2nd IFAC Workshop on Advanced Maintenance Engineering,
Services and Technology
Universidad de Sevilla, Sevilla, Spain. November 22-23, 2012

A Robust Fault Detection Algorithm Using q-LPV Interval Observer Together with an Accommodation System Based on Actuators Reconfiguration

H. Bolandi*, M. Abedi**
and M. Haghparast***

School of Electrical Engineering, Iran University of Science and Technology, 16846-13114, Tehran, Iran (Tel: +98-21-77204040; e-mail: h_bolandi@ iust.ac.ir)
*** School of Electrical Engineering, Iran University of Science and Technology, 16846-13114, Tehran, Iran (e-mail: mos.abedi3235@ gmail.com)*
**** School of Electrical Engineering, Iran University of Science and Technology, 16846-13114, Tehran, Iran (e-mail: h_haghparast@ elec.iust.ac.ir)*

Abstract: This paper presents robust fault detection based on adaptive thresholds for a satellite described by means of a linear parameter varying (LPV) model. Adaptive threshold is generated using an interval LPV observer that produces a band of predicted outputs considering both bounded parametric modeling errors and measurements noises. This strategy propagates the effect of satellite parameter uncertainties into the alarm limits and so enhances the robustness of fault detection system at the decision making stage. The developed method can minimize the missing alarm rates due to modeling uncertainties; also this approach detects small or incipient faults more effectively than the classical robust fault detection algorithms with constant thresholds. In this paper also an accommodation system based on reconfiguration of available actuators has been designed. Accordingly, after isolation of faulty reaction wheels, they turned off and replaced by suitable magnetic torquers. Therefore, despite occurrences of several failures in the ACS, attitude control error was kept limited. In the presented simulation results, some scenarios are developed to verify the performance of the proposed method.

Keywords: Adaptive threshold, interval observer, q-LPV model, satellite, fault detection.

1. INTRODUCTION

Satellite pointing accuracy is one of the main requirements that its satisfaction depends on the perfect-healthy performance of the attitude control system. Investigation of fault events in different missions shows that many of occurred faults in the attitude control system (ACS) actuators have led to the degradation of expected services, loss of vehicle control or in case of total failures, catastrophic loss of mission. This system provides the pointing accuracy and stability in satellites. Accordingly, there is a need to develop fault tolerance tools in a safety critical system such as ACS, capable of detecting and isolating any component faults.

Existing analytical techniques in fault detection are often model based approaches that can be considered today as a mature and structured field of research within the control community. These approaches are relied on consistency tests that confront the measurements from a physical system with the information contained within the model. The resulting differences are called residuals and are assumed to be sensitive to faults in the system. An inconsistency occurs if a residual is different from the zero. However, modeling errors and disturbances in complex engineering systems are inevitable leading the residuals to non-zero values even in the absence of faults (Hwang et al. (2010)). Therefore, there is a need to develop fault detection and isolation (FDI) algorithms that are robust against the uncertainties. One of the approaches to robustness, known as active, is based on generating residuals that are insensitive to uncertainty, whilst at the same time sensitive to one or more faults. Several diagnosis methods have emerged in the ACS which utilizes the above idea. Fault detection methods based on Extended Kalman Filter (EKF) (Pirmoradi et al. (2009)), Unscented Kalman Filer (UKF) (Soken et al. (2010)), also observer based methods such as sliding mode observer (Jiang (2010)) and UIO (Patton et al. (2010)) are some of approaches that extensively used in the ACS.

In the mentioned methods, although the robustness with respect to unknown disturbances has been solved, but the robustness with respect to parametric uncertainties is more difficult to solve. In fact, in case of models with uncertainty located in the parameters, perfect de-coupling of residuals from uncertainties is limited by the number of measurement signals available from the system. So these approaches are suitable only for a limited number of parametric uncertainties (Khan et al. (2011)). In case of an unlimited number of modelling uncertainty, there is an alternative strategy, the so-called passive approach that has been considered in this article. This method has been introduced in the recent decades and is based on enhancing the robustness of the fault diagnosis system at the decision making stage. For this purpose, first the ACS has been described as a quasi linear

978-3-902823-17-5/12/$20.00 © 2012 IFAC 10.3182/20121122-2-ES-4026.00009

parameter model in which the satellite parameter uncertainties are taken into account. Next, using the interval arithmetic tools (introduced in the section 3) an interval LPV observer has been designed that produces a band of predicted outputs considering both bounded parametric modelling errors and measurement noises. So, the model uncertainty and noise effects are propagated to alarm limits of residuals or in the other word, adaptive thresholds are generated. When the residuals are outside the alarm limits, it is argued that model uncertainty alone cannot explain the residual and therefore a fault must have occurred. So, this strategy minimizes the missing alarm rates. Also, compared with classical robust approaches with constant thresholds, the small or incipient faults in the actuators can be detected more effectively. In this paper also, In this paper also an accommodation system has been designed that is based on reconfiguration of available actuators. For this, the intended satellite has been equipped with four reaction wheels which one of them is redundant. So, it provides fault accommodation against occurrence of one fault or failure in the reaction wheels. But in hostile condition of space, there might be condition of two or more failures. In this case, a systematic procedure has been executed that is based on replacing the proper magnetic tourqers instead of faulty reaction wheels. It is shown that according to the above reconfiguration, the control error is kept limited and so avoids the degradation of attitude control performance. So, the above reconfiguration function provides the recovery feature besides the mentioned abilities.

