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A Comparative Study of Three Differentiation Schemes for the Detection of Runaway Faults in Aircraft Control Surfaces

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Abstract: In this paper, three different differentiation schemes are studied for the development of a generic fault detection scheme. The case of runaway fault is investigated. A runaway is an uncontrolled deflection of a control surface which can go until its physical limitation if it remains undetected. The proposed technique is a signal-based one that relaxes the need of an accurate actuator modelling. The core element of the proposed fault detection scheme is a differentiation scheme. In this context, a comparative study is made by using noisy signals. Note that the assessment of differentiation is done by using the Absolute Mean Error (AME) ratio, the percentage Variance Accounted For (VAF) and the Index of Agreement (IoA). *Copyright © 2016 IFAC*

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1. INTRODUCTION

Robust and early diagnosis (Zolghadri *et al.*, 2014) of faults that have an influence on structural loads has received considerable attention these last decades. Quick detection of such failures allows the designers to save weight by avoiding structure reinforcement and so improve the overall aircraft performance in terms of fuel burn, noise, range and environmental footprint (Goupil *et al.*, 2013). The paper deals with a challenging failure case which may affect the structural load: the runaway (a.k.a hard-over) in aircraft control surfaces. A runaway is an uncontrolled control surface deflection that can go until its physical limitation if it remains undetected, see Fig. 1. In the case of high speed runaway, additional loads can affect the aircraft structure. If the control surface deflection is too high at the moment of the fault detection, compared to structural design objectives, then the aircraft structure must be reinforced, which means additional weight. Its detection is thus of great importance.

The current industrial practices for control surface runaway detection relies on consistency checks between two redundant signals computed in two flight control computer channels (Zolghadri *et al.*, 2011), (Gheorghe *et al.*, 2013). If the difference between both signals is greater than a given threshold during a given time, the detection is confirmed. Beyond this industrial practice, several model-based works have been published to deal with runaway faults. In (Varga, 2007), the design of residual generators with least dynamical orders is addressed for a Boeing 747-100/200 model. To take into account the wide operation range of an aircraft, some Fault Detection and Diagnosis (FDD) solutions are based on Linear Parameter Varying (LPV) techniques, see (Varga *et al.*, 2011), (Vanek *et al.*, 2014), (Varga & Ossmann, 2014) and (Henry *et al.*, 2014, 2015) to name a few. A set-membership scheme based on interval prediction is also proposed in (Combastel *et al.*, 2014) to improve the detection of the runaway failure case. Thanks the promising results of (Alwi & Edwards, 2013) and (Efimov *et al.*, 2013) for the oscillatory failure case detection, a second order sliding mode observers is developed in (Alwi & Edwards, 2014) to the runaway reconstruction from the equivalent output error injection signals.

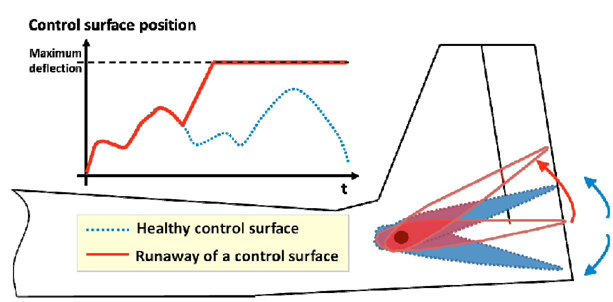

Fig. 1: Hard-over failure in control surface position

Despite the good results obtained in the aforementioned schemes, many of them are highly dependent on the type of actuator. Due to the advent of the new generation of actuators like Hydraulic, Electro-Hydrostatic (EHA) and Electro-Backup-Hydrostatic (EBHA), the need of fault detection scheme that is independent of actuator modelling is becoming of primary interest. In this trend, a generic method for

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actuator lock-in-place failure detection is proposed in (Cieslak *et al.*, 2014). This signal-based FDD scheme uses the sliding-mode differentiator of (Levant, 2003) to provide derivatives of measurable signals in noisy environment. Even if good fault detection performances are obtained to the jamming failure case by assessing it on the System Integration Bench (SIB) of Airbus SAS, a comparative study (Yan *et al.*, 2014) of different differentiation schemes will be welcome to better evaluate the potential of this technique. In addition, the use of a differentiation scheme must be extended to other diagnosis issues in order to be considered as a viable candidate and expect an implementation in a Flight Control Computers (FCC).

In this context, the paper presents a signal-based strategy for early and robust detection of control surface runaway. The core element of the proposed FDD method is a differentiation scheme able to provide derivatives of measurable signals in noisy environment. Three differentiation methods are considered in the next section: i) the finite difference method fitted with a moving average filter (Golestan *et al.*, 2014), ii) the usual sliding-mode differentiator defined in (Levant, 2003) and iii) the uniform robust exact differentiator (Cruz-Zavala *et al.*, 2011). The derivative estimate of each method is assessed by using the Absolute Mean Error (AME) ratio, the percentage Variance Accounted For (VAF) and the Index of Agreement (IoA) defined in section 3. Finally, the application to fault detection is presented in section 4.

