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DETECTION AND CORRECTION OF ACTUATOR AND SENSOR FAULTS IN ACTIVE MAGNETIC BEARING SYSTEMS

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ABSTRACT

This paper deals with the detection and correction of sensor and actuator faults in active magnetic bearing (AMB) systems with decentralized control. Algorithms for the detection and correction of the faults are presented, and their effectiveness is shown on an experimental test rig. Special attention is attributed to the interaction of the algorithms with one another and other control components like unbalance compensation.

INTRODUCTION

Safety and robustness to faults and failures in system components are issues of great interest in the field of active magnetic bearing systems. This is even more the case since the range of application of AMB systems broadens and interest arouses in employment of AMBs in highly safety critical applications like aircraft turbines, which is a current research topic [1,2].

Active magnetic bearing systems are ideally suited for diagnosis and correction purposes since the bearing system is already equipped with sensors and actuators. In addition to serving for control purposes, the sensor signals can be analyzed to obtain information on the system's operating condition. Furthermore, the bearing magnets can be used to apply test signals to the system, the response to which can again be analyzed, yielding detailed information about the system that allows for identification of the complete system dynamics [3] and detection of changes in system behavior. In conjunction with an adequate system model this information can be used for fault detection.

With the demand for ever increasing efficiency in all fields of application, the requirement for on-line analysis of processes increases. This pushes forward the demand for process monitoring and diagnosis tools.

In AMB machinery, such tools can be implemented with particularily little additional cost since the key hardware components required for monitoring and diagnosis are already present in the machines and in many cases the additional requirements are restricted to software, which, once developed, does not significantly increase the price of AMB machinery.

The trend towards machinery with diagnosis and monitoring software is therefore beneficial for the AMB industry in two ways. Firstly, the development of new tools will lead to better exploitation of the potential of AMB technology and make its advantages transparent to potential users. Secondly, the competitive position of AMB manufacturers is strengthened, since the (currently still significant) difference in initial cost compared to conventional machinery is reduced, since conventional machines must be equipped with sensors and actuators before being suited for diagnosis.

In recognition of the economic potential of machines with diagnostic and correction capabilities, the European Union funded the project IMPACT (Improved Machinery Performance using Active Control Technology),[4]. The goal of this project is the development of smart machinery capable of continously monitoring the system state, making predicitons concerning its development, and deriving suitable correction measures that are finally applied to the machine.

In the context of this project, AMB technology has been introduced to different applications like centrifugal pumps and grinding machines, and software for monitoring and diagnosis of faults in the processes has been developed for these applications [5, 6]. A second direction of research aimed at diagnosis and correction of faults in the AMB system itself. The work presented in this paper has been coducted in context of the IMPACT project and is concerned with this second approach.

SENSOR FAULTS

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 bearings are the consequence.

Both the detection and the correction of sensor faults require redundancy of sensors. In the context of this work, the redundant sensors are assumed to be arranged in pairs of two in additional sensor planes. This approach accomodates employment of self-sensing bearings as redundant sensors, as would be of interest when fault tolerance is to be added to smart machinery that for process monitoring purposes is equipped with conventional primary sensors (due to their superior bandwidth).

Detection Approach

Based on the redundant sensors in the system, the following algorithm for detection of sensor faults and failures has been developed. The central assumption of the algorithm is that the rotor can be described as a straight line (this is absolutely correct for straight, rigid rotors only, but still holds with sufficient accuracy for flexible rotors since the rotor's deformation is very small compared to the sensors' measurement range). Based on the sensor measurements and the known geometry of the plant (distances between sensor planes, orientation of sensors), the rotor's position in space is estimated by fitting a straight line to the sensor values. The quality of this fit is evaluated by computing the sum of the squares of the distances between the sensor output and the line at the respective measurement locations. This difference is a so-called residual.

Based on such residuals, faults and failures are detected in the following way: With *2n* sensors in the system, the procedure is repeated *2n* times, and each time a different sensor is excluded from the approximation.

If now sensor measurement *j* is erroneous, this has an influence on all *2n-1* estimates that rely on sensor *j* and increases the corresponding residuals, whereas in the estimation in which sensor *j* has been excluded, no effect on the residual can be seen. As a consequence, whenever all but one residual increase it can be concluded that the fault occurred on the sensor not involved in the computation of the "good" (small) residual is erroneous.

