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RESEARCH

Failure Mode and Effect Analysis of Active Magnetic Bearings

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A B S T R A C T

In the present research work Failure Mode and Effect Analysis (FMEA) of an Active Magnetic Bearing (AMB) has been presented. Various possible failures modes of AMBs and the corresponding effects of those failures on performance of AMBs have been identified. The identified failure modes of AMBs will facilitate designer to incorporate necessary design features that would prevent the occurrence of the failure. The severity, occurrence and detection of the failures modes are determined based on a rating scale of 1 to 5 to quantify the Risk Priority Number (RPN) of the failure modes. The methods to eliminate or reduce the high-risk-failure modes are proposed.

1. INTRODUCTION

The non-contact operations (zero and negligible friction) of magnetic bearings [1-4], makes it more inspiring than other conventional journal [5,6] and roller bearings [7-10]. Magnetic bearings are broadly classified as two types (i) passive [11-15] and (ii) active [16-18]. In Passive Magnetic Bearing (PMB), the load is levitated by the repulsive force between the rotor and stator permanent magnets. These bearings have advantages of contact free operation, high rotational speeds and zero wear at the cost of following disadvantages:

- Low load carrying capacity and stiffness [12-14].
- Unstable at least in one direction [19].

Therefore the setup using PMBs requires an extra actuator to control the force at least in one of the directions.

- Almost negligible damping characteristics.

Therefore, during acceleration and deceleration of rotor, the setup may go through excessive vibrations, which may result mechanical contact between stator and rotor. Being brittle materials, rotor and stator magnets may break.

On other hand active magnetic bearing (AMB) requires [20] three/four/eight/twelve poles electromagnet, proximity sensors and controllers. The initial cost of the controller and sensors is very high. In addition, the continuous requirement of current in each electromagnet makes the running cost of the AMB also high.

Above all these disadvantageous, AMB have following advantageous:

- No physical contact between rotating and stationary components for long range of operating frequency.
- AMBs can be used in harsh environmental conditions, including extremely low temperatures, zero-gravity, and corrosive environments
- Dynamic testing, health-monitoring, and data-logging features are integrated into the control electronics. With conventional bearing machines, these features must be externally supplied, implemented, and maintained.
- Dynamic properties (stiffness and damping) of magnetic bearings are easily measured and readily changed through built-in control firmware. Changing the dynamic properties of conventional bearings requires a complete re-design, re-manufacture, re-test, and re-installation of the bearings.
- AMBs provide precise control of the nominal shaft center under load.

To design a reliable and safe AMB for various applications [21-25], it is necessary to understand the possible failure mechanisms of AMB. In the present work, an attempt has been made to identify the various failure modes of AMB and their effect on the system using the FMEA (Failure Mode and Effect Analysis) [25]. Failure Modes and Effects Analysis (FMEA) is methodology of predicting the various potential failure modes can occur in the product early in the development cycle. FMEA also determine their effect on the operation of the product, and identify actions to mitigate the failures. FMEA therefore enhances the reliability of the product during design stage. AMB being new developing and mechatronic products, it is necessary to understand the various failure modes of AMB, so the designer can incorporate necessary design features that would prevent the occurrence of the failure. After performing FMEA, the critical failures have been identified and few suggestions to minimize the failure have been provided.

To after perform FMEA, in the present research various failure encountered by different researchers [4,22-24] have been considered and the failure faced by the authors in developing AMB is also included. Moreover the suggestions to minimize the failure have been provided.

2. FMEA OF AMB

Failure of any of components of AMB affects its performance. To overcome/reduce the failure of components systematic procedure of FMEA can be followed. In FMEA, first the detailed study of the system is performed to identify the various components prone to failure. Potential failure modes of each component and their root cause modes are analyzed. After studying the failure modes the ranking based on severity (consequence of the failure should it occur), occurrence (Frequency of the failure occurring) and detection (Probability of failure being detected) of each failure mode is provided. Among these failure modes, the critical failure mode is determined by finding the Risk Priority Number (RPN). The value of (RPN) of each failure mode is determined by multiplying the ranks of severity, occurrence and detection. After identifying the critical failure mode, list the control/prevention methods. After implementing the control/prevention methods, the value of RPN is again calculated. It is observed that whether the value of RPN is in satisfactory margin else again other possible control/prevention methods are identified for the critical failure modes. The discussion step by step followed in FMEA is given below.

Step 1- Detailed study of system to identify different components: A schematic representation of an AMB is shown in Fig. 1. In this figure, AMB setup consists of a pair of diametrically opposite poles of electromagnet, each carrying current i_b+i_c and i_b-i_c respectively with i_b as the bias current and i_c being the control current. Sensors measure the position of the rotor (x, y) and sends to proximitor which modulates the proximity signal in the form of voltage.

