

Fault Tolerance of Active Magnetic Bearings for Critical Applications

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Abstract

This paper presents a comprehensive fault tolerance strategy for active magnetic bearing (AMB) systems in critical applications. AMBs offer numerous advantages, including reduced wear, minimal maintenance, and improved vibration performance; however, these systems must be carefully designed to manage fault conditions that could compromise stability or cause catastrophic machine failure. The primary objective of this study is to define system-level failure modes, establish a clear methodology for fault classification, and evaluate redundancy options for AMB components to enhance overall system reliability.

The paper introduces a fault tolerance framework that classifies failure modes into four categories: operation outside allowable limits, performance reduction, unintended machine downtime, and catastrophic damage. These categories are mapped to specific AMB failure scenarios. The methodology emphasizes early fault detection, appropriate hardware redundancy, and the implementation of software control strategies that enable drop prevention and drop recovery. A systematic evaluation of hardware fault tolerance options is provided for actuators, position sensors, magnetic bearing controllers (MBCs), and touchdown bearings. Redundancy configurations such as 1+1, N+1, and active-active load-sharing topologies are assessed for their feasibility and system impact.

The paper also details drop detection, fault prevention, and drop recovery strategies, supported by adaptive control algorithms, synchronous force rejection, and bias current management. Field-tested drop recovery software, previously demonstrated on a rotary-disc atomizer, is reviewed as a basis for future applications. Results show that integrating fault tolerance measures in both hardware and software significantly improves AMB system resilience. The conclusions support continued development and validation of fault-tolerant AMB architectures to meet the reliability demands of space, defense, and mission critical rotating machinery.

Keywords : Active Magnetic Bearings, Fault Tolerance, System Redundancy, Drop Detection, Drop Prevention, Rotor Vibration Control, Magnetic Bearing Controllers, Adaptive Control, Amplifier Saturation, Touchdown Bearings

1. Introduction

Active Magnetic Bearings (AMBs) represent an advanced and reliable bearing technology. AMBs use electromagnetic forces to levitate and support rotating shafts without physical contact, offering benefits such as reduced wear, maintenance, and vibration. However, the complexity of AMBs necessitates a comprehensive understanding of their individual components and the inherent requirement for fault tolerance, especially in critical applications such as space, defense, and high-performance machinery.

The primary components of an Active Magnetic Bearing system include:

1. **Electromagnetic Actuator:** The actuator generates the magnetic field necessary to levitate the shaft and maintain its position. This actuator is driven by an electric current via solid-state amplifiers, controlled by the magnetic bearing controller.
2. **Position Sensor:** The sensors provide real-time feedback on the shaft's position, enabling the magnetic bearing controller to adjust the electromagnetic forces to maintain stability and performance.
3. **Magnetic Bearing Controller (MBC):** The MBC is the brain of the system, continuously processing feedback from the position sensors and adjusting the actuator's output to maintain the shaft's levitation.

4. Touchdown Bearings: These provide a mechanical backup system in case of a failure in the active magnetic levitation, ensuring that the shaft does not experience damaging contact with the surrounding structure.

For an AMB system to operate reliably, particularly in critical applications, fault tolerance should be evaluated and (if warranted) incorporated into each of these components. Fault tolerance is paramount for applications in the space and defense sectors, where system failures can result in mission failure, loss of equipment, or jeopardize public safety. Such consequences highlight the need for robust design and operational redundancy. Ensuring system reliability requires careful consideration of fault detection, prevention, and recovery mechanisms.

In addition to hardware redundancy, software algorithms can be implemented in the MBC to aid in system fault tolerance. Fault detection must be implemented to ensure either a control reaction or transition to the backup machine hardware. The control reaction can be further broken up into actions for fault *prevention* and *recovery*. The most commonly discussed AMB fault is the rotor *hard drop* event, whereby the rotor will contact the touchdown bearings and require a deceleration to 0 rpm while spinning on the bearings. This is contrasted with the rotor *soft drop* or *intermittent drop* event, whereby the rotor contacts the touchdown bearing due to a temporary condition, and then recovers without decelerating to 0 rpm on the touchdown bearings. This can be caused by power loss, external disturbances, or dynamics from the base/structure. Drop fault prevention features can be used to prevent a drop when the system is experiencing a condition previously known to cause drops. Drop recovery features can be used to recover the rotor from a drop with or without stopping the machinery. These software features are explored in later sections.

