An Approach for the Holistic Integration of Fault Detection and Diagnosis into Active Magnetic Bearing Systems

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Abstract

Present research on fault detection and diagnosis on magnetic bearing systems aims on the diagnosis of the state of single components, such as sensor and actuator faults or fault states of the plant. Although these methods often have the potential to detect more than one fault state, there is no fault detection method allowing the detection of all possible faults. This paper describes aconceptional approach to combine different fault detection methods aiming on a holistic online diagnosis of the active magnetic bearing system consisting of the functional components controller, actuator, plant and sensor. On the example of a centrifugal pump in active magnetic bearings this approach gives the possibility to combine fault detection methods detecting internal faults of the bearing system as well as the determination of the overall system status, e.g., the duty point of the pump, based on the signals of the active magnetic bearing system. This approach allows integrating new functions into the active magnetic bearing system via an enhancement of the software without changing the widely developed hardware of active magnetic bearings.

1 Introduction

This paper describes an approach for the holistic integration of fault detection and diagnosis methods into active magnetic bearing systems (AMB) aiming on the diagnosis of the overall system status. Section two starts with a general overview on fault detection and diagnosis methods, following up fault detection with AMB systems is focused and main aspects for future research are derived. In section three requirements for a parent method coordinating the execution of several fault detection methods established based on this results. The section continues with the suggestion of a parent method allowing for the automated and targeted execution of fault detection methods for the purpose of detecting different kinds of faults calling for specific fault detection methods. This also facilitates to detect simultaneous occurring faults and unknown fault states. The integration of the parent method is shown in section four at the example of a centrifugal pump in active magnetic bearings. Thru the deep-going understanding of the hydro-mechatronic system new aspects arise for the fault detection. The paper concludes with a discussion of the described approach.

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2 Fault Detection and Diagnosis

Monitoring of the systems status is a function of modern machines. The knowledge of the systems current condition enables the operator to recognize deviations from the desired system status at an early stage, in order to initiate remedial action if necessary. In this context an error is defined as an unacceptable deviation of at least one characteristic property of the system from an acceptable state [1] [2]. The monitoring itself is divided into the fault detection and fault diagnosis. The fault detection extracts error-significant features from the measured data, called the symptoms. Based on the symptoms the fault diagnosis takes place, wherein the condition of the system as well as the type and location of a fault are determined.

The fault detection methods can be divided into three categories. According to [1] these are:

- Conventional methods
- Signal-model-based methods
- Process-model-based methods.

The conventional methods are based on the observation of directly measurable values in terms of their trends or of the crossing of thresholds. Signal-model-based methods use the temporal course of directly measurable quantities. Regarding deterministic signals a transformation of the signals in the frequency domain is used to generate signal functions. In case of non-deterministic signals signal parameters can be generated, for example by a statistical analysis, which allows concluding on the faults. [1, 3].

Process-model-based methods usually use the measured input signals and the corresponding output signals of the process. Based on this, the behavior of the process is compared with the behavior of a model of the process allowing for the determination of possible faults. Commonly used methods are parameter estimation methods, neural networks, state observer and parity equations [1]. In many cases a stimulation of the process with a test signal is necessary. Especially for process-model-based methods deep system knowledge about the dynamic behavior of the underlying process is required.

Regardless of the method features are generated in the first step of the fault detection. These are time-varying parameters extracted from the measured signals of the process. In the following step the symptoms result from a change detection of these features. The symptoms then form the basis for the subsequent fault diagnosis. Figure 1 shows this process.