The developed approach can easily be used both for diagnosis of suddenly occuring complete failures of sensors (e.g. broken sensor cable) and slowly evolving changes like changing gain and offset values. Furthermore, the method can be used to diagnose multiple sensor faults - once a fault has been detected on a sensor, this sensor is excluded from all estimations, and detection is continued with *2n-2* different estimations.

Position Estimator. The position of a straight line in three dimensional space can be expressed by two equations,

$$\begin{aligned} x &= m_x z + d_x, \\ y &= m_y z + d_y \end{aligned} \qquad (1)$$

where x and y denote coordinate axes perpendicular to the rotor axis, which is aligned with the z coordinate of the coordinate system when the rotor is in its nominal position.

For each plane of two perpendicular sensors, the line's position in the xz- and yz-coordinate planes can be described by

$$\begin{aligned} m_y p_i + d_y &= \cos(\alpha) s_{i,\tilde{x}} - \sin(\alpha) s_{i,\tilde{y}} \\ m_x p_i + d_x &= \sin(\alpha) s_{i,\tilde{x}} + \cos(\alpha) s_{i,\tilde{y}} \end{aligned} \qquad (2)$$

where $s_{i,\tilde{x}}$ and $s_{i,\tilde{y}}$ denote the sensor readings of sensor pair i in local ($\tilde{x}, \tilde{y}$-) coordinates, p_i represents the z-position of the sensor plane and α is the angle by which the sensors' coordinate frame is rotated around the z axis with respect to the reference frame.

By replacing one of the sensor measurements in each of the above equations by an estimation value $e_{i,\tilde{x}}$ or $e_{i,\tilde{y}}$ of the measurement in each of the two equations above, a set of four equations is obtained. Each of these equations can be rearranged such that the term containing the remaining sensor value is placed on the right hand side of the equation like in the following example:

$$-\sin(\alpha) e_{i,\tilde{y}} + m_y p_i + d_y = \cos(\alpha) s_{i,\tilde{x}} \qquad (3)$$

The sets of equations for the different sensors can be rearranged and merged to a single linear system of equations of the form

$$\mathbf{A}\underset{\sim}{e} = \mathbf{B}\underset{\sim}{s}, \qquad (4)$$

where $\underset{\sim}{e}$ is the vector of estimated sensor signals and estimated rotor position information,

$$\underset{\sim}{e} = \left[e_{1,\tilde{x}}\ e_{1,\tilde{y}}\ \dots\ e_{n,\tilde{x}}\ e_{n,\tilde{y}}\ m_x\ m_y\ d_x\ d_y \right], \qquad (5)$$

and $\underset{\sim}{s}$ is the vector of sensor measurements.

The matrix $\mathbf{A}$ is a coefficient matrix directly resulting from the above equations and $\mathbf{B}$ is a matrix resulting from a multiplication of the right hand side scalar coefficients with a transformation matrix mapping the sensor measurements in $\underset{\sim}{s}$ to their corresponding equations.

The above mentioned omission of individual sensors from the estimation can be achieved by eliminating the two equations containing the sensor measurement from the above system.

For each eliminated pair of rows, the column corresponding to the estimate of the sensor perpendicular to the eliminated sensor becomes zero. These columns are elimitated and the vector $\underline{e}$ is adjusted accordingly by eliminating the components belonging to the corresponding vectors.

For *n* sensor planes in the system and *k* sensors to be omitted the size of the matrix **A** in the above system is *4n-2k*2n+4-k*, that of matrix **B** is *4n-2k*n-k*. This system is solveable as long as matrix **A** is 'tall', i.e. as long as $k \leq 2n-4$.
By applying the pseudo-inverse of **A** to the system, one obtains

$$\tilde{\underline{e}} = (\mathbf{A}^T\mathbf{A})^{-1}\mathbf{A}^T\mathbf{B}\tilde{\underline{s}}, \tag{6}$$

where $\tilde{\underline{e}}$ and $\tilde{\underline{s}}$ are the vectors resulting from elimination of unestimable variables and omitted sensors from the vectors $\underline{e}$ and $\underline{s}$.

The above system can be extended in to deliver estimates for *all* parameters contained in $\underline{e}$ by premultiplying the system's right hand side with a matrix **X** that essentially is a extended unity matrix containing additional rows of the form

$$e_{i,\tilde{x}} = \begin{bmatrix}\cos(\alpha) & \sin(\alpha)\end{bmatrix}\begin{bmatrix}0 & \ldots & 0 & p_i & 0 & 1 & 0 \\ 0 & \ldots & 0 & 1 & p_i & 0 & 1\end{bmatrix} \tag{7}$$

for the missing sensor estimates. This amounts to an a posteriori computation of sensor estimates based on the estimates of the rotor position.