Below is a generic depiction of an Active Magnetic Bearing system with the key components highlighted for clarity:

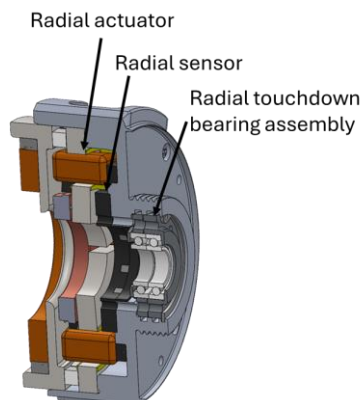


Figure 2. AMB system mechanical hardware with key components



Figure 1. Magnetic Bearing Controller

2. Fault Tolerance Definitions and Design Methodologies

Fault Tolerance for AMB systems requires consistent definition of several factors and impacts along with a systematic methodology for fault mitigation in a design. Designers and end users with varied backgrounds can have different interpretations of what it means to create a fault tolerant system.

Fault tolerance should first aim to define failure modes for the AMB system and the rotor that they support. Depending on risk tolerance of the particular application, a failure can be interpreted as a failure causing a reduction in system performance, operation outside of allowable specifications, unintended machine downtime, or catastrophic damage to the machine. Specific to magnetic bearings, a failure could result in a reduction in system performance such as available load capacity or dynamic performance, could result in excessive vibration or a reduction in available stability margin, could prevent the system from operating altogether (stable levitation in the case of an AMB system), or could cause damage to the AMB components (i.e. after a rotor drop event). Defining the failures of the system is highly dependent on the application. Clear definitions are a critical step of the design process of a fault tolerant system. Table 1

summarizes the system-level definitions of failure modes and some specific ways these failures can manifest in a magnetic bearing system, in order from the most conservative failure modes to the most catastrophic failure modes.

Table 1. AMB System – Example Failure Modes and Failure Mode Category

System-Level Failure Mode Category	Result of failure	Example AMB Failures
Operation Outside Allowable Limits	System operates, but key parameters exceed specified thresholds	Excessive synchronous vibration, stability margins above acceptable ISO 14839-3 threshold, excessive controller or machine temperature
Performance Reduction	System remains operational, but with degraded capability	Reduced dynamic load capacity due to excessive noise on system, inability to store data logs due to dead on-board battery
Unintended Machine Downtime	System unexpectedly shuts down or cannot maintain intended operation	Fault due to controller/cable short to ground, fault due to amplifier saturation
Catastrophic Damage	Physical damage to system components or failure leading to unsafe operation	Excessive rotor drop events causing catastrophic damage to rotor or AMB components, catastrophic damage of power electronics components

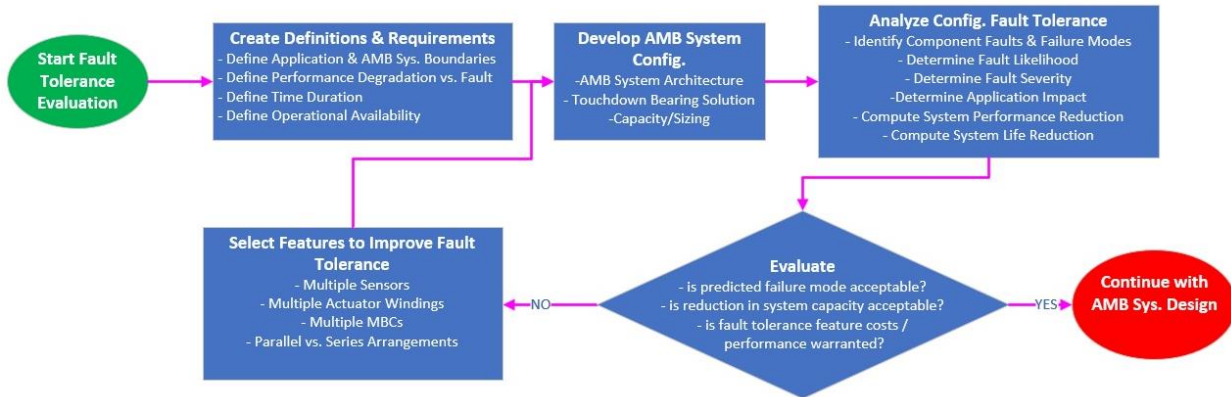
It is important to identify what level of fault tolerance is required. An Example in an AMB application of defining the type and level of fault tolerance is whether the intent is to prevent machine downtime by dropping of the AMB system or to prevent any reduction in performance from the AMBs by a loss in capacity. Defining the goals and levels of fault tolerance has numerous capability trade offs in addition to cost.

