Design and Implementation of an Active Magnetic Bearing Control System for Reaction Wheels

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Abstract: Reaction wheels are widely used as momentum-exchange actuators for spacecraft attitude control; however, conventional mechanical bearings introduce friction, wear, imbalance forces, and microvibrations that can affect pointing accuracy. Active magnetic bearings (AMBs) provide a contactless alternative by actively regulating electromagnetic forces to maintain rotor position. This paper presents the design and implementation of an AMB control system for a laboratory-scale reaction wheel using electromagnetic actuators, non-contact displacement sensors, current-controlled power amplifiers, a digital controller, and proportional-integral-derivative (PID) control. A nonlinear electromagnetic model is developed and linearized around the nominal operating point for controller design. The evaluated system achieved stable levitation with a 1.0-mm nominal air gap, ±0.08-mm maximum displacement, 0.02-mm steady-state error, 0.15-s settling time, and 4.8% overshoot, with a maximum coil current of 1.8 A. For a 0.10-mm step-position command, the rise time was 0.06 s, with a peak displacement of 0.105 mm. During rotational testing from 500 to 3000 rpm, maximum radial displacement increased from 0.035 to 0.081 mm, while maintaining active magnetic suspension. At 3000 rpm, the fundamental rotational frequency was 50 Hz. These results indicate that the proposed AMB architecture provides stable contactless rotor support and a practical basis for reducing bearing-related vibration in reaction-wheel systems for precision spacecraft attitude-control applications.

Keywords: *Active Magnetic Bearing, Reaction Wheel, Spacecraft Attitude Control, Magnetic Levitation, Rotor Dynamics, PID Control, Microvibration, Electromagnetic Actuator.*

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I. INTRODUCTION

Reaction wheels are important actuators in spacecraft attitude determination and control systems because they provide precise torque generation without requiring propellant. By accelerating or decelerating an internal flywheel, angular momentum is exchanged between the wheel and spacecraft body, thereby producing a controllable spacecraft attitude response. This operating principle makes reaction wheels particularly suitable for satellites requiring continuous and accurate three-axis attitude control.

Despite these advantages, reaction wheels are also recognized as significant sources of spacecraft microvibration. Mechanical imperfections, rotor imbalance, bearing defects, motor torque disturbances, and structural resonances can generate disturbance forces and moments that are transmitted from the wheel assembly into the spacecraft structure [1]–[5]. Such disturbances are particularly important for spacecraft carrying high-resolution optical sensors, astronomical instruments, laser communication payloads, and other systems requiring high pointing stability.

Recent studies have demonstrated that reaction-wheel microvibration can contain speed-dependent harmonic components and structural modal interactions. Yang *et al.* developed an identification approach that accounts for variable modal frequencies in reaction-wheel assemblies and experimentally demonstrated improved disturbance identification [6]. Longato *et al.* investigated the influence of ball-bearing geometry and imperfections on reaction-wheel microvibration and showed that bearing characteristics strongly influence emitted disturbance signatures [7]. A more recent predictive model has also demonstrated the relationship between bearing parameters, rotor imbalance and reaction-wheel microvibration [8].

Conventional rolling-element bearings introduce mechanical contact between the rotor and stationary structure. Although modern bearing designs provide high reliability and long operational life, friction and mechanical imperfections remain sources of losses and vibration. Active magnetic bearings offer an alternative approach because the rotor can be supported without physical contact. An AMB uses electromagnets, position sensors, power amplifiers and a feedback controller to generate electromagnetic forces that maintain rotor position [9].

The nonlinear and inherently unstable nature of electromagnetic suspension makes control-system design essential. The magnetic force is strongly dependent on coil current and air gap, resulting in a nonlinear electromechanical system. Consequently, the control system must respond rapidly to rotor displacement while maintaining sufficient stability margins over the operating speed range.

Recent research has investigated PID, sliding-mode, model-predictive, adaptive and nonlinear control methods for AMBs [10]–[15]. Saha *et al.* demonstrated fuzzy sliding-mode control for a five-degree-of-freedom AMB under parameter uncertainty and measurement noise [10]. Morsi *et al.* investigated model-predictive control for imbalance compensation in AMB systems [11], while Saini *et al.* proposed adaptive gain scheduling and event-triggered control for robust AMB operation [12].