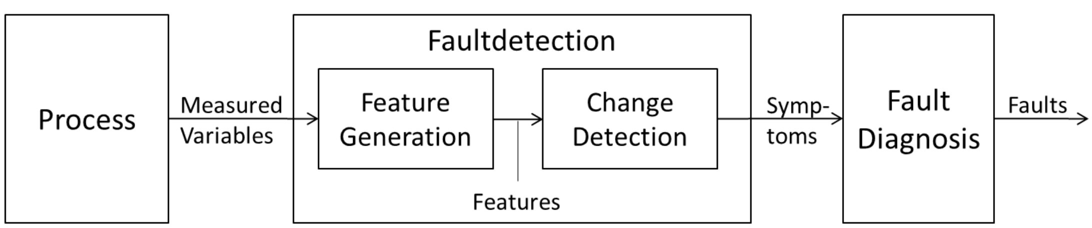

Figure 1: General scheme for fault detection and fault diagnosis [1]

In the context of fault diagnosis information about the condition of the system as well as the type and location of a possible fault are extracted from the symptoms by using pattern-based classification methods or rule-based interference methods [1]. The classification methods capture the relationship between a change in symptoms and the system state using estimation and optimization methods. Examples include geometric methods, neural networks or fuzzy classification [1, 3]. The interference methods map expert knowledge for example on causal relationships, if-then rules or fault trees.

In literature the fault diagnosis is often divided into the steps fault isolation (determination of the location) and fault identification (determination of the faults type and size) [3, 5]. [5] notes that often the benefit of the identification does not justify the large effort. Therefore, fault diagnosis is also used as a synonym for the step fault isolation. In this case only the faulty component is determined, not the type of error.

In literature different approaches for the combination of fault detection methods to determine multiple faults are mentioned [6], [7]. In [8] a neuro-fuzzy-based algorithm is presented for the diagnosis using symptoms gained with various fault detection methods.

2.1 Fault Detection and Fault Diagnosis on Active Magnetic Bearing Systems

Conventional methods of fault detection are already part of current active magnetic bearing systems. Examples are limit checking of the rotors orbit and overload conditions as well as the stability of the controlled system. In particular the use of process-model-based methods arises, because the active magnetic bearing system contains measured information about the systems input in form of the bearing currents as well as the systems output in form of the rotors displacements. Also, the actuators can be used to stimulate the system with a test signal, allowing the measurement of the system transfer behavior. The required software tools are already integrated into present AMB-Systems, but their use is often limited on the commissioning and revision of the systems. The use of these tools even during normal operation for fault detection is possible by means of software expansions without changing the hardware of the systems. However, a deep-going understanding of the system is required.

Faults occurring on AMB systems are classified following [9] into internal faults occurring within the AMB-System itself, external faults acting from outside on the AMB-System and mixtures of internal and external faults. Table 1 gives an overview of possible faults.

Category	Location	Component	Effect
Intern	Actuator	Power amplifier	Changing in the dynamic behavior (e.g., caused by heating or aging), failure
		Coil	Fall out of single windings or complete coil
	Sensor	Position sensor	Signal disturbance (e.g., crosstalk, mechanical damage of sensor-target), failure
	Control system	Hardware	Failure of channels, total failure
		Software	Instability (e.g., caused by changing in the dynamic behavior of components)
Extern	Plant	Rotor	Dynamic excitation caused by process forces, overload, unbalance, changing in the dynamic behavior (e.g., caused by inaccurate assembly, fluid-structure-interaction, crack of the rotor)
		Substructure	Changing in the dynamic behavior (e.g., caused by inaccurate assembly), dynamic excitation caused by nearby processes
Intern /Extern	Plant	Rotor / Housing	Rub between rotor and housing
	Complete system	All active components	Power supply failure

Table 1: Examples of faults on active magnetic bearing systems divided in intern and extern faults

With the aim to increase the reliability of active magnetic bearing systems by detection and compensation of faults of the AMB-system itself, different works concentrate on the internal sensor and actuator faults. The focus here is on redundant structures, allowing the detection of the failure of individual components and an automated switching from the faulty component to the redundant component [10, 11, 12]. [13] for example, uses a rigid-body model of the rotor, with whom the functionality of the individual position sensors is analyzed. [14] uses a model of the active magnetic bearing to detect sensor faults based on the measured displacements, the bearing currents and the bearing forces. A detection of offset, multiplicative sensor faults and noise is possible with the use of Luenberg observers.