The voltage from proximitor is fed to the controller. The controller has (i) software and (ii) hardware components. The based on the input voltage signal from the proximitor, the output current (i_c) from the controller is decided based on algorithm for bringing the rotor at the set point. If the rotor moves to one side, say top for vertical alignment of rotor, the current in the top electromagnet has to be reduced and the current in the bottom electromagnet has to be increased. As the system works in the differential mode, the controller needs to feed a negative value of i_c resulting reduction in top electromagnet current (i_b+i_c), and higher current in bottom electromagnet (i_b-i_c). Similarly, if the rotor moves towards bottom, a positive value of i_c has to be given by the controller. Therefore the controller gives the value of the control current i_c according to the position sensor value x. The digital signals are converted to analog voltage signals using high speed controller (hardware) and given input to power amplifier. A touchdown bearing is provided for avoiding failure of AMB during power failure. The AMB system needs to be firmly mounted on a base. From the above discussion, the identified components of AMB are: (i) Amplifier, (ii) Position sensors, (iii) Coil, (iv) Software, (v) Rotor (vi) Touchdown bearings and (vii) base.

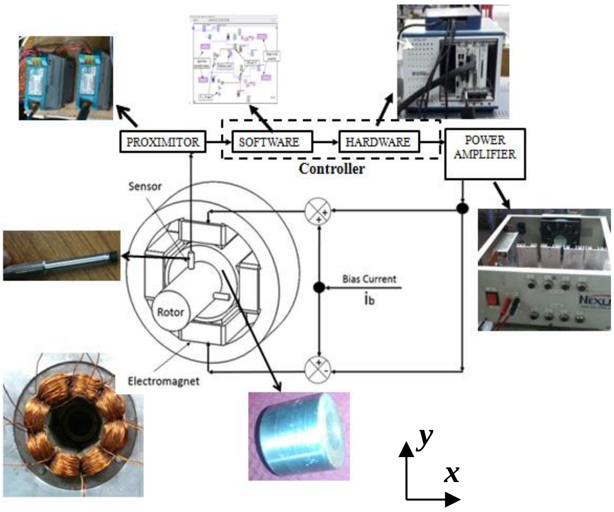
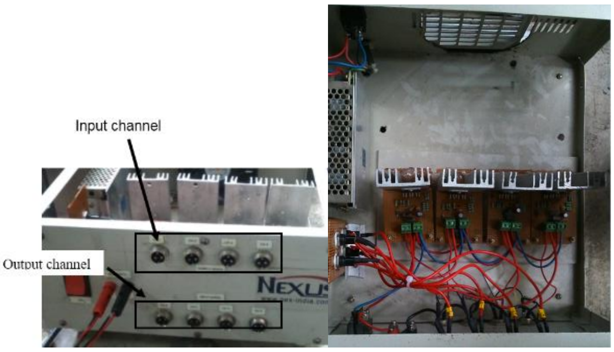


Fig. 1. Schematic representation of an AMB.

Step 2 - Determine all potential failure of each component and their root causes modes: The potential failures of different components are as follows:

Amplifier: Though the amplifiers are solid state technology, faults may occur due to environment conditions, internal heating in the amplifier or large demand due to external load. The failure of the amplifier due to short circuit or any other reasons will result in zero output power or no amplification from the amplifier resulting in failure of full AMB system. The front amplifier used for the present work is shown in Fig. 2. Figure 2(a) shows the front view and Fig. 2(b) shows the top view. The voltage amplifier has four input and four output channels. It is capable to amplify the input voltage from the controller to six times and current of maximum 5A (in the present work the voltage from controller vary from -10V to 10V with maximum current of 0.3A) and ampere rating was based load.



(a) Front View (b) Top view

Fig. 2 Amplifier.

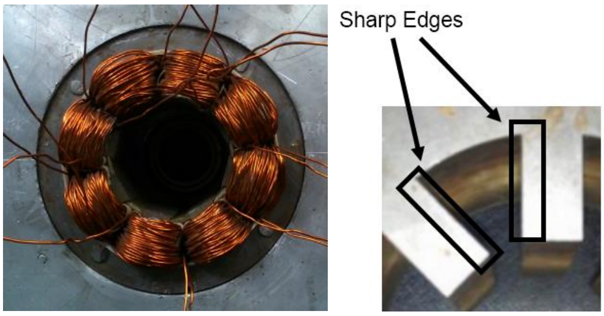
Position Sensor: Failure of the sensor may be due to circuit failure (like proximitor, supply power to the sensor) in the sensor electronics, damage of the sensor due to physical contact during the operating condition, physical damage to the circumference of the shaft in the measurement plane or debris on the surface will tend to produce glitches in the measured signals. The eddy current sensors are used to sense the position of the shaft requires an input power supply of 24 volts. The fluctuation in this power supplied to the sensor from DC power source, will affect the output of the sensor. Figure 3(a) shows the proximitor, Fig. 3(b) shows the DC power supply and figure 3(c) shows a proximity sensor.

