Energy Management by Means of Fault Conditions on Active Magnetic Bearing Systems

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Abstract: This paper presents the use of fault conditions on active magnetic bearing (AMB) systems as an energy management tool to improve the operation of AMB systems. Fault conditions on AMB system are broadly classified into external faults and internal faults, where external faults normally have some external disturbance acting on the system. These external disturbances will always have a transient component and possibly a steady state component. Internal fault conditions mostly refer to signal processing faults or failures. It can be seen that by analyzing these fault conditions, the operation of the AMB system can be improved. The use of fault condition on AMB systems therefore provides a valuable energy management tool.

Keywords: Energy management, active magnetic bearings, fault conditions, failures.

I. INTRODUCTION

Active magnetic bearing (AMB) systems are widely used in industry due to numerous advantages, such as no mechanical contact and lubrication, high operational speed, high precision operation, and adjustable stiffness and damping. High production cost and low reliability are some of the disadvantages of AMB systems [1].

Industries expect safe and reliable operation and of their machines, high efficiency and availability at all times. In order to satisfy these requirements integrated diagnosis and failure detection becomes increasingly important.

It is therefore important to invest in energy management projects that can improve the operation of AMB systems. This paper focuses on presenting fault condition on AMB systems as an energy management tool.

System faults can be broadly classified as either internal or external to the AMB control system. This classification then relates to the way in which the faults can be dealt with following occurrence. Fig. 1 provides an overview of the most common fault conditions on AMB system. The fault conditions presented in this figure are classified into external and internal conditions to the AMB system. Some other fault conditions also exist and occur on the AMB system, but are not presented in this paper.

Condition monitoring of the internal parts of a radial AMB system can be performed by means of Cepstrum analysis, Wigner-Ville Distributions (WVD) and enveloped Equi-Sampled Discrete Fourier transforms (ESDFT) [1].

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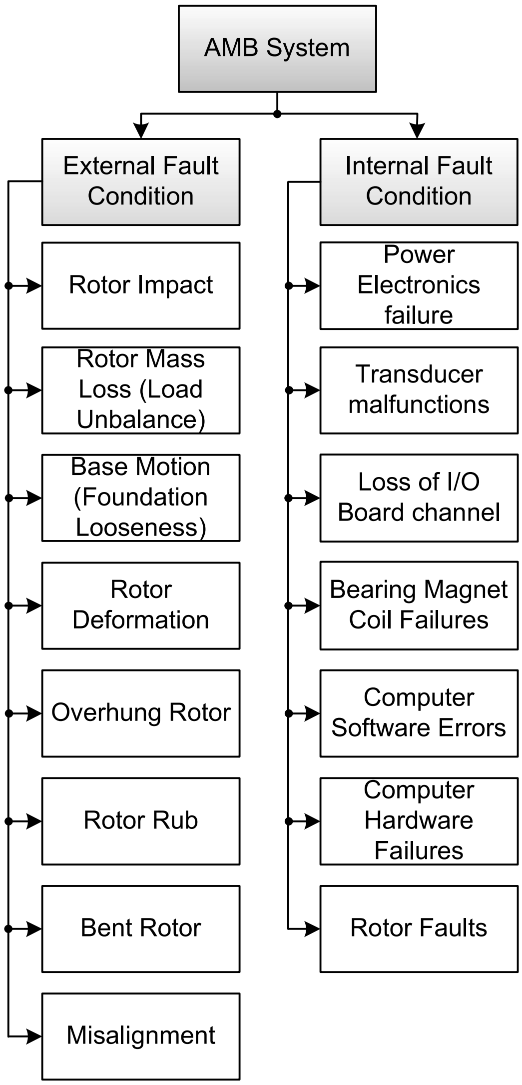

Fig. 1. Overview diagram of fault conditions on AMB systems.

