Vibration and Control in Outer Rotor Type Magnetic Bearings

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Abstract

The magnetic bearings described here has been developed for high speed rotating machinery. The manufactured experimental model is 4-axis-active type with simple structure. Since the model is so called outer-rotor type, resonance frequency of the rotor could set higher than rotating frequency, and only first resonance frequency of the stator shaft is in the rotating region. In this paper, we describe the analysis and experimental results to obtain stable high speed rotation. Firstly, stability of the gyroscopic motion of rigid mode is examined at low speed rotation. Subsequently, influence of flexibility of the stator shaft on stability is discussed. Then we indicate that nonlinearity of the power amplifier plays an important role in stability of the system. Finally, a suppression method using notch-filters and inter-axis cross coupling feedback at relatively high speed rotation is discussed.

1.Introduction

The 4-axis-active control magnetic bearings is composed of two radially-controlled magnetic bearings which utilized permanent magnets. As the results, the rotor is passively stabilized by the restoring force of the magnets in the thrust axis direction. Since no active thrust bearing is used, this model has a simple structure and easy to assemble compared to five-axis control type. The permanent magnets enable virtually zero power(VZP) method, which can levitate rotors with zero DC power and also can compensate the sensor drift.

Thus, the model has several advantages, so we have been researching the model in order to realize the practical use. The most difficult problem is control in high-speed rotating region. In this paper, we describe analysis and experimental results which are performed to investigate and to suppress the whirling motions of the model. Mainly, we deal with the gyroscopic and flexible stator shaft problems which must be resolved to obtain stable high speed rotation.

2. 4-Axis Active Control Magnetic Bearings

2.1 Structure and Static Characteristics of the Model

The model, shown in Fig.1, is composed of two radially-active type magnetic bearings which are located on both ends of the high speed motor. This model is so called outer rotor type and has an oblong shape (moment of inertia ratio = 0.504). Axial stiffness of the bearings keeps the rotor 0.3mm drop from geometrically symmetric point due to the gravity force when the rotating axis is vertical. These static characteristics of the model are shown in table.1.

Table.1 Static characteristics

Rotor Mass	$M = 5.7$ [kg]
Rotor Inertia	
Spin Axis	$I_p = 15.9\times10^{-3}$ [$kg \cdot m^2$]
Radial Axis	$I_d = 31.5\times10^{-3}$ [$kg \cdot m^2$]
Ratio	$\gamma = I_p / I_d = 0.504$
Axial Stiffness	$K_z = 2.46\times10^5$ [N/m]
Radial Unbalance Stiffness	$K_u = 12.7\times10^5$ [N/m]

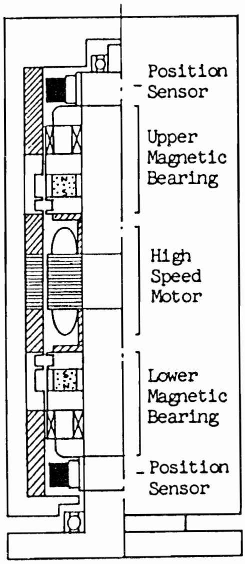


Fig.1 Structure of the model.

2.2 Block diagram of the system

The motion of the rigid rotor which rotate at ω is separated into translational and rotational motion. A block diagram of the system including gyroscopic motion is shown in Fig.2, where, l_1 and l_2 are the distance from the top and the bottom sensors and L_1 and L_2 are the ones from the top and bottom actuators, to the center of the gravity, respectively. g_{x1}, g_{x2}, g_{y1} and g_{y2} are distances of the rotor from neutral position of the gap for each axis, respectively. F_{cx1}, F_{cx2}, F_{cy1} and F_{cy2} are the control force of actuators for each axis, respectively. H(s) represents a transfer function of each control circuit.

2.3 Control circuit

The independent control method, which does not separate the motion into translational and rotational one, was adopted for simplicity in structure. Every axis has the same compensator, which consists of a lead-lag element and a first order lag power amplifier positively fedback by an integrator for VZP.