(a) Poximitor (b) DC power supply

(c) Proximity Sensor

Fig. 3 Poximitor, DC power supply and proximity sensor.

Coil: The failure of coil is mainly caused due to the short circuiting arising from the removal of wire insulation either due to heating or by constant friction induced between wires due to its movement. This may also happen when proper care is not taken during the winding process while heating of the coil occur due to the passage of higher current. The sharp edges in the coil will result-in removal of insulation and hence leakage of flux. Figure 4(a) shows the electromagnet with winding and figure 4(b) shows the sharp edges.

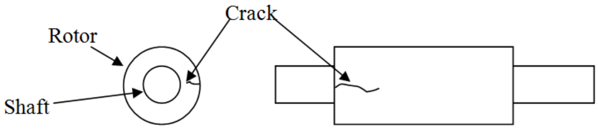


(a) Core and winding (b) sharp edges

Fig. 4 Electromagnet with winding.

Software Error: Software for AMB has been developed based on the theoretical prediction of the system behavior and the software must be real time i.e. the completion of each loop of the system, starting from the acquiring the signals from the proximity sensor to actuation of the electromagnet (as explained in Fig. 1) must be same for all iterations. Though the software might work perfectly from the predicted theoretical behavior of the system, but when the software is tested with the actual system, the software may fail as the rotor may have imbalance which may differ at the dynamic condition. Therefore the software shall be developed by performing number of trials by modifying the control algorithm based on the system behavior. Therefore the real time control software shall be developed. The time set for completion of loop also play important role as different components have different actuation/sensing timing.

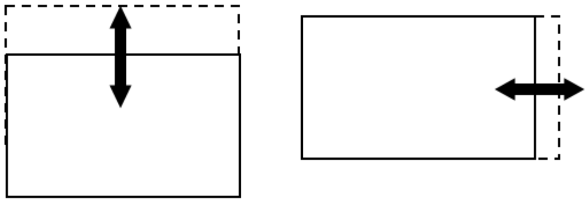
Rotor: The failure of rotor in AMB occurs due to dynamic loading and crack in rotor. The dynamic loading occurs due to unbalancing of the rotor caused by deposition/erosion of the material from shaft, loss of parts like blade, external aerodynamic/fluid dynamic effects, etc. The crack in the rotor may be existing-one in the rotor that might be neglected during inspection; and may be formed due to rubbing or thermal expansion at higher rotational speed. A sketch of cracked rotor is shown in Fig. 5.



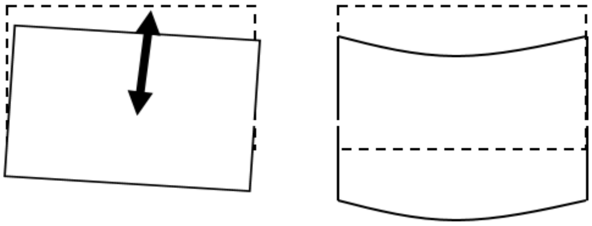
(a) Side view (b) Front view

Fig. 5 Cracked rotor.

Abnormal base motion: The vibration caused by seismic events, mobile base (e.g. ship) or accident leads abnormal base motion. Base motions, shown in figure 6, are analogous to an inertial force applied to the rotor which influences motion of rotor relative to base motion. Figure 6(a) shows the vertical motion, Fig. 6(b) shows the horizontal motion, 6(c) shows the tipping motion and Fig. 6(d) shows the non-uniform motion of the foundation. The motion can also be combination of the motions.



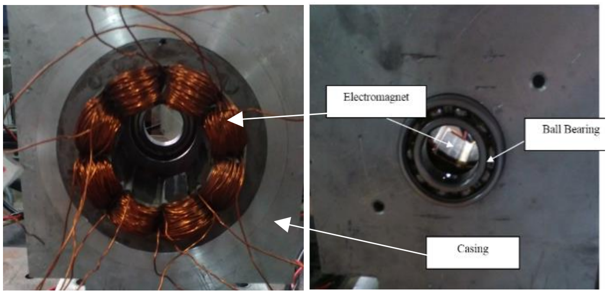
(a)Vertical motion (b) Horizontal motion



(c) Tipping motion (d) Non-uniform motion

Fig. 6. Base motion

Touchdown bearings: Touchdown bearings, often termed as back-up bearings, are usually retainer rings or special ball bearings [6]. One typical back-up bearing is shown in Fig. 7. Such bearing is supposed to support the rotor in case of extraordinary conditions (i.e. start, stop, failure of AMB, external temporary disturbance).



(a) Front view (b) back view

Fig. 7. Backup bearing.