As a result, the system

$$\underline{e} = \mathbf{X}\tilde{\underline{e}} = \mathbf{X}(\mathbf{A}^T\mathbf{A})^{-1}\mathbf{A}^T\mathbf{B}\tilde{\underline{s}} = \mathbf{Y}\tilde{\underline{s}} \tag{8}$$

is obtained.

Finally, in order to reduce the computational complexity, he last four rows yielding the estimates of the parameters m_x, m_y, d_x, and d_y can be removed from the matrix $\mathbf{Y}$. The resulting matrix then has dimension *2n*2n-k*.

Residual Generation and Fault Detection. Sensor fault detection by means of estimators of the above type is done as follows. During operation when *k-1* sensors have been identified to be defective already, the system successively solves equations of the type (8), using estimators where the *k-1* defective sensors and in addition one of the working sensors are omitted from the computation. The additional sensor is changed in each step.

The estimates related to the good sensors are compared to the actual sensor measurements. The sum of the squares of the differences is computed, yielding a residual describing the correspondance of the sensor measurements with the line fit to the measurements.

If a residual exceeds a predefined threshold, a comparison of the residuals resulting from the following cycle of computations can be used for diagnosis; if a sensor fails, the faulty signal enters all but one of the estimators. The residual belonging to this estimator will remain small, while the other residuals become large. The defective sensor can hence be easily identified.

The estimators required for this procedure can be easily precomputed off-line.

Detection of multiple sensor faults. In order to generate meaningful residuals, at least six radial sensors must be operational in the system. This will lead to sets of five sensors being included in the estimation procedure, which is just enough to obtain an overdetermined system of equations. Five active sensors will lead to four sensors being considered in each estimator, which will always yield a perfect match of the position estimate to the sensor readings, entailing zero residuals and hence prohibiting isolation of a fault.

However, failures *can* be isolated and compensated for on systems with only one redundant sensor if assumptions on the kind of fault are made (sudden failure), [7]. Without such assumptions, the number of sensor faults that can be diagnosed can be up to *2n-5*.

Correction Approach

Upon detection of a sensor fault by the diagnosis module the fault information is passed on to the correction module. This module then deactivates the defective sensor and chooses from the set of remaining operational sensors an optimal subset for stably controlling the system. Furthermore, the diagnosis is continued with a new set of estimators that all exclude measurements from the new set of faulty sensors.

When switching to a new set of active sensors, the corresponding controllers are also updated with controllers matching these sensors. This is necessary in particular in conjunction with flexible rotors, where flexible eigenmodes of the system may be destabilized when the sensor position is changed without suitably adapting the controller.

Like the estimators, the controllers used can be computed before taking the system into operation.

ACTUATOR FAULTS

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. In this work, actuator faults are restricted to open circuit failures that can be tolerated by the system, i.e. failure 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 (horizontal) 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 bearings are the consequence.

Detection of Actuator Faults

In the considered setting, actuator faults are diagnosed from comparison of measured coil currents with the computed set currents. Any unexpectedly large difference in these quantites over a certain period of directly indicates an actuator failure. Detection is based on a threshold that defines an allowable difference between the set current and the measured current together with a time limit that states for how long the threshold may be exceeded before the error is diagnosed (required to avoid false alarms due to dynamical effects).

Correction of Actuator/Amplifier Faults

Upon detection of an actuator fault on a lower coil by the diagnosis module, the fault information is passed on to the correction module. An algorithm then adjusts the controller for the control channel concerned to be compatible with the single-sided actuator. To this end, the integrator gains and controller gains are adjusted, and the integrator values are set to the value that ensures that the rotor remains in the center position. This is done very quickly, in order to force the rotor to stay in the center position with only a small disturbance.

EXPERIMENTAL RESULTS

Test Rig Description

Hardware setup. The algorithms described above have been implemented and tested on an experimental test rig that was specifically designed for testing of control, diagnosis and identification algorithms. The system was equipped with four additional radial sensors arranged in two additional sensor planes. To enable maximum fault tolerance, the measurement directions of the new sensors were rotated with respect to those of the original sensors by 45 degrees. Furthermore, the system was designed to allow for variation of the rotordynamic properties. To this end, the rotor was equipped with conical ends and a moveable clamping element located at its midspan. This allowed for configuring the rotor in many different ways by attaching discs of different mass and diameter, thus changing the rotordynamic properties of the test rig in a wide range. The key technical data of the rig is given in Table 1. A picture of the rig can be seen in Figure 2.