Once the various failure modes have been identified, it is necessary to explore how each component can contribute to a failure mode and the likelihood and severity of a component failure. Depending on the AMB system topology and component types, an infinite combination of likelihoods and severities exist. Some representative examples are explored in section 3 for hardware considerations.

After definition of failure mode likelihood and severity of a baseline AMB system design, evaluation of hardware features to prevent and/or recover from failures is conducted. These can include:

- Topology: Active Redundant vs. Standby Redundant. Arrangement of parallel vs. series components
- Component Quantity / Types
- Fault sensing and compensating algorithms

As with any engineering design choice, there are costs and complexities associated with adding features to mitigate fault occurrence. In evaluating the respective failure modes, their likelihood and severity, the cost and complexity of fault tolerance improvement features (hardware & algorithm) an optimal selection chosen. Methods employed for multifactor analysis and optimization can be employed to arrive at an optimal system solution for what may otherwise be a subjective / qualitative choice. Figure 3 provides some of the typical steps considered in a portion of the AMB system design for incorporating fault tolerant features.



3. Hardware Considerations

Figure 3. Design Process Considerations of Fault Tolerance

In order to achieve a fully fault tolerant AMB system, redundancy must be incorporated into each of the system's key components. Given that AMBs are used in critical applications, any failure could result in significant operational or safety hazards. Therefore, redundancy and fault tolerance strategies are important to maintain system integrity. This section reviews some of the key failure modes of the major AMB components and how redundancy can be achieved/implemented for each component.

1. Redundancy in Electromagnetic Actuators: To ensure continuous levitation even in the event of actuator failure, multiple redundant actuators are often employed [1]. These redundant actuators may be (over) designed and controlled in a manner that allows them to take over the load from any failed unit. Other actuators may feature separate windings that allow for a portion to fail and a reduction in available load capacity to occur but limited operation still enabled. By using either parallel or series configurations, the failure of one actuator can be compensated by others, ensuring that the shaft remains levitated and stable.
2. Redundancy in Position/Displacement Sensors: Position sensors are vital for providing feedback to the Magnetic Bearing Controller (MBC) to ensure accurate actuator adjustments. Several strategies can be implemented to achieve sensor redundancy and ensure continued system operation in the presence of faults. One approach involves incorporating backup sensing capabilities that automatically take over when anomalies or failures are detected in the primary sensing path, allowing for uninterrupted functionality. Another approach relies on using multiple sensing elements to provide overlapping measurements. The system evaluates the consistency among the various inputs and adjusts its control decisions by prioritizing the most reliable data. This helps isolate degraded signals and maintain accurate system behavior even when some measurements become unreliable. These strategies can enhance fault tolerance and support safe, continuous operation without relying on any single point of failure.
3. Redundancy in Magnetic Bearing Controllers (MBC): The MBC serves as the central processing and control unit that interprets feedback from position sensors and adjusts the actuator forces accordingly. The MBC typically consists of a digital signal processor (DSP) where the main control loop is implemented, a sensor processing/power board, and a power amplifier control board with switching power devices. Given its crucial role, the MBC is typically made fault-tolerant through both hardware and software redundancy. Multiple controllers can be implemented, with one acting as a backup to take over in the event of a primary controller failure. Further fault tolerance considerations exist in the connection and combination of redundant MBCs with electromagnetic actuators and sensors; various serial vs. parallel vs. transferable connections could be made depending on the topology that best achieves the system fault tolerance needs.
4. Redundancy in Touchdown Bearings: Touchdown bearings act as a fail-safe to prevent the shaft from contacting critical structures in the event of an AMB failure. These bearings are often designed in a way that allows for multiple levels of redundancy. For example, two or more independent sets of touchdown bearings may be placed at different locations on the shaft, ensuring that if one set of bearings is compromised, others can take over and protect the system.