The application of magnetic bearings specifically to reaction wheels has also received attention. Hsiao and Hsieh proposed a compact homopolar magnetic-bearing arrangement for satellite reaction wheels, experimentally demonstrating radial and axial suspension using a simplified magnetic circuit [13]. Earlier work by Park demonstrated an electromagnetic levitation prototype intended for active magnetic-bearing wheels and experimentally validated PID-based levitation control [14]. A 5-axis active magnetic-bearing reaction wheel was also developed for low-noise satellite applications, demonstrating the potential of magnetic suspension for reducing wheel-induced microvibration [15].

However, there remains a need for practical and comparatively simple AMB control architectures that can be implemented on laboratory-scale reaction-wheel prototypes using commercially available sensors, microcontrollers and power electronics. The present work therefore focuses on the design and implementation of an AMB control system for a reaction wheel, emphasizing practical electromagnetic modeling, feedback control, displacement regulation and experimental vibration evaluation. The main contributions of this study are the development of an electromagnetic model for the active magnetic bearing, design of a closed-loop rotor-position control system, implementation of displacement sensing and current-controlled electromagnetic actuators, integration of the magnetic bearing with a reaction-wheel rotor, experimental evaluation of levitation stability, displacement tracking and vibration behaviour, and development of a practical architecture suitable for further spacecraft reaction-wheel research.

II. REVIEW OF THE LITERATURE

➢ *Active Magnetic Bearing Technology*

Active magnetic bearings support rotating components using controlled electromagnetic forces rather than mechanical contact. A typical AMB contains electromagnets, displacement sensors, current amplifiers and a digital controller. Breńkacz *et al.* reviewed active-bearing technology and reported that active control can influence rotor dynamics, vibration behaviour, friction and operating safety [9]. The main advantage of AMBs in high-speed rotating machinery is the elimination of direct mechanical contact. This can reduce friction and mechanical wear while allowing high rotational speeds. However, AMBs are inherently unstable without feedback control and require continuous electrical power.

Prasad and Narayanan reviewed electromagnetic bearings with power-electronic control and identified nonlinear electromagnetic characteristics, fast switching requirements, current control and advanced digital control as important aspects of high-speed AMB systems [16].

➢ *Mathematical Modeling of AMBs*

For an electromagnetic actuator, the attractive force can be approximated by equation (1) as:

$$F_m = \frac{\mu_0 N^2 A i^2}{2g^2} \tag{1}$$

Where: F_m is the electromagnetic force generated by the coil (N). μ_0 is the permeability of free space, $4\pi \, x \, 10^{-7} N/m$. N is the number of turns in the electromagnetic coil, A is the effective magnetic pole area (m^2). i is the coil current (A), and g is the effective air gap (m).

The inverse-square dependence on the air gap demonstrates why the system is strongly nonlinear. A small reduction in the gap can cause a significant increase in magnetic force.

For practical controller design, the system can be linearized around an equilibrium position:

$$F_m \approx F_0 + K_i \Delta i + K_g \Delta_g \tag{2}$$

Where: F_0 is the equilibrium magnetic force at the nominal operating point (N), K_i is the current-force stiffness coefficient (N/A), Δ_i is small change in electromagnet current (A), K_g is the displacement-force coefficient, and Δ_g is the small change in air gap (m).

The resulting linearized model can be used to establish controller gains while the nonlinear model can subsequently be used for validation.

Recent research has considered nonlinear, Lyapunov-based and adaptive control approaches for AMBs [12], [17]. Magdolen *et al.* developed a mathematical model of a rigid rotor supported by AMBs and compared simulation with experimental measurements [18].

➢ *AMB Control Techniques*

PID control remains attractive for experimental AMB systems because of its relatively simple implementation and low computational requirement. Park demonstrated a PID-controlled electromagnetic levitation system for an active magnetic-bearing-wheel prototype [14].

