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Balancing filters: An approach to improve model-based fault diagnosis based on parity equations

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ABSTRACT

Model-based fault detection often deals with the problem that fault states cannot be distinguished clearly. One way to improve the results is the use of balancing filters. The purpose of these filters is to balance the magnitude response over its full frequency range, since fault states show deviations from the nominal behavior at different frequencies and therefore at diverse magnitude levels. Their application aims on increasing the magnitude response levels in frequency ranges where it is low and to decrease it where the magnitude is on a higher level. Hence, the influence of the deviations caused by the fault states is weighted equally at all examined frequencies. The compensation of the system's basic characteristics leads to a stronger influence of the fault-caused deviations. Since these are useable features for fault identification, balancing filters lead to a better distinction between the states and faults. To apply such filters on real systems they must be designed and adapted to the particular system.

This paper describes the idea of balancing filters for a diagnosis concept based on feature extraction by means of parity equations and shows several methods to design these filters. The first design method is based on placing poles and zeros heuristically to model the global characteristics of the frequency response and inverting this model to get a balancing filter. In contrast to this, the second approach uses measured data by inverting an experimentally identified model of the process. For the third method simple Butterworth filter elements are used to build up an inverted model of the global frequency behavior of the system directly. Since an adaptation of the filters to the investigated system is required experimental results show the improvements induced by these filters. The filters' effects are investigated on a test rig of a centrifugal pump with magnetic bearings. A second system that shows a more complex transfer behavior is used for the evaluation of the repeatability of the resulting improvements. Finally the idea of balancing filters, the presented design methods and the achieved experimental results are discussed in details.

1. Introduction

Several principle approaches to model-based fault diagnosis can be found in literature. Isermann categorizes fault-detection methods based on process models considering the usage of parameter estimation, neural networks, observers, state estimation and parity equations [1]. The majority of today's works on model-based fault-diagnosis focus on using

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parameter estimation, state observers and parity equations. Parameter estimation based fault detection methods have the main idea to identify certain system parameters continuously and generate features by the comparison of these to reference parameters representing the nominal system state. Examples are given in references [2–5]. Fault-diagnosis based on observers utilizes common state observers as well as unknown-input and diagnostic observers [6]. While the first two are estimating the full system state [7], diagnostic observers focus on reducing the system's order and estimating especially the output correctly [6]. Methods based on parity equations create analytical redundancy by the simulation of one or more models in parallel to the system and the comparison of different signals (e.g. the outputs) ([1,8]). They are used in [9,5] and also provide the basic principle for the multi-model concept used in this paper. The main idea behind this concept is to use deviations within the systems transfer behavior that are caused by different fault states for the diagnosis.

Due to the mechatronic system's general transfer behavior these deviations might occur at diverse magnitude levels (e.g. lowpass characteristics of the mechanical subsystem). This can be critical for the sensibility of diagnosis methods based on parity equations. Especially fault states showing deviations at low magnitude levels, which usually occur at higher frequencies, are hard to detect, since their influence on the output of the parity equations is minor. To prevent this effect and improve parity equation based methods the authors proposed balancing filters in [10–12]. The aim of these filters is to equate the magnitude levels at which the differences between states (nominal state and investigated fault states) occur and thus focus on the deviations caused by the faults. This differs from the purpose of other frequency weighting methods such as the matched filter known from communications engineering ([13,14]), which perform an inversion of a model behavior in order to reach an optimized signal-to-noise ratio. Balancing filters isolate the deviating behavior between different fault states and the nominal behavior to improve the analysis of these deviations.

This paper compares three different methods to design such filters. After a description of the fault diagnosis concept in the second section the main idea of these filters and design methods are described in section three. In the fourth section a test rig of a centrifugal pump in magnetic bearings is used to compare the results achieved with filters designed with the different methods. Subsequently, the repeatability of the method is evaluated on a second test rig with different system properties leading to a more pronounced frequency behavior. In the final section the idea of balancing filters, the presented design methods and the experimental results we achieved are concluded and discussed in detail.

2. Diagnosis concept

The model-based fault diagnosis concept used here is based on the simulation of several models representing the different system states in parallel to the running process to provide analytical redundancy. Fig. 1 depicts a block diagram of the whole concept including balancing filters. To perform the fault detection, both process and models are applied with the same test signal for online comparison. For that purpose the system can be excited via the reference input w or the disturbance input d. Here the system is stimulated via the disturbance input d, since this leads to a direct excitation of the process without a frequency limitation by the controller. Hence, the models represent the behavior of the process sensitivity transfer function, which contains all characteristics that are necessary for fault diagnosis. To compare process and models the residual output error $r(t)=y_{\text{process}}(t) - y_{\text{model}}(t)$ is calculated for every state, providing the residuals $r_1 \dots r_n$. Under ideal circumstances the residual of the model matching the process current state is equal to zero, whereas the non-matching models show residuals with a higher absolute value. The residuals are then used as features for fault isolation and analysis by a classifier that detects the system's current state by choosing the one that is represented by the model with the lowest residuals [1]. Using the standard deviation of the residuals as features enables to apply a comparison of these for the classification. Thus, the classifier has a less complex structure in comparison to other diagnosis concepts. According to the categorization by Isermann [1] this approach is based on parity equations utilizing analytical redundancy (see [8]). The n identical balancing filters are used to improve the quality of the residuals as described in the further sections.

To describe the different system states' process sensitivity transfer functions linear time invariant SISO models in modal state space representation are used. In order to set up such models one can choose to develop them analytically or identify the systems transfer behavior experimentally. In this case, early testing showed that analytical models were not precise

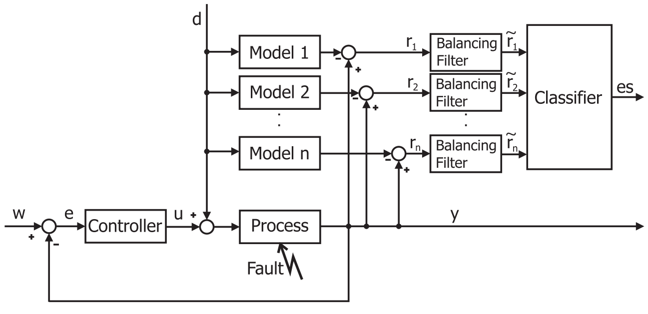

Fig. 1. Block diagram of the fault diagnosis concept.