

Influence of temperature on the stiffness coefficient of AMB electromagnetic force

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Abstract

Active magnetic bearings (AMBs) have significant advantages over conventional rolling-element bearings in high-temperature rotating machinery, including lubrication-free operation, reduced cooling requirements, and compact structural design. However, elevated temperatures induce thermal expansion of bearing components and alter material electromagnetic properties, consequently affecting their load-bearing characteristics. Understanding temperature influence on AMB electromagnetic force is important for accurate dynamic prediction and optimal control performance. This work presents a parameter identification method that requires only rotor vibration displacement and coil current data, eliminating the need for specialized testing equipment. By placing the AMB-rotor system in a heating device, the variation law of electromagnetic stiffness at different temperatures is obtained, and the influence mechanism of temperature on electromagnetic force is explained through simulation analysis. The research results can be used for dynamic modeling and control optimization of AMB systems in high-temperature environments.

Keywords: Active magnetic bearings, High temperature, Stiffness coefficient, Parameter identification, Electromagnetic force

1. Introduction

Active magnetic bearings (AMBs) can operate in high-temperature environments through specialized design, making them an attractive solution for high-temperature rotating machinery such as aeroengines and gas turbines. Taking aeroengines as an example, higher turbine outlet temperatures directly correlate with improved thrust-to-weight ratios and thermal efficiency. While conventional rolling-element bearings suffer from performance degradation and lubrication failure at elevated temperatures, AMBs offer distinct advantages: (1) significantly reduced cooling requirements, (2) elimination of lubrication systems, and (3) compact axial rotor arrangements that enhance dynamic performance. Furthermore, AMBs' inherent capabilities, including active vibration suppression, real-time condition monitoring, and high-speed operation, endow them with unique competitive advantages in high-temperature rotating machinery applications (Provenza et al., 2005, Schweitzer and Maslen, 2009).

Nevertheless, while AMBs can work in high-temperature environments, thermal conditions induce significant changes in their operational characteristics. The structural thermal expansion of both stator and rotor components, combined with temperature-dependent variations in core permeability and coil conductivity, collectively degrade the system's support characteristics and load capacity. For accurate dynamic simulation, reliable performance prediction, and optimized controller design, it becomes imperative to quantitatively understand these temperature effects on AMB electromagnetic forces (Ma et al., 2023).

For AMBs using differential driven configuration, the electromagnetic force model is usually linearized by using current stiffness and displacement stiffness coefficients to characterize the force-current and force-displacement relationships. These two stiffness coefficients are related to parameters such as effective magnetic pole area, nominal air gap, number of turns, magnetic permeability, and magnetic circuit length. Elevated temperatures induce significant variations in these parameters, particularly through thermal expansion effects that alter both the nominal air gap (due to differential expansion between stator and rotor) and effective pole area (resulting from three-dimensional thermal deformation of magnetic poles). While finite element analysis or analytical methods could theoretically evaluate these

thermal effects, practical challenges arise from non-uniform temperature distributions, assembly-induced uncertainties, discrepancies between simulated and actual conditions, and limitations of linearized models that neglect leakage flux effects. These combined factors make it difficult to obtain accurate results through analysis or numerical calculations.

Experimental testing provides a more direct approach, and compared to testing a single AMB, testing on assembled rotating machinery will be more closely aligned with actual working conditions. The commonly used method is to obtain the relationship between force and displacement/current by applying external force while keeping current/displacement constant. This usually requires the use of additional force sensors and other devices. In addition, it is difficult to have enough space to arrange these devices in an assembled machine (Liu and Liu, 2015, Voigt et al. 2016, Molina et al. 2018, Sun et al., 2020).

In this work, a parameter identification method for AMB electromagnetic stiffness coefficients was proposed, which only requires the collection of rotor vibration displacement and coil current - information that needs to be collected during AMB operation - to be calculated without the need for specialized testing equipment. In this work, the AMB-rotor is enclosed in a heating device and heated to different temperatures to obtain changes in the electromagnetic stiffness coefficients at different temperatures. After the experiments, some brief simulations were also conducted to illustrate the reasons for the influence of temperature on electromagnetic force.