External faults are considered for various applications. Using a signal-model-based method of wavelet-analysis [15,16] detect rotor unbalance and auxiliary bearing contact. [17] uses conventional and signal-model-based methods to monitor a grinding spindle in active magnetic bearings, detecting faults like "failure of the coolant supply", "crack of the grinding disc" and deviations in the workpiece initial state.

[18] uses an additional active magnetic bearing applied to a rotor in conventional bearings to detect a crack of the rotor. This is achieved with a process-model-based method based on the frequency response estimation, detecting a change of the third elastic natural frequency of the rotor. The combination of different kinds of fault detection methods is presented in [19] via a staged procedure. After the detection of limit crossing, signal model-based methods are used for the classification. In the following step a numerical rotor model of the AMB system is simulated. The model parameters are fitted with an optimizer to the measured state, allowing to determine the type and severity of the fault.

In some publications centrifugal pumps in active magnetic bearings are investigated. Blair [20] uses a process-model-based method to detect dryrun via a shift of the first natural eigenfrequency of the rotor. The influence of the fluid on the dynamic behavior is described similar to an adding of mass to the rotor. Process-model-based methods are also used in [21]. Via the estimation of the frequency response and the determination of modal parameters the fault cases “dry run”, “worn balance piston”, “loosened shaft nut” and “loosened bearing block” are detected. This work is continued by [22] where the robustness of the methods is increased and the calculation time is dramatically reduced, so the methods can be used for online fault detection and diagnosis. Particularly promising is the method based on parity equations, for which models of different fault states are simulated in parallel to the process. The fault detection is based on the comparison of the signals in the time domain. A better separation of the resulting features is possible with so called balancing filters. Herewith it is ensured that differences in the frequency response of the (faulty) system, which are at different amplitude levels, can be used equally for the fault detection. This work is continued by [23] with the development of analytical design strategies for such filters.

A disadvantage of the process-model-based method is the necessity to stimulate the system with a test signal. On the one hand, additional energy must be introduced into the process; on the other hand the process is disturbed by the stimulation forces. In many plants excitation forces resulting out of the process are present. [24] shows on the example of a centrifugal pump in active magnetic bearings that these excitation forces are not adequate conditioned for a stimulation of the process by means of the fault detection methods.

Based on these publications the following conclusions can be drawn:

- First, a deep-going understanding of the system allows the integration of fault detection and diagnosis methods for the detection of internal faults of the active magnetic bearing system as well as the detection of external faults.
- Second, there is not one overall fault detection method allowing the detection and diagnosis of all possible faults. Instead the different methods are suited differently well for the detection of different fault states. Critical points are the simultaneous occurrence of several fault states, since they usually cannot be detected with one single method and the occurrence of unknown fault states. For such a determination of the state different methods should be combined.
- Third, a holistic approach for such an integration of a multitude of fault detection and diagnosis methods into the AMB system is necessary. A parent methodology has to be integrated into the system which coordinates the targeted execution of the different methods. Therefore the parent methodology should take three main aspects into account: the results of the already executed methods, the specific characteristics of the methods to be executed (e.g., the demand of time and computational power) as well as the disruption the fault detection methods bring to the process.

3 A Parent Method for the Automatic Execution of Fault Detection Methods

3.1 Requirements

The proposed parent method must fulfill several requirements. For the monitoring of several simultaneously occurring or unknown fault states conventional, signal-model-based and process-model-based fault detection methods should be combined. The guiding principle here should be to start with fast and less complex methods, allowing for a basic diagnosis of the overall system state. In the following steps specific methods should be executed based on the results of the first diagnosis steps, aiming on the detailed diagnosis of characteristics of the system. After each execution of a fault detection method the system state should be diagnosed as deep as possible. Those for, all until then captured symptoms of the different executed fault detection methods should be taken into account. In case of the detection of a critical system state the parent method also must immediately trigger an appropriate action.

The configuration of such a MIMO (Multi Input Multi Output) system for fault detection leads to the generation of a variety of symptoms that have to be evaluated by the fault diagnosis. At the same time [23] has shown that the features leading to the symptoms of various fault states are often not independent; in many cases a redundancy of content exists. This redundancy should be used for the targeted selection of the fault detection methods to be executed as well as for the validation of the results of specific fault detection methods.