Step 3- Determine the severity of each failure mode: The effects of each failure modes are as follows:

Amplifier: The failure of the amplifier means either no-power or no-amplification of voltage/current supplied to electromagnet; which results in failure of full AMB system. In the present work it was decided to measure the output voltage from the voltage amplifier for a given voltage input for different loading condition i.e. the external load (current) connected to the system was varied. This can be performed by applying torque on the motor. The output voltage from the voltage amplifier for the given one volt as input is shown in figure 8. It is expected that for constant input voltage (i.e. 1 V) the constant output voltage (6 V) has to be supplied by the voltage amplifier for different loading (current) conditions. However it has been observed that till the load of 1.5 A, the output voltage remained 6V however on increasing current load from 1.5 A to higher value, the amplifier stopped working.

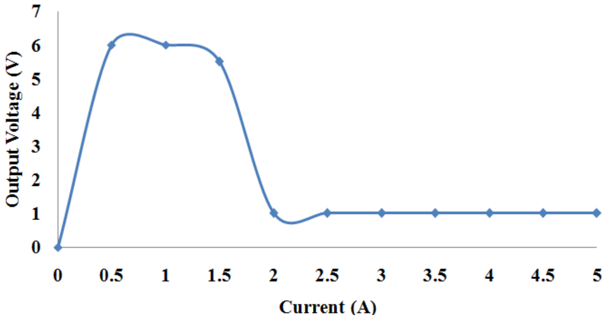


Fig. 8. Output voltages for one volt input voltage at different current supply.

Position Sensor: The faults/failure in the position sensors will result in permanent error in the acquired signal. As a result, rotor gets destabilized and starts hitting the retainer ring/back up bearings. The fluctuations in the DC power supply due to improper earthing will result in variation in the output voltage from the sensor.

(a)Good Sensor (b) Failed Sensor

Fig. 9. Proximity sensors.

Figure 9 shows failure eddy current proximity sensor which got damaged due to the physical contact of the rotor. This sensor was not able to provide the voltage variation with displacement of the shaft.

Coil: In a coil when the insulation is tear off and the voltage leaks out to the core. The development of magnetic field in coil gets affected, which in turn results no levitation force by the electromagnet. In our early work, negligible magnetic flux was observed even after supplying power to an electromagnet. Continuity was observed between the core and wire which indicated the touching of un-insulated part of core-wire. Figure 10 shows the wire with torn insulation after unwinding.

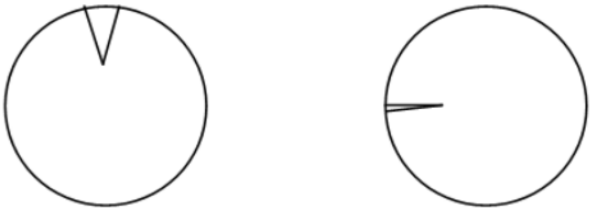
Fig. 10. Un-insulated parts of wire.

The passage of higher current in the coil results in heating of the coil which affects the coil resistance and reduction in the magnetic flux density of the electromagnet. This reduces the load carrying capacity of the electromagnet.

Software Error: The software error can be eradicated by taking small precaution like selecting appropriate loop timing and performing number of trials before deriving final software code. So the effect due to software error is null.

Rotor: The maximum load carrying capacity of the AMB depends on either the saturation limit of electromagnet or the maximum current can be supplied by the controller. Therefore when disturbance occurs due to imbalance in rotor and if it is in the margin of load carrying capacity of AMB, the vibration can be controlled by the controller itself. However when the dynamic loading on the rotor becomes greater than the load capacity of the AMB, rubbing with touchdown bearing occur.

With the crack on the rotor, breathing of crack (i.e. opening and closing of crack) at different rotating positions (shown in Fig. 11) will induce vibration with synchronous and higher harmonic frequencies.



(a) Crack at 0^{0} (b) Crack at 90^{0}

(c) Crack at 180^{0} (d) Crack at 270^{0}

Fig. 11. Breathing of cracked rotor.

Abnormal base motion: High acceleration of base motion could cause large rotor to base displacements and hence contact with a touchdown bearing.

Power failure: The loss of power supply to the sensors, hardware etc. will result in delivering no signals to electromagnets and complete loss of the AMB forces. The without AMB force the rotor will touch the touchdown bearing.

Touchdown bearings: The failure in any components of AMB will result in hitting the touchdown bearing. If failure is temporary, the AMB can recover the contact free levitation after going through (i) sub-harmonics and higher harmonics frequencies; and (ii) thermal bending of the rotor vibrations [22]. When the AMB loses its complete levitation of the rotor will result in: (i) backward whirl of the rotor, (ii) synchronous, sub synchronous and chaotic motions (iii) spirally increasing bending vibration caused by rub induced hot spots on the rotor and (iv) shear of the rotor due to high induced friction.

Step 4- List current control/prevention of each cause: The prevention of failure modes are as follows:

Amplifier: The faults in amplifier overcome by providing back up (redundant) amplifier [23, 24], at the cost of increased complexity. Successful implementation of amplifier redundancy requires automatic identification of faulty subsystems and rapid switching of responsibilities.