The outline of this paper is as follows. In section 2, the q-LPV model of satellite is derived. Design of the fault detection system is proposed in section 3. Design steps of the accommodation system are detailed in section 4. Numerical simulations for a number of faulty scenarios in the reaction wheels are presented in section 5. Finally, the article is concluded in section 6.

2. DERIVATION OF THE q-LPV MODEL FOR THE SATELLITE

2.1 Satellite Dynamic Model

The satellite considered in this paper is a three axis stabilized satellite in which four reaction wheels are used (Fig. 1). It is modelled as a rigid body having the moments of inertia matrix along the principal axes of rotation $I_t = Diag_{3\times 3}\{I_x, I_y, I_z\}$. With the above considerations, satellite attitude dynamics which describes the relations between angular velocities and applied torques is obtained as following (Sidi (1997)):

$$\dot{\omega} = I_t^{-1}(I_t\omega \times \omega) - I_t^{-1}(CI_W\omega_W \times \omega) + I_t^{-1}(T - \dot{h}_W) + I_t^{-1}d(t) \qquad (1)$$

where $\vec{\omega}_{3\times 1}$ is the angular velocity vector of the satellite, $\vec{\omega}_{w_{4\times 1}} = \begin{bmatrix} \omega_{wx} & \omega_{wy} & \omega_{wz} & \omega_{wr} \end{bmatrix}^T$ is the angular velocity vector of the reaction wheels, $\dot{h}_{w_{4\times 1}} = \begin{bmatrix} \dot{h}_{x_W} & \dot{h}_{y_W} & \dot{h}_{z_W} & \dot{h}_{r_W} \end{bmatrix}^T$ is the control torque applied to the satellite by the reaction wheels,

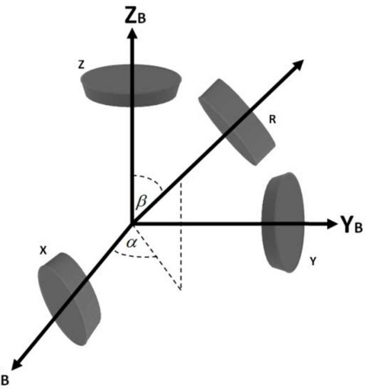

Fig. 1. Considered structure of reaction wheels in the satellite

$I_{w_{4\times 4}} = Diag_{4\times 4}\{I_{wx}, I_{wy}, I_{wz}, I_{wr}\}$ is the moments of inertia matrix of the reaction wheels, d is the disturbance torque, $T_{3\times 1}$ shows the value of torques generated by the actuators and I_t is the moments of inertia matrix of the satellite. Also, C_f is the formation matrix of reaction wheels that is computed as (2). In this matrix, α and β are angles that have been defined according to Fig. 1:

$$C_f = \begin{bmatrix} 1 & 0 & 0 & \sin\beta\cos\alpha \\ 0 & 1 & 0 & \sin\beta\sin\alpha \\ 0 & 0 & 1 & \cos\beta \end{bmatrix} \qquad (2)$$

Equation (1) could be rewritten as:

$$\begin{aligned} \dot{\omega} = {} & I_t^{-1}(I_t\omega)^{\otimes}\omega + I_t^{-1}(C_f I_w \omega_w)^{\otimes}\omega + I_t^{-1}(T - C_f \dot{h}_w) \\ & + I_t^{-1}d(t) \end{aligned} \qquad (3)$$

In the above equation, the $\otimes$operand has been used to perform the following operation on a matrix:

$$P^{\otimes} = \begin{bmatrix} 0 & -p_z & p_y \\ p_z & 0 & -p_x \\ -p_y & p_x & 0 \end{bmatrix} \qquad (4)$$

2.2 Satellite q-LPV model

Considering the nonlinear dynamics in (3) with additive disturbances $d(t)$, noise $n(t)$ and faults $f(t)$, the state space relationship can be written as:

$$\begin{aligned} \dot{\omega} = {} & I_t^{-1}(I_t\omega)^{\otimes}\omega + I_t^{-1}(C_f I_w \omega_w)^{\otimes}\omega + I_t^{-1}(T - C_f \dot{h}_w) \\ & + I_t^{-1}d(t) + f(t) \end{aligned} \qquad (5)$$

$$y(t) = C\omega(t) + n(t) \qquad (6)$$

where C is a unitary matrix. According to the above dynamics, the following q-LPV representation can be derived:

$$\dot{\omega} = A(\omega,\theta)\omega + B(\theta)u + B(\theta)d(t) + f(t) \qquad (7)$$