2. DIFFERENTIATION SCHEMES

2.1 *Differentiation scheme with a moving average filter*

The first differentiation method consists to estimate the time derivative of a noisy signal $f(t)$ by using the finite difference method over a time windows. A Moving Average Filter (MAF) is used to 'denoise' the signal. MAF is a linear finite-impulse-response (FIR) filter that can operate as a low-pass filter (Golestan *et al.*, 2014). A MAF is defined according to

$$\zeta(t) = \frac{1}{T_w}\int_{t-T_w}^{t} f(\tau)d\tau \tag{1}$$

where $f(t)$ and $\zeta(t)$ are the input and output signal of the MAF respectively. T_w is the window length. From (1), it is possible to derive the following transfer function:

$$\frac{\zeta(s)}{f(s)} = \frac{1-e^{-T_w s}}{T_w s} \tag{2}$$

From (2), it is easy to see that the wider the window length, the slower the MAF transient response will be. Let two consecutive readings of position signal $\bar{y}$ be considered. By using Euler approximation, the derivative estimate is

$$\dot{\zeta}(t) = \frac{\zeta(t)-\zeta(t-h)}{h} \tag{3}$$

where h denotes the sampling period. In the case of a noisy signal $\zeta(t)=\zeta_0(t)+v(t)$ where $\zeta_0(t)$ is the useful information and $v: R \to [-\lambda_0, \lambda_0]$, $0<\lambda_0<+\infty$ denotes the bounded measurement noise, the derivative estimate is defined according to:

$$\dot{\zeta}(t) = \frac{\zeta_0(t)-\zeta_0(t-h)}{h} + \frac{v(t)-v(t-h)}{h} \tag{4}$$

From (4), it can be observed that the measurement noise is amplified for sampling periods smaller than 1.

2.2 *Levant differentiator*

The second differential scheme is based on the Sliding Mode Differentiator (SMD) of (Levant, 2003). It is given by

$$\begin{cases} \dot{z}_0 = -\alpha_0\sqrt{|z_0-\zeta|}\times sign(z_0-\zeta)+z_1 & (5)\\ \dot{z}_1 = -\alpha_1 sign(z_1-\dot{z}_0) & (6)\end{cases}$$

where $z_0 \in R$, $z_1 \in R$ are the state variables of the differentiator. α_0 and α_1 are positive tuning parameters. ζ is the input signal of SMD defined according to the previous sub-section, i.e. $\zeta(t)=\zeta_0(t)+v(t)$. From (5), the following mathematical development can be derived:

$$\begin{aligned} sign(z_1-\dot{z}_0) &= sign\left(z_1 - z_1 + \alpha_0\sqrt{|z_0-\zeta|}\times sign(z_0-\zeta)\right)\\ &= sign\left(\alpha_0\sqrt{|z_0-\zeta|}\times sign(z_0-\zeta)\right) \end{aligned} \tag{7}$$

Since the quantity $\alpha_0\sqrt{|z_0-\zeta|}$ is positive by definition, equation (7) becomes:

$$sign(z_1-\dot{z}_0) = sign(z_0-\zeta) \tag{8}$$

From (8), it is thus possible to reformulate the differentiator (5)-(6) according to:

$$\begin{cases} \dot{z}_0 = -\alpha_0\sqrt{|z_0-\zeta|}\times sign(z_0-\zeta)+z_1 & (9)\\ \dot{z}_1 = -\alpha_1 sign(z_0-\zeta) & (10)\end{cases}$$

Introducing variables $e_0 = z_0-\zeta_0$, $e_1 = z_1-\dot{\zeta}_0$, the system (9)-(10) can be rewritten as follows:

$$\dot{e}_0 = -\alpha_0\sqrt{|e_0|}sign[e_0]+e_1+\delta_0 \tag{11}$$

$$\dot{e}_1 = -\gamma\, sign[e_0]+\delta_1, \tag{12}$$

where $\delta_0 = \alpha_0(\sqrt{|e_0|}sign[e_0]-\sqrt{|e_0-v|}sign(e_0-v))$ and $\delta_1=\alpha_1\left(sign(e_0)-sign(e_0-v)\right)$ are the disturbances generated by the presence of noise v. $\gamma=\alpha_1+\ddot{\zeta}_0\, sign[e_0]$ is a strictly positive function if α_0 and α_1 are selected according to (Levant, 2003). Thanks to the property $\left|\sqrt{|a|}sign(a)-\sqrt{|b|}sign(b)\right| \le \sqrt{2|a-b|}$, $a\in\Re$, $b\in\Re$ and $|v|\le\lambda_0$, it follows that $|\delta_0|\le\alpha_0\sqrt{2\lambda_0}$. $|\delta_1|\le 2\alpha_1$ since $\delta_1=0$ when $|e_0|\ge\lambda_0$ and $\delta_1=2\alpha_1 sign(e_0)$ for $|e_0|<\lambda_0$. Hence, the accuracy of derivatives is given by:

Theorem 1. (Levant, 2003) *Let ζ_0 be continuously differentiable, $|\ddot{\zeta}_0(t)|\le L$ and $|v(t)|\le\lambda_0$ for all $t\ge 0$. Then, there exist a finite-time $0\le T<+\infty$ and some constants $c_0>0$, $c_1>0$ such that for all $t\ge T$:*

$|z_0-\zeta_0|\le c_0\lambda_0$, $|z_1-\dot{\zeta}_0|\le c_1\lambda_0^{0.5}$. ■