Table 1: Test Rig Properties

rotor length	491mm
rotor mass	3.38-6.91 kg
first flexible mode	101-216Hz
second flexible mode	364-616 Hz
maximum bearing force	104N
control system	dSPACE 1103 (with 333MHz PowerPC)

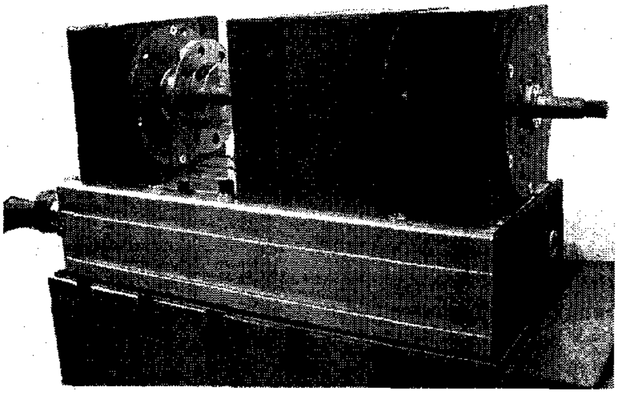

FIGURE 2: Test Rig with moveable clamping element and conical ends.

Sensor Failures

To test the fault detection algorithm described above, sensor failures were inflicted on the rig by manually removing arbitrary sensor cables from the eight radial sensors.

Behavior without Correction. 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 leads to a destabilization of the system, entailing violent contact of the rotor with the backup bearings.

Behavior with the Developed Correction Algorithm.

Figure 3 shows the behavior of the rotor upon the same fault when the diagnosis and correction algorithms are active. Due to the quick reaction to the fault, contact of the rotor with the housing can be prevented.

The remaining disturbance from the center position is a result of the threshold settings of the diagnosis module. Due to non-linearities and sensor noise, these thresholds cannot be set too tight if false alarms are to be avoided. While theoretically the rotor's deviation from the center position can be made arbitrarily small, a small disturbance will always remain in practice. This disturbance is very short (about 0.01s) and without consequences for most practical applications. The size of disturbance can be further minimized by ensuring that the geometry information used in the diagnosis module precisely matches the system geometry and by resetting the controller's integrator to its nominal value by hand. (This could not be implemented due to limitations of the SIMULINK-based programming interface. Implementation on real systems should be possible without any difficulty.)

Actuator Failures

Like sensor failures, actuator failures have been inflicted on the rig by suddenly removing cables from the setup.

Behavior without Correction . Without correction, the predicted instability was observed.

Behavior with the Developed Correction Algorithm.

Upon detection of an actuator fault by the diagnosis module, the fault information is passed on to the correction algorithm. This algorithm then adjusts the controller for the control channel concerned to be compatible with the single-sided actuator. To this end, the integrator gains and controller gains are adjusted, and the integrator values are set to the value that ensures that the rotor remains in the center position. This happens very rapidly, and the rotor stays in the center position with only a small disturbance, see Figure 4.

Interaction of Algorithms

For full implementation of the Smart Machine Technology, it is not sufficient to analyze the performance of each individual fault detection and compensation algorithm, but it also has to be ensured that the ensemble of algorithms works together well without any undesired interactions. This addresses robustness issues like incorrect diagnosis of faults (e.g. sensor faults leading to detection of actuator faults, or the correction of an actuator fault leading to diagnosis of a sensor fault.)

To this end, the behavior of the system with both algorithms active has been investigated. Additionally, an unbalance compensation as described in [8] has been implemented and activated during the tests.

The test showed the algorithm's performance to be a flawless, no performance deterioration was observed. As an example, Figure 5 shows the rotor's response to a sensor fault with unbalance compensation, actuator fault correction, and sensor fault correction activated. The behavior upon occurrence of an actuator fault is very similar to that of Figure 4.

Finally, it is worth remarking that the ensemble of algorithms in fact exposes *improved* robustness over the individual algorithms. When an actuator failure occurs on a system solely equipped with sensor fault correction, instability is inevitable. The resulting violent rotor motion and deformation result in (false) detection of multiple sensor faults on the system, a behavior that is avoided when adding the actuator fault compensation to the algorithm for sensor fault correction.

