# Control Techniques and Failure Mode of Active Magnetic Bearing in Machine Tool System

**Shishir Bisht, Nitin Kumar Gupta, and G. D. Thakre**

**Abstract** Bearing is an integral part of the machine tools system, but due to contact stress, wear is induced, which decreases the life of the machine tools and bearing system. Stress developed due to contact between mating surfaces, i.e., contact stress and friction forces, is the main factor which is affecting the efficiency of a system. To achieve efficiency or to make contact-less levitation, active magnetic bearing are most suitable. This paper gives a basic idea on control techniques and failure modes and their effect on the active magnetic bearing system, by which frictional forces and the vibration should be minimised, which are the primary cause of wear and tear and decentralisation of the shaft. AMB systems are more suitable to increase the life and performance of the machine tools.

**Keywords** Active magnetic bearing · Control techniques · Failures in AMB

## 1 Introduction

Bearings play a major role in machine tools system; they are used to minimise the friction between two components whenever there is a relative motion between them. An electromagnetic bearing uses a magnetic force which will levitate the shaft; hence, due to absence of mechanical wear, it reduces friction and also increases its reliability and life [1, 2]. Magnetic bearings are generally of two types, namely active magnetic bearings (AMB) and passive magnetic bearings (PMB). There is no feedback control in passive magnetic bearings, i.e., passive magnetic bearings [3, 4] do not require active control. However, in active magnetic bearings (see Fig. 1), there is feedback

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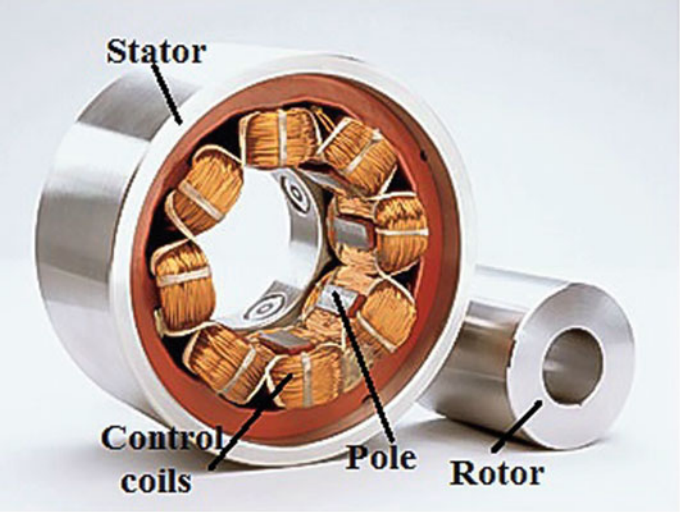

**Fig. 1** Typical active magnetic bearing [1]

control or closed-loop control which ensure that there is no physical contact between the rotor and the stator.

Electromagnetic forces are used for rotor levitation, which will be developed when some amount of current flow through the copper wires. An active magnetic bearing consist of three major components which are a position sensor which indicates or measures the rotor's position from its initial position and gives actively feedback to the controller; a stator consists of electromagnets which generate the electromagnetic force and the rotor or shaft [5, 6]. Active magnetic bearing (AMB) have several advantages if compared with the traditional or mechanical bearings [2, 7], including contact-less operation hence less mechanical wear and friction, the absence of lubrication, lower maintenance costs, higher life, etc. (Fig. 2).

Although these bearings have some disadvantages include limitation in size, high initial cost as well as high running cost. But, due to many advantages, active magnetic bearings have wide area of applications, such as in machine tool systems, magnetically levitated vehicle, high-speed turbines, flexible rotor dynamic systems, compressors [2].

