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The development of an adaptive threshold for model-based fault detection of a nonlinear electro-hydraulic system

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Abstract

This paper presents a practical approach to combine model-based fault detection with an adaptive threshold. The suitability of the proposed technique is illustrated through its application to the condition monitoring of a nonlinear electro-hydraulic plant. The paper begins by outlining the difficulties associated with modelling the plant and the steps taken to identify the uncertain factors that influence the accuracy of the resulting model. A linearised model is applied in this study. The reason for this is because of the availability of many well-developed model-based approaches and model parameter estimation techniques for linear systems. The errors due to the linearisation and stochastic factors are studied both experimentally and theoretically and are compensated for by using an adaptive threshold. The combined linearised model-based approach and adaptive threshold is not only easy for on-line implementation but also takes into account the unknown influences such as model errors, measurement noise, temperature fluctuation and hence leads to a reliable fault detection scheme. The performance of the proposed fault detection scheme is demonstrated in detecting several different fault types associated with the control components, actuator and sensor.

Keywords: Model-based; Fault detection; Electro-hydraulic system; Adaptive threshold; Non-stationary process; Residual analysis

1. Introduction

Model-based fault detection has been studied extensively and many applications have been developed in the monitoring of control systems (Simani, Fantuzzi, & Patton, 2003). Among the applications, several cases have been reported that attempt to apply model-based approaches to nonlinear electro-hydraulic systems (Yao, Bu, Reedy, & Chiu, 2000). Yu and Shields (1996) tested both the linear and nonlinear fault detection methods in a hydraulic position system. The nonlinear fault detection observer takes into account the quadratic and bilinear terms which arise from the hydraulic system. Compared with the linear method, the nonlinear method demonstrated better sensitivity to faults associated with both the sensor and pump. Similarly, Leuschen, Walker, and Cavallaro (1999) started with linear method to detect faults on a hydraulic wheel actuator and later (Leuschen, Walker, Joseph, & Cavallaro, 2003) extended the work by developing nonlinear methods which were shown to be effective at detecting the faults from servo-valve winding, sticking wheel and sensor. These works illustrate the growing trend in applying nonlinear methods to detect faults in electro-hydraulic systems.

The use of nonlinear methods for monitoring electro-hydraulic systems seems instinctive since the behaviour of such systems contains a certain degree of nonlinearity. However, in comparison with linear models, nonlinear techniques require not only an increase in the complexity of the system and the associated intensive computation requirements but there are also several other problems arising from their application. Firstly, nonlinear models may not be implementable for

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Nomenclature

a	distance from the rotating shaft to the area of magnetic current (mm)
A	state matrix of the system
A_e	area of the cylinder in non-rod chamber (mm^2)
A_N	area of the nozzle (mm^2)
A_s	area of the spool (mm^2)
b	distance between nozzle centre and the spool centre (mm)
B	input matrix
B_a	resistance of the armature (Ω)
B_c	resistant coefficient of the cylinder
B_s	coefficient of resistance of the spool
C	output matrix
C_d	flow rate coefficient
D_s	diameter of the spool (mm)
F_L	load force to the cylinder (N)
F_s	friction coefficient of the spool
i	current in the coil (A m)
J_a	moment-of-inertia of the armature
k	time index
K_c	spring coefficient of the cylinder
K_f	rigidity of the feedback rod (N/mm)
K_m	magnetic stiffness of the torque motor
K_s	rigidity of the boring spring (N/mm)
K_t	torque coefficient in null position
K_u	gain of the amplifier
L_1	negative resistance length
L_2	positive resistance length
l_g	length of magnetic gap (mm)
M_c	equivalent mass of the cylinder (kg)
M_s	equivalent mass of the spool (kg)
n	number of sampling sets
N_c	number of turns in each coil
P	probability
$(p_a - p_b)$	pressure difference between the nozzles (Pa)
p_L	load pressure (Pa)
p_s	supply pressure (Pa)
Q	flow rate to the cylinder (l/s)
r	rotating radius of the boring spring (mm)
R	resistance of each coil (Ω)
r_a	inner resistance of amplifier (Ω)
r_{es}	real residual signal (mm)
R_g	magnetic resistance
T	sampling period
T_L	load torque (Nm)
U	input matrix
u_g	control voltage to the amplifier (V)
X	state variable matrix
x_{f0}	clearance when the flapper is in null position
x_s	displacement of the spool valve (mm)
y	displacement of the cylinder (mm)
Y	output variable matrix
z	threshold coefficient
α	confidence level
Φ_a	magnetic-current
Φ_g	polar magnetic current
θ	rotating angle of the armature (rad)
θ_f	orifice angle across the spool (deg)
$\delta_{u,t}$	adaptive threshold
η	mean values of the process
ρ	density of the oil (kg/m^3)
σ	standard deviation of the process
ζ	density coefficient
λ_a	area coefficient
$K_{ab}, K_p, K_{qc}, K_\theta$	combined coefficients

state-estimation, control and monitoring purposes because nonlinear estimation, control and monitoring are more complex and computationally intensive (Bhagwat, Srinivasan, & Krishnaswamy, 2002). Secondly, errors in estimating the parameters in a nonlinear model can be much more significant, in terms of modelling accuracy, than similar errors in a linear model. These difficulties are the reasons that there has been an increase in the use of non-parametric model approaches such as neural networks, fuzzy models and hybrid models (Simani et al., 2003). On the other hand, there are many well-known, industrially accepted techniques that exist for linear system analysis, parameter estimation, control algorithm design and fault detection.

In this paper, therefore, a linearised model is applied to the electro-hydraulic plant. To cater for the resulting modelling errors this model is combined with an adaptive threshold. Chen and Patton (1999) addressed the usefulness of using adaptive threshold for model-based FDI. Moreover, as the adaptive threshold takes measurement noise and model uncertainty into account (Patton, Frank, & Clark, 1989; Frank, 1991), this combined approach improves the monitoring performance with increased detection sensitivity and fewer false alarms (Höfing, Pfeufer, Deibert, & Isermann, 1995). The reduction of false alarms is a crucial consideration for any on-line application of a condition monitoring technique.

The paper is divided into seven sections. Section 2 outlines the modelling of electro-hydraulic systems, and highlights the factors which influence model accuracy. Section 3 selects a residual signal generation method by which a model-based approach can be implemented through a linearised model and an output observer. Section 4 studies the residual characteristics