Performance Analysis of Active Magnetic Bearing Systems in High-Speed Motor Drives

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ABSTRACT

Active Magnetic Bearings (AMBs) are a good alternative to mechanical bearings for high-speed motor drive applications, especially because they operate contactless and cause less friction loss and better dynamic performance. This study was conducted by simulation method to analyse the performance of an Active Magnetic Bearing based high speed motor drive system. An electromagnetic force generation model, a rotor dynamics model, a displacement sensing model and a PID control model were all integrated into a mathematical model and implemented in MATLAB/Simulink. Evaluated the system under various operating conditions including nominal operation, sudden load disturbances, rotor balance and high-speed acceleration. The simulation results showed that the proposed AMB system could maintain the stable suspension of the rotor and perform the accurate positioning of the rotor over the entire operating range. The maximum rotor displacement under nominal condition was limited to 12 μm, while under load disturbance and rotor imbalance condition, the rotor displacement reached 25 μm and 30 μm respectively. The controller was able to stabilize the system with a settling time of 0.12 s, overshoot of 4.5% and steady-state error of 0.8%. Using AMBs, the vibration amplitude was decreased from 80 μm in conventional bearing systems to 22 μm, which led to a vibration reduction of ~72.5%. In addition, the percentage of energy lost went down from 12.5% to 5.8%, signifying increased efficiency of operation. The results validated Active Magnetic Bearings significantly improve rotor stability, vibration damping, dynamic response and energy efficiency over conventional bearing technology. Hence, the proposed AMB system was concluded as a successful and effective system for future high speed motor drive applications, which have high precision, low maintenance and good operating performance.

Keywords: *Active Magnetic Bearings, High-Speed Motor Drives, Rotor Dynamics, PID Controller, Vibration Suppression, Rotor Stability, Energy Efficiency, Electromagnetic Suspension.*

1. Introduction

Active Magnetic Bearings (AMBs) are gaining popularity for high-speed motor drives that include aerospace systems, turbo-compressors, flywheel energy storage and machine tool spindles because they are capable of supporting higher speeds, better efficiency and compact designs[1,2]. However, conventional bearings will have the problems of friction, wear, lubricating needs, and thermal restriction which will result in less reliability in high-speed operations, and more maintenance cost[3,4]. AMB resolves these problems by suspending the rotor without mechanical contact due to electromagnetic forces: reducing wear, improving system dynamic performance, and prolonging system life[5-8].

At high rotation speeds, on the other hand, the AMB systems suffer from several problems such as rotor instability, electromagnetic nonlinearity, controller tuning, and disturbance rejection[9–11]. Thus, detailed performance evaluation is necessary to evaluate the rotor stability, vibration suppression and energy efficiency[12].

In this study, the authors have designed and tested an integrated AMB based high-speed motor drive model that investigates the rotor displacement, vibration reduction, dynamic stability and energy efficiency under different operating conditions. Different from previous studies that primarily addressed the design of the controller or rotor dynamics, this paper provides a comprehensive analysis framework to investigate AMB performance under normal operation, load disturbance, rotor imbalance and high speed acceleration.

The study is focused on assessing the performance of the rotor displacement, vibration characteristics, settling time, overshoot and energy consumption and on investigating the effectiveness of the usage of the feedback controlled AMB for enhancing stability and mechanical losses. The development of a mathematical model that incorporates the electromagnetic actuators, rotor dynamics, and control systems; implementation of a rotor stabilization framework; and extensive performance assessment for a variety of operating scenarios represent some of the key contributions. The results showed that AMBs have a promising application prospect in the field of high-speed, reliable and energy-saving industrial motor drive.

2. Literature Review

2.1 Active Magnetic Bearing Technology

Active Magnetic Bearings (AMBs) are a type of contactless rotor support that utilizes electromagnetic forces, avoiding friction, wear, and lubrication needs of traditional bearings[13,14]. The benefits they provide have made them popular in a variety of applications such as turbo compressors, propulsion systems in the aerospace industry, flywheel energy storage systems and high-speed motor drives, enabling greater reliability, efficiency, and operational speed[15].

2.2 Control Strategies for AMBs

Control strategies are crucial to the effectiveness of AMBs. PID controllers were used for the normal operating conditions to stabilize the rotor and control the displacement in the early studies[16]. In more challenging environments, however, their performance was constrained by nonlinear dynamics and parameter changes. More sophisticated techniques like state-space, adaptive, robust and optimal control were thus developed to enhance the stability and disturbance rejection properties of the systems in high speed applications[17]. Adaptive and robust controllers have been shown to provide better performance in a number of load and uncertainty conditions[18].