By incorporating redundancy into these core components of AMBs, system reliability can be greatly improved, ensuring that the AMB continues to perform even under fault conditions. Furthermore, advanced monitoring and diagnostic systems are employed to detect component degradation before failure occurs, allowing for predictive maintenance and reducing the risk of catastrophic failure in mission-critical applications.

4. Drop Detection/Fault Architecture

In an Active Magnetic Bearing (AMB) system, detecting faults before they result in catastrophic failure is critical for ensuring system reliability and longevity. A robust fault detection architecture is essential for identifying problems and triggering appropriate control actions. The Calnetix fault architecture is designed to detect a wide range of fault conditions, including but not limited to excessive rotor vibration, abnormal controller temperature, and potential amplifier saturation.

1. **Excessive Rotor Vibration:** Vibration often serves as an early warning sign of instability in the levitation system. Vibration can be indicative of a rotor unbalance problem, component misalignment, a malfunctioning actuator or sensor, or an issue with the control feedback loop.
2. **Excessive Temperature:** Temperature is a critical parameter to trend to ensure the long-term reliability of the Magnetic Bearing Controller (MBC), sensor, and actuator. Excessive heat can impair the functionality of the MBC and other associated electronics, potentially leading to a system failure. The fault architecture incorporates temperature sensors within the MBC and bearing stator components to monitor heat buildup. When temperatures rise beyond acceptable limits, a fault condition is flagged, and control strategies are enacted to protect the system.
3. **Amplifier Saturation:** Amplifier saturation occurs when the switching power amplifier(s) used to drive the actuator approach 100% duty cycle. Monitoring the bearing voltages and currents helps detect early signs of saturation. The fault detection architecture compares real-time amplifier performance against predefined limits and triggers protective actions when necessary.

By integrating these detection mechanisms into the fault architecture, the AMB system can ensure early identification of potential issues, allowing for control/isolation action to maintain rotor stability, prevent machine shutdown, and/or prevent damage to any part of the system hardware.

5. Drop Prevention

Preventing a rotor drop fault is a critical aspect of ensuring the stability and reliability of an Active Magnetic Bearing (AMB) system. A rotor drop fault occurs when the levitating forces provided by the AMB fail, causing the rotor to come into contact with the touchdown bearings. Such an event can lead to mechanical damage, excessive wear, and potentially catastrophic system failure. To mitigate the risk of a rotor drop fault, several strategies are employed, focusing on preventing rotor vibration, managing controller temperature, and avoiding amplifier saturation.

Once a fault is detected, the MBC can take preventative control/isolation actions which can limit the number of touchdowns. The Magnetic Bearing Controller (MBC) plays a pivotal role in this phase by executing control algorithms that adjust the system's operation to mitigate potential failure scenarios.

5.1 Preventing Rotor Vibration

Rotor vibration can be a precursor to instability, leading to a potential drop if not properly controlled. There are two primary approaches to preventing excessive rotor vibration:

- (1) **Adaptive Adjustment of the AMB Compensator:** To minimize rotor vibration, the AMB compensator can be dynamically adjusted based on real-time feedback from position sensors and vibration measurements. This adaptive compensation allows the system to react to changes in the rotor's dynamic behavior, such as varying load conditions or disturbances, by adjusting the control forces applied by the AMB. The compensator's parameters can be modified in real-time to reduce vibration, ensuring stable levitation and preventing conditions

that could lead to a drop.

- (1) **Synchronous Force Algorithms:** Synchronous force algorithms are used to manage rotor vibration by adding a force vector at the rotor's spin frequency. There are two types of synchronous force algorithms employed to minimize vibration and maintain system stability: synchronous force rejection and synchronous damping.