## 1.1 Active Magnetic Bearing—Control Techniques

To control the high amplitude vibrations in AMB system, it is necessary to select an appropriate control technique which will affect the life as well as performance of the AMB system. Following are some control techniques used in the AMB system [1, 8]:

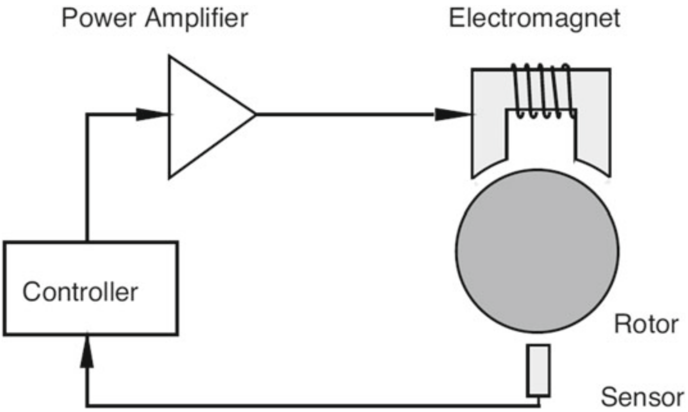

**Fig. 2** Basic working principle of an active magnetic bearing [5]

**PID**. The proportional-integral-derivative (PID) is a traditional closed-loop feedback control technique, and because of its ease of use, this technique has been widely used in AMB systems. But because of unmeasured parameters variations and unavoidable external disturbances, this control technique is not very accurate; therefore, many kinds of control techniques have been developed such as fuzzy control and sliding mode control. These control techniques not only improve the stability of AMBs systems but also improve their performance in many ways.

**Fuzzy Control**. It is based on fuzzy logic, and fuzzy logic is the logic which can be expressed as “partially true” instead as ‘true’ or ‘false’. It describes the problem’s solution in a form that can be easily understood by human operators, so it is easy to utilise in the design of the controller. Because of its nonlinear properties, fuzzy control has advantages in magnetic suspension system applications, and also, it is widely used in applications related to machine control system.

**Sliding Mode Control**. It is a nonlinear control technique to change the dynamic behaviour of the said system into a linear system by use of a discontinuous control signal. SMC technique is usually used in the field of magnetic bearings due to its associated robustness. Chattering will affect the stability and precision of SMC technique which can be easily controlled by the filtering method.

**Model Predictive Control**. Model predictive control technique has the advantage that with wide bandwidth, it can easily control the current which passes through the coils in order to improve the performances of the active magnetic bearing system. MPC can easily apply over other techniques because of its fast dynamic response and unavailability of modulation.

**Fault Tolerant Control**. In any AMB system, the rotor displacement from its initial position has to be measured precisely for its better working performance and stability. But if there is any error in the position sensor, the stability as well as the performance of the AMB system gets affected. So to avoid this, self-sensing technology is used, in which rotor displacements is directly calculated from the

**Table 1** Comparison of different control techniques [1, 8]

| Control techniques | Advantages | Disadvantages |
|---|---|---|
| PID | Development process is simple | Not suitable for unknown and variable model |
| Fuzzy control | For unknown or variable model | It does not provide the précised control to the system |
| Sliding mode control | Completely self-adaptive against external disturbances | Chattering will affect the precision and stability of the AMB system |
| Model predictive control | Fast dynamic response, unavailability of modulation | Difficult to apply for the nonlinear and time-varying system |
| Fault tolerant control | Reduce the risk of failure in the AMB systems whenever there is any unexpected component failure occurs | Difficult for fault detection and identification of nonlinear system |

current that passes through the coils and its voltage, so it provides a new and effective method for achieving controlled stability of the AMB system, and this causes the system to be more reliable. Table 1 presents various type of control technique with their advantages and disadvantages.

## 2 Literature Review

This current review paper deals with the control aspects and failure modes of the AMB system.

### *2.1 Active Magnetic Bearing*

Ludvig and Kuczmann [9] did an analysis on an active magnetic bearing (AMB) system to find out the optimal shape and dimensions of the legs of the stator and air gap for the maximum electromagnetic force. The analysis was done with the help of finite element method and the magnetic vector potential formulation. The study focused on the eight-pole bearing that contains eight electromagnets. His calculation was done with a maximum and the constant current value of 12 A (DC) and 80 turns on each leg, the number of turns will also be constant, and then, it determines the maximum holding force. He has done his simulation on COMSOL Multiphysics software, which has a user-friendly interface, and after many calculations simulated, AMB can provide maximum 800 N as holding force over 1 mm thick air gap.