2.3 Intelligent and Hybrid Control Approaches

In recent years, intelligent control techniques such as fuzzy logic controller and neural network controller have been investigated to overcome the nonlinear rotor dynamics without having to use a precise mathematical model[19,20]. Hybrid methods using PID, fuzzy logic and neural networks have resulted in better vibration suppression, quicker settling times, and higher robustness. Predictive maintenance and fault diagnosis have also been tackled using machine learning techniques in AMB systems[19].

2.4 Rotor Dynamics and Vibration Suppression

The performance of AMB is greatly affected by rotor dynamics. Research shows that the use of active feedback control can compensate for rotor imbalance, shaft flexibility and external disturbances and vibration reduction, as well as maintaining the rotor centering[21]. The experimental and simulation studies proved a significant reduction in vibration and stable operation through critical speed regions as compared to conventional bearings[22].

2.5 Energy Efficiency and High-Speed Operation

The magnetic levitation technique reduces mechanical friction losses, thus increasing energy efficiency and reducing the heat generation[23]. AMBs will allow for stable operation at speeds outside of the capability of conventional bearings, accurate rotor positioning, mechanical stress reduction, and longer system life. The use of AMB systems in industry has been further improved by recent developments in power electronics and digital control technologies[24].

2.6 Fault Detection and Reliability Enhancement

Fault detection, condition monitoring and fault-tolerant control techniques have been developed to increase the reliability of AMBs. Monitoring systems based on sensors enable early detection of abnormalities in the rotor, actuators and controllers, thus allowing for preventive maintenance[25]. The use of fault-tolerant control strategies enhances the resilience and safety of the system when the sensors or actuators malfunction[26].

2.7 Research Gap

Despite the advances in design of controllers and the dynamics of rotors, vibration suppression and energy efficiency, most studies consider these functions separately[27]. However, there is little research that has considered all major factors of dynamic stability, vibration reduction, rotor displacement, settling characteristics, and energy efficiency in concert in the context of a high-speed motor drive. Moreover, there are very few comprehensive analyses available for combined operating conditions, like rotor imbalance, load disturbances and varying speed[28]. Thus, a comprehensive performance evaluation system is required to attain an all-round evaluation of AMB supported motor drives.

3. Problem Statement

A reliable bearing system is necessary for a high speed motor to operate without any fluctuations in rotation speed at high RPMs[29]. Standard bearings suffer from friction, wear, need for lubrication, generation of heat and vibration, which restrict their performance in challenging applications. Active Magnetic Bearings provide a contactless solution that can result in better stability and reduced mechanical losses, but are influenced by rotor dynamics, electromagnetic nonlinearities, disturbances, load variations, and controller effectiveness[30]. In addition to maintaining a precise rotor position, preventing unwanted vibration and energy loss is difficult, especially in different operating conditions. Previous research tends to concentrate on individual aspects of performance, resulting in the need for a holistic approach that encompasses stability, displacement control, vibration suppression, and energy efficiency. This kind of evaluation is vital for optimizing AMB performance, improving reliability and efficiency of high-speed motor drive systems[29,30].

4. Methodology

The proposed methodology is based on simulation evaluation of the Active Magnetic Bearing (AMB) system coupled with a high-speed motor drive. Firstly, a motor drive model with electromagnetic bearings is designed, in which the rotor is not physically supported but is only hung by the magnetic force of the electromagnetic bearings. The location of the rotor is continuously controlled by the position sensors and the displacement information is sent to a PID controller, which provides control signals to keep the rotor stable and centered. The whole system is realized in MATLAB/Simulink for analysis of its performance under various operating conditions: normal operation, sudden load disturbance, rotor imbalance, high-speed acceleration. For each simulation run, important performance indexes are collected like rotor displacement, vibration amplitude, settling time, overshoot, and overall stability are collected and evaluated. The benefits of the Active Magnetic Bearing system in terms of vibration reduction, dynamic response, and operational efficiency of high-speed motor drives are then compared.

4.1 System Modeling of Active Magnetic Bearing-Based High-Speed Motor Drive

The mathematical model of the active magnetic bearing based high-speed motor drive system are established. Mathematical models of the active magnetic bearing based high speed motor drive system are constructed. The methodology proposed in this work is to analyze the dynamic performance of an Active Magnetic Bearing (AMB) system along with a high-speed motor drive. The system consists of a rotor shaft, electromagnetic actuators, displacement sensors, a feedback controller, and a power amplifier. The rotor is floated above the stator with magnet levitation created by the electromagnets. The goal is to position the rotor in a stable manner with the lowest possible vibration and displacement at various operating conditions.