2. Test rig

The test rig equipped with high temperature AMB is illustrated in Fig. 1. The 10.5 kg rotor is supported by two radial AMBs (AMB A and AMB B) and one thrust AMB, and is driven by an external electric motor through a flexible coupling. The radial AMBs employ an eight-pole C-type configuration. AMB B is housed within a heating device provided controlled operating temperature environments, while AMB A and the thrust AMB operate at room temperature. The heating device can provide a high-temperature environment of up to 400°C while maintaining temperature stability. Both the AMB and rotor are heated simultaneously to accurately simulate the real operating conditions. Temperature sensors are installed at critical locations, including near the bearings, around the rotor, and inside the heating device. The actuators and sensors of AMB B are specially designed to ensure operational reliability under elevated temperatures, including heat-resistant coil windings and temperature-compensated sensors. The displacement sensors and power amplifiers used in this test rig are designed and fabricated by the research team. AMB system is stabilized by augmented PID control. Control execution, excitation output, and signal acquisition are implemented through a dSPACE MicroLabBox platform, providing 20kHz sampling and control.

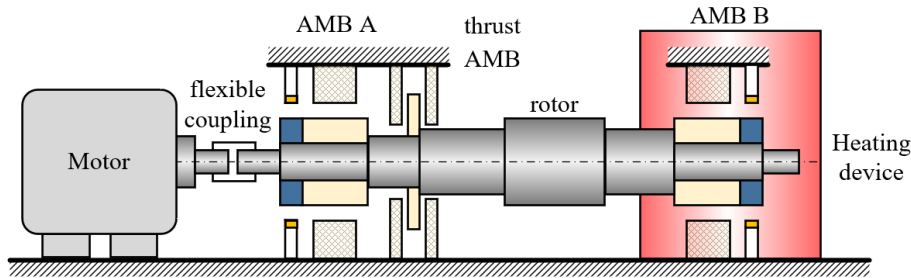


Fig. 1 Schematic diagram of AMB-rotor test rig.

3. Stiffness coefficient identification method

The rotor in the aforementioned test rig operates at speeds significantly below its bending critical speed. As illustrated in Fig. 2, the rotor is assumed to be rigid, where point C represents its geometric center. The axial distances from point C to AMB A and AMB B are denoted as l_{bA} and l_{bB} , respectively, while l_{sA} and l_{sB} represent the corresponding axial distances from point C to the displacement sensors. The dynamic behavior of this system can be described by Eq. (1):

$$M\ddot{\mathbf{q}}_c + \mathbf{G}\dot{\mathbf{q}}_c = \mathbf{T}_b \mathbf{F}_{AMB} + \mathbf{F}_u \quad (1)$$

where $\mathbf{q}_c = [x_c \quad \alpha \quad y_c \quad \beta]^T$ is the rotor displacement and angle at point C. \mathbf{M} is the mass matrix. \mathbf{G} is the gyroscopic matrix. \mathbf{F}_{AMB} is the AMB electromagnetic force matrix, and \mathbf{F}_u is the unbalanced force matrix.

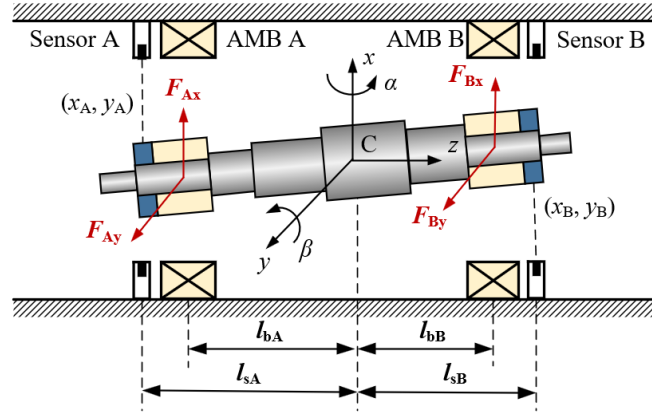


Fig. 2 Modeling of AMB-rigid rotor.