3.2 Developed Parent Method

Figure 2 shows a diagram of such a parent method based on a state machine which selects and executes specific fault detection methods. Fault detection methods based on signal models are fast providing symptoms about the fundamental system state. In contrast to this, methods based on process models often need a test signal to stimulate the system and more computational power to generate the symptoms, but allow for a deeper insight into the system. The symptoms provided by the executed methods are passed to a classifier which identifies the current system state as far as possible based on all collected symptoms. Based on this, the state machine decides whether the systems state is already identified sufficiently or executes a specific fault detection method to identify in detail. The results of the diagnosis, in form of the diagnosed system state, are then forwarded to the user interface and the plant automation.

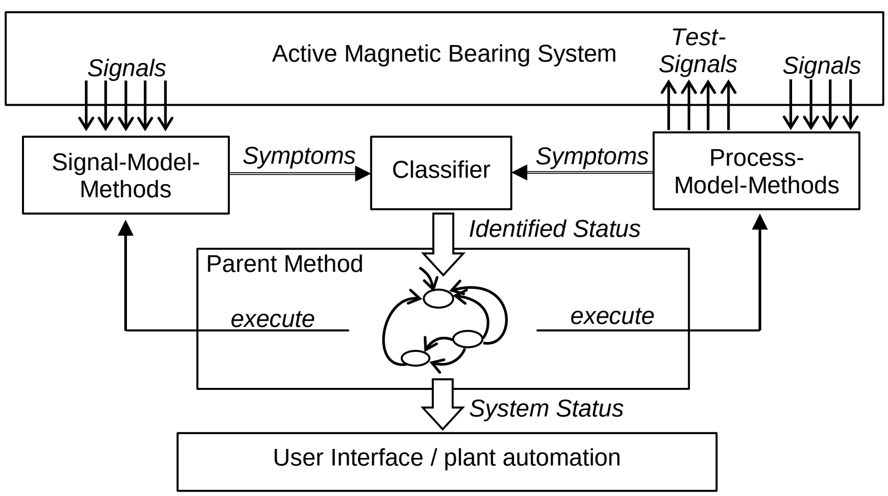

Figure 2: Diagram of the concept

Figure 3 gives the state diagram of the state machine. The various fault detection methods are carried out sequentially (A2) until the state of the system is completely diagnosed (E5, E6). For the diagnosis, as already mentioned, all previously recorded symptoms are available (A2). When the collected symptoms allow to narrow the systems state (E4), specific methods are conducted, validating the diagnosed system state (A4). The fault detection and diagnosis process ends with the complete diagnosis of the system state (E5) and distributes the output to the user interface. When necessary an appropriate action is undertaken (A5). In case of the diagnosis of an unknown system state (E6) its severity is estimated and if necessary the system is converted into a safe condition (A6). Table 2 gives the different states and actions.

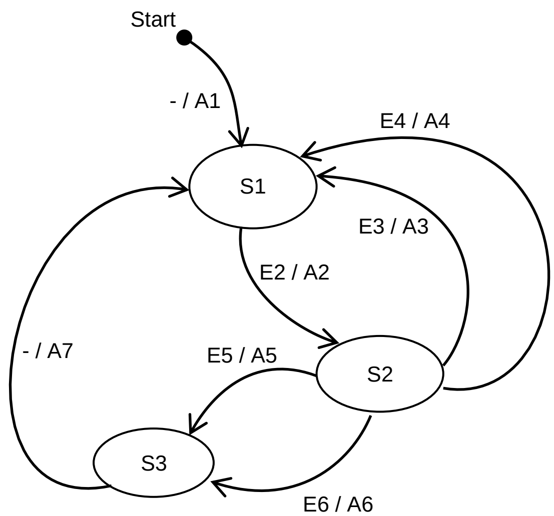

Figure 3: Diagram of the state machine, showing the different states (S), the events (E) and the actions (A)

