Study on the Controllability for Active Magnetic Bearings

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Abstract. One of the main challenges in AMB is its controllability which means it is difficult to get a stable spindle and controller. To solve this problem, some methods have been developed previously, but the value of the controllability of AMB was not calculated. The subject of our study is to develop a new method and find a mathematical model that aims to research the controllability of AMB, the status at passing through levitation process, running, a critical speed and achieve high-speed rotation. The stiffness and damping of AMB, which changes randomly along with the rotor running, are determined by the controller system. How to get the relationship between the stiffness and damping with dynamic coefficients of rotor-AMB system is a key problem to get an optimization controller. In this paper, a mathematical model of the relationship is established. Stiffness and damping of AMB can change if the parameter of controller modulated. Based on rotor dynamics theory, the dynamic characteristics of rotors such as critical speeds, system stability and unbalanced excitation are analyzed. Computer simulations are carried out and the effectiveness of the presented procedure is investigated.

1. Introduction

Active magnetic bearings (AMB) are used for high precision applications that demand very clean, no contracting bearing support. The primary function of a typical magnetic bearing is to provide support to an object only. Many excellent examples of high precision magnetic bearings are outlined in some references.

For example, magnetic suspension technology has applied in vacuum pumps, tools machine, pipeline compressors/expanders, turbomachines and others. An advantage offered is their contactless nature, which eliminates friction. Also the controllability dynamic of the magnetic bearings is a great advantage. These characteristic features permit new constructions, operation without mechanical wear and for that reason less mechanical maintenance as well as high speed with the possibility of vibration reducing. New idea can be realized at the construction of the magnetic bearings in order to obtain an improvement of the properties [1,2].

The sketch of the magnetically suspended ball (Figure 1) represents the AMB system. It consists of a ferromagnetic ball, an electromagnet, control electronics, amplifier and a displacement measurement with a sensor and an evaluation unit. The sensor measures the position of the body. The control...
electronics then calculates the required current to suspend the ball. The current is set by the amplifier. Figure 2 is a test fixture that we developed (Max. 36000 rpm).

Whereas one of the main challenges in AMB is its controllability which makes it difficult to get a stable spindle and controller. In other words, the controllability of AMB is the control of stiffness and damping. To solve this problem, some methods have been developed previously. For example, in [1], present which stiffness and damping can be controlled. In [3,4], author simply studied the characteristics of stiffness and damping. But how do we control, how the value of the controllability of AMB will be calculated. What is the mathematical model of stiffness and damping? This work studies the effective adjustment of stiffness and damping of AMB.

2. Modeling of the stiffness and damping

2.1. Motion equation

Usually, there have two magnetic actuators in AMB system (Figure 1). The force applied to the target is simply the vector sum of the two actuators acting separately:

\[ f_x = f_+ - f_- = k \left( \frac{(i_0 + i_x)^2}{(x_0 - x)^2} - \frac{(i_0 - i_x)^2}{(x_0 + x)^2} \right) \cos a \]  

where \( k = \frac{\mu_0 N^2 A}{4} \), other parameters reference to [1].

Equation (1) can be linearized and written in the form:

\[ f(i, x) \approx f(i_0, x_0) + k_i (i - i_0) + k_s (x - x_0) \]  

where \( k_i = \frac{\mu_0 N^2 A i}{2x^2}, k_s = \frac{\mu_0 N^2 A i^2}{2x^2} \).

2.2. Mechanics relation of rotor system

The equation of motion for a single mass \( m \) supported by a magnetic bearing can be expressed as follows:

\[ m \frac{d^2 x}{dt^2} = f - mg + p(t) \]  

Having simplified equs.(2)-(3), and \( \Delta i = i - i_0, \Delta x = x - x_0 \), we obtain the equation of the system:

\[ m \frac{d^2 x}{dt^2} + k_i i + k_s x = p(t) \]  

Equs. (4) can be expressed in the frequency domain as:

\[ mS^2X(S) - k_i S I(S) + k_s X(S) = P(S) \]  

2.3. Control equation

Generally speaking, there have two control manners in controller system of AMB. They are current control and voltage control, respectively. Control manner is different; the mathematics model is different too. The advantages and disadvantages about them can reference to [1]. In our controller system we use current control. Figure 3 is model of the magnetic bearings.
The displacement of rotor $X(S)$ is input, the control current $I(S)$ is output, its transfer function as:

$$\frac{I(S)}{X(S)} = G_x(S)G_c(S)G_p(S)$$

(6)

Where: Transfer function of sensor is

$$G_x(S) = K_x$$

(7)

Transfer function of PID controller is

$$G_c(S) = K_p + K_D S + \frac{K_I}{S}$$

(8)

Transfer function of amplifier is

$$G_p(S) = \frac{K_p}{1 + T_p S}$$

(9)

Having simplified equs.(5)-(9), we obtain the equation of the system:

$$\frac{X(S)}{P(S)} = \frac{1}{m S^2 + k_x - K_x K_p (K_p - T_p K_I) \frac{K_p}{1 + T_p^2 \omega^2}}$$

(10)

$S=j\omega$ era in equs.(10), simplified:

$$\frac{X(j\omega)}{P(j\omega)} = \frac{1}{-m\omega^2 + k_x - k_x K_p (K_p - T_p K_I) \frac{K_p}{1 + T_p^2 \omega^2} - \frac{K_x K_p}{1 + T_p^2 \omega^2} (K_D \omega - \frac{K_I}{\omega} - T_p K_p \omega) j}$$

(11)

Based on vibration theory, we obtain the equivalent stiffness and damping ration.

$$K_e(\omega) = k_x - k_x K_p (K_p - T_p K_I) \frac{K_p}{1 + T_p^2 \omega^2}, \quad \xi_e(\omega) = \frac{K_x K_p}{1 + T_p^2 \omega^2} (K_D \omega - \frac{K_I}{\omega} - T_p K_p \omega)$$

(12)

The mathematical model of the stiffness and damping has been established. When we change control parameter, the stiffness and damping will change.

3. The relation of stiffness and natural frequency

Figure 4 shows the rotor component of AMB that we designed. The middle of rotor is motor rotor; other two are the rotor of radial magnetic bearing; the disk
is the rotor of axial magnetic bearing.

Figure 4 can be transformed calculated model as shown in Figure 5.

We use the transfer function method that analyzes the relation of stiffness and natural frequency. Here we used computer simulation. The result is shown in Figure 6.

4. Conclusions
This paper dealt with the controllability of the magnetic bearings. General expressions of stiffness and damping were derived for the AMB. Finally, as mentioned earlier, the design objective is achieved.

In the present works, the subject of our study is to develop a new method and find the mathematical model that aims to research the controllability of AMB, the status at passing through levitation process, running, a critical speed and achieve high-speed rotation.

5. Acknowledgement
This work was supported by the National Science Foundation of China under Grant 50375113.

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