Dynamic Characteristics of Flexible Rotor System of High Speed Motor with Magnetic Bearings

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Abstract

High speed motor with magnetic bearings has been developing due to its advantages of small size, high power density, no mechanical wear and low maintenance cost. In order to reduce vibrations, dynamic characteristics of the flexible rotor system of high speed motor for operation rotation speed 200000r/min with magnetic bearings are investigated. Results show that high speed motor may pass through some critical speeds and it is accurate to consider the motor shaft as a flexible rotor. Meanwhile, it is necessary to take measures to reduce the amplitude of resonance region of high speed motor such as increasing system damping. The critical speed increases with the increase of the bearing stiffness, which is a good way to remove the critical speed below working rotation speed.

Keywords: Magnetic bearings, High speed motor, Dynamic characteristics, Modal analysis

1. Introduction

High speed motors have many advantages including high power density and reliability, small size, light weight, which can meet the special requirements of high-end equipment. The contactless characteristic of the magnetic bearing enables the rotor to operate at a very high speed. Its advantages of no lubrication and low bearing loss can make the equipment have lower maintenance cost and longer service life. Therefore, high-speed magnetic bearing motors have been paid more attention by researchers.

High speed motor usually refers to the motor whose speed exceeds 10000r / min. Among all kinds of motors, induction motor, permanent magnet motor and switched reluctance motor are the main ones to achieve high speed (1). The maximum speed of high-speed induction motor is 180000r/min, and the power is 10kW. Adopting magnetic bearing and solid rotor structure, the linear speed can reach 219m/s, and the efficiency is about 85%. When the high speed induction motor is running at high speed, the conventional laminated rotor cannot bear the huge centrifugal force. Special high strength lamination or solid rotor structure is required. Because of the poor tensile strength of permanent magnet material for high speed permanent magnet motor, the problem of rotor strength is more prominent.

Many studies on the dynamic characteristics of flexible rotor magnetic bearings have been done. Smith (2) used the finite element method to analyze the causes of the rotor damage of a high speed permanent magnet synchronous motor with a speed of 30000 r/min and a power of 100kW. It is suggested that the friction and shear stress between the sheath and the permanent magnet can be reduced by using lubricant. Yon (3) proposed a laminated binding structure. Arumugam (4) determined the magnetic stainless steel structure of surface machining by finite element analysis and calculation, which meets the structural, thermal and magnetic. Lin (5) developed a comprehensive model to calculate the thermal characteristics of bearings under different preloads. It is found that the heating problem of high-speed motor in operation is related to the bearing preload. Huynh (6) analyzed the stator loss, rotor eddy current loss and wind friction loss of high speed permanent magnet motor. The analytical expressions of each loss are put forward. In order to ensure that the rotor has enough strength, the rotor of high-speed motor is mostly slender. Therefore, compared with the constant speed motor, the possibility of the rotor system of the high speed motor approaching the critical speed is greatly increased. Palazzo (7) used active magnetic bearing to control flexible rotor to study on dynamic characteristics, control of flexible rotor. The influence of support structure on the dynamics of rotor system was studied by Cavalca (8). Eissa (9) studied the dynamic response of the rotor supported by active magnetic
bearing under harmonic excitation. Besides, in order to avoid resonance, the critical speed of rotor system with magnetic bearing must be accurately predicted. But the determination of bearing stiffness increases the difficulty of accurate prediction.

The authors have developed a high-speed magnetic bearing motor with operation rotation speed 200000r/min. Dynamic characteristics of rotor system of high speed motor with magnetic bearings are investigated. Magnetic bearing is equivalent to elastic support of the rotor system are obtained by numerical method. Besides, operating modal analysis is carried out with rotation speed 200000r/min. The influence of the support stiffness of magnetic bearings on the dynamic characteristics provides the improvement methods.

2. Dynamic modeling

In the magnetic bearing, the magnetic poles are generally simplified as shown in Figure 1. It consists of controller, power amplifier, sensor, rotor and electromagnet. When the rotor is in the middle of the gap, in order to establish the magnetic field, there is equal current \( I_0 \) (Bias current) in the upper and lower pole coils. If the rotor is offset \( y \), the air gap between the rotor and the upper magnet becomes:

\[
F_y = \frac{\mu_0 A_y N^2}{4} \left[ \left( (I_0 + i_y) / (C_0 + y) \right)^2 - \left( (I_0 - i_y) / (C_0 - y) \right)^2 \right]
\]

(1)

where vacuum permeability \( \mu_0 \), air gap cross section \( A_y \), turn number of coil \( N \), clearance \( C_0 \)

![Fig. 1. Electromagnet differential drive mode](image)

If the rotor makes small displacement disturbance near its static balance position, through Taylor expansion of Eq. (1), linearity of the increment of force can be done. Taking \( y \) direction as an example, when rotor displacement disturbance \( y \) occurs, the resultant stress between the two poles is

\[
F_y = \frac{\mu_0 A_y N^2}{4} \left[ \left( (I_0 + i + j) / (C_0 + y) \right)^2 - \left( (I_0 - i - j) / (C_0 - y) \right)^2 \right]
\]

