Chapter 1

Introduction

The presented work is concerned with state space adaptive control of a rigid rotor suspended in active magnetic bearings. In this chapter a short presentation of the objectives, related works and the chosen way to a solution is presented.

1.1 Problem

In many active magnetic bearing applications the design of the entire control system is performed under the assumption that all system parameters are exactly known in advance and do not change during operation. For these type of plants adaptive control is not necessary. It is sufficient to design a robust controller for a limited range of operation.

In high performance turbomachinery, however, a change in system parameters, such as a sudden change of pressure in a turbo pump may easily occur. This event may lead to a change in stiffness parameters of a sealing and finally to destabilising non-conservative cross-coupling forces, for example. In this case an adaptive controller is absolutely necessary.

Another possible application for adaptive control is a milling spindle suspended in active magnetic bearings. The exchange of the milling tool results in the change of system parameters like the rotor mass or the moments of inertia. In those cases the parameter change does not destabilise the entire system, but may deteriorate its performance. Adaptive control, however, can guarantee a desired performance for a wide range of operation.

Therefore, the objectives for this work are the modelling of a rotor bearing system, the derivation of a linear discrete time model for a point of operation, the search for a proper algorithm which can cope with parameter changes of the controlled system, and the proof of the performance by means of simulation.

1.2 Related work and different approaches

Adaptive control in the discrete time domain was up to now no topic in the field of advanced control for active magnetic bearing systems. Research work primarily focuses on robust control (μ-Synthesis [Stephens and Knospe, 1996, Nonami and Ito, 1994] and H_∞-control [Sivrioglu et al., 1996, Nonami et al., 1994]), i.e. controller design in the frequency domain. On the other hand, identification is mostly performed off-line and mainly in order to identify physical parameters of the electro-mechanic system [Herzog and Gähler, 1994, Gähler and Herzog, 1994, Gähler et al., 1996] and [Lottin and Saïdi, 1994].

In many applications, controller design is carried out in the continuous time domain to keep physical parameters transparent. Digital control is implemented in so far, as all designed controllers are transformed into the discrete time domain, because they are commonly implemented in a digital signal processor in the end. Summarising, this means that there is a need in adaptive digital control for active magnetic bearing systems.

In terms of parameter estimation several problems are involved with adaptive control for an active magnetic bearing system, which is an open loop unstable multiple input multiple output system (MIMO-system). Therefore, identification has to be performed in closed loop operation. This results in convergence problems of all estimated parameters, since the model input is correlated with the output, i.e. statistically not independent. Under certain conditions this obstacle can be circumvented [Aling, 1990, Jiang and Doraiswami, 1987, Schumann, 1982, Ng et al., 1977].

More problems result from the choice of the estimation algorithm for an open loop unstable MIMO-system. One has to consider certain constraints for an adaptive control algorithm being used for a real time implementation within a digital signal processor. No iterations should be included within one sample period, because the calculations could run into a timeout. Additionally, the algorithm should be numerically stable. This means that matrix inversions and all complex algebra should be avoided. The most important constraint is, however, that not every algorithm can be applied to an open loop unstable MIMO-system.

Nevertheless, a great variety of algorithms remain. Generally speaking, adaptive control can be based on a state space representation of the system or on a transfer function matrix model.

1.2.1 Identification of a transfer function model

The first approach in system identification is the estimation of a transfer function matrix with a simple least squares algorithm (LS-algorithm, [Isermann, 1992a]). Unfortunately, this model depends on an auto regressive (AR) model of the noise filter including all system poles. Since a magnetic bearing system is open loop unstable, such a noise model cannot be used. What remains, is to switch to a more sophisticated noise model with more degrees of freedom. An extended least squares algorithm (ELSalgorithm, [Isermann, 1992a]) could cope with the problem, because unstable poles can be cancelled by zeros of the noise filter, if the order of the numerator polynomial is chosen high enough. Then, however, the convergence of the entire algorithm suffers from the slow convergence of the noise filter parameters and the algorithm could never follow sudden parameter changes.

More complex identification algorithms like generalised least squares (GLS) including iterations, Cor-LS or the instrumental variable method (IV, [Isermann, 1992b]) could solve the identification problem. For these algorithms there are no restrictions to the noise model or to the properties of the noise (Cor-LS), which needs not necessarily to be white. The complexity of these algorithms, however, causes problems in a real time application regarding the guarantee of a constant sampling time or numerical stability.

Another possibility is the estimation of the weighting sequence and the application of generalised predictive control (GPC) or the derivation of a transfer function in a second step. Because of the open loop instability bicausal weighting functions have to be used [Kouvraritakis and Rossiter, 1992], which makes the use of GPC difficult. Again it seems not to be reasonable to use that algorithm for two reasons. Firstly, the estimation of bicausal weighting sequences for a MIMO-system results in a very complicated algorithm which is not applicable in real time. Secondly, long weighting sequences are necessary to render the system behaviour properly which results in a huge number of parameters to be estimated.

To identify the transfer function matrix is one aspect in adaptive control. The crucial point for the identification algorithm is the subsequent controller design. Basically, there are two possibilities.

