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Control Engineering Practice 13 (2005) 1307–1314
CONTROL ENGINEERING PRACTICE
www.elsevier.com/locate/conengprac

Actuator fault compensation for a winding machine

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Received 1 March 2004; accepted 30 November 2004

Abstract

In this paper a method for fault-tolerant control in dynamic systems is presented. The proposed approach is composed of two stages. The first stage is the detection and isolation of the failed component using a directional filter designed under a particular eigenstructure assignment. The second stage is represented by the reconfiguration mechanism which makes possible the compensation of the fault effects. This approach was applied to the web tension control of winding machine and gave good results for actuator fault accommodation.

Keywords: Fault-tolerant control; Fault accommodation; Isolation filter; Winding system; Web tension control

1. Introduction and problem statement

In most large-scale plants, like those which can be found in Mining Mineral or Metal industries, distributed control systems are used to simultaneously control thousands of process variables. Due to the huge number of instruments, and the increasing number of possible faults, the system reliability can be seriously degraded. It is known that those abnormal situations due to instrument or component failures can prevent or even endanger continuous operation. Increasing plant availability and reliability may have an impact on improving economic efficiency even larger than improving process optimal operation. This can be achieved through the early detection of anomalies (variances or irregularities in the equipment), and by switching to fault tolerant control (FTC) strategy and/or providing predictive and real-time maintenance. The main task to be tackled in achieving fault-tolerance is the design of a controller with suitable structure to guarantee stability and satisfactory performance, not only when all control components are operational, but also in the case when sensors, actuators (or other components e.g. the control computer hardware or software) are operating under faulty modes. In order to show the effectiveness of FTC strategies in presence of actuator faults a winding plant is proposed for illustration purpose. Actually, web transport is very common in metal industry and the main goal is to increase the web velocity as much as possible while controlling the tension of the web. In this respect, several advanced control strategies have been recently proposed in the literature (Grimble & Hearns, 1999; Knittel, Laroche, Gigan, & Koc, 2003; Koc, Knittel, Mathelin, & Abba, 2002). But, to our knowledge fail safe control is not considered in these works, although web transport systems are very sensitive to the presence of faults which can even cause serious damages to the process. Therefore, it is important to implement FTC strategies in order to minimize degradation of product quality and economic loss. Various approaches for fault-tolerant control have been suggested in the literature (Rausch, 1995; Patton, 1997). Actually, fault-tolerant control concepts can be separated into "passive" and "active" approaches. The key difference between them consists in that the active FTC system includes a fault detection and isolation (FDI) system and the fault

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0967-0661/$ - see front matter
doi:10.1016/j.conengprac.2004.11.016

handling is carried out based on information on faults delivered by the FDI system, while in a passive FTC system the system components and controllers are so designed that they are robust to possible faults to a certain degree (Zhao & Jiang, 1998). There are a great number of new developments in control system design aiming at providing more reliable control in the presence of fault conditions. Major fault conditions may often require the system to be retuned for optimum performance (Gao & Antsaklis, 1992). Adaptive control seems to be the most natural approach to accommodate faults: the faults effects appear as parameter changes and are identified on line, and the control law is reconfigured automatically based on new parameters (Bodson & Groszkiewicz, 1997; Jiang & Zhao, 1998; Theilliol, Noura, & Sauter, 1998; Wu, Zhang, & Zhou, 2000; Zaid, Ionnaou, Gousman, & Rooney, 1991). A classical way to achieve fault-tolerant control relies on supervised control where an FDI unit provides information about the location and time occurrence of any fault. Faults are compensated via an appropriate control law triggered according to diagnosis of the system (Noura, Sauter, & Hamelin, 1997; Noura, Sauter, Hamelin, & Theilliol, 2000; Theilliol et al., 1998; Theilliol, Noura, & Ponsart, 2002). Nevertheless, it is to be noticed that only few methods have been applied to real plants (Aubrun, Sauter, Noura, & Robert, 1993; Ballé, Fisher, Fussel, Nelles, & Isermann, 1998; Noura et al., 2000). The paper is organized as follows: Section 2 describes the winding machine under study. This machine is similar to those which can be found in steel or paper making industries. The proposed approach for FTC is based on the use of fault diagnosis and identification scheme combined with a control reconfiguration algorithm. Fault isolation filter and reconfiguration mechanisms are presented in Section 3. Section 4 illustrates the application of the fault tolerant controller to the winding machine.

