The impact of nonorthogonality of the axial electromagnetic bearing disk on the stability region of a rigid rotor on a full electromagnetic suspension

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Abstract. The paper presents the results of a research of the stability of a rigid homogeneous rotor with a symmetrical relative to the middle arrangement of radial EMB, supported in the vertical direction by an axial EMB. In the first part of the work, the researches were held using a proportional-differential regulator in the system. In the second part of the work was considered the impact of the control function parameters in the cases of instantaneous generation of the displacement signal and with delay.

1. Introduction

A rotor rotating in bearing supports is the main element of many machines. The increase in power and rotation speeds in rotary machines while reducing weight and dimensions poses the problem of increasing the durability of bearing assemblies as a priority. In addition, a large number of fields of modern technology require bearings that are capable of working reliably in extreme conditions: at high and low temperatures, in vacuum, in aggressive environments, etc. The solution to all these problems can be the use of bearings, which use magnetic and electric fields to create support reactions [1, 2]. Electromagnetic bearings (EMB) are used in tasks related to nuclear power, wind power, energy conservation and energy efficiency [3-6]. Special attention is paid to the stability of such systems [7-8].

The movement of a rigid homogeneous rotor with a symmetrical relative to the middle arrangement of radial electromagnetic bearings (REMB) (Figure 1) is considered. In the vertical direction, the rotor supports an axial electromagnetic bearing (AEMB). AEMB limits the vertical movements of the rotor in a given range, and also creates a vertical force that balances the weight of the rotor. AEMB includes a disk that is rigidly connected to the rotor, and ring magnets located on the stator.
Figure 1. Vertical rigid rotor with a symmetrical relative to the middle arrangement of REMB, supported by AEMB

The equation describing the asymmetric shape of the rotor oscillations is:

\[ \frac{1}{3} m \cdot \ddot{a}(t) = -2M \frac{l}{l}(\theta - \frac{2}{l}a(t)) + 2 \left( K \frac{I_{\text{right}}^2}{(s_0-a(t))^2} - K \frac{I_{\text{left}}^2}{(s_0+a(t))^2} \right), \]  

where \( a(t) \) – displacement of the rotor at the locations of REMB, \( m \) – rotor mass, \( l \) – rotor length, \( M \) – constant moment due to the impact of AEMB and increasing the angle of inclination of the disk, \( \theta \) – mounting nonorthogonality of the disc plane of the rotor axis, \( K = \frac{S_0}{2} \), \( L \) – inductance at zero rotor displacement, \( S \) – effective clearance, \( I_{\text{right}}, I_{\text{left}} \) – amperages in the opposing windings.

2. Research of the stability of a rigid rotor using a proportional-differential regulator in the system

When using a proportional differential regulator (PD-regulator) in the control system, the dependence of the current \( I \) on the movement of the rotor \( a(t) \) in the cross section of the radial EMB location is given by expression:

\[ I = b \dot{a}(t) + ca(t), \]

where \( b \) and \( c \) – the parameters of the PD-regulator.

Expressions for amperages in the opposing windings \( I_{\text{right}}, I_{\text{left}} \) are:

\[ I_{\text{right}} = I_0 - ca(t) - b\dot{a}(t), I_{\text{left}} = I_0 + ca(t) + b\dot{a}(t). \]  

(2)

Using expressions (2) the equation of motion of the rotor (1) will take form:

\[ \ddot{a}(t) + \frac{24K}{mS_0^2} I_0 \cdot \dot{b}(t) + \left( \frac{24K}{mS_0^2} I_0 \cdot c - \frac{24K}{mS_0^2} I_0^2 - 12 \frac{M}{ml^2} \right) a(t) = 0. \]
The study of the characteristic equation for this system shows that the equilibrium state will be asymptotically stable under the following conditions:

\[ \{ b > 0, c \} \]

3. Research of the stability of the rigid rotor with respect to the control parameters of the system

Expressions for amperages in the opposing windings \( I_{\text{right}}, I_{\text{left}} \) are:

\[ I_{\text{right}} = I_0 - I, I_{\text{left}} = I_0 + I. \]  

Using expressions (3) the equation of motion of the rotor (1) will take form:

\[
m \cdot \ddot{a}(t) = \left( \frac{12M}{l^2} + I_0^2 - \frac{24K}{S_0^3} + I^2 \frac{24K}{S_0^3} \right) a(t) - \left( 6 \frac{M}{l} \theta + \frac{24 \cdot K}{S_0^2} I_0 I \right) \]  

(4)

The dependence of the amperage in the inductive coils is determined from the following equation:

\[
T \frac{dI}{dt} + I = w, \]

(5)

where \( w \) – control system signal function, \( T = \frac{L}{R} \), \( L \) – the inductance of the coil, \( R \) – resistance.

In case of instantaneous generation of a displacement signal, the control function in equation (5) is:

\[ w = b \dot{a} + ca. \]

In case of a delayed displacement signal in the equation for the amperage in the inductive coils (5) the expression for the control function \( w \) is:

\[ w = b \dot{d} + cd. \]

To determine the parameter \( d \), characterizing the readings of the rotor displacement sensors, the equation is used to generate displacement signal in the following form:

\[ T_1 \frac{d}{dt} + d = a, \]

where \( T_1 \) – the time constant of the sensor.

Researches carried out in the vicinity of the equilibrium state of the system allow us to determine the stability region depending on the control parameters \( b \) and \( c \).

The calculations were carried out with the following system parameters: \( L = 0.01625 H, R = 1.86 \Omega, m = 270 kg, K = 0.244 H \cdot \text{mm}, I_0 = 1 A, S_0 = 1.5 \text{ mm}, \theta_0 = 0.01, M = 0.008 N \cdot \text{mm}. \)

Figure 2 and Figure 3 highlight the stability regions in case of instantaneous signal formation depending on the control parameters \( b \) and \( c \) in the absence of mounting non-orthogonality of the rotor axis disk (\( \theta = 0 \)) and if there is one. Figure 4 and Figure 5 show similar results in case of the formation of a displacement signal with delay.
Based on the results obtained, it can be concluded that the presence of mounting nonorthogonality of the disk plane of the rotor axis in case of instantaneous formation of the displacement signal does not affect on the stability of the rotor. However, in case of signal formation with delay, the marked nonorthogonality narrows the stability area on the plane of control parameters (c, b), and to ensure reliable operation of such systems, it is necessary to minimize this structural feature.

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