FAULT DETECTION USING PARAMETER ESTIMATION FOR A HYDRAULIC SERVO-AXIS

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Abstract: A model-based, real-time capable fault detection and diagnosis system employing a Least-Squares parameter estimation approach is developed in this paper. A physical-based model of the proportional valve and the differential cylinder is derived. The performance of the current linearized flow model is evaluated and severe deficiencies are observed. Therefore, a nonlinear flow model is introduced, which governs the behavior of the hydraulic flow as a function of the valve spool displacement. Also, temperature effects are investigated and subsequently introduced into temperature dependent thresholds. Experimental results at a testbed with both intact and defective components show the good performance of the presented fault-detection and diagnosis method.

Keywords: Hydraulic Actuators, Parameter Estimation, Fault Detection, Fault Diagnosis, Nonlinear Models, Thermal Properties

1. INTRODUCTION

Hydraulic systems are employed in manifold applications. Generally speaking most applications can be linked to two areas: The first is the area of industrial hydraulics and the second the area of mobile hydraulics. This paper will focus on the fault detection and diagnosis for industrial hydraulic components, which for example might be used as part of clamping devices, presses, drives for transfer lines, injection molding machines, elevators and other.

Due to the ongoing trend of integrating mechanic and electronic components together with information technology toward mechatronic systems (Isermann, 2003), it is nowadays possible to augment the functionality of such components with regard to e.g. more intelligent control and component based fault detection and diagnosis. Hydraulic systems are also becoming more and more integrated mechatronic systems. This allows to add fault detection and diagnosis methods to hydraulic actuators such as differential cylinders, proportional valves and complete hydraulic servo-axes as well.

An overview of fault detection and diagnosis methods for hydraulic systems can be found in (Murrenhoff *et al.*, 2004). In contrast to the sophisticated methods used in academia, fault detection in industry is still based on very simple, so-termed *conventional fault detection* methods, such as e.g. limit switches, pressure switches and such. These simple methods are very reliable but at the same time suffer from their insensitivity against small incipient faults. Only very large faults can be detected.

This motivated the application of modern, model-based methods for fault detection and diagnosis, see e.g. (Gertler, 1998; Isermann, 2005). The model-based approaches can further be subdivided into *state estimation* (e.g. Extended Kalman Filter) and *parity equations* as well as *parameter estimation*. For physics-based fault detection of hydraulic systems, only the Extended Kalman Filter has been employed in academia, see (Kazemi-Moghaddam, 1999; Kress, 2002). The major disadvantages of the Kalman filter are the difficult parameterization and the high computational demand. To overcome these problems, a Least Squares parameter estimation approach will be investigated in this paper. The main focus is on simple and reliable algorithms that can easily be implemented in the presence of constrained computational resources and real-time requirements. This precludes the use of iterative data-driven modeling approaches.

The paper is divided as follows: A physical-based model of the considered hydraulic components is derived in Sec. 2. The resulting model contains different scalar parameters and the coefficient of valve flow as a function of the valve spool displacement. This function must be parameterized. So far, a linear approximation has been used to represent the valve characteristics. The performance of this traditional approach is investigated in Sec. 3. As the linear approximation will prove insufficient for many valves, a nonlinear approach is suggested, see Sec. 4. Furthermore the valve flow characteristics vary strongly with temperature, so the effects of varying fluid temperatures are investigated and further on introduced into the design of the thresholds in Sec. 5. The resulting fault detection and diagnosis approach is then tested with experiments at a real testbed (Sec. 6). Conclusions (Sec. 7) end this paper.

2. MODELING OF A HYDRAULIC SERVO AXIS

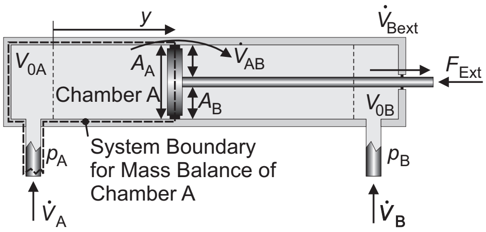

Fig. 1. Scheme of a Hydraulic Cylinder

A model of the cylinder chambers can be derived from the *mass balance* (Spurk, 1996) of the individual chambers. For chamber A (see Fig. 1) , the resulting model is given as

$$\begin{aligned}&\frac{(V_{0A}+A_A y(t))}{E(p_A,T)}\dot p_A(t)+A_A\dot y(t)\\&=\dot V_A(p_A,p_B,p_P,T,y_V)-\dot V_{AB}(p_A,p_B,T),\end{aligned} \quad (1)$$

where V_{0A} is the so-termed *dead-volume* (residual volume at $y=0$), A_A the active piston area and E the bulk modulus. Furthermore, p_A and p_B denote the cylinder chamber pressures and p_P the supply pressure. y stands for the piston displacement and T for the fluid temperature. On the left side, (1) contains the *compressibility flow* as the first addend and the *kinematic flow* as the second. On the right side are the flow into the hydraulic cylinder as determined by the proportional valve and the leakage flow, which is typically modeled as a *laminar flow*,

$$\dot V_{AB}(p_A,p_B,T)=G(T)\,(p_A(t)-p_B(t)) \quad (2)$$

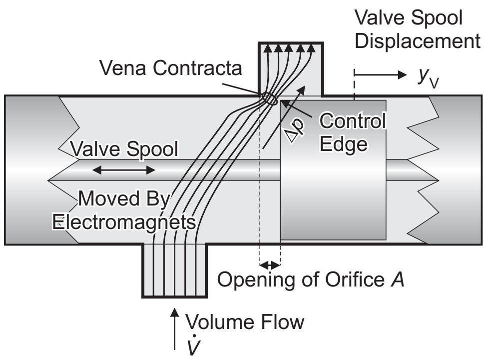

Fig. 2. Scheme of Valve Orifice in Spool Valve

The only remaining unknown is thus the flow over the control edges of the valve, see Fig. 2. This flow is modeled as a *turbulent flow*,

$$\dot V=\alpha_D(y_V)A(y_V)\sqrt{\frac{2}{\rho(p,T)}}\sqrt{|\Delta p|}\,\mathrm{sign}\,\Delta p. \quad (3)$$

Here, $A(y_V)$ is the cross-sectional area of the valve opening and Δp the pressure drop across the control edge. The factor $\alpha_D<1$ takes into account the contraction of the jet while passing through the orifice. The flow is affected by the density, which in turn varies with both the pressure and the fluid temperature. All coefficients of (3) which show a dependency on temperature (T) or spool displacement (y_V) will be collected into the auxiliary quantity b_V. Thus the flow becomes

$$\dot V=b_V(y_V,T)\sqrt{|\Delta p|}\,\mathrm{sign}\,\Delta p. \quad (4)$$

with

$$b_V(y_V,T)=\alpha_D(y_V)A(y_V)\sqrt{\frac{2}{\rho(p,T)}}. \quad (5)$$

(4) must be formulated for each of the four control edges, with the term b_V being identified from measurements. The numbering of the control edges is shown in Fig. 3 The measurements of b_{V2} as a function of y_V and T taken with a flowmeter are shown in Fig. 4 to get a feel for the behavior and running of the $b_V(y_V)$ functions.

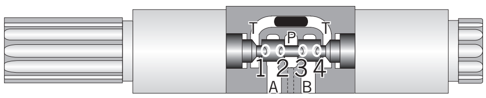

Fig. 3. Location and Numbering of the Control Edges

3. LINEAR VALVE CHARACTERISTICS

As can be seen from Fig. 4, the flow over the control edge is clearly a nonlinear function of y_V. Despite