In one of our application, overheating of voltage amplifier was observed due to which amplifier was not able to amplify voltage at higher load (current). The heating problem in the amplifier was overcome by providing exhaust fan as shown in Fig. 12. After putting the exhaust fan the output voltage from voltage amplifier was again measured by giving one volt input supply and the reading is plotted in Fig. 13.

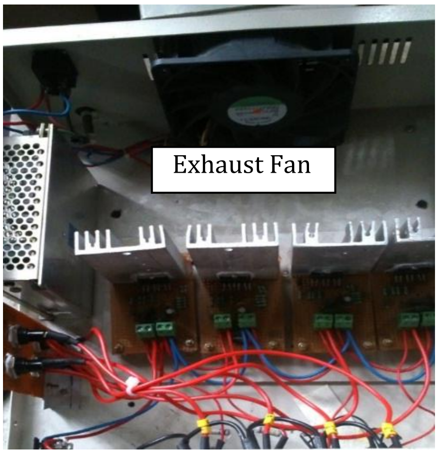


Fig. 12. Amplifier with exhaust fan.

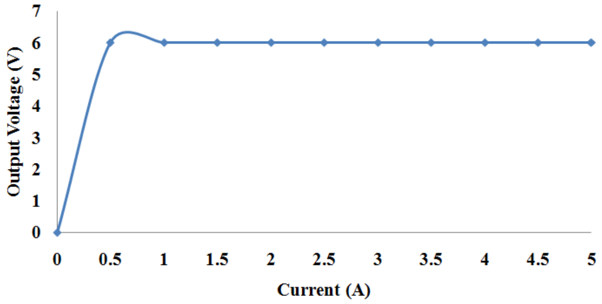
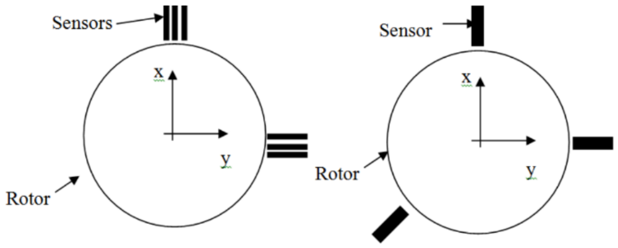
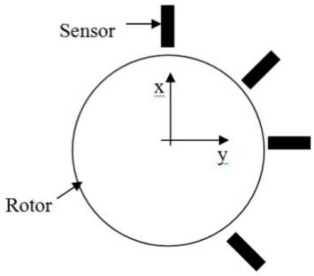


Fig. 13. Output voltages for one volt input voltage at different current supply.

Position Sensor: The problem in sensors can be overcome by using redundant sensors a shown in Fig. 14. There are two different kinds of redundancies (i) Hardware and (ii) Analytical [4]. If the failure of a single component cannot be corrected and is critical for the system's safety, the function of this component should be guaranteed by redundant hardware. Two or more of these same components have to be arranged in parallel, in order to replace any failed component (Fig. 14(a)). Appropriate failure detection and switchover schemes are crucial, and the increase in the number of components. If the function of a component is at least partially performed by another component as well, then the functional relation between these components can be used as an analytical redundancy to replace the failed component, or to reduce the extent and cost of a hardware redundancy (Figs. 14(b) and 14(c)). Figure 14(b) shows the analytical redundancy with three position sensors [24] and figure 14(c) shows the analytical redundancy with four position sensors.



(a) Hardware redundancy (b) Analytical Approach 1



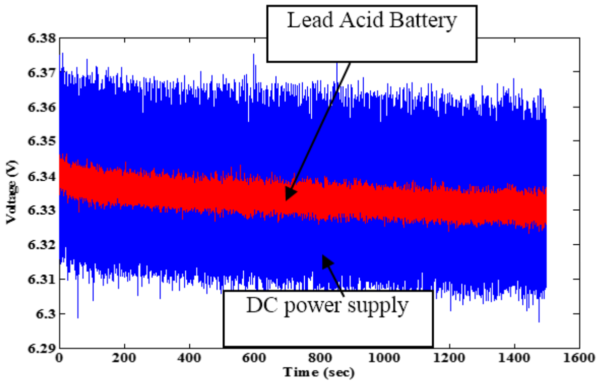
(c) Analytical redundancy: Approach 2

Fig. 14. Cross-section of the rotor/bearing with redundant sensors.

The problem faced with the redundancy of sensor is the, lack of space to place the sensors or due to the size of the shaft. However as per Schweitzer and Bleuler [4], minimum of two axial planes with orthogonal-sensors pairs are required to achieve stable levitation for single AMBs.

As discussed earlier the proximity sensors require an input supply of 24 volts which was initially supplied by using DC power supply. These supplies will fail when the power to them is disrupted. Therefore it was decided to replace the DC power supply with Lead acid batteries which as shown in Fig. 15(a). The comparison of between the obtained reading using from batteries and DC power supply is shown plotted in Fig. 15(b). From this figure it can be observed that the span of sensor reading obtained using batteries is lesser than the reading obtained using the power supply. Due to improper earthing of power supply, noise in signal is higher, while the noise is reduced by using batteries which does not required power supply.