CONCLUSIONS

Algorithms for detection and correction of sensor and actuator faults have been presented. The algorithms show robust performance even when used together and in conjunction with unbalance compensation.

CONCLUSIONS

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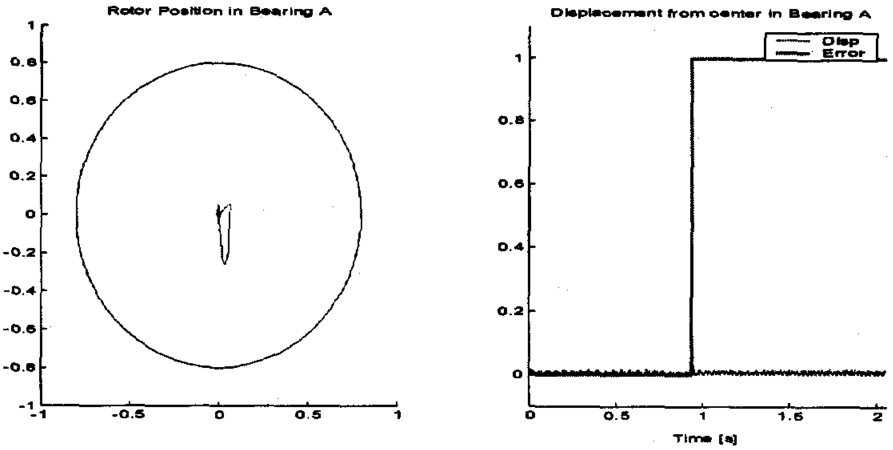

FIGURE 3: Behavior upon sensor fault with sensor fault diagnosis and correction modules switched on

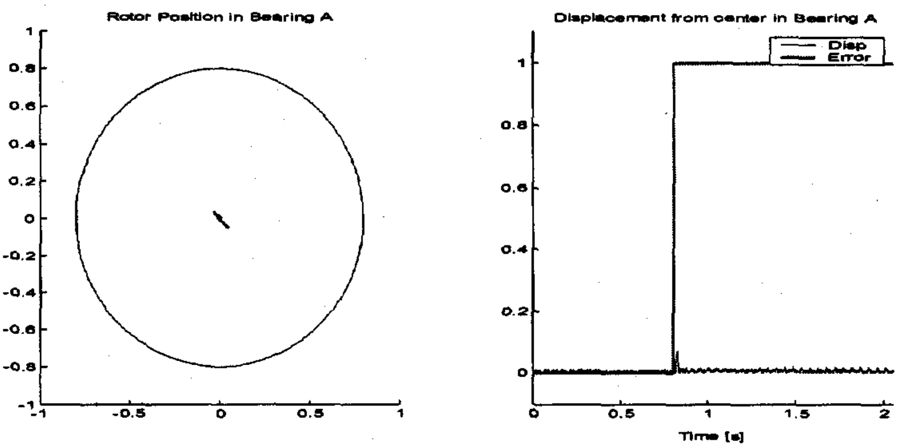

FIGURE 4: Behavior upon actuator fault with actuator fault diagnosis and correction modules switched on

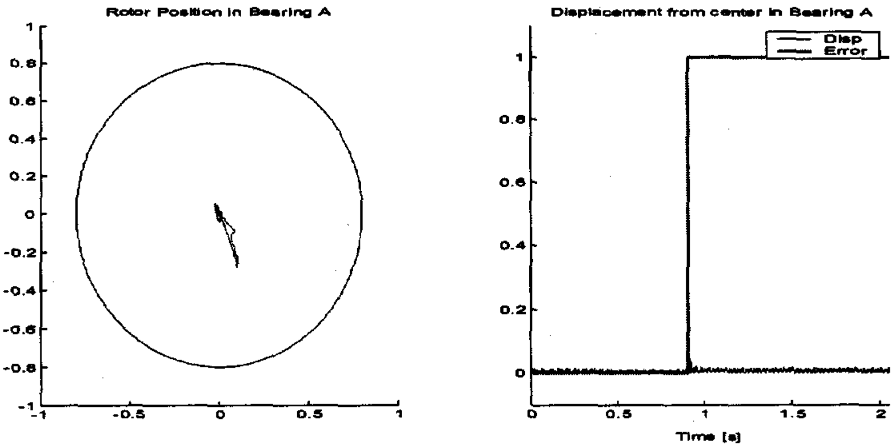

FIGURE 5: Behavior upon sensor fault with both sensor and actuator fault diagnosis and correction modules as well as unbalance compensation switched on