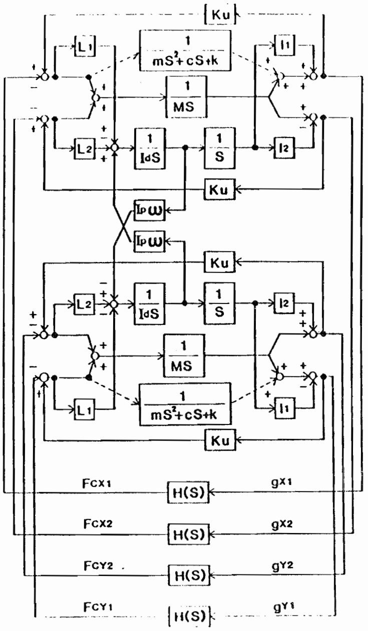
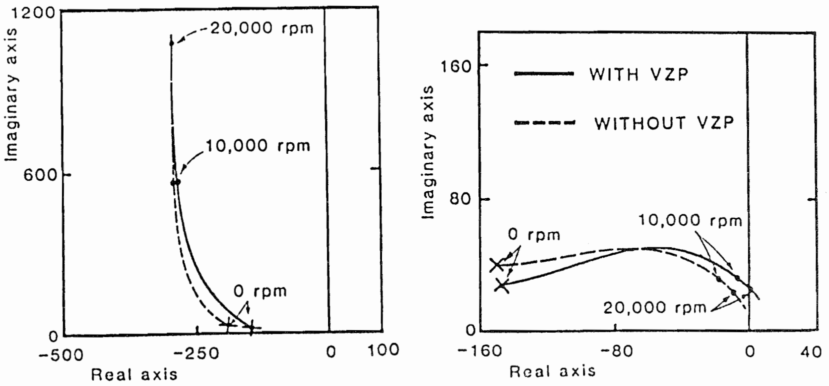


Fig.2 Block diagram of the system.

3. Rigid mode

3.1 Stability of conical motion

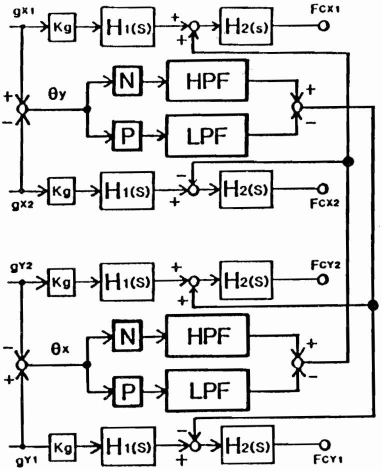
Though the system has unstable poles caused by control force of the permanent magnets and VZP, adjustment of loop gain of every axis stabilize these roots which start from the unstable poles. When rotation of the rotor is taken into consideration, the roots move due to the gyroscopic effect. Root-loci of the conical motion for variations of rotational speed are shown in Fig.3. The characteristic roots of precession mode(long period mode) move into the unstable region at approx. 20,000 rpm. This instability is caused by the phase lag at low frequency of the control circuit on account of VZP.



(a) Nutation (b) Precession

Fig.3 Root-loci of the conical motion (influence of VZP).

