PROGRESS TOWARDS FAULT TOLERANT ACTIVE CONTROL OF
ROTOR-MAGNETIC BEARING SYSTEMS

Matthew O T Cole, Patrick S Keogh, Mehmet N Sahinkaya and Clifford R Burrows

Department of Mechanical Engineering, University of Bath, Bath BA2 7AY, UK.

Abstract: This paper considers methods for improving fault tolerance of rotor-magnetic bearing systems. Possible system failure modes are surveyed and classified according to whether they are internal or external to the magnetic bearing control system. Improved tolerance to specific external faults is achieved through multivariable controller design with $H_\infty$ disturbance rejection criteria. Tolerance to internal faults generally requires more than robust controller design and a re-configurable control strategy is introduced as a suitable method of achieving it, particularly for control input-output channel malfunctions. Methods for introducing fault tolerance and detection in a rotor vibration cancellation strategy are also discussed.

Keywords: Magnetic bearings, rotors, fault-tolerant systems.

1. INTRODUCTION

Magnetic bearings enable contact-free rotor levitation and have a number of important advantages over conventional bearings. These include lubrication-free operation, high rotational speeds and the potential for active vibration control. One of the main issues in the design of magnetic bearing systems, for both current and potential machine applications, is improvement of fault tolerance. The principal objective for fault tolerant control is to allow the continued safe running of the rotor during the occurrence of a fault so that it can subsequently be run down safely and the machine shut down for repair, or alternatively repairs can be made during operation.

Failure of a single system component can give rise to destructive rotor dynamic behaviour, particularly if the rotor is not constrained effectively by auxiliary bearings. The issue of actively controlling the non-linear dynamic response of the rotor when interaction with auxiliary bearings occurs is also an important aspect of fault tolerance. However, the focus of this paper will be the design of control systems aimed at maintaining rotor levitation following occurrence of a fault. One requirement for achieving this is that system stability can be conserved during a fault condition. In addition, there may be performance requirements to ensure, for example, safe rotor rundown through critical speeds.

Overall system design considerations also play an important role in maximising fault tolerance, including selection of bearing/sensor configuration and levels of component redundancy. However, improving fault tolerance may incur a cost of decreased maintainability. Introducing redundant components can facilitate improved fault tolerance, but the probability of component failure actually increases, due to the increased number, and so maintainability is degraded. There is, therefore, a strong argument for achieving fault tolerant control with the minimum system complexity.

2. POTENTIAL FAULT CONDITIONS

System faults can be broadly classified as either internal or external to the magnetic bearing control system. This classification then relates to the way in which the fault can be dealt with following occurrence.

2.1 External Faults

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:

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 an impulsive force acting directly on
the rotor, the magnitude of which would depend on velocity, mass and material hardness.

b) Rotor mass loss. 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 modelled by a step change in amplitude of the synchronous forces acting on the rotor.

c) Base motion. Motion of the system base, on which the bearings are mounted, can occur in various applications and environments. 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.

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 modelled 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. A change in the steady state bearing 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 total weight of the rotor.

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 characterised 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.

2.2 Internal Faults

a) Power electronics - 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, 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 bearings.

b) Transducer malfunctions. 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.

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. 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 behaviour 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 (Yates and Williams, 1988). The alternative is to rapidly restart the processor, which would require reloading of the control program, initialising and restarting. It is doubtful whether this could be achieved in the necessary time-scale.

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.

g) Rotor faults. Mechanical faults in the rotating element of 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 and as such have already been discussed in section 2.1. 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.

3. FAULT TOLERANT CONTROL STRATEGIES

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.

Control systems that possess tolerance to internal faults can generally be classified as robust, reconfigurable or a combination of both. A system is robustly fault tolerant if a fixed controller retains satisfactory performance in the presence of parametric variations or component failures. However, if the underlying mathematical configuration of the control system is altered on occurrence of a fault, then the control system is classified as reconfigurable, e.g. a control algorithm that changes in order to by-pass a faulty sensor. A further classification, which lies somewhere between these two, is adaptive fault tolerance. Here, a system, rather than changing distinctly, continuously adapts to parameter variations or component faults. For any of these strategies to succeed there is a fundamental requirement that the system has a sufficient level of redundancy to enable conservation of system stability and performance. The inability to achieve fault tolerance by reconfiguring control will certainly preclude the use of robust control, for which the controller is fixed. Therefore, reconfigurable control has the greatest potential for dealing with a wide range of fault conditions and particularly those that involve the functional loss of a control input or output.

The approach to designing controllers in each of these classes is different, and the applicability of each method depends greatly on the type of system to be controlled. Following a brief discussion of system requirements, three different methods of introducing fault tolerance in a magnetic bearing control system will be reviewed.

