Parametric Fault Diagnosis of an Active Gas Bearing

Recently research into active gas bearings has had an increase in popularity. There are several factors that can make the use of gas bearings favourable. Firstly gas bearings have extremely low friction due to the usage of gas as the lubricant which reduce the needed maintenance. Secondly gas bearings is a clean technology which makes it possible to use for food processing, air condition and applications with similar requirements. Active gas bearings are therefore useful for applications where downtime is expensive and dirty lubricants such as oil are inapplicable. In order to keep as low downtime as possible it is important to be able to determine when a fault occurs. Fault diagnosis of active gas bearings is able to minimize the necessary downtime by making certain the system is only taken offline when a fault has occurred. Usually industry demands the removal of any sensor redundancy in systems. This makes it impossible to isolate faults using passive fault diagnosis. Active fault diagnosis methods have been shown able to isolate faults when there is no sensor redundancy. This makes active fault diagnosis methods relevant for industrial systems. It is in this paper shown possible to apply active fault diagnosis to diagnose parametric faults on a controllable gas bearing. The fault diagnosis is based on a statistical detector which is able to quantify the quality of the diagnosis scheme.

Closed Loop Fault Detectability Based on a Gap-metric

Systems are often controlled using feedback loops. Fault diagnosis schemes are usually designed assuming that there is no feedback loop. Therefore fault diagnosis methods need to accommodate for the feedback loop. One such method is active fault diagnosis based on a fault signature system. This method is derived using the YJBK parametrisation, named after Youla, Jabr, Bongiorno and Kucera. It uses the derived fault signature system to determine the detectability of possible faults in the system. Deriving the fault signature system requires knowledge about the controller. This paper demonstrates the possibility of estimating the detectability of faults in the fault signature system using a gap-metric. The gap-metric has the advantage of only requiring knowledge about the plant. By using the gap-metric it is possible to
estimate the detectability of faults without using information about the controller.

Closed loop identification of a piezoelectrically controlled radial gas bearing: Theory and experiment

Gas bearing systems have extremely small damping properties. Feedback control is thus employed to increase the damping of gas bearings. Such a feedback loop correlates the input with the measurement noise which in turn makes the assumptions for direct identification invalid. The originality of this article lies in the investigation of the impact of using different identification methods to identify a rotor-bearing systems' dynamic model when a feedback loop is active. Two different identification methods are employed. The first method is open loop Prediction Error Method, while the other method is the modified Hansen scheme. Identification based on the modified Hansen scheme is conducted by identifying the Youla deviation system using subspace identification. Identification of the Youla deviation system is based on the Youla–Jabr–Bongiorno–Kucera parametrisation of plant and controller. By using the modified Hansen scheme, identification based on standard subspace identification methods can be used to identify the Youla deviation system of the gas bearing. This procedure ensures the input to the Youla deviation system, and the noise is uncorrelated even though the system is subject to feedback control. The effect of identifying the Youla deviation system compared to direct subspace identification of the gas bearing is further investigated through a simulation example. Experiments are conducted on the piezoelectrically controlled radial gas bearing. A dynamic model is identified using the modified Hansen scheme as well as using Prediction Error Method identification. The resulting models are compared for different imperfect nominal models, to examine under which conditions each method should be used.
Detector design for active fault diagnosis in closed-loop systems

Fault diagnosis of closed-loop systems is extremely relevant for high-precision equipment and safety critical systems. Fault diagnosis is usually divided into 2 schemes: active and passive fault diagnosis. Recent studies have highlighted some advantages of active fault diagnosis based on dual Youla-Jabr-Bongiorno-Kucera parameters. In this paper, a method for closed-loop active fault diagnosis based on statistical detectors is given using dual Youla-Jabr-Bongiorno-Kucera parameters. The goal of this paper is 2-fold. First, the authors introduce a method for measuring a residual signal subject to white noise. Second, an optimal detector design is presented for single and multiple faults using the amplitude and phase shift of the residual signal to conduct diagnosis. Here, both the optimal case of a perfect model and the suboptimal case of a model with uncertainties are discussed. The method is successfully tested on a simulated system with parametric faults.

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Fault Diagnosis and Identification of Electro Mechanical Systems - Methods for Closed Loop Systems.

We are on the verge of the fourth industrial revolution also known as industry 4.0[1]. The goal of industry 4.0 is to increase the incorporation of sensor information into decision making for machinery. This in turn increases the popularity of feedback control, and by extension, closed loop schemes. With the increasing popularity of closed loop control it is important that the impact of the feedback loop is handled appropriately. Because of the feedback loop, signals that might normally be uncorrelated are suddenly not and assumptions often used for identification and fault diagnosis schemes are no longer realistic to achieve.