3.2 Modification of control circuit

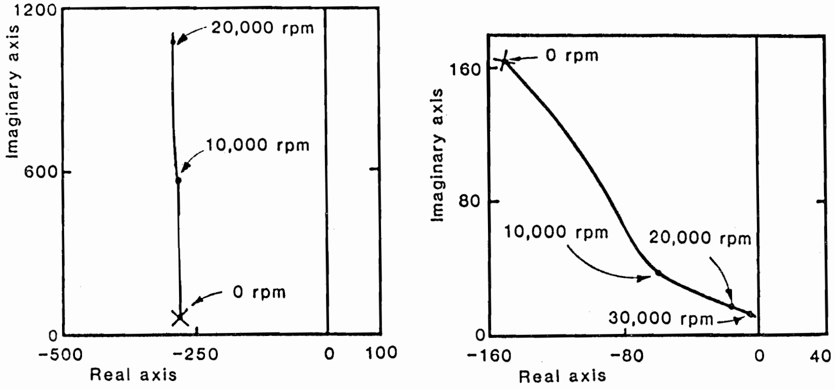


$$H_1(s) = \frac{1+T_1 s}{1+T_2 s}$$

$$H_2(s) = \frac{K_c T_i s}{T_c T_i s^2 + T_i s - K_c K_I}$$

Fig.4 Control circuit including cross-feedback.

In rigid mode with restoring control force, there are two conical or whirling motions i.e. precession(long period, backward) and nutation(short period, forward) motion [1], which should be suppressed by adequate control circuits. If we can get rate information of the rotor, the control circuit becomes rather simple, but we have no rate sensor in the model. Instead of the rate signals, we can use inter-axis cross coupling feedback(cross-feedback) method for that, provided that rotational directions of the coning motion are known. Fortunately, as each mode has different frequency at high rotation speed, we can separate each mode by simple filters. A low-pass-filter(LPF) is used for precession control(P-circuit) and a high-pass-filter(HPF) is used for nutation control(N-circuit). The separated signals can be mixed in opposite sign and cross-fedback. A control circuit including the cross-feedback is shown in Fig.4. As analytical results show unstable precession at high rotation speed, P-circuit is applied to suppress it. The root-loci of



(a) Nutation (b) Precession

Fig.5 Root-loci of the conical motion (effect of P-circuit).

conical motion in case of cross-feedback of P-circuit are shown in Fig.5, where the precession mode is clearly improved.

4. Experiments

In experiments without P-circuit, amplitude increase of the precession at about 10,000 rpm was observed. By insertion of the cross-feedback of P-circuit, problem of the precession is cleared. However, when the rotation frequency approaches to a resonance frequency of the stator shaft(about 530 Hz), the system became unstable.

5. Flexible mode

As the model is an outer-rotor type, resonance frequency of the rotor could be set at rather high value. But the first bending mode frequency of the stator shaft is in the rotational region.

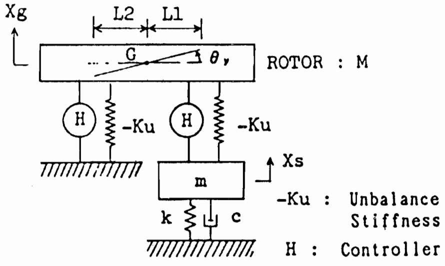


Fig.6 Structural model.

5.1 Structural model

As the stator shaft has a cantilever shape, the top part swings large, whereas the bottom little. Therefore, we adopt a structural model shown in Fig.6, where the flexibility is considered only at the upper side magnetic bearings. In block diagram of Fig.2, the flexibility is shown by dotted line.

5.2 Analysis of characteristic roots

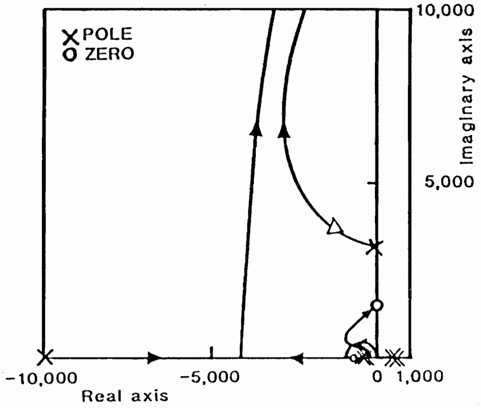


Fig.7 Root-loci of the system with flexible stator shaft.