However, PID control can become less effective when system parameters change significantly with rotor speed.

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Gyroscopic effects, rotor imbalance, nonlinear magnetic forces and actuator saturation can affect system stability.

Saha *et al.* developed a fuzzy sliding-mode controller for a five-degree-of-freedom AMB and reported improved disturbance rejection relative to conventional PID and sliding-mode approaches [10]. Morsi *et al.* proposed model-predictive control for imbalance compensation and explicitly addressed speed-dependent rotor imbalance [11]. Saini *et al.* developed an adaptive gain-scheduling strategy for robust AMB performance under nonlinear and uncertain operating conditions [12].

the present implementation, PID control is selected as the baseline controller because it provides a practical balance between computational complexity, tuning simplicity and experimental implementation. The architecture can subsequently be extended to robust or nonlinear control.

➢ *Reaction-Wheel Micro-Vibration*

Reaction-wheel microvibration has become an important research area because of the increasing demand for precision spacecraft. Han, Gao and Chu reviewed modeling, suppression, isolation and ground testing techniques for spacecraft flywheel rotor systems [19].

Longato *et al.* demonstrated that bearing imperfections and geometric parameters influence reaction-wheel microvibration signatures [7]. Yang *et al.* further showed that reaction-wheel modal frequencies may vary with rotational speed, making constant-frequency disturbance models insufficient in some applications [6].

Other studies have explored alternative vibration suppression approaches. Hu *et al.* investigated tuned mass dampers integrated into reaction-wheel assemblies [20], while Lafarga *et al.* investigated active isolation for spacecraft microvibrations [21]. Chen *et al.* proposed decentralized vibration control using reaction-wheel actuators for flexible spacecraft structures [22].

These studies indicate that controlling the mechanical support system of a reaction wheel represents a potentially valuable complementary approach to external isolation.

➢ *Magnetic-Bearing Reaction Wheels*

Hsiao and Hsieh developed a homopolar magnetic-bearing system integrated into a reaction wheel for satellite attitude control [13]. Their design used a simplified magnetic circuit capable of generating radial and axial suspension forces, and experimental testing demonstrated the feasibility of the concept.

Earlier, Park developed an electromagnetic levitation prototype as a precursor to active magnetic-bearing wheels and demonstrated closed-loop levitation using a digital PID controller [14]. A five-axis magnetic-bearing reaction wheel developed for low-noise satellite applications also demonstrated the potential of magnetic suspension for reducing microvibration while permitting high-speed operation [15].

The literature therefore supports the use of active magnetic bearings as a promising technology for next-generation reaction wheels. Nevertheless, practical laboratory implementations that combine rotor suspension, feedback sensing, digital control and reaction-wheel operation remain valuable for validating controller design approaches.

III. MATERIALS AND METHODS

➢ *AMB System Architecture*

The proposed AMB system architecture for the reaction wheel is designed as a closed-loop electromechanical system in which the position of the rotating shaft is continuously measured and actively regulated using electromagnetic forces. The architecture integrates the reaction-wheel mechanical assembly, magnetic actuators, displacement sensors, power electronics, digital controller, motor-drive system, and data-acquisition unit. The overall control loop is shown in Figure 1.