The thesis aims at introducing the reader to design methods with proper handling of noise for closed loop systems. In order to achieve this goal, it is investigated how to transform a closed loop identification problem into an open loop identification problem. Such a transformation is already well known, however the excitation signal design is not intuitive when applying such a transformation. The shape of the excitation signal is of paramount importance for the quality of the identified model. By making the design of the excitation signal more intuitive, it should be possible to increase the quality of identified models.

Another interesting closed loop application is fault diagnosis. More and more systems will be part of a closed loop scheme in the future in accordance with industry 4.0. Often, systems are designed without sensor redundancy, and with disturbance rejecting controllers. Methods which are not limited in isolability due to sensor redundancy, and which decouple the effect of the disturbance rejecting controller, are therefore of huge interest. Active fault diagnosis obtains the required information through a known excitation signal instead of the sensor redundancy. Design of detectors based on active fault diagnosis can therefore make fault diagnosis possible for systems where installation of extra sensors are too cost demanding.

The methods were developed with a piezoelectric rotor-bearing application in mind. The bearing is using air as the
lubricant between the bearing and the shaft and is therefore referred to as a gas bearing. Gas bearings have relative low
damping compared to high friction bearings such as ball bearings. Feedback control is therefore employed to increase the
damping of the Gas Bearing. This makes Gas Bearings a prime example of technology following with the industry 4.0
standard.

Active Fault Detection Based on a Statistical Test
In this paper active fault detection of closed loop systems using dual Youla-Jabr-Bongiorno-Kucera(YJBK) parameters is
presented. Until now all detector design for active fault detection using the dual YJBK parameters has been based on
CUSUM detectors. Here a method for design of a matched filter detector is proposed instead, based upon the
NeymanPearson criterion for optimal detector design. Furthermore alternative ways to design the excitation signal which
relates to indirect identification methods are presented. Examples are given on detection of actuator faults using a
simulated gas bearing for both one and multiple possible parametric faults.

Closed loop identification using a modified Hansen scheme: Paper
It is often not feasible or even impossible to identify a plant in open loop. This might be because the plant contains
unstable poles, or it is simply too expensive to remove the plant from its intended operation, among other possibilities.
There are several methods for identifying a plant in closed loop [4], and one such method is the Hansen scheme [1].
Standard identification using Hansen scheme demands generating the identification signals indirectly. In this paper it is
instead proposed to use the relationship between the Youla factorization of a plant and its stabilizing controller to directly
measure the signals used for identification. A simulation example and identification of a gas bearing is given to show the
method in action. Rotors supported by controllable gas bearings are open loop stable systems. However as the rotational
speed is increased feedback control is necessary in order to keep the system stable. Furthermore because the dynamics
of such a system depends on the rotational speed it is needed to conduct an identification while the system is part of a
closed loop scheme. The authors believe the paper able to contribute towards a simpler and more direct way of identifying
closed loop plants using Hansen scheme.
Identifying parameters in active magnetic bearing system using LFT formulation and Youla factorization

In this paper, a method for identifying uncertain parameters in a rotordynamic system composed of a flexible rotating shaft, rigid discs and two radial active magnetic bearings is presented. Shaft and disc dynamics are mathematically described using a Finite Element (FE) model while magnetic bearing forces are represented by linear springs with negative stiffness. Bearing negative stiffness produces an unstable rotordynamic system, demanding implementation of feedback control to stabilize the rotordynamic system. Thus, to identify the system parameters, closed-loop system identification techniques are required. The main focus of the paper relies on how to effectively identify uncertain parameters, such as stiffness and damping force coefficients of bearings and seals in rotordynamic systems. Dynamic condensation method, i.e. pseudo-modal reduction, is used to obtain a reduced order model for model-based control design and fast identification. The paper elucidates how nodal parametric uncertainties, which are easily represented in the full FE coordinate system, can be represented in the new coordinate system of the reduced model. The uncertainty is described as a single column vector of the system matrix $A$ of the full FE model while it is represented as several elements spread over multiple rows and columns of the system matrix of the reduced model. The parametric uncertainty, for both the full and reduced FE model, is represented using Linear Fractional Transformation (LFT). In this way the LFT matrices represent the mapping of the uncertainties in and out of the full and reduced FE system matrices. Scaling the LFT matrices easily leads to the amplitudes of the uncertainty parameters. Youla Parametrization method is applied to transform the identification problem into an open-loop stable problem, which can be solved using standard optimization methods. An example shows how to decouple and identify an uncertainty in the linear bearing stiffness of a reduced FE rotordynamic system.
Projects:

**Fault Diagnosis and Optimal Control of Electro - Mechanical systems**
Sekunda, A. K., PhD Student, Department of Electrical Engineering
Niemann, H. H., Main Supervisor
Poulsen, N. K., Supervisor
Santos, I., Supervisor
Galeazzi, R., Examiner
Kinnaert, M., Examiner
Kallesøe, C. S., Examiner
Technical University of Denmark
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