State		Event		Action	
S1	Waiting until executed method is completed	E1	-	A1	Execution of first fault detection method (i=1)
S2	Waiting for diagnosis results	E2	New symtoms available		Execution of the fault diagnosis
S3	Fault detection and – diagnosis completed	E3	System status not diagnosed	A3	Execution of a fault detection method (i+1)
		E4	System status narrowed down	A4	Targeted execution of a fault detection method
		E5	System status diagnosed	A5	Output of fault diagnosis results and trigger of an appropriate action
		E6	Unknown system status	A6	Assessment of system status and convertion of the test rig into safe state if necessary
		E7	-	A7	Re-start of the parent methods (i=1)

Table 2: Description of the different states, events and actions of the state machine in Figure 3

4 Integration of the Parent Method

The integration of the depicted parent method is described for a test rig of a centrifugal pump in active magnetic bearings. Figure 4 gives the block diagram of the closed-loop control circuit of the multi-input multi-output (MIMO) system: The force of the bearing actuator F_M results from the bearing currents i and the size of the air gap q_M. The bearing forces act on the rotor as well as on the substructure. Accordingly the size of the air gap is dependent on the displacements of the rotor q_R and the elastic deformation of the substructure q_S. Concurrent, fluid-structure interactions occur due to the movement of the rotor q_R in the fluid, which act as forces F_F on the rotor. In addition, external forces, for example resulting from the hydraulic process, can interfere with the system. The resulting air gap q_M is measured with a position sensor and finally the control loop is closed via the feedback path. For the purpose of fault detection the input and output of the system, in terms of the bearing currents i, and the resulting measured rotor displacements S_Y, are both available. Test signals can be applied as reference setting w or as disturbance u.

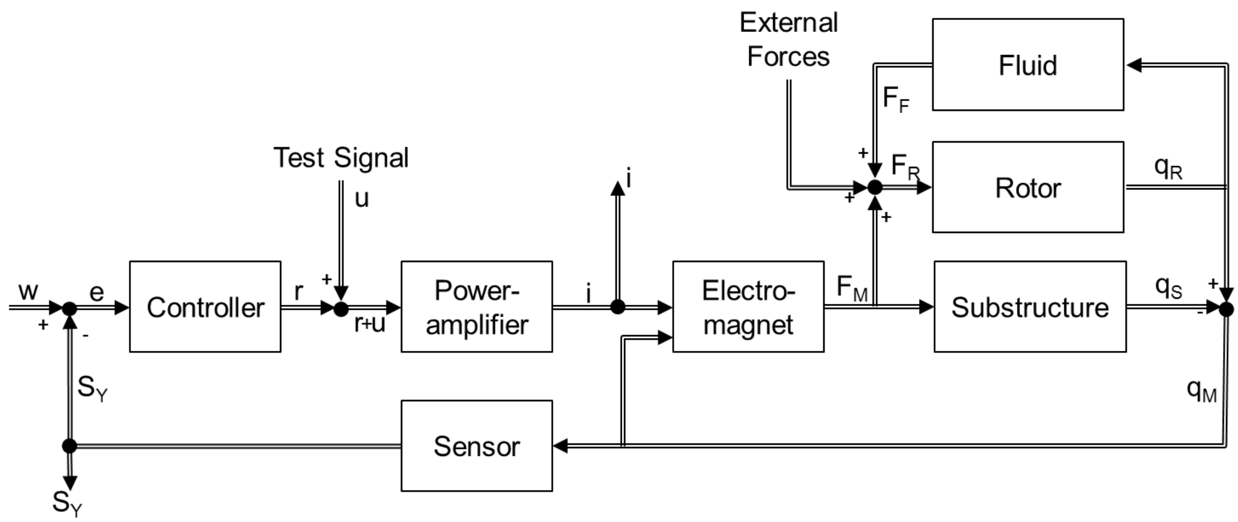

Figure 4: Block diagram of the test rig of a centrifugal pump in active magnetic bearings

Figure 5 represents the total data acquisition scheme of the test rig. The host computer is able to communicate with the digital AMB controller. This platform controls the rotor displacements and provides the bearing currents via the integrated power electronics accordant to the control law. An additional data acquisition system accesses the position sensor signals of the magnetic bearings and the set bearing currents. The shaft torque and the rotation speed are detected as reference for alignment purposes; additional sensors capture the hydraulic variables of the system e.g., the volume flow and different pressures.