Newton's second law of motion can be used to describe the overall dynamic behavior of the rotor:

$$m\ddot{x} + c\dot{x} + kx = F_m + F_d$$

The rotor is shown in the figure by *m* is, the damping coefficient is represented by *c* is, the stiffness of the shaft is represented by *k* is, the displacement of the rotor is represented by *x* is, the electromagnetic force of the magnetic bearing is represented by F_m is, and the external disturbance force acting on the rotor is represented by *F*. This equation represents the relationship between the forces affecting the stability in the system and the movement of the rotor.

4.2 Electromagnetic Force Modeling

The magnetic bearing generates an electromagnetic force to keep the rotor lifted and to position it. This force is a function of the coils current and the distance of the air-gap between the electromagnet and the rotor. The EM force is represented by:

$$F_m = \frac{\mu_0 N^2 A i^2}{2g^2}$$

In which μ_0 is the permeability of free space, *N* is the number of coil turns, *A* is the area of the pole face, *i* is the magnitude of the current through the coil, and *g* is the air-gap length. The equation shows that the magnetic force created is a function of the square of the coil current but is a function of the inverse square of the air gap.

The magnetic force is very sensitive to small changes in air gap and current, making control of these variables essential to keeping the rotor well suspended. So, it's important to continually monitor and tweak the electromagnetic force while it is being used.

4.3 Rotor Position Sensing and Feedback Mechanism

Displacement sensors continuously measure the position of the rotors in the radial and axial directions to ensure the accurate stabilization of the rotors. A position error is calculated by comparing the measured position signal with a reference position that has been predefined. The error signal is given by:

$$e(t) = x_{ref}(t) - x(t)$$

where $x_{ref}(t)$is the desired rotor position and $x(t)$is the actual measured rotor displacement. The error signal generated is input to the controller which calculates the corrective action needed to bring rotor back to its desired position.

The feedback mechanism allows disturbances to be compensated real-time which enhances the system's stability and decreases vibration amplitude. Proper sensor measurement is crucial for the successful control performance.

4.4 PID Controller Design

The rotor position is controlled by a Proportional-Integral-Derivative (PID) controller and the control current is generated for the electromagnetic actuators. The controller continually changes the control signal as a function of the displacement error. The PID control law is shown as follows:

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt}$$

The controller output $u(t)$, proportional gain K_p, integral gain K_i and derivative gain K_d. The proportional block deals with the present error, the integral block removes steady state error and the derivative block enhances transient response and damping. The parameters of the controller are designed such that the overshoot is minimized, settling time is reduced and disturbance rejection is improved. It is important to tune these gains in order to get stable and efficient AMB operation.

Table 1: PID Controller Parameters Used in Simulation

Parameter	Symbol	Value
Proportional Gain	Kp	120
Integral Gain	Ki	50
Derivative Gain	Kd	10
Sampling Time	Ts	0.001 s
Reference Position	Xref	0 mm
Maximum Control Current	Imax	5 A
Minimum Control Current	Imin	0 A
Controller Update Frequency	fctrl	1000 Hz

The parameters of the PID controller which are used in the simulation, to control the rotor position and to ensure stable operation of the Active Magnetic Bearing system are presented in Table 1. Proportional, integral and derivative gains were carefully designed to give good fast response with little overshoot and low steady state error. The controller was able to adjust the electromagnetic forces in real time by making use of a sampling time of 0.001 s and an update frequency of 1000 Hz. These parameters were used to achieve a good rotor stabilization and good dynamic performance under different operating conditions.

4.5 Simulation Environment and Operating Conditions

The whole Active Magnetic Bearing system is modeled and simulated with MATLAB/Simulink. All the elements of rotor dynamics, electromagnetic force generation, displacement sensing and controller operation are modeled and simulated together in the same setup. The various operating conditions are evaluated to assess the system performance comprehensively.

In the first case, nominal conditions are assumed with the rotor rotating at the rated speed with no disturbances. The second case adds sudden load disturbances to test the robustness of the controllers. The third case is the study of the effects of rotor imbalance using external periodic forces. Finally, high speed acceleration conditions are considered to evaluate rotor stability at higher rotational speeds.

The rotational speed is calculated using:

$$\omega = \frac{2\pi N}{60}$$

The angular velocity is denoted by ω, and the rotational speed is denoted by N and is measured in revolutions per minute (rpm). This relationship is applied to studying the rotor under different speeds.

4.6 Performance Evaluation Metrics

Several dynamic performance indicators are used to assess the effectiveness of the proposed AMB system. Position stability is measured by rotor displacement and vibration suppression capability is checked by analyzing the amount of vibration. The settling time and overshoot are determined to assess the transient response properties. Also, the energy used is observed to measure the efficiency of the overall system.