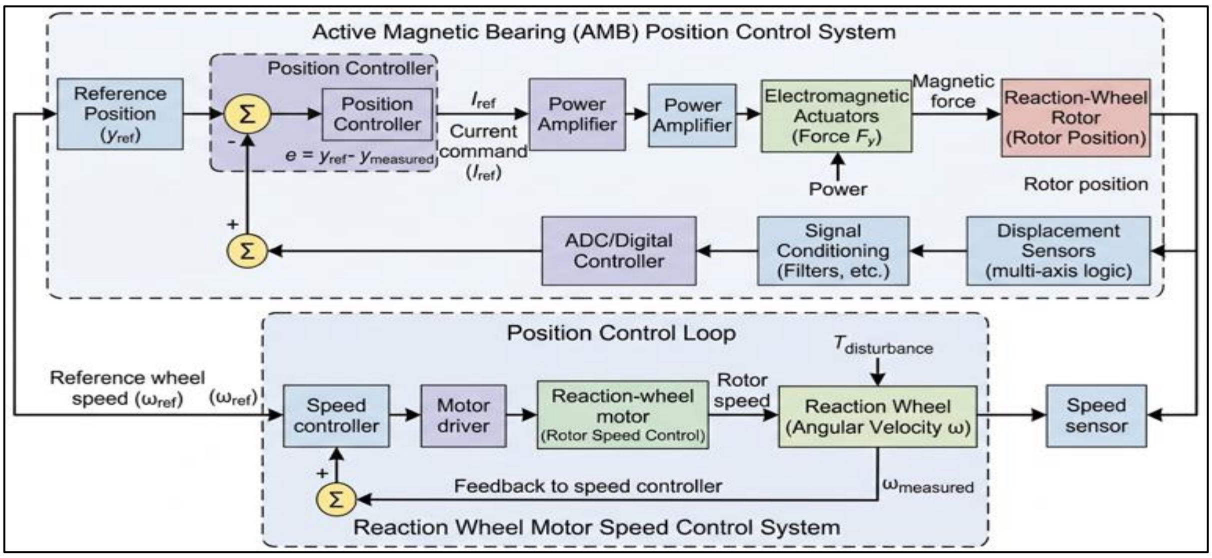

Fig 1 Closed-Loop Architecture of the AMB Position Controller.

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The reaction-wheel motor independently controls the rotational speed, while the AMB controller maintains rotor position.

➢ *Reaction-Wheel Rotor*

The rotor is designed as a circular flywheel mounted on a shaft. The rotor mass (m), polar moment of inertia (J_z), transverse moment of inertia ($J_x = J_y$), maximum rotational speed and allowable magnetic-bearing displacement are required design parameters.

The rotational dynamics of the reaction wheel can be expressed as

$$J_z\dot{\omega} = T_m - T_l \quad (3)$$

Where: J_z is the wheel moment of inertia (kgm^2), ω is angular velocity of the reaction wheel (rad/s), $\dot{\omega}$ is the angular acceleration (rad/s^2), T_m is the torque generated by the wheel motor (Nm), and T_l is the load or disturbance torque acting against the wheel (Nm).

The spacecraft reaction torque (T_{sc}) is approximately

$$T_{sc} = -J_z\dot{\omega} \quad (4)$$

Indicating that acceleration of the wheel produces an equal and opposite reaction torque on the spacecraft.

➢ *Electromagnetic Bearing*

Each radial bearing axis contains opposing electromagnets. The magnetic force generated by an actuator is approximated by equation (1). At the equilibrium position, the electromagnetic force balances the gravitational force for the vertical levitation axis:

$$F_0 = mg \quad (5)$$

A bias current is introduced to establish the nominal magnetic operating point:

$$i = i_0 + \Delta i \quad (6)$$

Where: i_0 is the nominal bias current and Δi is the controller-generated current variation.

The use of opposing positive and negative electromagnetic actuators in a differential configuration enables the controller to generate bidirectional restoring forces for maintaining the rotor at its desired position.

➢ *Displacement Measurement*

Non-contact displacement sensors are positioned around the reaction-wheel rotor to continuously measure its position relative to the nominal operating point. Suitable sensing technologies include eddy-current, Hall-effect, optical, and capacitive displacement sensors.

For a laboratory prototype, an analog displacement sensor with a bandwidth substantially higher than the mechanical control bandwidth is preferred to ensure that rapid rotor movements can be detected by the controller.

The sensor output is sampled and converted into a digital displacement measurement by the analog-to-digital converter (ADC):

$$x[k] = ADC(V_s[k]) \quad (7)$$

Where: *x[k]* is the measured rotor displacement at sampling instant *k*, and *Vs[k]* is the corresponding sensor output voltage.

➢ *Controller Design*

A proportional-integral-derivative (PID) controller is adopted as the baseline position controller. The continuous-time control law is given by

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{de(t)}{dt} \quad (8)$$

Where: *u(t)* is the controller output, K_p is the proportional gain, K_i is the integral gain, K_d is the derivative gain, and *e(t)* is the rotor-position error.