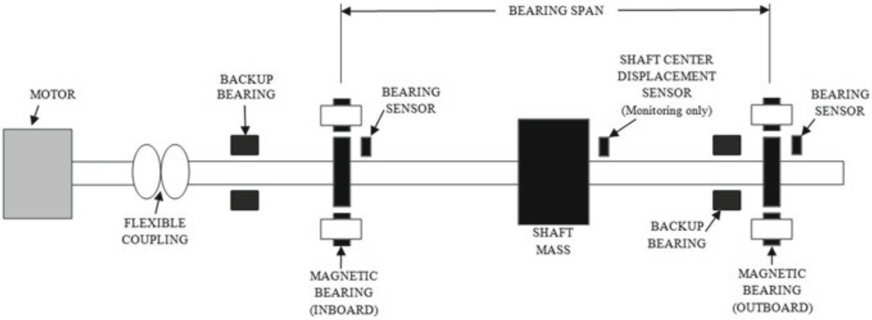

**Fig. 3** Experimental rotor: Williams et al. [11]

PID means proportional-integral-derivative, and this control method is based on voltage control for the determination of $K_P$, $K_D$ and $K_I$ which governs the PID controller that has been proposed by Muzakkir and Lijesh [10]. The main motive is to levitate the shaft statically by the implementation of a voltage controller. The PID controller has been designed using LABVIEW software. The result of his experiment was that by voltage control method, the system was easily controllable using only $K_P$ value and it did not depend on the $K_D$ and $K_I$ for its static levitation. In PID method, the output will be calculated by the measured error and the three controller gains which are $K_P$, $K_I$, $K_D$ means proportional gain, integral gain and derivative gain, respectively.

An approach has been presented which aims to design an active magnetic bearing system and test a digital control system for its stability, and the AMB is having an eight-pole configuration [11]. A test rig has been made in which the flexible shaft test rotor has to be supported by two of these bearings. Theoretical relationships are created to make relationship between the characteristics of a controller transfer function and the stiffness and damping properties of an active magnetic bearing system. A demonstration has been shown regarding the digitally controlled magnetic bearing's flexibility by the use of algorithm, which includes integral feedback and second derivative. The design approach shows the effect of these new algorithms on the active magnetic bearing performance.

For the reshaping of the part in the damping curve which consists of high-frequency, second derivative feedback was utilised and to make sure the effects of the algorithm on the rotor response that it would be effectively anticipated integral feedback was implemented (Fig. 3).

## 2.2 *Identification of Faults and Failure in AMB System*

Failure modes were found out by a test rig and seen that mostly the failure occurred was due to high vibration [12]. The conventional compression trains would be replaced by an AMB system in a hermetically sealed compressor. An AMB test rig has developed with two radial AMBs which are connected by an external controller and manipulated by computer software.

A test rig has been made (see Fig. 4) which is used to find out AMB failure modes. The primary cause of radial vibration in AMBs is to be the axial separation between the position sensor and bearing actuator. The failure modes that have been observed during normal machine operation are summarised in Table 2.

Failure of any component in AMB affects its performance, and hence, some major failure modes and their effects on the performance of AMBs have been identified [7] to make necessary changes in design to prevent these failures. So, failure modes and their effect have been found out for an AMB which will termed as FMEA means failure mode and effect analysis [12]. Risk Priority Number (RPN) will be discovered