The parameter identification is conducted under the condition where the rotor is levitated but remains stationary. Consequently, rotational speed-related factors such as gyroscopic effects \mathbf{G} and unbalance forces \mathbf{F}_u can be disregarded. The gravitational force acting on the rotor is also excluded from consideration as it represents a constant load. Under these assumptions, the mathematical model of the AMB-rotor system can be formulated as follows:

$$M\ddot{\mathbf{q}}_c = \mathbf{T}_b \mathbf{F}_{AMB} \quad (2)$$

When transformed into the displacement sensor coordinate system, Eq. (2) can be expressed as:

$$M\mathbf{T}_s \ddot{\mathbf{q}}_s = \mathbf{T}_b \mathbf{F}_{AMB} \quad (3)$$

where $\mathbf{q}_s = [x_A \ y_A \ x_B \ y_B]^T$ represents the four measurements of AMB displacement sensors.

$$\mathbf{M} = \begin{bmatrix} m & 0 & 0 & 0 \\ 0 & J_r & 0 & 0 \\ 0 & 0 & m & 0 \\ 0 & 0 & 0 & J_r \end{bmatrix}.$$

$$\mathbf{T}_s = \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & -l_{sA} & 0 & l_{sB} \\ 0 & 1 & 0 & 1 \\ l_{sA} & 0 & -l_{sB} & 0 \end{bmatrix}$$

represents the conversion relationship between the centroid and sensor coordinates.

$$\mathbf{T}_b = \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & -l_{bA} & 0 & l_{bB} \\ 0 & 1 & 0 & 1 \\ l_{bA} & 0 & -l_{bB} & 0 \end{bmatrix}$$

represents the conversion relationship between the force acting on the centroid position and

the magnetic force.

$$\mathbf{F}_{AMB} = [F_{Ax} \ F_{Ay} \ F_{Bx} \ F_{By}]^T.$$

The electromagnetic force of differential driven AMBs can usually be expressed in terms of current stiffness and displacement stiffness, taking Ax direction as an example,

$$F_{Ax} = K_{As} x_{Ab} + K_{Ai} i_{Ax} \quad (4)$$

where x_{Ab} is the rotor displacement at AMB electromagnet which can be obtained from \mathbf{q}_s , the current stiffness K_{Ai} and displacement stiffness K_{As} are related to the number of coil turns, effective pole area and nominal air gap. This linearization equation is commonly used, and its effectiveness has also been verified. But in fact, due to the influence of magnetic flux leakage and other effects, there are often some errors. It is particularly pointed out that when the AMB is in a high temperature environment, the expansion of the rotor and stator makes the air gap and magnetic pole area change, and the complex boundary conditions make it difficult to obtain the accurate value.

The method of current stiffness and displacement stiffness identification using the system model is introduced below.

Assuming that the current stiffness and displacement stiffness of the same AMB in two directions are consistent, by further modifying Eq. (3), the following equation can be obtained:

$$\ddot{q}_s = \Phi p \quad (5)$$

where $p = [K_{As} \quad K_{Ai} \quad K_{Bs} \quad K_{Bi}]^T$ is the parameter we need to identify.

$$\Phi = \begin{bmatrix} x_{Ab}q_1 & i_{Ax}q_1 & x_{Bb}q_2 & i_{Bx}q_2 \\ y_{Ab}q_1 & i_{Ay}q_1 & y_{Bb}q_2 & i_{By}q_2 \\ x_{Ab}q_3 & i_{Ax}q_3 & x_{Bb}q_4 & i_{Bx}q_4 \\ y_{Ab}q_3 & i_{Ay}q_3 & y_{Bb}q_4 & i_{By}q_4 \end{bmatrix}, \quad \begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \end{bmatrix} = \begin{bmatrix} 1/m + l_{bA}l_{sA}/J_r \\ 1/m - l_{bB}l_{sA}/J_r \\ 1/m - l_{bA}l_{sB}/J_r \\ 1/m + l_{bB}l_{sB}/J_r \end{bmatrix}.$$

where all elements in Φ are known or measurable, including rotor geometric parameters, coil current and rotor displacement.