The percentage overshoot is calculated as:

$$M_p = \frac{X_{max} - X_{ss}}{X_{ss}} \times 100$$

where $X_{max}$is the maximum displacement and $X_{ss}$is the steady-state displacement.

Similarly, vibration reduction efficiency is determined using:

$$VR = \frac{V_c - V_a}{V_c} \times 100$$

where $V_c$represents vibration amplitude with conventional bearings and $V_a$represents vibration amplitude with Active Magnetic Bearings.

Each of these performance measures gives a comprehensive evaluation of rotor stability, vibration suppression effectiveness, dynamic response quality and operational efficiency.

Table 2: Performance Evaluation Parameters

Parameter	Description
Rotor Displacement	Position stability measure
Vibration Amplitude	Vibration suppression indicator
Settling Time	Dynamic response speed
Overshoot	Transient response quality
Steady-State Error	Position accuracy
Energy Consumption	System efficiency indicator

The performance evaluation parameters for high-speed motor drive applications using the Active Magnetic Bearing system are presented in Table 2. The rotor displacement and steady-state error were used to indicate the position stability and control accuracy, and the vibration amplitude was used to represent the vibration suppression capability. During transient conditions settling time and overshoot are analysed to check the quality of the dynamic response. Energy use was added as an overall system efficiency and operational performance indicator.

5. Results and Discussion

5.1 Rotor Displacement Analysis

The nominal operating conditions were selected for the analysis of rotor displacement response to assess the ability of the Active Magnetic Bearing (AMB) system to keep the rotor centered. The results of the simulation show that the rotor maintained stability during the entire operation with acceptable values of displacement. The PID controller continually corrects the electromagnetic forces to correct small disturbances and to keep the rotor in place. The maximum displacement under normal operation was relatively small, which proved that the AMB system was able to generate accurate support for the rotor without physical contact.

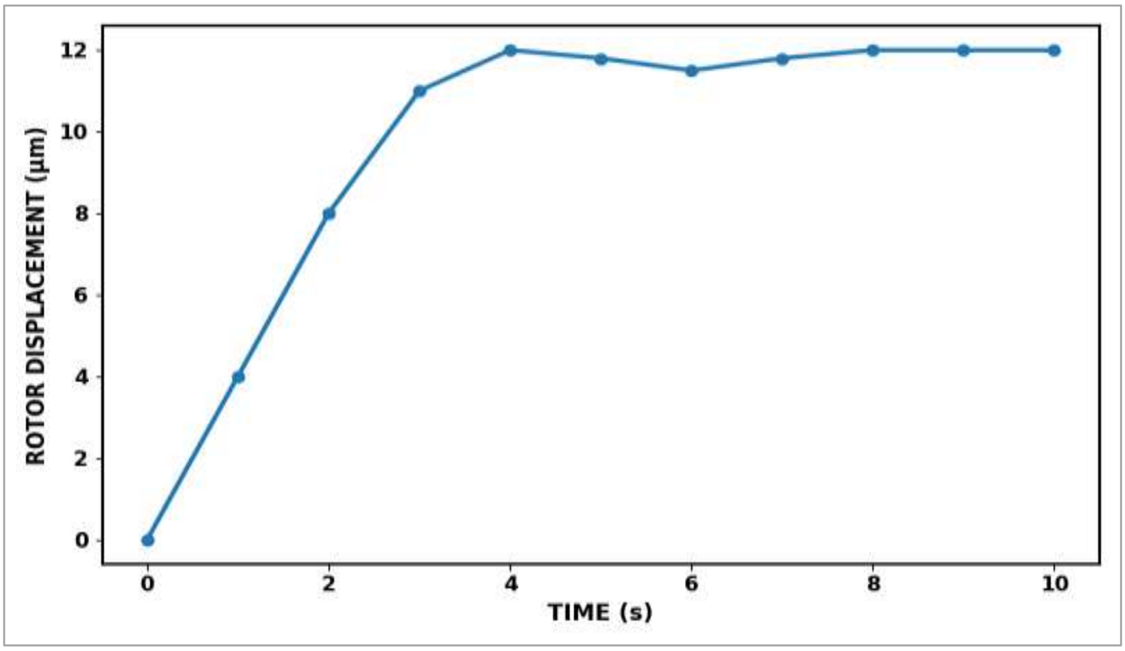

Figure 2: Rotor Displacement Response Under Nominal Operating Conditions

This Active Magnetic Bearing system is considered under nominal operating conditions and has a rotor displacement response as shown in Figure 2. The graph shows that the rotor displacement first increased when the system was started, and decreased at the end when the electromagnetic force was brought to a stable value by the PID controller. The transient behavior for the displacement was relatively short, followed by convergence to a steady value of ~12 µm, without significant oscillations. This behavior shows the effectiveness of the control system to keep the rotor stable and to enable the high-speed motor drive to operate with stability.