3.1 Requirements for Fault Tolerant Control

There are a number of system features that are necessary to enable the implementation of a fault tolerant control strategy. These conditions will apply whatever method of control is used and therefore should be considered at the initial system design stage, rather than at the controller design stage. To ensure that system stability can be preserved during a fault condition, there can be no loss of controllability or observability of any system modes that are not open loop stable. To achieve this will require a prescribed level of redundancy in the system components. System redundancy, referred to a set of sub-components or sub-systems, can be classified either as parallel or analytical. A system exhibits parallel redundancy when two or more components perform exactly the same operation, so that each could take-over the function of the other. Analytical redundancy occurs when system components perform different functions, but are not all required for satisfactory system operation.

Previous studies have investigated suitable methods of introducing redundancy in magnetic bearing systems. For example, magnetic bearings with redundant poles can be reconfigured following the functional loss of one or more coils (Maslen and Meeker, 1995; Na and Palazzolo, 2000). Other investigations have tried to incorporate modular redundancy into some (Yates and Williams, 1988) or all components of the system (Lyons et al., 1994; Maslen et al., 1999).

3.2 External Fault-Tolerance Through Multivariable Controller Design

Modern multi-objective controller design methods allow multiple disturbance attenuation criteria to be incorporated in model-based controller synthesis (Zhou et al., 1996). These techniques can be applied to magnetic bearing controller design to account for possible external fault conditions. As an example, controller design for system base motion and rotor mass-loss will now be considered.

The rotor-magnetic bearing system can be represented in the Laplace domain as a transfer function relating sensor measurements $y$ and control forces $u$ to rotor direct forces $f$ and base displacement $z$:

$$\begin{align*}
Y(s) &= \begin{bmatrix} T_{y^1} & T_{y^f} \end{bmatrix} Z(s) \\
U(s) &= \begin{bmatrix} T_{u^1} & T_{u^f} \end{bmatrix} F(s)
\end{align*}$$

Here,

$$\begin{align*}
T_{y^1} &= (I + G_b H)^{-1} G_b \\
T_{y^f} &= (I + G_b H)^{-1} G_f \\
T_{u^1} &= H(I + G_a H)^{-1} G_a \\
T_{u^f} &= H(I + G_a H)^{-1} G_f
\end{align*}$$

where $H(s)$ is the controller transfer function matrix and $G_a(s)$, $G_b(s)$ and $G_f(s)$ are the open loop transfer function matrices relating $Y(s)$ to $U(s)$, $F(s)$ and $Z(s)$ respectively.
A suitable controller can be obtained by minimising the $H_\infty$ norm of the combined closed loop transfer function $T$, augmented with suitable weighting transfer function matrices:

$$
\begin{bmatrix}
W_r(s)Y(s) \\
W_p(s)U(s)
\end{bmatrix} = T(W_r,W_p,W_u,H)\begin{bmatrix}
W_r^{-1}(s)Z(s) \\
W_p^{-1}(s)(F(s))
\end{bmatrix}
$$

(3)

The diagonal weightings matrices $W_\alpha(s)$ are chosen to shape the frequency dependent maximum singular values of the closed loop transfer functions in a desired manner and should reflect the possible frequency content of base motion and mass-loss related disturbances. Additional tolerance to structured perturbations, e.g. system gain variations may be included in the controller design through mu-synthesis techniques, which can be augmented within an $H_\infty$ design framework (Schönhoff et al., 2000).

Controllers designed in this way have improved performance under base motion and mass loss conditions compared to PID controllers and controllers designed without consideration of these possible fault conditions (Cole et al., 1998). Controllers were assessed on a flexible rotor system with two magnetic bearings (Fig. 1) under base motion, produced by an impulse to the stator foundation. A multivariable feedback controller designed for synchronous vibration attenuation alone gives poor performance when the system base is excited and consequently the rotor makes brief contact with the auxiliary bearing (Fig. 2). If base motion disturbances are considered in the controller design, as described, then the displacement of the rotor relative to the base is constrained much more effectively (Fig. 3). This level of controller performance can be achieved simultaneously with good vibration attenuation under synchronous forcing caused by steady unbalance and mass loss (Fig. 4). Good performance of such model-based controller designs is dependent on accurate system modelling, in this case achieved through finite element modelling of the rotor and experimental identification of the magnetic bearing characteristics.

3.3 A Reconfigurable Control Strategy With Automatic Fault Detection

The implementation of a reconfigurable control strategy has been successfully applied to a rotor-magnetic bearing system through the inclusion of a number of control sub-systems (Fig. 5):

1. Closed loop controller – this executes an appropriate control algorithm, selected from a predefined set of algorithms. Controllers designed around the framework described in section 3.2 have been used for this purpose. Ideally, the controller can switch algorithms while in operation without inflicting unwanted disturbances on the system.