The root-loci of the system is shown in Fig.7, where the feedback gain K_g of all compensator is varied at a time. Since the damping ratio of the flexible mode characteristic roots at operating point(△ mark in Fig.7) is not so small, we don't think the flexible mode alone is a cause of the instability.

5.3 Nonlinear characteristics of the power amplifier

Transfer functions of power amplifiers have been expressed by linear lag elements so far. However, the results of detailed experiments about the system clarified the nonlinear characteristics of the power amplifier. The circuit of the power amplifier used in the system is shown in Fig. 8.

It has such nonlinearity as its phase characteristic is getting worse in the case where high frequency with large amplitude signals are applied. Fig.9 shows the experimental results of frequency response of the power amplifier for variations of input amplitudes. As is clear from the Fig.9, the larger the amplitude of input signals become, the worse the phase characteristics of the power amplifier become.

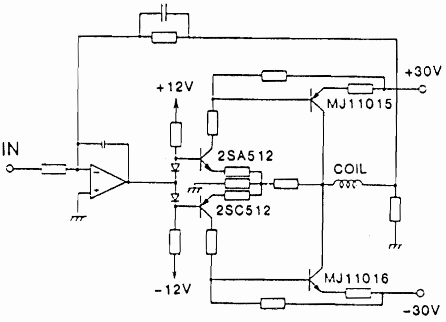


Fig.8 Circuit diagram of the power amplifier.

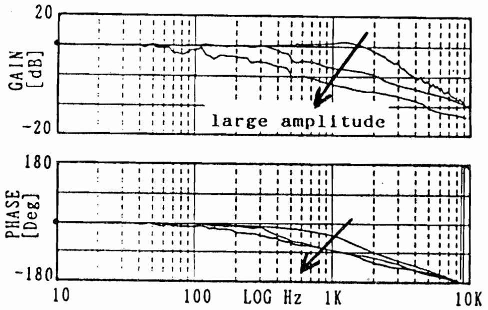


Fig.9 Frequency response of the power amplifier (experiments).

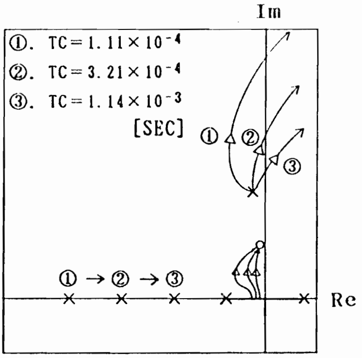


Fig.10 Variation of root-loci to TC.

In the case, where the frequency characteristics of the power amplifiers are approximated to a first order lag element, the variations of root-loci to three step changes of time constant(TC) of the element are shown in Fig.10. When TC is small(①), the flexible mode has wide stable region. But when TC becomes large(③), the roots of flexible mode move quickly to unstable region.

5.4 Stabilization of stator shaft vibration

The system is stable unless the resonance signals of the shaft are applied to the power amplifiers. The band-elimination-filters(BEFs or notch filters) are adopted as a compensator. According to the mode shape of the stator shaft, the BEFs are inserted in the detection circuits of upper bearings only. Fig.11 shows the root-loci of the system when the flexible mode is compensated by BEFs. The power amplifiers keep small time constants because of the BEFs, and the poles of flexible mode construct dipoles. The new roots, starting from the poles of the BEFs, have rather good damping ratio.

