speed motor to provide power
- High-efficiency power amplifier
- Integrated displacement sensors for AMBs
- Vacuum housing for operation test

The **TABLE** 1 and **Table** 2 show major specifications and the parameters of the magnetic bearings.

TABLE 1: Date of the momentum wheel

Item	Note
Bearing	5 DOF AMBs
Angular momentum	100Nms
Rotation speed	20000 rpm
Mass	13 kg
Moment of inertia	0.065kg.m^2
Power consumption	50w

TABLE. 2 Date of the AMBs system

Item	Value
adial magnetic configuration	Area: 250mm^2
	N=200
	Air gap=0.2mm
Axial magnetic	N=330
	Air gap=0.4mm
Sensor	Integrated eddy current

Moreover, a problem of displacement signal transporting form vacuum housing to controller should be considered. For conventional eddy current sensor, the signal is very weak between probe and preamplifier. it is easy to be disturbance or mixed with noise when it fetch up just there, such as passing through the connecter of vacuum, or a slip ring. Therefore, a special sensor is installed into housing by integrated with preamplifier.

A rigid body model is used for controller design stability and robustness analysis. The strong gyroscopic coupling of a flywheel is considered in the controller design. Decentralized control with analog circuit and centralized control with the RT-linux on Personal Computer are trying in detail.

Gyroscopic effects cause no serious problem to a rigid rotor with little gyroscopic coupling when it is at fast rotation. To such a rotor, a decoupled PID-controller works well for magnetic bearing systems. But to a rotor which is short and thick, such as flywheel, the gyroscopic effects will greatly influence the stabilization of the AMB.

CONTROLLER DESIGN

The nonrotating rotor on elastic supports has two pairs of two rigid-body eigenfrequencies which are equal for the x-z and y-z plane. With increasing rotational speed these eigenfrequencies change as a consequence of the gyroscopic coupling. The four eigenfrequencies are the nutation, two pendulous and the precession frequency. The nutation frequency increases with the rotational speed, while the precession frequency decreases. And the two pendulous frequencies will converge to the same constant value. Rotational speed dependence for the eigenfrequencies is shown in figure 1.

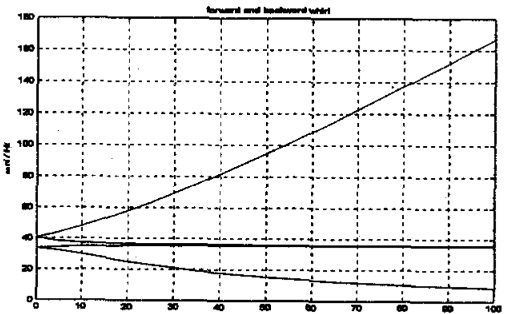

FIGURE 1: Eigenfrequencies of the rigid body model

For studying this kind of influence, some simulations based on SIMULINK of MATLAB are trying in detail. The results show that a well-behaved PID-controller on a decoupled rotor model can't stabilize the rotor at high speed at all, due to the strong gyroscopic effect. Simulation results (the rotor has an initial vibration excitation in the displacement) are shown in **FIGURE 2.** In fact, the precession's bad effects have also been observed in experiments.

More suitable control design techniques must be considered. Coupled controller is the choice. A method of gyroscopic force compensation was mentioned in [1]. Gyroscopic couple feedback control is effective. But here, a different method is discussed.

Firstly, the research on LQR (Linear Quadratic Regulator) is started. Controller design with LQR minimizes the cost function J, and therefore the actuator energy is

$$J = \int_{-\infty}^{+\infty} (x^T Q x + u^T R u) dt \qquad (1)$$

Where x is the state vector and u is the control ouput vector. The feedback law is

$$u = -Fx \qquad (2)$$

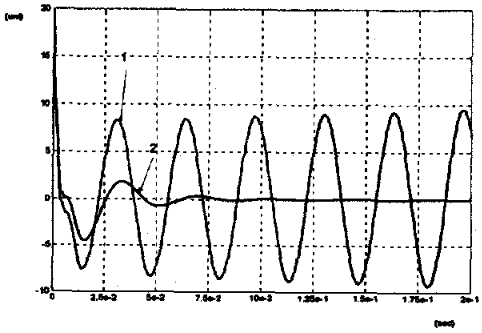

FIGURE 2: Response of the rotor at 0 and 300Hz

1: rotation at 0 Hz; 2: rotation at 300Hz

In a LQR controller design, selection of weighting matrixes Q and R is very important and greatly affect the behavior of the close-loop system. Choosing different Q and R, the simulation results in feedback matrixes F show that the couple elements of feedback matrix can't be ignored any longer, and the couple mainly focuses on the displacement elements.