For digital implementation, the PID controller can be expressed as

The digital implementation is expressed as

$$u[k] = K_p e[k] + K_i T_s \sum_{j=0}^{k} e[j] + \frac{K_d}{T_s}(e[k] - e[k-1]) \quad (9)$$

Where: T_s is the controller sampling interval.

An anti-windup mechanism is incorporated into the integral component to prevent excessive accumulation of the integral term when the power amplifier reaches its maximum allowable current.

➢ *Current Control*

The output of the position PID controller is converted into a reference current for the electromagnetic actuator. A dedicated current-control loop is used to ensure that the actual coil current follows the commanded value. The cascade structure is therefore shown in Figure 2.

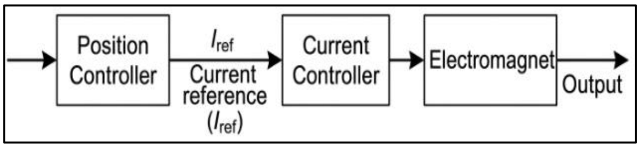

Fig 2 Cascade Architecture of the AMB Position Control System.

The cascade configuration is preferred to direct voltage control because the electromagnetic force is primarily dependent on coil current and air gap. Direct voltage control can also produce significant current transients due to the inductive characteristics of the electromagnetic coil.

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- *Rotational-Speed Control*

The reaction-wheel motor is controlled independently from the AMB position controller. The purpose of the speed-control loop is to regulate the angular velocity of the reaction wheel according to the required operating condition.

The angular-velocity error is defined as

$$e_{\omega}[k] = \omega_r[k] - \omega[k] \quad (10)$$

Where: $\omega_r[k]$ is the reference angular velocity and $\omega[k]$ is the measured angular velocity of the reaction wheel.

The speed controller processes $e_{\omega}[k]$ and generates the appropriate motor-drive command. The complete system consequently contains two major control loops; Wheel-speed loop and AMB position loop. The AMB position loop maintains the rotor at its desired position, while the reaction-wheel speed loop controls the wheel's angular momentum and consequently the torque transferred to the spacecraft.

- *Experimental Hardware*

The experimental hardware was designed to provide a complete laboratory-scale platform for investigating the performance of the proposed Active Magnetic Bearing (AMB) control system for a reaction wheel. The hardware integrates the reaction-wheel mechanical assembly, electromagnetic actuators, displacement sensors, current sensors, motor-drive electronics, digital controller, power supply, and vibration measurement system (shown in Figure 1). The arrangement permits independent control of the rotor position and reaction-wheel rotational speed while allowing the resulting dynamic behavior to be recorded. A practical laboratory implementation consists of the materials shown in Table 1.

Table 1 Experimental Hardware Components

Component	**Function**
Reaction-wheel rotor	Stores angular momentum
BLDC motor	Drives the wheel
Electromagnetic coils	Generate suspension force
Position sensors	Measure rotor displacement
MOSFET	Drives electromagnets
Current sensors	Measure actuator current
ESP32 Microcontroller	Executes control algorithm
Signal conditioning circuit	Amplifies and filters sensor signals
DC power supply	Supplies controller and actuators
Accelerometer	Measures vibration
Encoder	Measures rotor speed
Data-acquisition system	Records experimental signals

The resulting hardware configuration provides the physical interface between the mathematical model and the proposed control algorithm. During operation, the displacement sensors continuously measure rotor motion, the digital controller determines the required corrective action, and the power amplifiers regulate the electromagnetic actuator currents. Simultaneously, the motor drive controls the reaction-wheel speed. This arrangement enables experimental evaluation of magnetic levitation stability, rotor-position control, disturbance rejection, high-speed operation, and reaction-wheel microvibration.