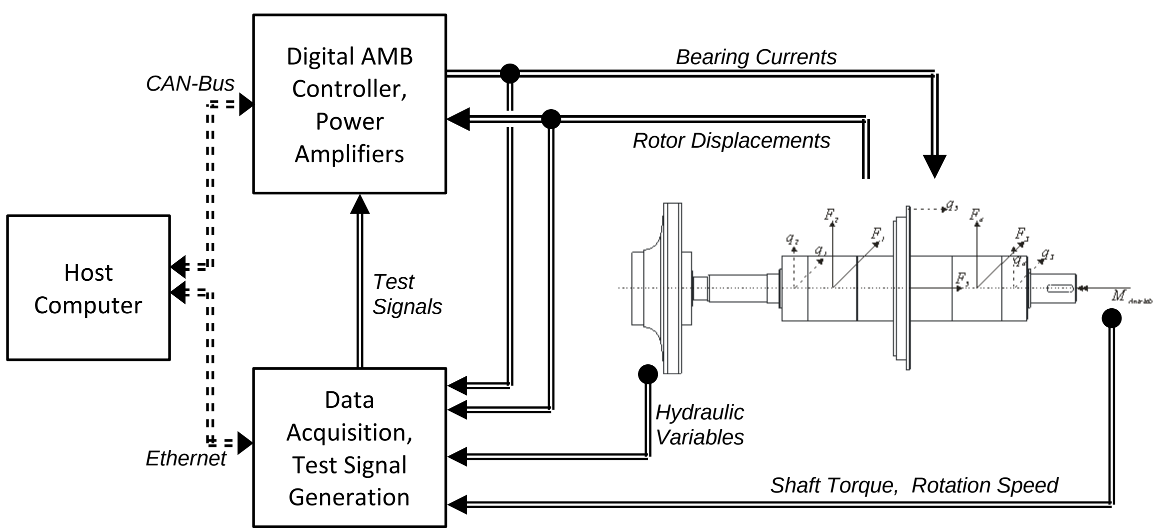

Figure 5: Structure of the test rig for the investigation of the parent method for the fault diagnosis

4.1 Detectable System variables

Summing up, there are measures which describe the displacements and the active magnetic bearings forces. Based on the bearing forces the fluid forces that act at the impeller of the pump can be determined; herewith forces resulting from the energy transfer from the impeller to the fluid can be analyzed. Shown in Figure 6, the equivalent circuit diagram of the hydro-mechatronic system highlights this issue once again. The power of the drive is introduced via the impeller and the volute casing of the pump into the fluid. On the other hand fluid forces result out of the pumping process and have to be provided by the active magnetic bearings.

Additionally figure 6 shows the locations where inlet and outlet pressure as well as the fluid flow rate are measured typically on centrifugal pumps. These conventional measuring methods are based on the reactions between the impeller, the suction pipe as well as the volute casing. With the active magnetic bearings these force resulting from the power transfer via the shaft to the fluid can be determined directly. Besides the figure shows where internal and external faults occur following the definition given in section 2.