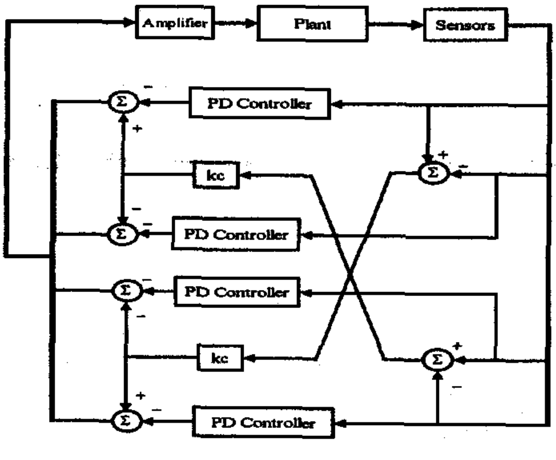

Fig. 3: PD-controller with displacement cross feedback

This implies that it will be an effective way to control the rotor with displacements cross feedback in control channels. In physical essence, it is just the compensation of deflection torque. When the deflection of the rotor is detected, the controller feedbacks an inverse torque proportional to the displacements difference of the vertical plane at two Radial bearings. By this way the PD-controller is designed with displacements cross feedback. Its structure is shown in **FIGURE** 3.

Simulation result with PD-controllers and results with additional displacements cross feedback of different proportional parameters is shown in **FIGURE** 4. The numbers signed in the plot represent different cross feedback coefficients. The numbers 0.0 means control without cross feedback. All the simulations' rotational speeds are 24,000 rpm.

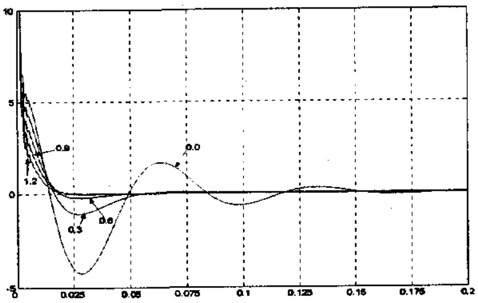

FIGURE 4 Response of the rotor with different cross feedback

The results show that displacements cross feedback can greatly reduce the vibration of low frequency precession and improve the stabilization of the AMBs, and the displacements cross feedback influences the eigen-frequencies too. With cross feedback of 0.045, the rotational speed dependence for the eigen-frequencies is shown in **FIGURE** 5.

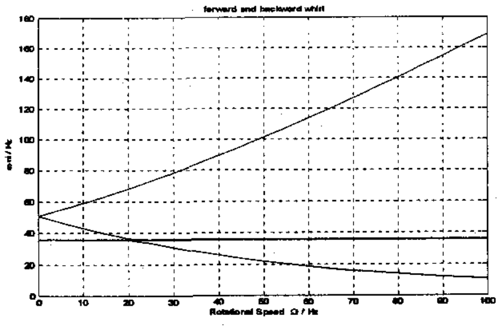

FIGURE 5: Diagram for the rigid body model with cross feedback

In addition, though a suitable cross feedback works well for system's stability, the cross parameters can't be too large. And the cross feedback parameter should be proportional to the rotational speed. But the damp for the rotor is limited. Controller with too much displacement cross feedback will excite vibration of the rotor's nutation and do harm to the stabilization. These simulation results are shown in **FIGURE** 6 (the parameters signed in the plot represent different cross feedback coefficients).