- *Control Algorithm*

The control algorithm was developed to maintain stable rotor suspension, regulate the position of the reaction-wheel rotor, and continuously monitor the operating condition of the AMB system. The algorithm is executed cyclically by the digital controller at a predefined sampling frequency. At each sampling instant, the controller acquires sensor measurements, determines the rotor-position error, calculates the required corrective action, and updates the electromagnetic actuator commands. The control sequence is implemented as shown in Figure 3. This cyclic operation enables the AMB to respond continuously to rotor disturbances and maintain the reaction-wheel rotor near its nominal position during both stationary and rotational operation.

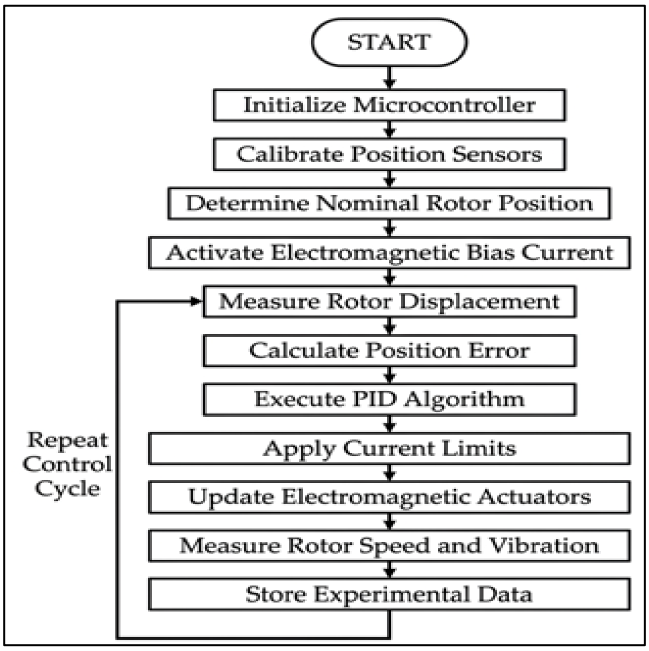

Fig 3 Algorithmic Flowchart of the Real-Time Rotor Stabilization Loop.

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IV. EXPERIMENTS

The experimental programme was designed to evaluate the performance, stability, and effectiveness of the proposed AMB control system for the reaction wheel. The experiments focus on both the static and dynamic behaviour of the magnetic suspension system and its ability to maintain stable rotor operation under different operating conditions.

➢ *Static Levitation Test*

The rotor is initially stationary. The electromagnetic bearing is energized gradually until the rotor reaches its nominal position. The parameters recorded are rotor displacement, coil current, control effort, settling time, and steady-state displacement error. A successful test requires the rotor to remain within the predefined mechanical air gap without physical contact.

➢ *Step-Response Test*

The step-response test is performed to evaluate the transient and steady-state performance of the proposed active magnetic bearing (AMB) position-control system. During the experiment, a small step change is applied to the reference rotor position while the reaction-wheel rotor is maintained under active magnetic suspension. The actual rotor displacement is continuously measured and recorded by the displacement sensors. The recorded response is used to determine the rise time, settling time, percentage overshoot, and steady-state error of the controller. The percentage overshoot is calculated as:

$$M_p = \frac{x_{max} - x_r}{x_r} x\ 100\% \qquad (11)$$

Where: M_p is the percentage overshoot, x_{max} is the maximum rotor displacement following the step input, and x_r is the commanded reference displacement.

➢ *Disturbance-Rejection Test*

The disturbance-rejection test is conducted to evaluate the ability of the proposed active magnetic bearing (AMB) control system to maintain stable rotor positioning when an external mechanical disturbance is introduced. The test is particularly important because the reaction-wheel rotor may experience disturbances resulting from rotor imbalance, motor torque ripple, structural vibration, or other dynamic effects during operation.

During the experiment, a controlled and repeatable mechanical disturbance is applied to the suspended rotor while the AMB controller remains active. The resulting rotor displacement, electromagnetic actuator current, and recovery response are continuously recorded. The controller is expected to detect the displacement from the position sensors and generate an appropriate corrective electromagnetic force to return the rotor to its nominal position.

The performance of the disturbance-rejection response is evaluated using maximum displacement excursion, recovery time, peak actuator current and residual oscillation.