II. EXTERNAL FAULT CONDITIONS

This section provides the external fault conditions that can occur on AMB systems. Faults are considered to be external when either the fault manifests itself as, or the effect of the fault can be replicated by, some external disturbance acting on the system. These disturbances will always have a transient component and possibly a steady state component. Typical faults that can be classified in this way include the following:

Faults that are external to the magnetic bearing/control system do not generally require any reconfiguration of the control system itself although some adjustment or adaptation of the control algorithm may improve operation.

Consideration of abnormal, or fault related, system disturbances in the controller design will also improve robustness to certain aberrations from normal operating conditions [2].

A. Rotor impact

A direct impact of the rotor with a foreign body could occur in a number of applications. For example, a pump or turbine fluid/air intake could be contaminated with solid matter. This type of fault would result in impulsive force acting directly on the rotor, the magnitude of which would depend on velocity, mass and material hardness [3].

B. Rotor mass loss (Load unbalance)

This type of fault is well documented for high-speed turbines where loss of compressor or turbine blades, though uncommon, can occur. Typically, sudden loss of a blade occurs due to a fracture at the blade root. This can be modeled by a step change in amplitude of the synchronous forces acting on the rotor [4].

C. Base motion (Foundation looseness)

Motion of the system base, on which the bearings are mounted, can occur in various applications and environments [5]. In transport applications, motion of the vehicle will be transmitted to internally mounted machines. Base motion may also arise from external vibration sources (e.g. other machines), seismic events and accidental impacts or explosions [6].

D. Rotor deformation

Deformation of the rotor while in operation could occur for a number of reasons. For example, a plastic deformation of the rotor or ancillary component may occur due to excessive loading/wear. Another possibility is thermal deformation, for example, due to rotor rub. This effect can be modeled by synchronous forces acting directly on the rotor, but for control purposes should not be treated the same as unbalance.

E. Sudden changes in loading (Overhung rotor)

A change in the steady state load could occur due to some fault conditions. For example, in compressor or pump applications, a sudden change in fluid pressures due to an external fault or error will result in a step-change in the axial rotor loading. Rotor mass loss events will also cause a step change in mean loading due to a change in the total weight of the rotor [7].

F. Rotor rub

Contact of the rotor with stationary components causes vibration both of the rotor and the surrounding ancillaries. This may occur for a variety of reasons e.g. rotor deformation, unbalance changes or component damage. It will generally be characterized by directly forced rotor vibration, mainly at the synchronous frequency, although sub-harmonics and higher frequencies will also be present. Rotor rub can significantly alter the closed loop dynamics of the system and if so, treatment as an external fault may be inappropriate.

G. Bent rotor

In the case of a bent rotor, the excitation is proportional to the magnitude of the bow along the rotor [8], [9]. A bent rotor gives rise to synchronous excitation, as with mass unbalance, and the relative phase between the bend and the unbalance causes different changes of phase angle through resonance than would be seen in the pure unbalance case, as described in references [10], [11].

H. Misalignment

Misalignment occurs when there are geometry changes due to assembly procedures. Misalignment is typically caused by the following conditions [12]:

- Inaccurate assembly of components, such as motors, pumps, etc.
- Relative position of components shifting after assembly
- Distortion due to forces exerted by piping
- Distortion of flexible supports due to torque
- Temperature induced growth of machine structure
- Coupling face not perpendicular to the shaft axis
- Soft foot, where the machine shifts when hold down bolts are torqued.

If the machine speed is varied, the vibration due to imbalance will vary as the square of the speed. If the speed is doubled, the imbalance component will rise by a factor of four, while misalignment-induced vibration will not change in level [13].

III. INTERNAL FAULT CONDITIONS

This section provides the internal fault conditions that can occur on AMB systems.