Fig. 1. Radial heteropolar magnetic bearing

Fig. 2. Rotor base motion reponse with controller with designed for synchronous vibration attenuation only ($\Omega = 110$ rad/s)

Fig. 3. Rotor base motion reponse with controller designed for rotor vibration attenuation under mass loss and base motion ($\Omega = 110$ rad/s)

Fig. 4. Rotor response during mass loss with controller designed for rotor vibration attenuation under mass loss and base motion ($\Omega = 110$ rad/s)
2. **Fault detection and isolation system** – this sub-system monitors control input and output signals, as well as additional system measurements, in order to detect and identify failure modes as and when they occur. The system output will usually be in the form of a fault detection signal that can be monitored by the supervisory controller (3). The algorithm can be based on state estimation schemes (e.g. Hou and Patton, 1996), although alternatives such as artificial neural networks that are trained using empirical data have also shown potential in magnetic bearing applications (Cole et al., 1999).

3. **Supervisory controller** – this sub-system monitors the signals produced by (2) and on detection of a fault selects the most appropriate control routine from a set of predefined algorithms.

The advantage of a reconfigurable control system is that separate controllers can be designed for optimal control under each possible fault condition. Providing the failure mode can be identified, the appropriate control algorithm can then be selected to cope with the occurring fault. The major performance issue for a reconfigurable control system is speed and accuracy of fault identification. Providing sufficient redundancy exists in the system, designing suitable controllers is relatively straightforward.

Such a scheme has been evaluated experimentally on a flexible rotor supported by two magnetic bearings and having eight rotor displacement sensors (Cole et al., 2000). Following a fault on one sensor, the detection and identification of the faulty sensor allowed the controller to be automatically switched to operate using the remaining healthy sensors (Fig. 7). Without this reconfiguration, the rotor makes persistent hard contact with the auxiliary bearing, due to a loss of rotor stability (Fig. 6).

Such a scheme can be extended to deal with actuator failure if redundant bearings/magnet coils are included in the system design, although successful fault identification is harder to achieve when increased numbers of failure modes must be accommodated.

A simple and effective method to reduce multi-harmonic rotor vibration when using magnetic bearings is through a feed-forward control technique in which the amplitude and phase of frequency-matched control forces are adjusted automatically to minimise the measured vibrations along the rotor. An extension to the control strategy, which utilises the variances of the measured rotor vibration amplitudes and other identified parameters, enables faults to be detected and accounted for in order to achieve continued effective control of the rotor vibration (Sahinkaya et al., 2001). The approach can also identify changes in external factors, such as rotor unbalance and dynamics.

The dynamics of a flexible rotor-bearing system can be represented through a frequency response model appropriate to periodic multi-frequency disturbances:

\[
Y(j\omega) = Y_0(j\omega) + G_s(j\omega)U(j\omega)
\]

The vectors \( Y_0(j\omega) \) and \( Y(j\omega) \) are the spectral amplitudes of the measured rotor vibration with and without the application of the control forces respectively. The control input can be chosen to minimise the sum of squares of the synchronous vibration components \( Y_0(j\Omega) \) by selecting the synchronous control force component as

![Fig. 5. Block diagram of a reconfigurable control strategy](image)

![Fig. 6. Measured rotor response at bearing during local sensor failure (\( \Omega = 88 \text{ rad/s} \))](image)

![Fig. 7. Measured rotor response at bearing during local sensor failure with automatic control reconfiguration (\( \Omega = 88 \text{ rad/s} \))](image)
On-line identification of the matrix \( G_{\theta}(\bar{\omega}) \) can be achieved at various frequencies by perturbing each control input in turn with a sinusoidal test signal. The matrix \( G_{\theta} \) is not a function of the external disturbances, and is not expected to change unless there is change in system dynamics. Therefore, repeated on-line identification can be used as part of a condition monitoring and fault detection procedure that responds to changes in \( G_{\theta}(\bar{\omega}) \), as well as \( Y(\bar{\omega}) \).

The re-identified values of these parameters can be compared with reference values. The significance of any deviation is assessed using additional statistical information about the normal variation and measurement accuracy of the parameters. Thus the likelihood of a fault can be determined.

### 4. CONCLUSIONS

This paper has considered aspects of introducing fault tolerance in rotor-magnetic bearing systems. Improved tolerance to faults that are external to the control system can be achieved through appropriate controller performance and robustness criteria. Although robust control design methods can go some way to achieving tolerance to internal faults, a different approach is generally required if faults such as control input or output channel failure are to be handled effectively. In these cases, a change in control algorithm or a complete reconfiguration will be necessary to maintain rotor levitation.

It is proposed that, in order to achieve necessary levels of safety and reliability, rotor-magnetic bearing systems should incorporate a number of fault tolerant features. Firstly, systems should be designed with the required component redundancy that will allow fault tolerance to be achieved. Controllers should be designed using modern control techniques to give the optimum level of performance and robustness. Condition monitoring sub-systems, such as those described here, should provide real-time checks on the condition of operation of the system and monitor for faults. Finally, a supervisory controller should operate to respond to faults, as and when they occur, and take the appropriate action, whether it is reconfiguring the control system, changing the control algorithm, shutting down the system or notifying a human operator.

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### REFERENCES