2. Description of the winding machine

The winding machine under study is composed of three reels driven by DC motors (M1, M2, and M3),

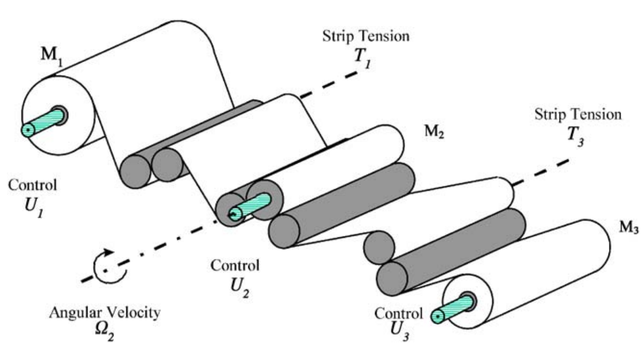

Fig. 1. The winding machine.

gears reduction coupled with the reels, and a strip (Fig. 1). Motor M1 corresponds to the unwinding reel, M3 is the rewinding reel, and M2 is the traction reel. The angular velocity of motor M2 (Ω_2) and the strip tensions between the reels (T_1, T_3) are measured using a tachometer and tension-meters, respectively. Each motor is driven by a local controller. Torque control is achieved for motors M1 and M3, while speed control is realized for motor M2.

The control inputs of the three motors are U_1, U_2 and U_3. U_1 and U_3 correspond to the current set points I_1 and I_3 of the local controller. U_2 is the input voltage of motor M_2. In winding processes, the main goal usually consists of controlling tensions T_1 and T_3 and the linear velocity of the strip. Here the linear velocity is not available for measurement, but since the traction reel radius is constant, the linear velocity can be controlled by the angular velocity Ω_2.

With the sampling interval $T_s = 0.1$ s, the linearized model of the winding machine around the operating point

$$u_0 = [-0.15 \;\; 0.6 \;\; 0.15], \quad y_0 = [0.6 \;\; 0.55 \;\; 0.4]$$

is given by the following discrete state-space representation:

$$x_{k+1} = Ax_k + Bu_k + w_k,$$

$$y_k = Cx_k + v_k. \tag{1}$$

$$x = [T_1 \;\; \Omega_2 \;\; T_3]^{\mathrm{T}}, \quad u = [u_1 \;\; u_2 \;\; u_3]^{\mathrm{T}}. \tag{2}$$

$$A = \begin{bmatrix} 0.4126 & 0 & -0.0196 \\ 0.0333 & 0.5207 & -0.0413 \\ -0.0101 & 0 & 0.2571 \end{bmatrix},$$

$$B = \begin{bmatrix} -1.7734 & 0.0696 & 0.0734 \\ 0.0928 & 0.4658 & 0.1051 \\ -0.0424 & -0.093 & 2.0752 \end{bmatrix}, \tag{3}$$

C is the identity matrix I_3. The system described by these matrices is completely observable and controllable.

The state and measurement noises w_k and v_k are zero mean uncorrelated random sequences with

$$E\left\{ \begin{bmatrix} \omega_k \\ v_k \end{bmatrix} [\omega_j^{\mathrm{T}} \;\; v_j^{\mathrm{T}}] \right\} = \begin{bmatrix} W & 0 \\ 0 & I \end{bmatrix} \delta_{k,j}, \tag{4}$$

where $W \geqslant 0$ and $V > 0$.

Under normal operating conditions, the nominal control law

$$u_k = -K\tilde{x}_k = -[K_1 \;\; K_2] \begin{bmatrix} x_k \\ z_k \end{bmatrix} \tag{5}$$

is set up according to the LQI technique (D'Azzo & Houpis, 1995) such that the following cost function