Synchronous Force Rejection:

Synchronous force rejection aims to minimize the forces applied at the rotor's spin frequency (“synchronous vibration”). Synchronous force rejection reduces synchronous control current, effectively dropping the stiffness of the compensator at the spin frequency to near zero. The goal of this algorithm is to ensure that forces at the spin frequency are minimized, thereby reducing vibration transmissibility, reducing audible/airborne noise, and preserving dynamic load capacity of the AMBs.

Synchronous Damping:

Synchronous damping, in contrast, is designed to apply a reaction force that is 90 degrees out of phase with the vibration amplitude at the spin frequency (damping). This algorithm is used when traversing a rotor mode. Both synchronous force rejection and synchronous damping are essential techniques for controlling rotor vibrations at the spin frequency, ensuring that the AMB system operates efficiently, with reduced vibrations and improved system reliability.

While the above synchronous compensation approaches can offer significant advantages to fault tolerance, there is a practical limit of compensation for both algorithms. For synchronous force rejection, the practical limitation is based on the acceptable synchronous displacement. For synchronous damping, the available dynamic force capacity will limit the amount of damping that can be applied at speed. Both algorithms attempt to compensate for residual mass imbalance of the rotor in different ways, and the .

5.2 Preventing Excessive System Temperature

Excessive temperature buildup within the AMB system—comprising the controllers, actuators, sensors, and amplifiers—can severely impact performance and potentially lead to system failure. Managing system temperature is crucial for maintaining the reliability and longevity of the system. To prevent excessive temperatures, several design strategies are employed:

Reduction of Bias Current: Control and bias currents directly affect the temperature of both the amplifiers in the Magnetic Bearing Controller (MBC) and the actuator coils. The bias current typically makes up the largest portion of the total AMB current. By dynamically adjusting the bias current, the system can lower the power dissipation within the MBC and the actuator coils. During periods of low load or reduced dynamic activity, reducing the bias current helps mitigate heat generation, preventing the system from reaching thermal limits. This adjustment ensures that both the MBC amplifiers and actuators operate within safe temperature thresholds while maintaining stable levitation.

Adaptive Adjustment of the AMB Compensator: As with controlling rotor vibration, advanced control algorithms can be used to modify the dynamic stiffness of the bearings. A source of excessive heat can include large, high-frequency reaction forces from the controller/bearings in response to an external load (e.g. shock load, earthquake). A way to reduce these reaction forces can be to reduce the gain of the compensator around the bandwidth of the load frequency until the external load condition has passed.

Modifying Sensor Drive Frequency: Sensor temperature can be influenced by adjusting the sensor drive frequency. By fine-tuning the frequency at which the sensors are driven, it is possible to minimize power dissipation within the sensors, reducing their thermal load. By implementing these strategies, the AMB system can effectively manage the thermal load across all critical components—actuators, sensors, and amplifiers—ensuring that the system operates within safe temperature limits and avoiding the risk of thermal failure.

5.3 Preventing Amplifier Saturation

Amplifier saturation is a critical issue that can result in the loss of control over the levitating forces, leading to a rotor drop. To prevent amplifier saturation, two key strategies are utilized:

Adaptive Adjustment of Voltage Demand: The system can adaptively reduce the voltage demand sent to the amplifier when saturation risks (high duty cycle or large high-frequency current demand) are detected. The controller can directly limit the duty cycle or limit the total current.

Reduction of AMB Compensator Gain: The gain of the AMB compensator can be reduced to prevent excessive control effort/amplification that could push the amplifier into saturation. By adjusting the compensator's gain, the system effectively limits the amount of control signal required. This is particularly important during periods of marginal stability or when the rotor is subjected a high-frequency vibration (such as a bending mode instability).

6. Drop Recovery

If preventative control actions are not sufficient or other incipient fault has resulted in a drop fault, a drop recovery mechanism can be used to limit the contact time of the spinning rotor on the touchdown bearings. Calnetix developed and field-tested a software drop prevention and recovery feature for a rotary-disc atomizer product in 2015 [2] using its MBC 3600 product. The drop recovery feature consists of two components: a recovery compensator which switches on for specific conditions to prevent instability in case of bearing overload and a feature to attempt recovery if instability prevention fails. Calnetix further enhanced and generalized this algorithm in 2022 for use with its updated MBC 3625 product. This section details the algorithm, reviews the fielded atomizer use case discussed in [2], and explores other potential use cases.

