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Detection and isolation of parametric faults in hydraulic pumps using a set-based approach and quantitative–qualitative fault specifications

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ABSTRACT

High performance hydraulic pumps are used in many applications such as airplanes, construction machines, ships and wind turbines. Due to their relatively high power density, hydraulic pumps are subject to wear and tear that can lead to loss of efficiency and ultimately to failure. Early detection and isolation of these parametric changes which are modeled by slowly varying parameters, is of paramount importance. This is, however, challenging due to nonlinearities, noise, uncertainties, as well as the combination of qualitative and quantitative process knowledge and fault specifications. We show how such quantitative and qualitative specifications can be used to derive parameter sets defining parametric fault candidate sets. These fault candidate sets are used for detection and isolation of faults by checking the inconsistency with process measurements. To account for imprecise and qualitative specifications in the design phase and uncertainties such as noisy measurements and model-plant mismatch in the process phase, and to allow for the nonlinear models and equations, we employ a set-based framework using convex relaxations. The set-based framework allows for a comprehensive description of the faults in the parameter-space by outer approximating the parameter values which are consistent with the nonlinear model and the quantitative–qualitative specifications. The set-based approach is used for parametric fault detection and isolation and is exemplified using experimental data.

1. Introduction

Hydraulic axial piston pumps and motors are central components in many applications ranging from mobile machinery as in mining or agriculture to stationary applications as in milling or molding industry. The basic principle of hydraulic axial piston units (see Fig. 1) is the conversion of mechanical power to fluid power (pump mode) and vice versa (motor mode). Hydraulic axial piston pumps are based on tribological phenomena, which are affected by wear and tear due to the usually high power density. Typical faults in hydraulic axial piston pumps have been examined in several works (e.g. Boog, 2010; Neubert, 2001; Torikka, 2011). Examples of such faults are depicted in Fig. 2.

Wear and tear lead to performance degradation and thus increased energy loss (Hast, Gottfried, & Findeisen, 2012; Neubert, 2001). Considering the high power density of these machines it becomes evident that detecting critical changes, which might finally lead to failure, is important. Faults related to parameter changes are usually denoted as incipient, parametric faults (Niemann & Stoustrup, 1999; Patton, Frank, & Clark, 2000) which connotes their property of affecting the parameters of a system, but not its structure. This means that parametric faults are not associated with abrupt changes in the system such as sensor or actuator losses, but rather with variations of the system's parameters (Niemann & Stoustrup, 1999). Thus, detection and isolation of parametric faults requires to identify parameter changes on a time-scale slower than the system dynamics, and to specify critical parameter values to differentiate between fault-free and faulty operation. This usually requires the definition of suitable parameter sets and fault models in the design of fault candidates.

In general, the detection and isolation of parametric faults in hydraulic pumps is difficult due to the multitude of applications, limited sensor capabilities and the limited knowledge of physical reasons and effects of faults. Recent approaches for fault detection and isolation for hydraulic pumps use artificial neural networks, fuzzy classification or genetic algorithms (Bayer & EngeRosenblatt, 2011; Byington, Watson, Edwards, & Dunkin, 2003; Ramden, 1998; Torikka, 2011). While these mainly signal-based approaches are widely used for some applications, the provided physical insight into faults and their respective causes is limited.

Model-based approaches to fault detection and isolation can provide deeper insights. They are often based on checking

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consistency of actual measurement data and virtual measurements from models describing the fault-free and faulty behavior of the plant (Blanke, Kinnaert, Lunze, & Staroswiecki, 2006), the so-called fault candidates. Physical models of hydraulic pumps were for example employed for fault detection and diagnosis in Yu (1997), who used a bilinear fault detection observer to detect faults in the fluidic and mechanical domain. Another application of model-based diagnosis can be found in Dabrowska, Stetter, Sasmito, and Kleinmann (2012), where an extended Kalman filter is used for leakage detection in hydraulic pumps.

In most practical applications such as considered here, modeling the system in fault-free and faulty condition is challenging due to nonlinearities, Sparse and sparse system knowledge (Blanke et al., 2006). Sparse system knowledge not only refers to limited abilities to model the process or fault mechanisms. It also refers to the fact that faults are specified not always by quantitative relationships between physical process variables; instead they are often expressed in a qualitative manner by the experienced process engineer in terms of specifications or relationships between plant performance indices and efficiencies. An example of such a qualitative fault specification is the decrease of the efficiency in a particular operation regime while, at the same time, the value of a certain process variable increases. *Qualitative* refers to the fact that the magnitude of the changes cannot be quantified or described by physical mechanisms; instead only relative changes of the considered variables are specified or empirically known.

