Control Engineering Practice 49 (2016) 194–203

Contents lists available at ScienceDirect

Control Engineering Practice

journal homepage: www.elsevier.com/locate/conengprac

Robust fault estimation using an LPV reference model: ADDSAFE benchmark case study

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ARTICLE INFO

Article history:
Received 22 May 2015
Received in revised form
2 December 2015
Accepted 11 December 2015
Available online 24 December 2015

Keywords:
Fault detection and diagnosis
Mixed $\mathcal{H}_-/\mathcal{H}_\infty$ optimisation
Reference model

ABSTRACT

This paper investigates a mixed $\mathcal{H}_-/\mathcal{H}_\infty$ linear parameter varying (LPV) fault estimator using an LPV reference estimator. LMIs are used to calculate the affine parameter-dependent gains of the LPV fault estimator. The design strategy is applied to a high fidelity nonlinear aircraft model provided by AIRBUS for use within the EU-FP7 project ADDSAFE, to estimate the yaw rate sensor faults in the Air Data Inertial Reference System in the presence of the parametric uncertainties. The fault detection performances in various flight conditions are evaluated using the parametric simulation.

1. Introduction

1.1. Background and motivation

Model-based fault detection and diagnosis (FDD) has already became a mature subject and has developed from well structured theory in the academic control community with a large amount of work described in Patton, Frank, and Clark (2000), Isermann (1997), Gertler (1998), Chen and Patton (1999), Isermann (2005), Ding (2008), and Bokor and Szabo (2009). Aerospace application-based FDD studies have also been well summarised, e.g. see the book chapter 'Fault detection and diagnosis for aeronautic and aerospace missions' by Henry, Simani and Patton (Edwards, Lombaerts, & Smaili, 2010). An approach to model-based FDD has already been implemented in the AIRBUS industry practice for detecting a Electronic Flight Control Systems failure known as oscillatory failure case (OFC) , which can cause a significant increase in the structural load due to erroneous oscillation. When coupled with the flexible modes of the structure, OFC can generate resonance phenomenon and cause unacceptably hight vibration and loads (Goupil, 2010b). Nevertheless, industrial applications of model-based FDD theory for aerospace systems are very limited or restricted (Zolghadri, 2012). The most recent study on the potential of FDD to aircraft flight control industry is the EU-FP7 project ADDSAFE (Advanced Fault Diagnosis for Sustainable Flight Guidance and Control). The aim of the project is to highlight the link between aircraft sustainability and fault detection, it can be demonstrated that improving the fault diagnosis performance in flight control systems facilitates the optimisation of the aircraft structural design (resulting in weight saving), which in turn helps us to improve aircraft performance and to decrease its environmental footprint (e.g. fuel consumption and noise) (Goupil & Marcos, 2011, 2012).

The motivation of this paper is to develop and apply a robust fault estimation scheme to estimate and detect the ADDSAFE actuator/sensor faults in above fault scenarios at an early stage of each fault development, in the presence of parametric uncertainties. Especially, the estimator is developed in an affine LPV manner. In recent years, LPV based FDD has been widely developed in the literature (Bokor & Balas, 2004; Henry, 2008). The most obvious benefit is that the analysis of the performance and stability, together with the synthesis method, is established over a wide range of changing parameters. Besides, the LPV design scheme can be considered as an extension of the LTI design scheme. For example, based upon the vertex property (Apkarian, Gahinet, & Becker, 1995), the LPV solution can be calculated by combining multiple LTI solutions calculated on the vertices of the polytope. This property fits well in aerospace gain scheduling designs. Additionally, a trade-off between computational load and design performance can be established by defining a number of suitable scheduling parameters (Marcos & Balas, 2004). This trade-off is an important part of the industry assessment of the design.

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http://dx.doi.org/10.1016/j.conengprac.2015.12.006
0967-0661/

However, from a practical view point, robustness issues associated with plant-model mismatch, aerodynamic database uncertainties, sensor noise and imperfect measurements of the scheduling parameters have to be taken into account. The desired performance of the LPV-based design is thus unattainable and the miss detection and false alarm will be generated.

In this paper, above uncertainties are considered parametrically bounded and an LPV reference model based design scheme is derived, based upon using an $\mathcal{H}_-/\mathcal{H}_\infty$ optimisation technique, to deal with these practical concerns. The purpose of combining $\mathcal{H}_-$ (Hou & Patton, 1996) with $\mathcal{H}_\infty$ is to allow a trade-off to be established, between sensitivity and robustness of the residual against the fault and disturbance, respectively. In the literature, $\mathcal{H}_-/\mathcal{H}_\infty$ based approaches can be divided into two categories. One category combines the $\mathcal{H}_-$ index and $\mathcal{H}_\infty$ performance as a multi-objective criterion (Ding, Jeinsch, Frank, & Ding, 2000; Wang, Yang, & Liu, 2007). In another category, the mixed $\mathcal{H}_-/\mathcal{H}_\infty$ is transformed into a uniform $\mathcal{H}_\infty$ problem (Henry & Zolghadri, 2005), which was extended to an LPV framework by Grenaille, Henry, and Zolghadri (2008) and Henry (2012). Recent work by Li, Mazars, Zhang, and Jaimoukha (2012) proposed a specific $\mathcal{H}_-$ index which allows the fault estimation to be achieved in the presence of external disturbances. The parameterisable solution of the fault estimator is then used to construct an $\mathcal{H}_\infty$ optimisation procedure.