(a) Lead acid battery and DC power supply



(b) Reading from sensor

Fig. 15. DC power supply and lead acid batteries.

Coil: Sensing of coil current/voltage or flux in the integral feedback operation of amplifier can be used to overcome the coil failure. The removal of insulation due to sharp edges and flux leakage to the core can be avoided by providing a thin insulation between the core and the winding as shown in Fig. 16. Also a plastic strip is provided to prevent the loosening of the winding.

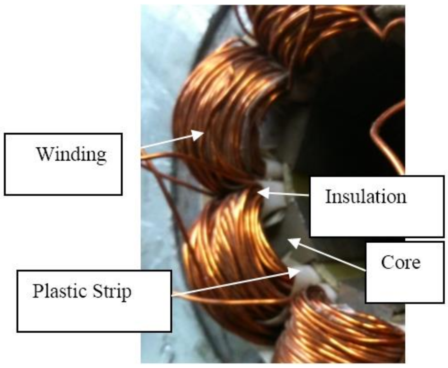


Fig. 16. Insulation between the core and winding.

Software Error: This error can be overcome by programming in real time and constantly improving the software based on the requirements. The loop timing should be selected by considering the frequency of all the acquiring/actuating systems and it should be the lowest frequency among all the acquiring/actuating systems. The different frequencies considered for developing AMB system is shown in Table 1. From this it can be observed that the sensor has the lowest frequency hence the loop timing was kept as 0.1 MHz. The sample program developed in LABVIEW is shown in Fig. 17.

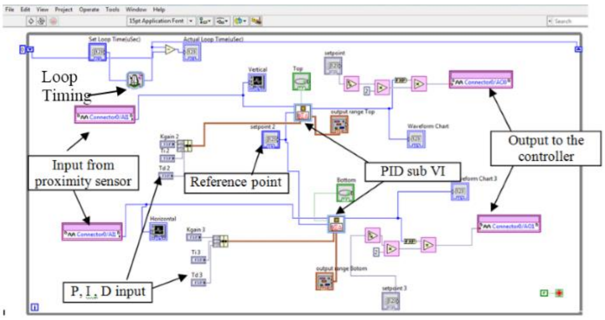


Fig. 17. LabVIEW program.

Table 1. Frequencies of different components.

Component	Frequency (MHz)
Controller	10
Amplifier	0.6
Sensor	0.1

Rotor: If the dynamic loading due to imbalance in rotor is lesser than the load carrying capacity of the AMB, the vibration can be controlled by the controller. However the larger dynamic loading results in the dropping down of rotor on the backup bearing.

Abnormal base motion: This problem can be overcome by using multi objective controller design to obtain an acceptable compromise in bearing characteristics. Using the measured base acceleration as additional controller inputs would be beneficial.

Rotor Crack: Since magnetic bearing system is ideal for monitoring and controlling the vibration such failure can be easily controlled.

Power failure: A backup power supply, such as battery/generator/UPS, can be provided to overcome this failure.

(a) Bearing with elastomer (b) Bearing with O-ring

Fig. 18. High damping material on outer ring of back up bearing.

Touchdown bearings: The general guidelines for designing the touchdown bearings to operate safely are:

- The surface of the landing sleeve should be made of high strength material with low friction and great hardness to avoid early wear.
- The touchdown bearing should have high damping which can be done by providing ribbons between the outer ring and the housing (as shown in Fig. 18).
- An elastic soft support with damping may limit the whirl frequencies and limit the whirl amplitude and loads.
- Care has to be taken to avoid driving the unloaded ball bearing by air drag and causing

Step 5: Define scale table for severity, occurrence and detect: The scale for the severity, occurrence and detection of problem in AMB is scaled from 1 to 5 with 1 being the lowest ranking and 5 the highest. The severity scaling is an estimation of how serious the effects would be if a given failure did occur. This can be estimated based on the available knowledge and expertization as shown in Table 2. The best method for determining the occurrence scale is to use actual data from the process as shown in Table 3. This may be in the form of failure logs. When actual failure data are not available, occurrence of failure can be simulated. All identified failures must be noted in the FMEA worksheet, so that the potential effects of each failure mode can be analyzed. This step must be thorough because this information will feed into the assignment of risk rankings for each of the failures. The scaling of detection is made based on the techniques and the stages at which the problem is identified as shown in Table 4.

Table 2. Severity guidelines for active magnetic bearing FMEA.

Effect	Rank	Criteria
No	1	No effect on bearing performance
Slight	2	Slight rubbing of back up bearing
Moderate	3	Touchdown with no failure of backup bearing
Major	4	Touchdown and backward whirl of rotor
Serious	5	Failure of backup bearing

Table 3. Occurrence guidelines for FMEA of AMB.