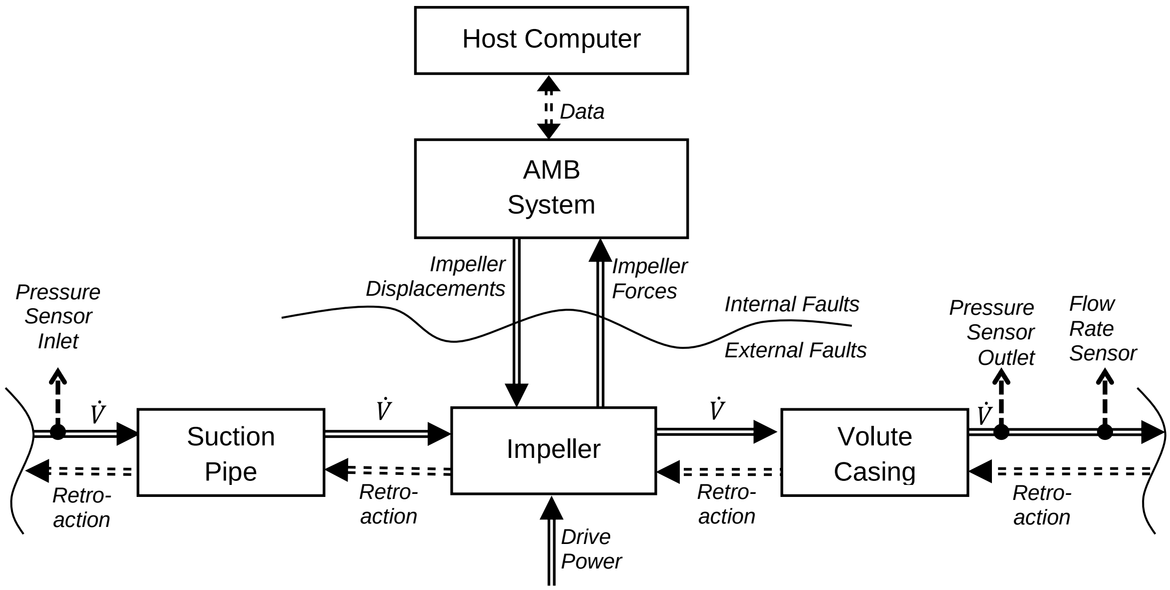

Figure 6: Force- and torque transmission to impeller; the sensor positions of the hydraulic system and the separation in terms of internal and external fault in relation to the AMB system

Apart from the detection of fault states (cf. section 2.1) this architecture of the overall system thus enables one to conclude for more general system characteristics beneath fault states. [25,26, 27] are detecting deviations in the static bearing forces in correlation to the duty point of the pump. Based on the signals gained from the active bearing system additional information can be derived. Hence capabilities to determine operating parameters of the system such as rotating speed, flow rate, pressure ratios and the operating point. This allows to set up analytical redundancy of conventional sensors, or even their replacement. Furthermore it allows to observe characteristics of the hydraulic system which by so far can only be captured with large technical effort or still not. Examples are the determination of leakage flows within the pump and predictions about cavitation.

5 Discussion and conclusion

Present research on fault detection has gained a multitude of fault detection and diagnosis methods aiming on the detection of the state of single system properties. Anyway there is no universal method allowing the detection of all possible fault states. For a detailed diagnosis of the overall system status the combination of several fault detection methods is necessary. Hence the execution of those different fault detection methods has to be coordinated. Therefor the authors suggest the setup of a state machine based parent method, coordinating the different fault detection methods taking the expected results as well as the required time and computational power into account. In respect to the fault diagnosis the parent method allows the use of all symtoms gained with the various executed fault detection methods, enabling for the diagnosis of simultaneously occurring faults as well as the detection of unknown fault states.

The integration of such a multitude of fault detection methods into active magnetic bearing systems based on a deep-going understanding of the system allows as well the detection of internal faults of the AMB system as well as the detection of external faults. Relating to the complete process, with the AMB system as one component, the detection and diagnosis of external fault states can provide additional information that are usually captured with conventional sensors. The identified potentials for fault detection techniques in the example of a centrifugal pump in active magnetic bearings shows that fault detection methods can be used to detect system states that must not necessarily be a fault state. Thus the fault detection methods can also be used for general system status detection.

The presented approach of a holistic integration of fault detection and diagnosis methods into active magnetic bearing systems offers the ability to augment added value to the mechatronics system by software improvements – without changing the widely developed hardware. In case of a centrifugal pump there are prospects to save conventional sensors (e.g., pressure and flow rate), to set up a redundancy for these sensors or even to observe parameters and process characteristics that are not available in conventional setups.

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