A. Power electronics – power amplifier failure or malfunctions

To power each magnet coil, a solid state amplifier is commonly used. Although, these units are inherently reliable, their dynamic performance depends on a number of variables (e.g. ambient temperature and power demand). The amplifiers are usually configured for either voltage or current control. Voltage amplifiers are more prone to current overload, as there is no internal regulation of the output current. When amplifiers and magnet poles are configured in opposing pairs, loss of a single amplifier and pole will result in an attractive force from the remaining opposite pole. Unless this can be turned off quickly the rotor will collide with the auxiliary (backup) bearings [3].

Actuator faults in AMB systems may have a number of causes. Problems may arise in any point in the series connection of amplifier, wiring, and coil. Connectors or cables may fail, amplifiers and fuses may burn. For experimental purposes actuator faults can be restricted to open circuit failures that can be tolerated by the system, i.e. failures of a lower sensor coil such that the current suddenly goes to zero. Without correction, such a failure can be modeled as a decrease in bearing stiffness combined with the disability to exert downward forces onto the rotor, as a consequence of the changes in the actuator. The system may become unstable in one channel. Like in the case of uncorrected sensor faults, unstable behavior with violent crashes of the rotor against the retainer (backup) bearings is the consequence [14].

B. Transducer malfunctions (Sensor fault)

The malfunction of a transducer could produce a variety of erroneous signals. However, a short circuit or an open circuit is likely to produce a dc signal. Other than an electrical fault, physical damage or deterioration is a likely cause of sensor malfunction. For example, damage to the shaft or debris at the measurement surface will affect proximity detectors [15].

Without correction, failure of a sensor leads to the controller being provided with incorrect position information. As a consequence, the controller outputs inadequate set currents, which inevitably entails a destabilization of the system. Violent crashes of the rotor against the retainer (backup) bearings are the consequence [16].

C. Loss of I/O board channel

The complete loss of a channel on the computer input/output board would produce a zero-valued control input or output signal. A possible cause of this type of fault would be a circuit break or short in the connection cable.

D. Bearing magnet coil failures

The failure of a magnet coil usually occurs due to a breakdown in winding insulation, resulting in a short circuit. Depending on where the short occurs, there will be a reduction in the number of effective coil windings.

E. Computer software errors (Controller fault)

Real-time control software can be susceptible to latent programming errors that may arise unexpectedly and may be difficult to pre-detect. These types of errors will result, at best, in unpredictable behavior or, at worst, in program termination. The key to avoiding this type of situation is well structured programming and thorough program testing. Code can be written with a certain degree of built in tolerance to run-time errors. However, a complete program execution failure would require a redundant microprocessor to take over control [17]. The alternative is to rapidly restart the processor, which would require reloading of the control program, initializing and restarting. It is doubtful whether this could be achieved in the necessary time-scale [18].

F. Computer hardware failures

A failure of microprocessor hardware is relatively uncommon, but would probably have similar consequences to a program termination. Again the only hope for dealing with this type of problem would be if back-up hardware were available to take over the control operation [19].

G. Rotor faults

Mechanical faults in the system could be catastrophic if the system cannot retain adequate control. Possible faults of this nature include fatigue, cracking, deformation of the rotor or detachment of part of the rotor. Also, problems not directly attributable to the rotor can occur, such as external rubbing, ancillary parts becoming loose or unexpected impacts or loading. Some of these faults could also be considered as external faults. Many mechanical abnormalities in the rotor can be considered as a variation in system parameters. As such, there is a realistic chance that these types of faults can be included in robustness specifications during the controller design stage.

IV. CONCLUSION

This paper presented the use of fault conditions on AMB systems as an energy management tool to improve the operation of AMB systems. The fault conditions were categorized into external faults and internal faults to the AMB system, where external fault normally have some external disturbance acting on the system. These external disturbances will always have a transient component and possibly a steady state component. Internal fault conditions mostly refer to signal processing faults or failures. It can be seen that by analyzing these fault conditions, the operation of the AMB system can be improved. The use of fault condition on AMB system therefore provides a valuable energy management tool.

REFERENCES

[1] R. Gouws, "Active magnetic bearing condition monitoring," World Journal of Engineering, Vol. 10, No. 2, pp. 179-188, 2013.