(2)

where \( i \) is the control current. It can be obtained by converting the offset signal into the feedback regulating signal by the microprocessor controller after power amplifier. Through Taylor expansion of Eq. (2), it can obtained

\[
F_y = F_{y0} + \frac{\partial F_y}{\partial y} y + \frac{\partial F_y}{\partial i} i + \cdots = F_{y0} + k_{yy} y + k_{yi} i + \cdots
\]

(3)

where \( k_{yy} \) is defined as the force-displacement stiffness coefficient. It is the same as that of spring stiffness coefficient in general system. \( k_{yi} \) is defined as force current stiffness coefficient.

\[
\begin{align*}
\frac{\partial F_y}{\partial y} &= -\frac{\mu_0 A_y N^2 (I_0^2 + i^2)}{C_0^2} \quad k_{yy} = \frac{\mu_0 A_y N^2}{C_0^2} I_0 \\
\frac{\partial F_y}{\partial i} &= \frac{\mu_0 A_y N^2}{C_0^2} \quad k_{yi} = \frac{\mu_0 A_y N^2}{C_0^2} \quad k_{yi} = k_{yi} I_0
\end{align*}
\]

(4)

when the higher order small quantity is omitted, the increment of dynamic force is

\[
\Delta F_y = F_y - F_{y0} = k_{yy} y + k_{yi} i
\]

(5)

When \( i_0 \ll I_0 \), the effect of removing \( I_0 \) can be ignored. In this case, Eq. (4) can be simplified as

\[
k_{yy} = \frac{\mu_0 A_y N^2 I_0^2}{C_0^2}, k_{yi} = \frac{\mu_0 A_y N^2 I_0}{C_0^2} \quad (6)
\]

In general, the static feedback current \( I_0 \) is much smaller than the bias current \( I_0 \). Therefore, Eq. (6) is used to describe the stiffness coefficient of the electromagnet bearing. Fig. 2(a) gives the dynamic model of the rotor system of magnetic bearing motor. As shown in Fig. 2(b), the spring element is used to simulate the elastic support of the bearing.
3. Discussion on dynamic characteristics

3.1 Critical speed analysis

In this paper, parameters are used as follows: Young modulus $E = 2.06 \times 10^{11}$ Pa, Poisson's ratio $\mu = 0.25$, density $\rho = 2750$ kg/m$^3$. The results of critical speeds with support stiffness $k_x = k_y = 1.03 \times 10^6$ N/m are as shown in Figure 3. Results show that it will pass through three critical speeds when the shaft reaches the working speed (200000 r/min). It is necessary to reduce the amplitude of resonance region by fast passing through resonance region or increasing system damping. Besides, it is more accurate to consider the motor shaft as a flexible rotor when designing the main shaft.

3.2 Operating modal analysis

To reduce the vibration of magnetic bearing motor, the following presents modal analysis in the working state with operating rotation speed 200K r/min. Figure 3 shows natural frequencies and mode shapes of the rotor system. It can be found that there are many lower order natural modes below the working frequency. The working frequency and its super-harmonic components need to avoid the natural frequencies. The results indicate that it is more accurate to consider the motor shaft as a flexible rotor when designing the main shaft. In addition, the results can also provide foundation to analyze the observability and controllability of the magnetic bearing motor.

![Campbell diagram of the rotor of magnetic bearing motor](image)

![Enlarged view of the region (1)](image)

![Different modes](image)
1726Hz; (d) 1844Hz; (e) 8928Hz; (f) 9366Hz

3.3 Effect of support stiffness on critical speed

In order to remove the critical speed below the operating speed, Table 1 compares the effect of different support stiffness. It can be seen that the critical speed increases with the increase of the bearing stiffness. The third critical speed is larger than the operating rotating speed for support stiffness $1 \times 10^3 \, \text{N} / \text{m}$. That means the rotor will pass through two critical speeds when the shaft reaches the working speed, which reduces the risk of resonance.

Table 1. Comparison of critical speed under different support stiffness

| Different support stiffness | Critical speed (rad/s) |
|----------------------------|------------------------|
|                            | Mode 1                 |
| $1 \times 10^4 \, \text{N} / \text{m}$ | 1684.3                 |
| $1 \times 10^5 \, \text{N} / \text{m}$ | 5314.0                 |
| $1 \times 10^6 \, \text{N} / \text{m}$ | 15631.1                |

4. Conclusions

Dynamic characteristics of rotor system of high speed motor with magnetic bearings are investigated with operation rotation speed 200000r/min. Results indicate that the rotor system pass through three critical speeds when the shaft reaches the working speed. It is necessary for high speed motor to reduce the amplitude of resonance region by fast passing through resonance region or increasing system damping. It is more accurate to consider the motor shaft as a flexible rotor when designing the main shaft. Besides, the critical speed increases with the increase of the bearing stiffness, which can reduce the risk of resonance through removing the critical speed below working rotation speed.

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