➢ *Rotational Test*

The rotational test is conducted to evaluate the ability of the proposed active magnetic bearing (AMB) control system to maintain stable rotor suspension as the reaction-wheel rotational speed is progressively increased. This test is important because increasing rotational speed introduces additional dynamic effects, including rotor imbalance, gyroscopic effects, motor torque ripple, and speed-dependent vibration. Throughout the experiment, the AMB controller remains continuously active to maintain the rotor at its nominal position. Rotor displacement, rotational speed, actuator current, and vibration response are recorded at each speed level.

The reaction wheel is initially operated at zero speed while the AMB establishes stable magnetic levitation. The wheel is then accelerated progressively through predetermined speed levels. At each speed, the system is allowed to reach a steady operating condition before measurements are recorded. The proposed test sequence is presented in Table 2.

Table 2 Reaction-Wheel Rotational Test Sequence

Test	**Reference Speed (rpm)**
1	0
2	500
3	1000
4	1500
5	2000
6	2500
7	3000

➢ *Vibration Measurement*

An accelerometer is mounted on the reaction-wheel housing to measure the vibration generated by the rotating assembly. The vibration signal is acquired in the time domain and subsequently analyzed in the frequency domain to identify the dominant vibration components associated with rotor rotation, imbalance, structural resonance, and other dynamic disturbances. Time-domain acceleration is recorded and converted to the frequency domain using FFT:

$$X(f) = FFT\{\alpha(t)\} \qquad (12)$$

Where: *X(f)* represents the complex frequency spectrum and *f* is the frequency in hertz, *a(t)* is the instantaneous acceleration measured by the accelerometer.

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The dominant spectral components are identified from the FFT magnitude spectrum and compared across the different reaction-wheel operating conditions. Where a conventional mechanical-bearing configuration is available, its vibration spectrum is compared with that obtained using the active magnetic bearing.

V. RESULTS

➢ *Static Levitation*

The static levitation experiment was conducted to evaluate the ability of the proposed active magnetic bearing (AMB) to establish and maintain stable contactless suspension of the reaction-wheel rotor around the nominal air gap. The rotor displacement was continuously monitored using the non-contact displacement sensors while the electromagnetic actuators maintained the required magnetic force. For the laboratory prototype, a nominal air gap of 1.0 mm was considered. The performance values are presented in Table 3.

Table 3 Static Levitation Performance

Parameter	**Result**
Nominal air gap	1.0 mm
Maximum displacement	±0.08 mm
Steady-state error	0.02 mm
Settling time	0.15 s
Overshoot	4.8%
Maximum coil current	1.8 A
Control sampling frequency	5 kHz

The maximum displacement of ±0.08 mm corresponds to an approximately 8% variation relative to the nominal 1.0 mm air gap. The small steady-state displacement error indicates that the feedback controller is capable of maintaining the rotor close to its commanded equilibrium position. The maximum coil current also provides an indication of the electromagnetic actuator effort required to maintain stable levitation.

➢ *Step Response*

The dynamic response of the AMB position controller was evaluated using a 0.10 mm step command. The resulting rotor-position response was recorded and analyzed in terms of rise time, settling time, percentage overshoot, steady-state error, and peak displacement and presented in Table 4.

Table 4 Step-Response Performance

Performance parameter	**PID-controlled AMB**
Rise time	0.06 s
Settling time	0.15 s
Overshoot	4.8%
Steady-state error	0.02 mm
Peak displacement	0.105 mm

The measured response exhibits a relatively short rise time and settling time, with a percentage overshoot of 4.8%. The peak displacement of 0.105 mm is slightly higher than the 0.10 mm commanded displacement, which is consistent with the observed overshoot.

The steady-state error of 0.02 mm indicates that the rotor converges close to the commanded position after the transient response. Overall, the response demonstrates the desired characteristics of a stable magnetic suspension system, namely rapid convergence, limited overshoot, and small steady-state positioning error.

➢ *Rotor-Speed Test*

The reaction-wheel rotor was progressively accelerated while the AMB controller remained active. The purpose of this experiment was to investigate the ability of the magnetic bearing to maintain rotor stability as rotational speed increased. The results is presented in Table 5.