The drop recovery system consists of two primary components:

1. **Impulse Detection and Recovery (IDR) Algorithm:** Designed to automatically detect radial impulse overload events, switch to a recovery controller, and attempt to maintain levitation even during auxiliary bearing contact.
2. **Re-levitation Protocol:** Designed to re-establish levitation at operating speed after a full rotor drop if the IDR fails to prevent contact.

6.1 Impulse Detection and Recovery Algorithm

The IDR feature was designed to address the periodic, process-induced radial impulses that were observed to overload the AMBs in the atomizer system. These impulses resulted in rotor contact with the auxiliary bearings and subsequent loss of levitation. The IDR system operates in four key steps (with specific values noted for the rotary-disc atomizer case study), as depicted in Figure 4.

1. **Impulse Detection:** The MBC continuously monitors rotor position at all controlled axes using a high-speed sampling rate (12.5 kHz). An impulse event is declared if the radial position at either bearing exceeds 4.75 mils (121 μm) or the axial position exceeds 6 mils (152.4 μm).
2. **Recovery Compensator Activation:** Upon detection, the MBC automatically switches from the nominal control compensator to an Impulse Recovery Compensator (IRC) after 0.125 s. The IRC is designed for a significantly reduced stiffness at low frequencies and a small positive damping up to approximately 400 Hz, enabling stable control even when the rotor is in contact with the auxiliary bearings.
3. **Recovery Period:** The system continues to use the IRC while monitoring for rotor vibration/displacement. If the rotor recovers levitation with low vibration/displacement, the controller transitions back to the nominal compensator.
4. **Re-levitation Attempt:** If rotor stability cannot be regained within a set recovery window, the MBC discontinues control and initiates a controlled re-levitation attempt while the rotor remains spinning. The IRC is activated during the re-levitation attempt.

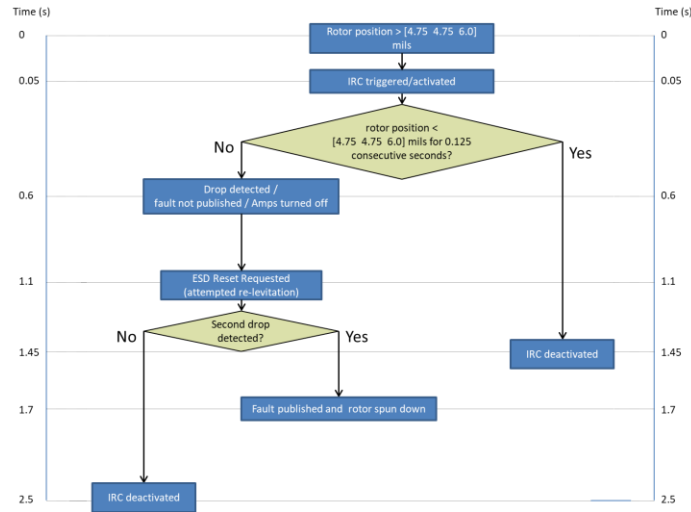


Figure 4. Timeline of impulse detection and recovery feature

This IDR system was validated in field operation on the rotary-disc atomizer product, where impulse events were found to occur periodically, approximately every 45 to 80 minutes depending on process conditions.

6.2 Recovery Compensator Design

The Impulse Recovery Compensator (IRC) was tuned specifically to stabilize the rotor in both levitated and auxiliary bearing contact conditions when a full/hard rotor drop is incipient. Compared to the nominal compensator, the IRC exhibits:

- Lower low-frequency stiffness to reduce the transmission of high reaction forces during contact.
- Increased damping across a broad frequency range to improve control robustness in the presence of flexible support elements and auxiliary bearing stiffness.
- Stability margins extended into the 100–400 Hz band to mitigate the effects of unstable auxiliary-bearing-supported rotor modes.

The ability of the IRC to maintain rotor control during auxiliary bearing contact was key to increasing the survival rate of rotor drops without requiring process shutdowns. The IRC compensator is depicted and compared to the nominal compensator in Figure 4.