Table 3: Rotor Displacement Analysis

Operating Condition	Maximum Displacement (µm)	Average Displacement (µm)
Nominal Operation	12	6
Load Disturbance	25	14
Rotor Imbalance	30	18
High-Speed Operation	18	10

The rotor displacement performance of the Active Magnetic Bearing system with various operating conditions is shown in Table 3. During nominal operation, the lowest maximum displacement of 12 µm was measured, which means that the rotor is positioned stable. The rotor imbalance, which leads to higher dynamic forces acting on the rotor, resulted in the highest displacement value of 30 µm, followed by load disturbance with 25 µm. Despite these differences, the controller was able to keep the displacement in acceptable bounds and exhibited good stabilizing and disturbing performance.

5.2 Vibration Suppression Performance

The major benefits of Active Magnetic Bearings (AMB) are the ability to lower rotor vibration. As a result of this simulation, it was found that the vibration amplitude reduced drastically as compared to the conventional bearing system. The vibration was kept at a minimum during normal operation thanks to continuous electromagnetic force correction. The controller was able to effectively suppress excessive vibrations and preserve system stability even under the rotor unbalance conditions. Decreased vibration results in higher motor reliability, decreased mechanical stress and longer equipment life.

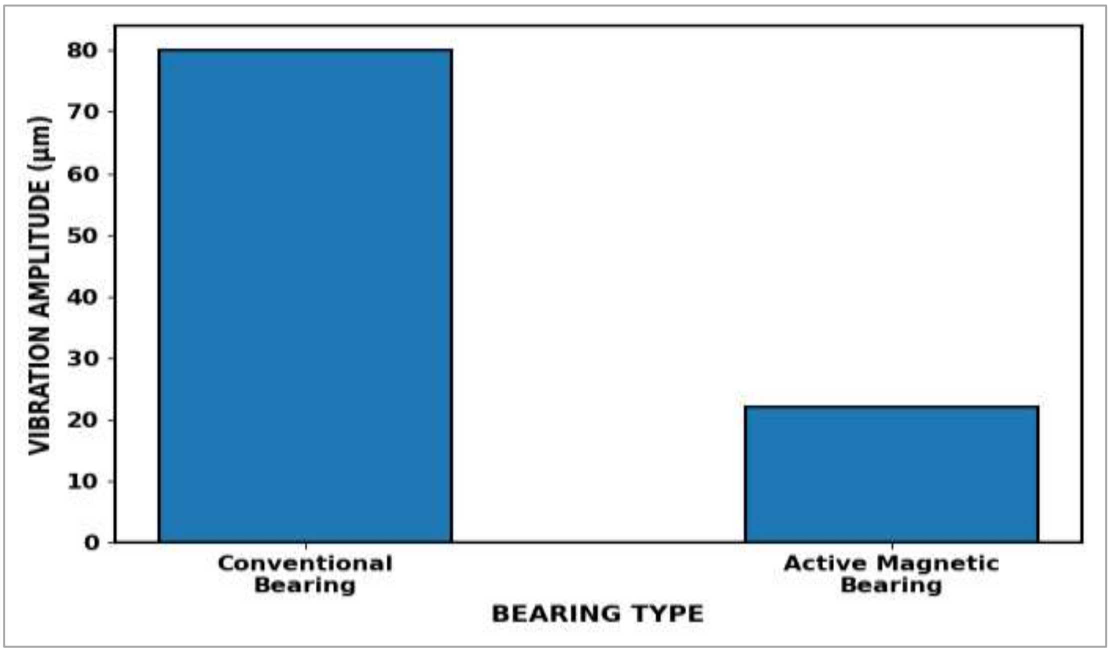

Figure 3: Vibration Amplitude Comparison between Conventional Bearings and AMBs

The comparison of vibration amplitude of conventional bearings with Active Magnetic Bearings (AMBs) is illustrated in Fig.3. According to the results, the vibration amplitude of the conventional bearing system is 80 μm, while the AMB system can reduce the vibration amplitude to 22 μm. The significant reduction is a clear expression of the effectiveness of electromagnetic control in reducing rotor vibrations and enhancing system stability. As a result, the application of AMBs produces more reliable operation, less mechanical stress and better smooth high speed operation of motors.

5.3 Dynamic Response under Load Disturbance

For the assessment of robustness of the controller, a sudden load disturbance was applied during operation. There was a short period of enhanced rotor displacement following the disturbance. The controller quickly produced corrective electromagnetic forces, and restored rotor stability within a few seconds. Excellent disturbance rejection capability was observed with a settling time of around 0.12 seconds and an overshoot below 5%. The results illustrate the success of the AMB control system in keeping the operations stable with various load conditions.