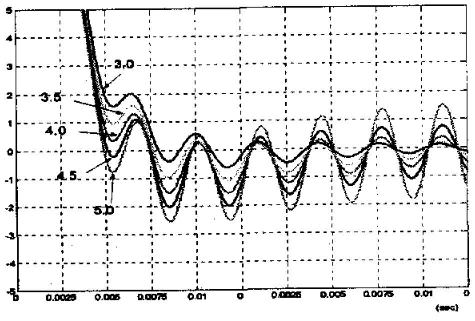

FIGURE 6: Response of the rotor with too large feedback

Meanwhile another problem must be pointed out that the well-done cross feedback parameters at different speeds or different PD parameters must be distinguished. In LQR controller design, a well-done controller at a high speed will be unstable at a low speed. A controller's behaviors at different speeds are shown in Fig.7 (the parameters signed in the plot represent different cross feedback coefficients).

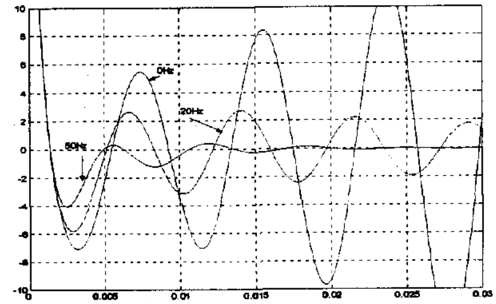

FIGURE 7: Response of the rotor at different speeds with the same cross feedback

A controller with a larger damp feedback parameter can endure larger cross parameters. Such will be good for precession vibration restraint. But a larger damp parameter will bring wider controlling bandwidth and bring more disturbance of high frequency. A compromise scheme of damp parameter and controlling bandwidth will be gotten through simulation and experience. And the cross feedback parameter of different rotational speeds will be found too. The simulation plot of LQR control is given at Fig. 8. It illuminates the relation between rotational speeds and suitable displacement couple feedback parameters, and will be helpful to determine the final running parameters.

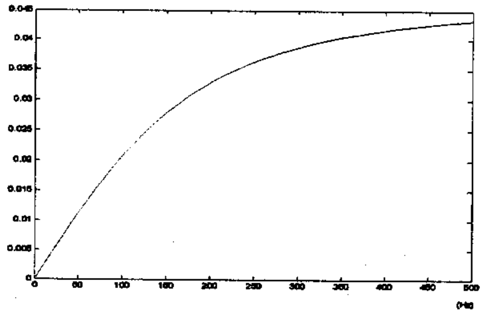

FIGURE 8: Suitable cross feedback of different speeds

CONTROL PLATFORM

To implement the control arithmetic, RTLinux on PC is selected. RTLinux is a free hard real time operating system. It uses many of the strengths of Linux without interfering with the general Linux development. For a PC, the worst case interrupt latency and jitter are 15 and 30 us, respectively. The resulting latencies are near those of the underlying hardware. So it is suitable for controlling the flywheel. In fact, there have been some researchers successfully realizing their AMBs controller on RTLinux.

By using RTLinux to build the platform has many advantages: C language can be used to program and far more efficiency can be gotten in realizing control arithmetic. Further more, the program in C will be reusable and easier to update than in assembler. And rich free software sources are provided and multi-task ability can be achieved easily. Cost is low; A/D, D/A cards can be gotten from commercial companies and hardware platform can be built up as soon as possible. The hardware structure of the system sketch map is shown in FIGURE.9.

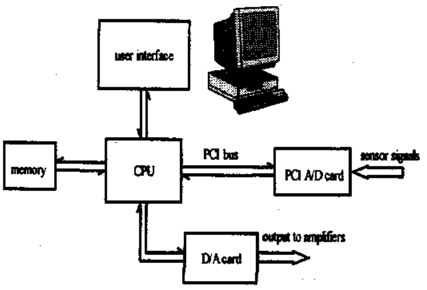

FIGURE 9: The hardware structure of the system

The structure of the control platform is shown in FIGURE10.