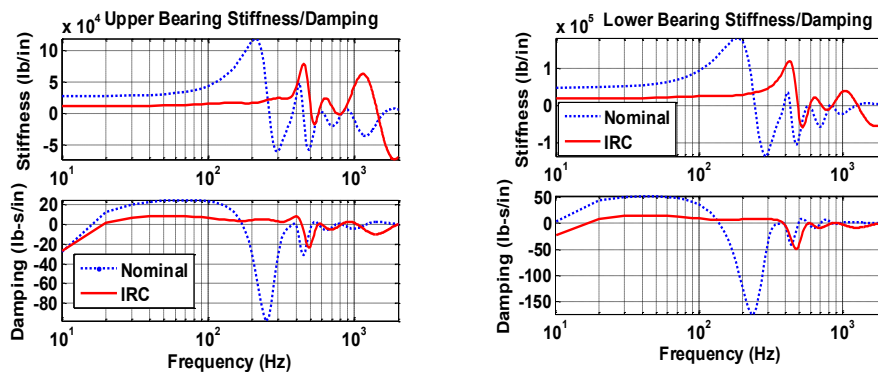


Figure 5. IRC compensator vs Nominal compensator

6.3 Re-levitation Performance

If impulse recovery was unsuccessful, the system attempted a controlled re-levitation. This protocol allowed the MBC to

stop commanding the actuators momentarily and then re-apply levitation forces, attempting to regain stable control while the rotor was still spinning at nominal speed.

Field experience showed that approximately 75% of rotor drops were successfully recovered without requiring the rotor to spin down to zero rpm. This dramatically reduced auxiliary bearing wear and extended their effective service life from approximately one month to over one year.

The drop recovery and re-levitation features combined to significantly improve system operability:

- Reduced the number of excessive vibration trips requiring process shutdown.
- Increased system resilience against process-induced impulse events.
- Extended auxiliary bearing life by minimizing uncontrolled rotor contact duration.

6.4 Field Validation Summary

During over 1000 hours of continuous field operation, the improved drop recovery system demonstrated:

- Robust levitation recovery following most impulse events.
- Successful prevention of full-speed coast downs in the majority of drop scenarios.
- Alignment between periodic impulse detection events and measured process disturbances, confirming the reliability of the detection threshold.

While the atomizer system experienced occasional process anomalies (e.g., excessive slurry buildup), the drop recovery feature provided a resilient response that substantially improved operational uptime.

7. Conclusions

This paper has explored several aspects of fault tolerance in AMB systems. Fault tolerance can enhance the reliability of AMBs. The key components of an AMB system—electromagnetic actuator, position sensor, MBC, and touchdown bearings—and the failure modes associated with each were examined. The importance of a systematic methodology for fault mitigation, including the definition of failure modes, assessment of likelihood and severity, and evaluation of hardware redundancy, has been emphasized.

Furthermore, this paper explored using software to achieve a more robust AMB system. The fault tolerant software system was aimed at drop detection, prevention, and recovery. A drop prevention and recovery algorithm was previously developed and tested for a fielded rotary-disc atomizer application experiencing repeat bearing overloads.

The integration of these fault tolerance measures significantly enhances the reliability and longevity of AMB systems, ensuring they can withstand unexpected failures and maintain operational integrity. By employing a combination of hardware redundancy, advanced control algorithms, and comprehensive monitoring systems, the risk of catastrophic failures in critical AMB applications can be substantially reduced.

Future work should focus on further refining fault detection and recovery algorithms, and exploring advanced hardware designs for enhanced reliability. Calnetix intends to build and test a fault tolerant AMB system, incorporating redundancy into the actuator, sensor, and MBC.

8. References

- [1] Fault Tolerant Active Magnetic Bearing. Patent Number 5300843. Assignee: General Electric Company (Schenectady, NY). Inventors: James P. Lyons, Mark A. Preston, Gerald B. Kliman. Application Number 7/970,197
- [2] Khatri et al. Demonstrated operability and reliability improvements for a prototype high-speed rotary-disc atomizer supported on active magnetic bearings. GT2015-43803. Proceedings of ASME Turbo Expo 2015. June 15-19, 2015. Montreal, Canada