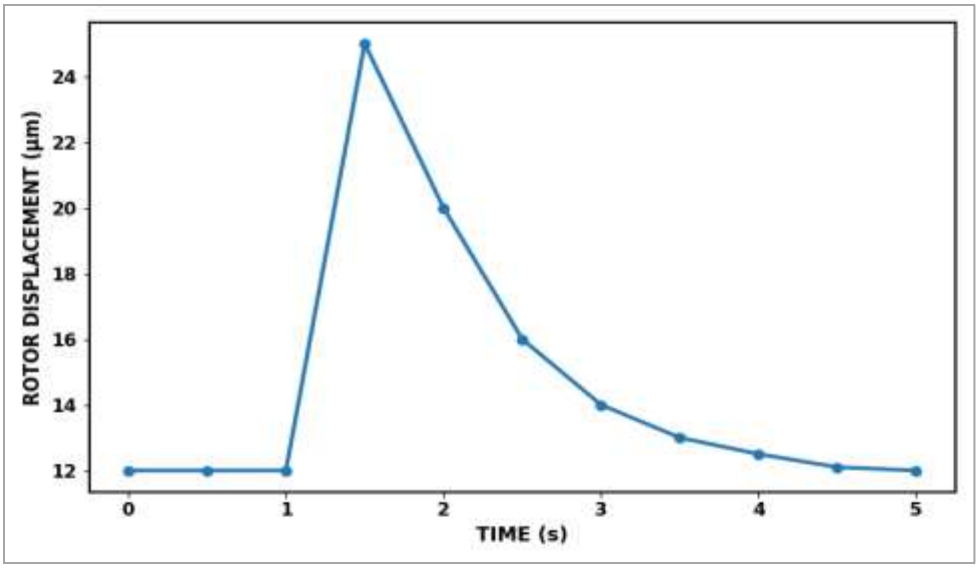

Figure 4: Rotor Response During Sudden Load Disturbance

The plot illustrates the Active Magnetic Bearing system's response under a sudden load disturbance, as depicted in Figure 4. The graph shows a short term increase in rotor displacement after the disturbance, followed by a very quick stabilization process by the PID controller. The steady state value was eventually restored, with a settling time of ~0.12 s and negligible overshoot. The strong disturbance rejection capability and dynamic stability of the AMB system under different load conditions shows the following results.

Table 4: Dynamic Response Characteristics

Parameter	Value
Settling Time	0.12 s
Overshoot	4.5%
Steady-State Error	0.8%
Rise Time	0.05 s

The dynamic response characteristics of the Active Magnetic Bearing system under transient operation are shown in Table 4. The results show that the controller has a good performance of fast rising time 0.05 s and settling time 0.12 s, which means that the controller can rapidly recover the rotor to the equilibrium position after disturbance. The overshoot was less than 4.5% and steady-state error as low as 0.8%, indicating high positioning accuracy. The performance parameters show the efficiency of the PID-controlled AMB system for stable and reliable rotor operation.

5.4 Performance at High Rotational Speeds

The operation scenario with high speed was performed to study the rotor stability at high revolution rates. The AMB system was able to keep the rotor lifted at increasing speeds of the motors and reduce excessive displacement. Since there is no mechanical contact, friction losses and wear were eliminated. The values of the displacement rose a little with the speed, but the controller proved to be effective in maintaining a stable operation. The results indicate that the AMB technology is well suited for applications that need to be operated outside the speed range of traditional bearing technology.