Effect	Rank	Criteria
Almost Never	1	Failure unlikely. History shows no failure
Slight	2	Few failures likely
Medium	3	Medium number of failures likely
High	4	High number of failures likely
Almost certain	5	Failure almost certain

Table 4. Detectability guidelines for active magnetic bearing FMEA.

Effect	Rank	Criteria
Almost certain	1	Proven detection methods available in concept stage
High	2	Simulation and/or modeling early stage
Medium	3	Tests on preproduction system components
Slight	4	Tests on product with prototype and system components installed
Almost impossible	5	No know techniques available

Step 6-RPN calculation: The risk priority number (RPN) is calculated by multiplying the severity ranking, the occurrence ranking times, and the detection ranking for each item based on the tables 1, 2 and 3, 2, 3 and 4 respectively.

Risk Priority Number = Severity × Occurrence × Detection.

The total risk priority number should be calculated by adding all of the risk priority numbers. The calculated value of RPN is shown in Table 5. This number alone is meaningless because each FMEA has a different number of failure modes and effects. However, it can serve as a gauge to compare the revised total RPN once the recommended actions have been instituted.

Table 5. FMEA work sheet.

Components	Root causes modes	Effects	Severity	Occurrence	Detection	RPN
Amplifier	External environment conditions	Touchdown/rubbing on back up bearing	1	5	1	5
	Over load	Touchdown/rubbing on back up bearing	3	3	3	27
	Short Circuit	Touchdown	4	1	5	20
Position sensors	Circuit failure	Touchdown	4	2	5	40
	Physical contact of the sensor by rotor	Levitation away from the center/rubbing on back up bearing	3	3	3	27
	Physical damage of the shaft	Levitation away from the center/rubbing in back up bearing	2	2	2	8
	Debris on the surface	Levitation away from the center/rubbing in back up bearing	1	3	1	3
Coil	Removal of wire insulation	Touchdown	4	2	1	8
Software error	Particular operating condition	Touchdown/Levitation away from the center	2	2	4	16
Dynamic rotor loading	changes in the loading conditions	Touchdown/rubbing in back up bearing/Levitation away from the center	3	5	3	45
Abnormal base motion	External vibration	Touchdown/rubbing in back up bearing/Levitation away from the center	2	3	4	24
	Mounted in the mobile application	Touchdown/rubbing in back up bearing/Levitation away from the center	3	1	4	12
Rotor Crack	No potential failure		1	1	3	3
Touchdown bearings	Permanent Failure	Touchdown	5	4	5	100
	Temporary disturbances	Rubbing in back up bearing	3	5	5	75

3. PASSIVE MAGNETIC BEARING AS TOUCHDOWN BEARING

Figure 19 shows the passive magnetic bearing which consists of rotor and stator magnets. Due to the repulsive force between these magnets, the rotor remains in the levitated position. It is necessary to analyze the behavior of PMB before it can be implemented as back up bearing. For this an experimental setup, as shown in figure 20, was developed. The setup consists of 3 phase, 2 hp induction motor rigidly mounted on a base plate. The motor is controlled by an ABB frequency drive (IP20/ul open type). The maximum rotation speed achieved using this motor is 3600 RPM. The setup consists of a stainless steel (grade 303) shaft whose one end is free and other is connected to motor using a spiral coupling. The performance of the PMB was measured using proximity sensors signals.

Two eddy current type proximity sensors were used to measure the displacement of the shaft in x and y directions. The data were acquired using DAQ (National Instruments) and stored in computer using LabVIEW interface. A disk of 1.5 kg mass, which acts as flywheel was mounted concentrically on the shaft.

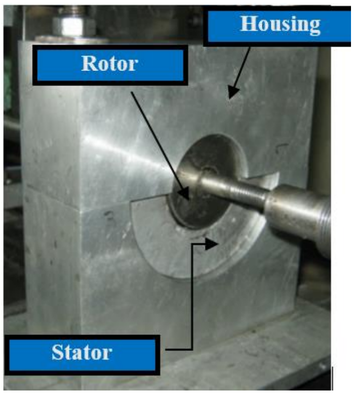


Fig. 19. Passive Magnetic Bearing.