[2] A. Korde, "Online condition monitoring of motors using electrical signature analysis," Diagnosis technologies India Pvt. Ltd., Advances in condition-based plant maintenance seminar, Mumbai, May 2002.

[3] M.O.T. Cole, P.S. Keogh, M.N. Sahinkaya, "Progress towards fault tolerant active control of rotor-magnetic bearing systems," Department of Mechanical Engineering, University of Bath, UK.

[4] T.G. Habetler and R.G. Harley, "Diagnostics and intelligent controls in electrical systems," Power Electronics and Motor Diagnostics Laboratory, Georgia Institute of Technology, February 2004.

[5] G.R.P. Singh, A.K. Paul, A.K. Chaterjee, "Improving equipment availability and reliability though condition monitoring at cold rolling mill complex of tata steel," [Online]. Available: http://www.reliabilityweb.com.

[6] Future Fibre Technologies, "Machine condition monitoring," [Online]. Available: http://www.fft.com.au/index.htm.

[7] A.C. Balbahadur, "A thermoelastohydrodynamic model of the Morton effect operating in overhung rotors supported by plain or tilting pad journal bearings", Faculty of the Virginia Polytechnic Institute and State University, Blacksburg, Virginia, February 2001.

[8] S. Edwards, A.W. Lees and M.I. Friswell, "Experimental identification of excitation and support parameters of a flexible rotor-bearing-foundation system from a single run-down," Department of Mechanical Engineering, University of Wales, Swansea, November 1999.

[9] T.G. Habetler, "On-line condition monitoring and diagnostics of electric machines," School of Electrical and Computer Engineering, Power Electronics and Motor Diagnostics Laboratory, Georgia Institute of Technology.

[10] J.C Nicholas, E.J. Gunter and P.J. Allaire, "Effect of residual shaft bow on unbalance response and balancing of a single

mass flexible rotor - Part 1 - unbalance response," Journal of Engineering for Power, Vol. 98, pp. 171-181, 1976.
[11] J.C. Nicholas, E.J. Gunter and P.J. Allaire, "Effect of residual shaft bow on unbalance response and balancing of a single mass flexible rotor - Part 2 – balancing," Journal of Engineering for Power, Vol. 98, pp. 182-189, 1976.
[12] J.T. Marshall, "A multi-point measurement technique for the enhancement of force measurement with active magnetic bearings," Faculty of the Virginia Polytechnic Institute and State University, Blacksburg, Virginia, May 2001.
[13] I. Green, "Real-time monitoring and control of mechanical face seal dynamic behavior," The George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, August 2000.
[14] F. Losch, "Detection and correction of actuator and sensor faults in active magnetic bearing systems," 8th International Symposium on Magnetic Bearing, Mito, Japan, August 26-28, 2002.
[15] M. Aenis and R. Nordmann, "Fault diagnosis in rotating machinery using active magnetic bearings," 8th International Symposium on Magnetic Bearing, Mito, Japan, August 26-28, 2002.
[16] S. Kim and C. Lee, "Diagnosis of sensor faults in active magnetic bearing system equipped with built-in force transducers," IEEE/ASME Transactions on Mechatronics, Vol. 4, No. 2, June 1999.
[17] S.W. Yates and R.D. Williams, "A fault tolerant multiprocessor controller for magnetic bearings," IEE Micro, Aug 6-17, 1988.
[18] Z. Shi, M. Zha, H. Peng, "The monitoring system of the PCU for the 10 MW high temperature gas-cooled reactor," 2nd International Topical Meeting on High temperature reactor technology, Beijing, China, September 22-24, 2004.
[19] A.R. Dolasa, "Computer-aided design software for the undamped two-dimensional static and dynamic analysis of beams and rotors," Faculty of the Virginia Polytechnic Institute and State University, Blacksburg, Virginia, May 1998.

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