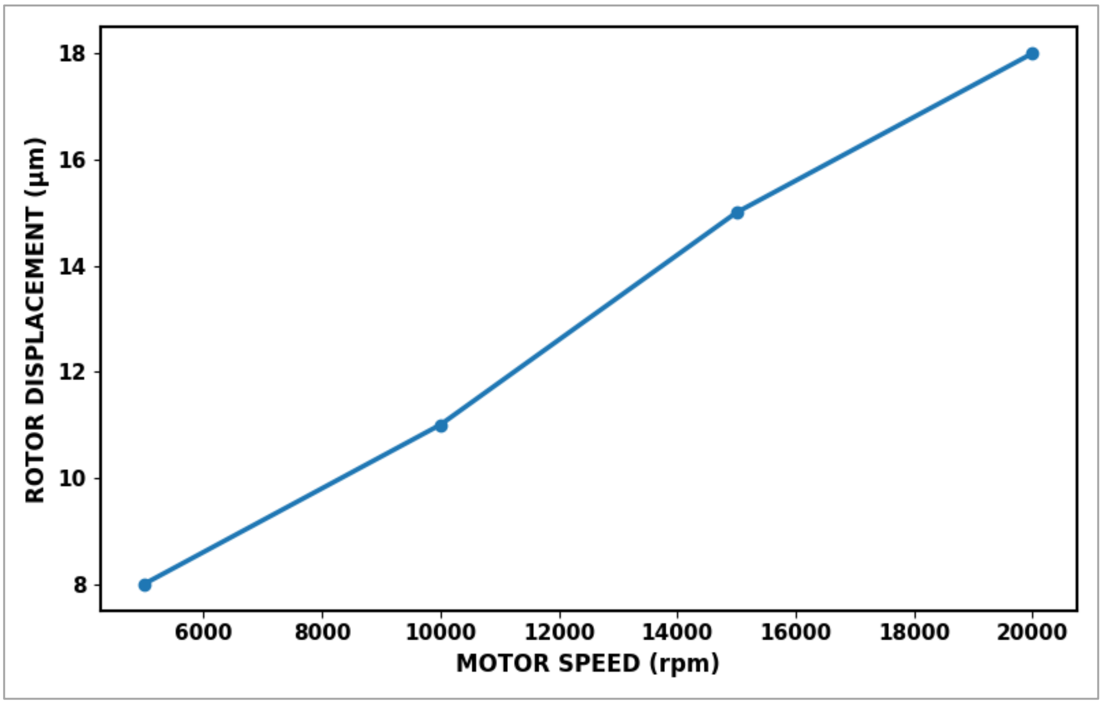

Figure 5: Rotor Displacement versus Motor Speed

The Active Magnetic Bearing system is shown to have rotor displacement versus motor speed characteristics as seen in Figure 5. The graph shows that rotor displacement gradually increased from 8 µm at 5,000 rpm to 18 µm at 20,000 rpm because of the increase in dynamic forces at higher speeds. This increase, however, kept the displacement within acceptable operating limits, thus showing effective electromagnetic control and rotor stabilization. The results indicate the capability of AMB system to operate reliably and provide stable rotor suspension at high operating speed.

Table 5: High-Speed Performance Evaluation

Speed (rpm)	Rotor Displacement (µm)
5,000	8
10,000	11
15,000	15
20,000	18

The rotor displacement behavior under different motor speeds of the Active Magnetic Bearing system is shown in the table below (Table 5). The displacement of the rotor gradually increased from 8 µm to 18 µm with an increase in the rotational speed, the centrifugal and dynamic forces on the rotor. The rotor displacements, however, were still within safe operating ranges, that show that the AMB controller has effectively stabilized the rotors. The results prove the ability of the system to operate in a stable and reliable way even at high speed.

5.5 Energy Efficiency Analysis

The contactless operation of Active Magnetic Bearings makes a significant contribution to the improvement of energy efficiency. Mechanical friction is eliminated, which greatly reduces losses from conventional bearings. The results obtained from the simulation show a decrease in overall power losses and in heat generation during operation. This enhanced efficiency renders AMB assisted motor drives particularly appealing for industrial systems where continuous operation and energy saving are key factors.