In order to obtain the data required for identification, AMBs are used for excitation, with the excitation injection point at the output voltage of the controller, as shown in Fig. 3. Generally speaking, the current stiffness and displacement stiffness are constant values at different frequencies. To ensure accurate parameter identification across a wide frequency band, the excitation frequency range must also span a broad spectrum. There are two excitation strategies. The first is multi-frequency excitation containing multiple frequency components where the amplitude and phase of each frequency component require meticulous optimization. The second is sequential single-frequency excitation. Individual frequencies are excited sequentially. Although this method is slightly more time-consuming, it eliminates inter-frequency interference.

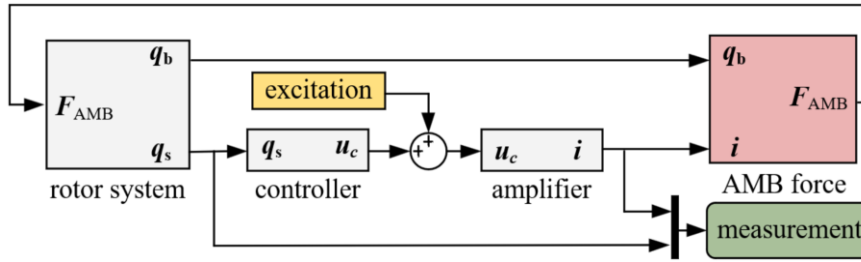


Fig. 3 Block diagram of excitation and signal acquisition.

Performing Fourier transform on experimental data, Eq. (5) can be expressed in the frequency domain as:

$$\ddot{q}_s = \Phi p \quad (6)$$

Define the cost function as:

$$J = \frac{1}{2} (\ddot{q}_s - \Phi p)^H W (\ddot{q}_s - \Phi p) \quad (7)$$

where W represents the weight of each frequency component. Identification values can be obtained using the least squares method (Yao et al., 2022):

$$p = \left[\text{Re}(\Phi^H W \Phi) \right]^{-1} \text{Re}(\Phi^H W \ddot{q}_s) \quad (8)$$

The calculated result is the identification or estimation value of the stiffness coefficient of AMB electromagnetic force. To demonstrate the effectiveness of this method, indirect verification was conducted through simulation. The specific process is to construct an AMB rotor system in MATLAB/Simulink and provide assumed values for stiffness coefficients. By applying excitation to the system, collecting current response and displacement response, obtaining the identification value of stiffness coefficients, and comparing them with the assumed values. To verify the robustness of the method, noise with different signal-to-noise ratios was added to the system. The results show that even in the presence of noise, the error between the identified value and the assumed value of the stiffness coefficient is very small and acceptable.

4. Influence of temperature on the stiffness coefficient

Parameter identification was conducted for the test rig described in Section 2. The procedure consisted of the following steps:

(a) The heating device was set to specified temperatures (50, 100, 150, 200, and 250°C), and the system was maintained at each temperature until the AMB and rotor reached thermal equilibrium.

(b) The rotor was levitated, and excitation signals were applied while simultaneously recording displacement sensor outputs and coil current signals.

(c) The identification was performed using the method presented in Section 3.

The identification results for current stiffness K_{Bi} and displacement stiffness K_{Bs} of the high-temperature AMB are presented in Table 1.