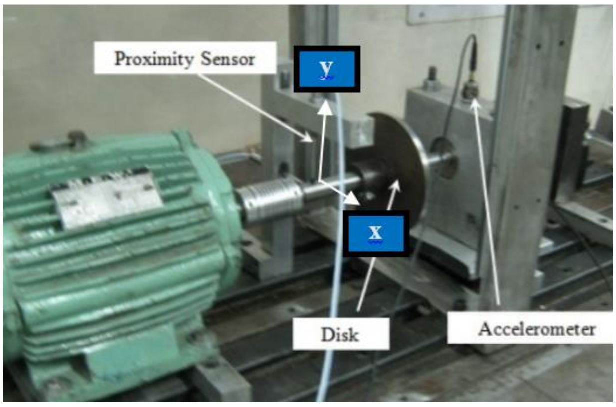
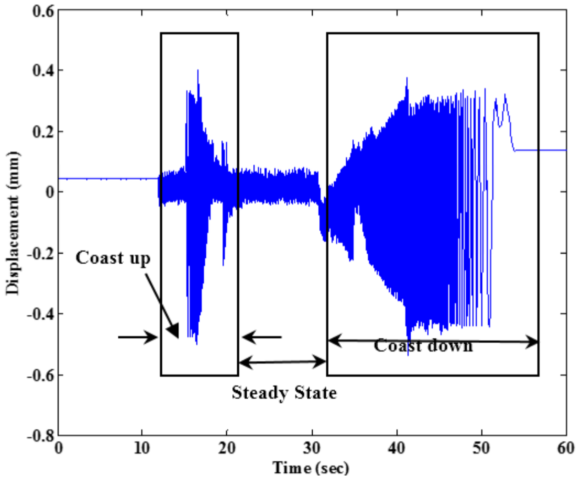
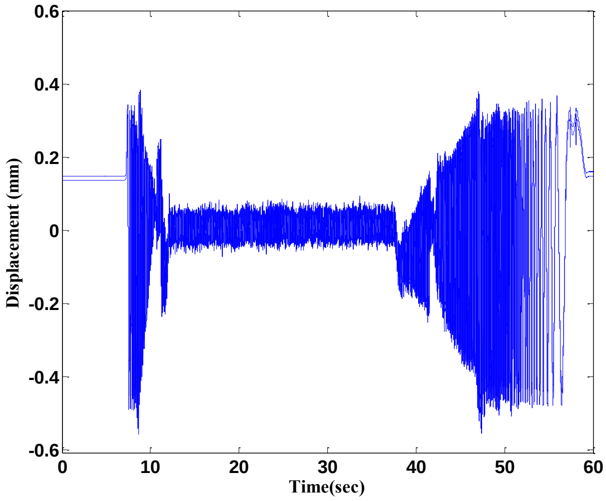


Fig. 20. Magnetic bearing setup.

The horizontal and vertical displacements, during the coasting up and coasting down, are shown in Figs. 21(a) and 21(b) respectively.



(a) Vertical signals



(b) Horizontal signals

Fig. 21. Vertical and Horizontal signals for full ring stator.

Table 6. Modified FMEA work sheet.

Components	Root causes modes	Effects	Severity	Occurrence	Detection	RPN
Amplifier	External environment conditions	Touchdown at lower RPM	1	5	1	5
	Over load	Touchdown at lower RPM	2	3	2	12
	Short Circuit	Touchdown at lower RPM	2	1	5	10
Position sensors	Circuit failure	Touchdown at lower RPM	2	2	5	20
	Physical contact of the sensor by rotor	Levitation away from the center	2	3	3	18
	Physical damage of the shaft	Levitation away from the center	2	2	2	8
	Debris on the surface	Levitation away from the center	1	3	1	3
Coil	Removal of wire insulation	Touchdown at lower RPM	2	2	1	4
Software error	Particular operating condition	Levitation away from the center	2	2	4	16
Dynamic rotor loading	changes in the loading conditions	Levitation away from the center	2	2	3	12
Abnormal base motion	External vibration	Levitation away from the center	2	3	4	24
	Mounted in the mobile application	Levitation away from the center	2	1	4	128
Rotor Crack	No potential failure		1	1	3	3
PMB Touchdown bearings	Permanent Failure	Touchdown at lower RPM	3	1	2	6
	Temporary disturbances	Levitation away from the center	2	1	2	4

The displacement in horizontal as well as vertical direction at lower rotational speed is high while the displacement at higher rotational speed is low. Therefore it can be inferred that at lower speed, the PMB is unstable while at higher speed the PMB is stable may be due to gyroscopic effect [26].

Therefore PMB can be a perfect touchdown bearing at higher speed and the severity of failure of bearing at lower speed will be low. Therefore using PMB the severity values and detection value will be reduced while the occurrence of failure remains same for few components. For example in the case of "Dynamic rotor loading", the PMB will be sharing the dynamic load along with AMB hence the value of severity, occurrence, and detection is reduced.

In the case of the short circuit of Amplifier and position sensor circuit, the occurrence of the failure cannot be reduced by using PMB, however the severity and therefore the detection of the failure value is reduced. The modified FMEA chart is shown in Table 6.

CONCLUSION

The failure mode and effect analysis for an active magnetic bearing has been performed. Eight possible modes of failure of magnetic bearing system have been identified. The severity, occurrence and detection of these failures modes are utilized in quantifying the Risk Priority Number (RPN). Any failure of the AMB components results in the touchdown and therefore the failure of touchdown bearing is identified to be the critical mode of failure. In order to reduce the criticality of the failure mode of a AMB system designed by considering the maximum dynamic load of the system, passive magnetic bearings as touchdown bearings are proposed which can share the static load and dynamic load at higher rotational speed.

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