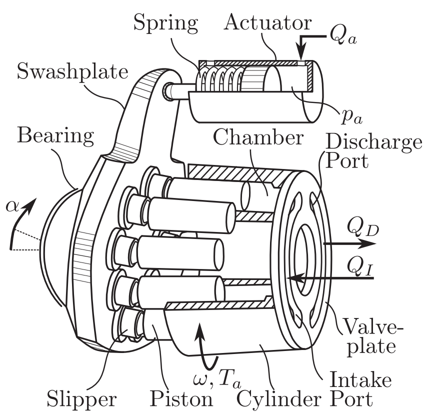

Fig. 1. Central part of a hydraulic axial piston pump. The cylinder is driven by a torque T_a and rotates with the angular velocity ω. The pistons assembled in the cylinder are attached to the swashplate via lubricated slippers. During a rotation of the cylinder the pistons are displaced due to the variable swashplate angle α. As a consequence the fluid flows into the piston chamber through the intake port and out of the piston chamber through the discharge port, respectively. The angle α is adjusted due to the actuator pressure p_a, given by the actuator flow Q_a.

In practical applications one usually demands modeling and analysis frameworks that can incorporate multiple types of knowledge and uncertainty as all available information should be used since this improves the results of diagnosis (Patton et al., 2000). However, most existing approaches do only allow in a limited way to consider qualitative or empirical knowledge of the processes and faults in the models and their analysis (Simani, Fantuzzi, & Patton, 2003). One possibility to include qualitative knowledge in fault detection and isolation is the use of qualitative reasoning (Kuipers, 1994) or the combined use of dynamical models and logical rules (Isermann, 1993).

We present a set-based approach for the detection and isolation of parametric faults which is well suited, but not limited to hydraulic pumps. In general, set-based approaches to fault detection and diagnosis (Savchenko, Rumschinski, Streif, & Findeisen, 2012; Wolff & Krebs, 2009) allow incorporating nonlinear models as well as qualitative relations between process variables and uncertain measurements (Rumschinski, Streif, & Findeisen, 2012). Furthermore, set-based methods facilitate guaranteed statements on fault model inconsistency as well as a comprehensive description of models by outer approximations of consistent parameter sets (Streif, Savchenko, Rumschinski, Borchers, & Findeisen, 2012).

Although guaranteed results can be advantageous, the computational demands of set-based approaches are usually high. To reduce the complexity of on-line computations, we split the detection and isolation in two phases (cf. Fig. 3): the design phase and the operation phase. We propose to use available a priori process knowledge and performance requirements to specify fault candidates in terms of parameter sets during the design phase. In the operation phase, only the consistency of each fault candidate needs to be checked, which is computationally efficient and fast. Furthermore, the approach allows one to consider quantitative model equations as well as qualitatively known relations in a systematic manner.

The paper is structured as follows: Section 2 defines the objectives of the paper and contains a brief introduction to the used set-based framework. In Section 3, a physical model of the considered hydraulic axial piston pump is presented, quantitative and qualitative relationships are formalized, and the model is experimentally validated. The focus of Section 4 is the design phase of fault candidates, where the fault candidate models are derived using the nonlinear model and quantitative–qualitative fault specifications. The application of the method in the operation phase using an industrial test-bench for experimental verification is presented and demonstrated at measurement data in Section 5. Section 6 discusses the proposed approach and the obtained results.

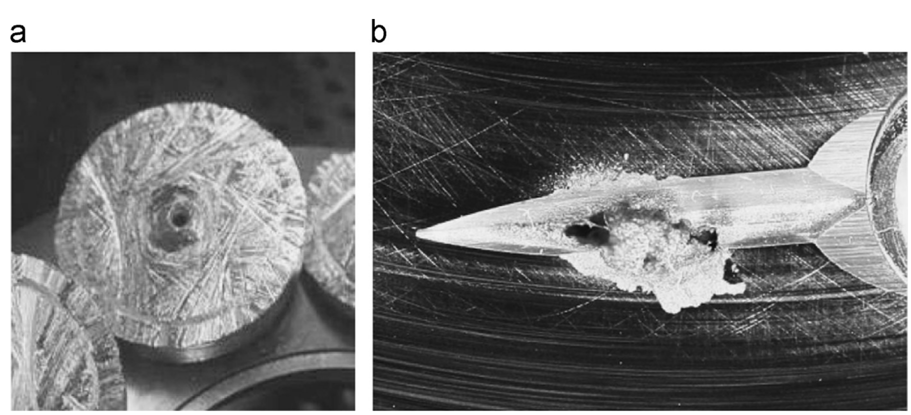

Fig. 2. Examples of possible faults in hydraulic axial piston pumps (Boog, 2010). (a) Weared piston slippers. (b) Cavitation erosion at the valve plate.