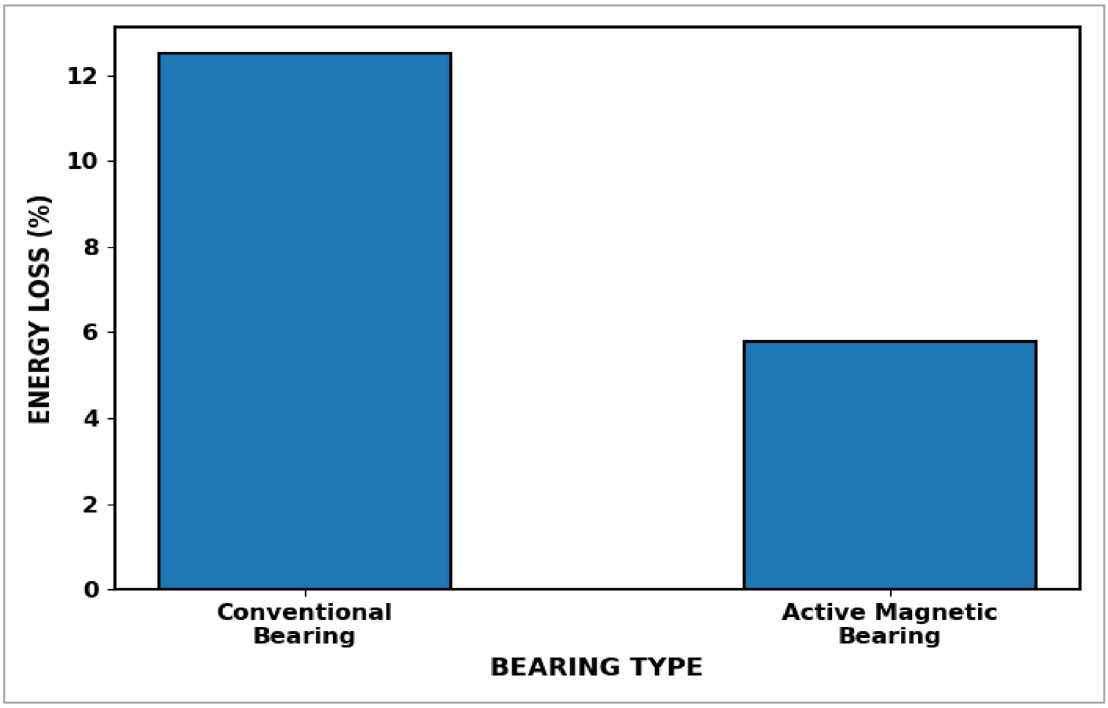

Figure 6: Energy Loss Comparison Between Conventional Bearings and AMBs

Figure 6 is a comparison plot of energy losses for conventional bearing systems and for Active Magnetic Bearings (AMB). The results show that because of its contactless operating mechanism, the AMB system can reduce the energy loss to 5.8%, while the conventional bearings lead to 12.5% energy loss. Eliminating mechanical friction had a tremendous effect on improving the energy efficiency and reduction of heat production during operation. The results demonstrate the benefit of AMB in improving the performance of high-speed motor drive systems in terms of efficiency and sustainability.

Table 6: Energy Consumption Comparison

Bearing Type	Energy Loss (%)
Conventional Bearing	12.5
Active Magnetic Bearing	5.8

The results of the energy consumption comparison between conventional bearings and Active Magnetic Bearings (AMBs) are displayed in Table 6. The conventional bearing system lost 12.5% of its energy, which was attributable to friction and mechanical contact, while the AMB system managed to reduce energy loss to 5.8% by using the contactless electromagnetic suspension. The energy loss reduction is very significant and highlights the superior efficiency of AMB technology. The outcomes suggest that AMBs can be successfully used in high-speed motor drive applications to enhance the use of energy and to lower operational costs.

Discussion

The results obtained certainly showed the benefits of employing the Active Magnetic Bearing technology for high speed motor drive applications. The AMB system was very effective to maintain the rotor stability under nominal conditions, load disturbances, rotor imbalance and high speed conditions. The contactless suspension mechanism eliminated mechanical friction and resulted in a substantial decrease in vibration and hence reduced maintenance needs and increased operational efficiency. Low settling times and a minimum in steady state errors are obtained due to the fast corrective action given by the PID controller. Moreover, disturbance rejection capabilities were high and the system could keep the rotor position stable in the difficult operating conditions. The comparison results demonstrated that the vibration suppression, energy saving, and dynamic behaviors were significantly improved when compared to the conventional bearing systems. The results highlight that Active Magnetic Bearings can provide a dependable and efficient solution in the field of next generation high-speed motor drives, especially where high precision and higher reliability and less mechanical wear is a requirement.

6. Conclusion and Future Work

This study gave a comprehensive performance analysis of Active Magnetic Bearing (AMB) system for the high-speed motor drive. The simulation results proved that the AMB system was able to keep the rotor stable, suppress the displacement, and greatly reduce the vibration levels in the rotor under various operating conditions such as normal operation, load disturbance, rotor imbalance, and high-speed acceleration. The suspension mechanism was contactless, which meant no mechanical friction or wear and better energy efficiency or maintenance. In addition, using a PID-based control system the correction time was fast, with minimum overshoot and stable rotor positioning throughout the operating range. Based on the comparison, it was found that the vibration suppression capacity, dynamic response, operation reliability and high-speed application suitability of Active Magnetic Bearings are superior to conventional bearing systems.

Based on the above research, future work can be directed to the application of advanced intelligent control techniques, like fuzzy logic, artificial neural networks, deep learning, and model predictive control to further improve the rotor stability and disturbance rejection performance. An experimental validation with a real-time hardware prototype can also be performed to check the simulation results in real operating conditions. Further, future research may focus on fault-tolerant controllers, rotor position estimation without sensors, energy-efficient design of electromagnetic actuators, and digital twin rotor monitoring. The introduction of Artificial Intelligence and Predictive Maintenance can further enhance the reliability, efficiency and the applicability of Active Magnetic Bearing systems in next-generation applications of high-speed motor drives.

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