Table 1 Identification results for K_{Bi} and K_{Bs} .

temperature [°C]	K_{Bi} [N/A]	K_{Bs} [N/m]
50	41.42	-3.36×10^5
100	40.33	-3.12×10^5
150	39.28	-2.97×10^5
200	38.10	-2.84×10^5
250	37.21	-2.66×10^5

Then, the identification results were substituted into the dynamic model of the test rig, the same excitation as the experiment was applied, and the displacement response results of the simulation model were collected. Fig. 4 shows the comparison between simulation and experimental results at 100 °C. It can be seen that the simulation results and experimental results have good consistency, which verifies the effectiveness of the identification method.

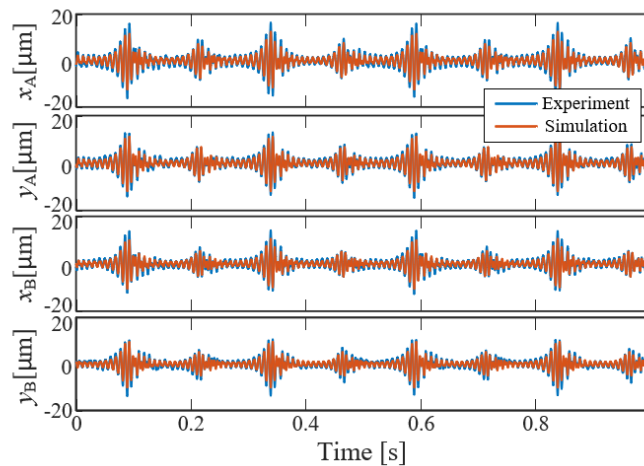


Fig. 4 Simulation and Experiment results of rotor displacement (at 100°C).

The results demonstrate that both the current stiffness and displacement stiffness of the active magnetic bearing decrease with increasing temperature, consequently leading to reduced electromagnetic forces. While this conclusion may appear straightforward, the key contribution of this work lies in proposing a simplified identification method for current and displacement stiffness that requires no additional instrumentation. Conventional measurement approaches face limitations due to test condition constraints, while theoretical estimations often yield significant errors under thermal conditions owing to coupled multi-physics effects. The proposed method provides a feasible solution for obtaining accurate stiffness coefficients under real operating conditions, which are essential for dynamic behavior simulation and control algorithm optimization and compensation.

To qualitatively investigate the reasons of stiffness reduction, finite element simulations were conducted focusing on thermal expansion of both rotor and stator components. The simulations reveal that while both the rotor outer diameter and stator inner diameter increase with temperature, the stator's thermal expansion exceeds the rotor's, resulting in an enlarged air gap. Since stiffness coefficients are highly sensitive to nominal air gap dimensions, this expansion pattern directly contributes to the observed stiffness reduction. Additionally, it was observed from the simulation that in addition

to radial expansion, the AMB stator magnetic poles also expand in the width direction, resulting in a certain increase in magnetic pole area. However, this area enlargement appears to have less pronounced effects on electromagnetic forces compared to air gap variations.

Due to the weakening effect of high temperature on electromagnetic force, the vibration of the rotor will intensify under the same control method and parameters. Therefore, it is necessary to compensate for electromagnetic forces at different temperatures, which can be achieved through control parameter optimization or development of novel control strategies specifically designed for high-temperature operation.

5. Conclusion

In this work, a parameter identification method is proposed for the electromagnetic stiffness coefficients of AMBs and investigates the influence of varying temperatures on these coefficients. The results demonstrate that elevated temperatures will diminish the stiffness. This thermal degradation must be accounted for during both the preliminary design phase and actual operation, where real-time stiffness compensation is essential to maintain optimal performance. This work establishes a foundational framework for subsequent research on the dynamic characteristics and control strategies of AMB-rotor systems operating under high-temperature conditions.

In fact, due to the ddy currents effects and other factors, there are certain differences in stiffness coefficients at different frequencies, which need to be considered in future work. In addition, we are considering establishing datasets at different temperatures and building a network to accurately predict electromagnetic forces by inputting parameters such as temperature, displacement, and current.

Acknowledgments and conflicts of interest

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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