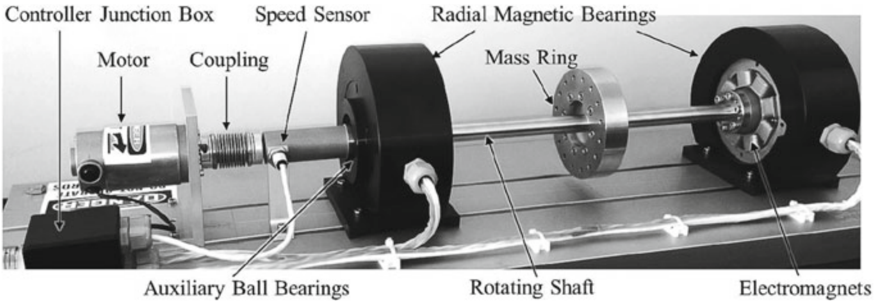

**Fig. 4** Test rig schematic: Prof. Melinda Hodkiewicz et al. [12]

**Table 2** Observed failure modes of AMB [12]

| Item and function | Functional failure | Failure mode—cause of failure |
|---|---|---|
| Radial AMB: support shaft and minimises shaft vibration | High vibration amplitudes | Super-synchronous vibration—controller tuning unsuitable for damping structural resonances |
| | Radial vibration | Axial vibration—coupling not sufficiently robust to damp axial vibration |
| Controller: control and monitor shaft rotation and levitation | Rotation deviates from command | CW motor acceleration following a deceleration to 0 RPM from CCW rotation—motor control logic failure |
| | Rotation prevented | Rotation disallowed by controller—max. allowed de-levitations onto auxiliary bearings reached |

by the assistance of severity, occurrence and detection of failures modes. In FMEA, first the system failures in the various components have been found out in each of the components of AMB system [13]. After that, the ranking is provided on a rating scale of 1–5 based on severity, occurrence and detection of each failure mode to calculate the Risk Priority Number (RPN). Hence, by the aid of Risk Priority Number, critical failure modes of AMB system have been found out. After identifying the critical failure mode and applying the control methods, the value of RPN is again calculated. The final FMEA worksheet is given in Table 3.

**Table 3** Failure mode and effect analysis worksheet [7]

| Components | Root-cause modes | Effects | RPN |
|---|---|---|---|
| Amplifier | Condition of external environment | Results in reduction in speed | 5 |
| | Over loading due to excess current supply | Results in reduction in speed | 12 |
| | Short circuit | Results in reduction in speed | 10 |
| Position sensors | Failure in electric circuit | Results in reduction in speed | 20 |
| | Physical contact between sensor and rotor | Rotor will levitate away from its original position | 18 |
| | Shaft will be damaged | Rotor will levitate away from its original position | 8 |
| | Presence of debris | Rotor will levitate away from its original position | 3 |
| Coil | Wire insulation decay | Results in reduction in speed | 4 |
| Software error | Failure occurs in operating condition | Rotor will levitate away from its original position | 16 |
| Rotor in dynamic loading | Loading condition has been changed | Rotor will levitate away from its original position | 12 |
| Motion in abnormal condition | Vibration from external source | Rotor will levitate away from its original position | 24 |
| | Mounted in portable applications | Rotor will levitate away from its original position | 128 |
| Active magnetic bearing touchdown bearings | Permanent damage | Results in reduction in speed | 6 |
| | Temporary errors in the system | Rotor will levitate away from its original position | 4 |

## 3 Conclusion

Active magnetic bearing provides contact-less operation, hence, mechanical wear and frictional losses reduce, and there is no use of lubrication, so the maintenance cost reduces, and life and reliability of the bearing will increase.

In this paper, different control techniques studied, from which PID has been widely used in industrial control system and AMB systems in comparison with others. Also, failure modes have been studied to minimise the faults and failures in AMB and to increase its life, performance and reliability. It has been observed that the high vibrations are the main cause of failure of AMBs which results in decentralised of the shaft and minimises the life as well as the overall efficiency of the system.

Work is ongoing in many project areas, mainly to reduce or to control the vibration in the AMB system. The current areas of exploration include to control the multiple axes magnetic bearing and decentralisation of shaft and to reduce the high amplitude vibrations.

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