Matrix polynomial controller

For a simple single input single output system (SISO-system), the controller design can be done in a straight forward manner [Isermann, 1987a, Isermann, 1987b], if some constraints are considered like the fact that cancellation of an unstable pole must not occur. If a MIMO-system is target for a controller design, things become a little bit more complicated [Schumann, 1982]. The inversion of the transfer function matrix generates new parasitic poles resulting from the open loop zeros in form of convolutions and sums between all numerators, and additional zeros outside the unit circle. An adaptive control algorithm using the inverse model of the plant must calculate all new poles outside the unit circle to avoid pole zero cancellation. Therefore, an algorithm must take into account these effects. In principle, the problem of an automated controller design can be solved, but the implementation fails for numerical reasons.

State space controller

Once a state space representation of the identified system is found, it is easy to derive a controller, e.g. an LQR-controller. The difficulties arise out of the transformation from a transfer function matrix to state space representation and from the state estimation [Hensel, 1990]. Essential work in this field was presented in

[Nour Eldin and Heisters, 1980] and its second part in [Nour Eldin and Heisters, 1981]. A state space representation can also be retrieved from the estimated transfer function matrix or even from the estimated weighting sequence using the Hankel-matrix [Tsui and Chen, 1983].

All proposed algorithms cause an enormous amount of calculation effort or are not applicable to an open loop unstable unstable MIMO-system and are ruled out for those reasons.

1.2.2 Identification of a state space model

Given the preceding restrictions, the estimation of a state space model becomes reasonable. A state space representation of an open loop unstable system makes controller design easier. The identification algorithm, however, must estimate both the system states and all system parameters at the same time. The system states are necessary for the state space controller. The most popular approach is the extended Kalman filter. This algorithm uses an extended state vector including both the system states and system parameters. The result is a nonlinear filter which tends to converge very slowly. Since an active magnetic bearing is a very fast system, an alternative algorithm has to be found.

1.3 Chosen solution

The *recursive prediction error method* (RPEM) presented in [Goodwin and Sin, 1984, Ljung and Søderstrøm, 1983] incorporates both state and system parameter estimation. In [Nazaruddin, 1994, Unbehauen and Nazaruddin, 1995] an implementation of that algorithm is presented in conjunction with pole placement control. These works provide the basis material used in this thesis. Its detailed structure is explained in the following.

In Section 2.1 of Chapter 2 the experimental setup and the rotor model are presented. The rigid rotor is suspended by two active magnetic bearings with four degrees of freedom. Non-conservative cross-coupling forces, simulating a system change, are applied to the rotor in a given plane along the rotor axis by an additional magnetic actuator. For simulation purposes a comprehensive nonlinear model including a rigid rotor, position and current sensors, analogue to digital converters, digital signal processor, digital to analogue converters, switching power amplifiers with pulse width modulators and magnetic actuators is established in Section 2.2.

In Section 2.3 a continuous time linear model is derived from the nonlinear model for a point of operation. Therefore, an internal current control loop is designed for the point of operation in order to reduce the order of the resulting linear system. Under these assumptions the magnetic actuator can be treated as a negative spring regarding the rotor position, and as a gain regarding the control current. From there, a continuous time state space model for the rotor bearing system is derived in Subsection 2.3.5 and transformed into a discrete time innovations model with its system matrices in canonical form [Schumann, 1982, Tolle, 1985]. This model is the basis for adaptive control performed on the entire system.

The third chapter, Chapter 3, is dedicated to the estimation algorithm and the controller design. The *recursive prediction error method* which can be used to identify the state space model under on-line conditions is introduced in Section 3.1. The recursive algorithm, consisting of several matrix operations, can be performed very fast, which is important for a real-time implementation. Within this algorithm a state space model and all states are calculated after each sampling time interval. To provide numerical stability, a special implementation of this algorithm is used [Bierman, 1988]. Additionally, an effective algorithm is proposed to trigger system parameter changes in order to initiate the adaptation algorithm. The last subsection, Subsection 3.1.7, deals with stability and convergence analysis.

In the second part of Chapter 3, Section 3.2, the design of a pole placement controller with and without integrative feedback is described. Since an active magnetic bearing system is open loop unstable, a controller and an observer have to be designed in advance. A deterministic approach is used for the design, because the statistical solutions like a Kalman filter depend on the knowledge of the covariance matrices of system and measurement noise, which are not known a-priori. The third part of Chapter 3, Section 3.3, deals with the closed loop analysis for the rotor bearing system under state space control in conjunction with the innovations model as state estimator.

Simulations are used to demonstrate the successful operation of the proposed algorithms. The results are presented in Chapter 4. A change of a system parameter, namely the non-conservative cross-coupling stiffness is simulated as well as a sudden appearance of an additional load. The simulation results show that the proposed identification algorithm can cope with parameter changes and the entire system can be stabilised even for high values of the non-conservative stiffness coefficients. Furthermore, changes in distortion like additional loads can be compensated by the integrative feedback loop.

The last chapter, Chapter 5, tries to draw final conclusions and gives an outlook on possible topics in the field of adaptive control for active magnetic bearing systems.