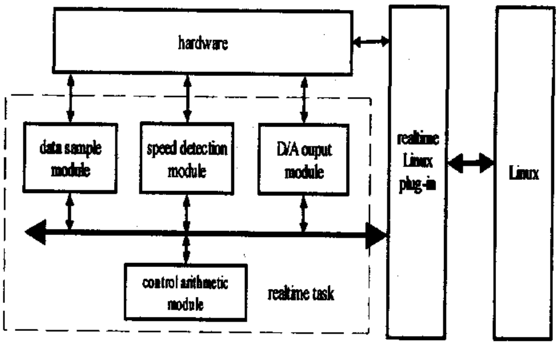

FIGURE 10: The structure of the control platform

PC used here is a PIII-800 and sampling card is a PCI card whose sampling rate is 800 kHz. The controller works at 10 kHz.

EXPERIENCE

To observe an obvious experience phenomenon and assure the safety of the system, the first experience is done at low rotational speed within 100 Hz. And the static stiffness of two radial AMBs is different. Then precession frequency will decrease to 13 Hz at rotational speed of 80 Hz. Open-loop bode plot of the system at zero rotational speed with decoupled PID controller is showed as follow (see **FIGURE** 11).

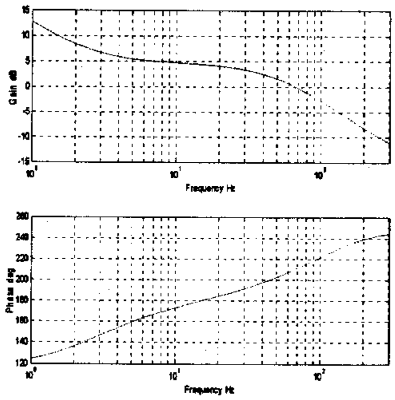

FIGURE 11 Open-loop bode plot of the system at zero rotational speed with decoupled PID controller

When rotational speed increases to 80 Hz, precession speed will decrease to 13 Hz. Then the integrator's phase lags will cause the precession to be unstable as the damp of controller is exasperated.

Experience result is shown as follow (see **FIGURE** 13).

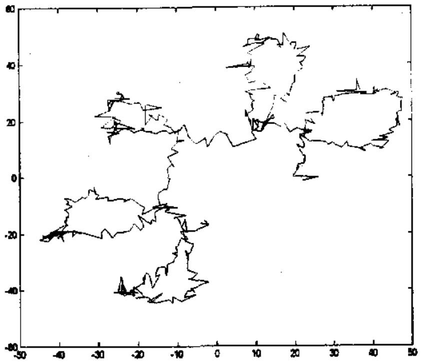

FIGURE 13: Experience result with obvious precession

The plot shows that precession becomes an unstable factor when rotor runs at fast rotation. As the control energy is limited and wider bandwidth will bring more high frequency noise, displacement couple feedback is used to solve this problem.

A simple test has been done. First, the rotor is excited without rotating. And the track of the axis center is a circle. When the rotor's rotational speed increases, the circle's radius decreases quickly.

With a suitable PID parameter, experience proves that rotational speed running stably can be increased obviously when the rotor runs at fast rotation above 260 Hz. **Fig.**14 show the photo of rotor

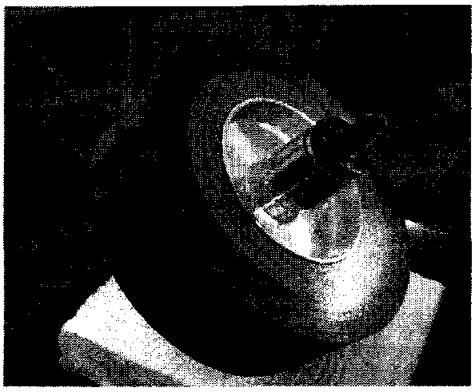

FIGURE 14 The photo of rotor

SUMMARY AND FUTURE WORK

The momentum wheel which suspended by AMBs for spacecraft attitude control was studied both theoretically and experimentally. The rotor has strong gyroscopic coupling which may cause unstable during operation. Therefore, it must be considered seriously in the control system designing. Cross feedback control is easy to realized and leads to better stability.

In a future, vibration control will be implemented and filter design has to be optimized. The cross feed back of displacement combine with gyroscopic force compensation will be trying future more. Meanwhile the power consumption will be decreased as the user's demand.

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