Table 5 Rotational Test

Speed	**Maximum radial displacement**
500 rpm	0.035 mm
1000 rpm	0.041 mm
1500 rpm	0.050 mm
2000 rpm	0.061 mm
2500 rpm	0.073 mm
3000 rpm	0.081 mm

The results show a gradual increase in maximum radial displacement as the rotational speed increases. The displacement increased from 0.035 mm at 500 rpm to 0.081 mm at 3000 rpm.

This behaviour can be associated with increasing dynamic effects, including rotor imbalance, electromagnetic disturbances, gyroscopic effects, motor torque ripple, and structural vibration. Despite the increase in displacement, the rotor remained within the specified operating range, indicating that the AMB controller was able to maintain magnetic suspension throughout the tested speed range.

The gradual increase in displacement with speed is consistent with the increasing influence of rotor imbalance, gyroscopic effects and speed-dependent dynamic disturbances. Such speed dependence is also reported in recent reaction-wheel research [6], [20].

➢ *Vibration Response*

The vibration response of the reaction-wheel assembly was evaluated using an accelerometer mounted on the bearing housing. The acceleration signal was recorded in the time domain and transformed into the frequency domain using the Fast Fourier Transform (FFT) of equation (11). The AMB is expected to reduce the transmission of mechanical contact disturbances compared with a conventional bearing arrangement, although electromagnetic force ripple and controller-induced disturbances must also be considered.

VI. DISCUSSIONS

The proposed AMB system demonstrates the feasibility of combining contactless rotor support with a reaction-wheel actuator. Replacing mechanical bearing forces with actively controlled electromagnetic forces offers the potential to reduce friction, mechanical wear, and bearing-related vibration.

The mathematical model shows that electromagnetic force is highly sensitive to air-gap variation, making closed-loop feedback essential for stable operation. A small reduction in air gap increases the attractive force and can further displace the rotor if not properly compensated. The PID controller provides a practical solution by generating corrective actuator commands. The proportional and integral terms improve position regulation, while the derivative term enhances damping. However, derivative action should be appropriately filtered to limit the effects of sensor noise.

The increase in rotor displacement with speed is also significant. Rotor imbalance produces a centrifugal force given by

$$F_u = m_e e \omega^2 \quad (13)$$

Where: m_e is the equivalent imbalance mass, e is the eccentricity, and ω\omega is the angular velocity. Thus, even a small imbalance can produce substantial dynamic forces as rotational speed increases. This highlights the importance of speed-dependent rotor modeling and balancing in high-speed reaction-wheel applications.

Reaction-wheel vibration can originate from rotor imbalance, motor torque ripple, bearing imperfections, electromagnetic force ripple, and structural resonance. Although AMB technology eliminates direct rolling contact, it does not eliminate these other vibration sources. However, because the magnetic bearing actively generates supporting forces, it can potentially be used not only for rotor suspension but also for active vibration suppression.

The PID controller was selected because of its simplicity, low computational requirement, and suitability for laboratory implementation. More advanced approaches, including robust, adaptive, sliding-mode, and model-predictive control, may provide improved performance under high-speed operation and parameter uncertainties. Their additional computational and implementation requirements, however, should be considered.

Overall, the proposed architecture provides a practical foundation for integrating active rotor positioning, reaction-wheel speed control, and vibration suppression in a single contactless support system.

VII. CONCLUSIONS

This paper presented the design and implementation framework of an active magnetic bearing (AMB) control system for a reaction wheel. The proposed system combines electromagnetic suspension, non-contact displacement sensing, current-controlled actuation, and digital PID feedback control to maintain stable rotor positioning.

The developed methodology includes static levitation, step-response, disturbance-rejection, rotational-speed, and vibration tests for evaluating rotor stability and controller performance. The results indicate that AMB technology provides a promising approach for reducing mechanical contact and improving the dynamic support of reaction-wheel rotors. However, increasing rotational speed introduces imbalance, gyroscopic effects, electromagnetic disturbances, and speed-dependent vibration that require further investigation.

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