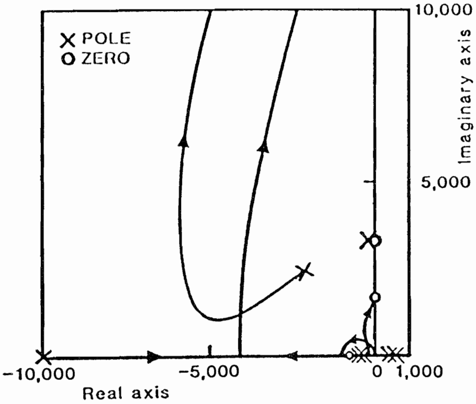
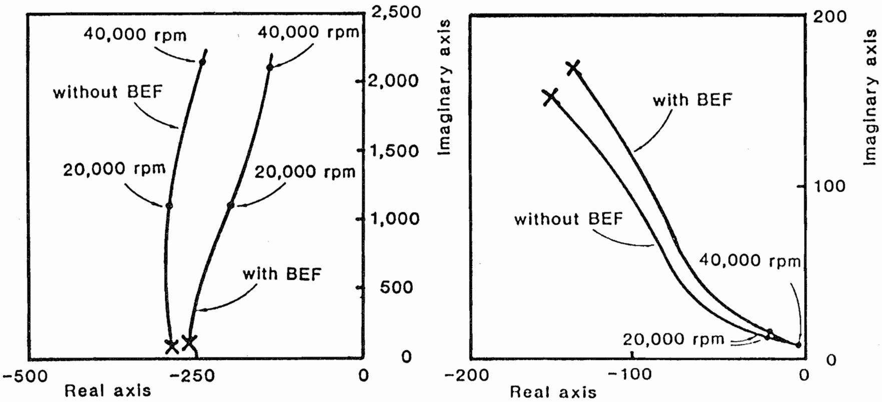


Fig.11 Root-loci of the system with BEF.

5.5 Influence of the BEFs on the conical motion

The root-loci of the conical motion of the system including P-circuit with and without BEFs for variations of rotation speed are shown in Fig.12. Influence of BEFs on precession mode is only little but the one on the damping ratio of the nutation mode is rather large.



(a) Nutation (b) Precession

Fig.12 Root-loci of the conical motion (influence of BEF).

5.6 Suppression of the nutation mode

In addition to the P-circuit, N-circuit is applied to compensate the characteristic root of the nutation mode, and the second order HPF were adopted to the N-circuit. Fig.13 is simulation results of upper side whirling motion, and we can see good convergence of the nutation mode but small flexible mode remains. The flexible mode is decaying by its own damping.

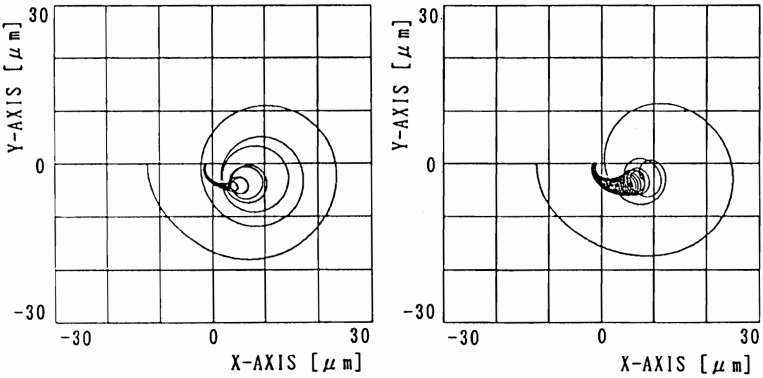


Fig.13 Transient response of relative motion of rotor and flexible stator shaft.

6. Conclusions

The results of this research are summarized as follows.

(1). In rigid mode, virtually zero power method cause unstable precession mode, which could be stabilized by cross-feedback of low-pass-filtered signals (P-circuit).

(2). The system falls into unstable due to interaction between flexible mode of the stator shaft and nonlinearity of the power amplifiers.

(3). Though notch filter(BEF) can eliminate nonlinearity of the power amplifiers, but may give bad influence on nutation mode.

(4). Cross-feedback of high-pass-filtered signals(N-circuit) can increase damping of nutation mode. Small flexible mode remains, but decays by its own damping.

Reference

[1].C.Murakami and I.Satoh : "A Suppression Method of Conical Motion of an Axi-symmetrical Spinning Rigid Rotor Suspended by Magnetic Bearings" , First International Symposium on Magnetic Bearings, June 6-8, 1988, ZURICH.Switzerland.