The idea of using a reference model based design scheme for FDD can be found in Zhong, Ding, Lam, and Wang (2003) and Frisk and Nielsen (2006). In design scheme, the reference fault estimator is developed first in the absence of the modelling uncertainty, and the robust fault estimator is then developed to minimise the distance between the reference and robust designs, based upon using the solutions of the reference estimator gains. The parametric uncertainties are thus restrained. Also, non-unique reference designs allow the robustness and stability properties of the robust design to be tuned. Compared with the other state-of-art approaches, this scheme is practical from an engineering point of view as the reference and robust design steps satisfy the requirements of different industrial evaluation phases. In this scheme, a fault estimator with good estimation performance is selected as the reference design evaluated in a preliminary phase of the ADDSAFE project. Also, reference estimator will not be implemented in advanced design phase, which does not generate the extra computational load.

1.2. Main contribution

This paper extends the LTI based $\mathcal{H}_-/\mathcal{H}_\infty$ technique (Li et al., 2012) to LPV system, therefore ensuring wide coverage of the operation conditions. On the other hand, an LPV reference model based design scheme is first introduced to mitigate the degradation of the LPV fault estimation performance in the presence of the parametric uncertainties, which includes the imperfect measurements of the LPV system scheduling parameters and aerodynamic uncertainties. This paper applies the proposed scheme to ADDSAFE benchmark problems and demonstrates the robustness of the design via parametric simulation. The fault estimation and detection results have already been evaluated on an industrial benchmark system.

1.3. Outline of the paper

The remainder of the paper is outlined as follows: Section 2 introduces some preliminaries associated with ADDSAFE benchmark problem. The fault estimation problem formulation and the technical development are discussed in Section 3. Section 4 describes the design scheme of the proposed fault estimation approach. The ADDSAFE model and the parametric simulation results based upon various fault scenarios of a high-fidelity nonlinear aircraft benchmark model are given in Section 5.

1.4. Notation

The notation and definitions used in the paper are summarised here. For a matrix A with a compatible dimensions, A', A^{-1} and $A^\dagger$ denote its transpose, inverse and pseudo-inverse, respectively. $A > 0 (A \geq 0)$ denotes that A is positive (semi-positive) definite. $\mathrm{He}\{A\}$ denotes a shorthand notation for $A + A'$. $\| v \|_2$ denotes the frequency domain 2-norm of the signal v. $\mathcal{L}_{2,\Omega}$ is the Lebesgue 2-space, wherein the signal is square integrable and norm bounded in a given finite frequency domain Ω, given by

$$\mathcal{L}_{2,\Omega} = \{v: \| v \|_{2,\Omega} < \infty\} \tag{1}$$

where $\|v\|_{2,\Omega}^2 = \frac{1}{2\pi}\int_\Omega v'(-j\omega)v(j\omega)\,d\omega$. The Lebesgue 2-space becomes infinite-horizon when $\Omega = [-\infty, \infty]$. Let a system to be denoted in boldface upper case, for example, a parameter dependent *system* $\mathbf{G}(\rho)$: $u \mapsto y$ is given by

$$\begin{aligned} \dot{x} &= A(\rho)x + B(\rho)u \\ y &= C(\rho)x + D(\rho)u \end{aligned} \tag{2}$$

where x, u, and y denotes the system states, inputs and outputs, respectively. $A(\rho)$, $B(\rho)$, $C(\rho)$, and $D(\rho)$ are affine parameter-dependent matrices with compatible dimensions. $\rho = [\rho_0, \rho_1, \ldots, \rho_{n_\rho}]' \in \Theta \subset \mathcal{R}^{n_\rho}$ are the available time-varying scheduling parameters, where Θ is a compact polytope.

The frequency-domain $\mathcal{H}_\infty$ performance and $\mathcal{H}_-$ index appropriate to a given finite frequency range Ω, are defined based upon the LPV system $\mathbf{G}(\rho)$, as follows:

$$\| \mathbf{G}(\rho) \|_{\infty,\Omega} = \sup_{\forall \rho \in \Theta, \forall u \in \mathcal{L}_{2,\Omega}} \frac{\| \mathbf{G}(\rho)u \|_{2,\Omega}}{\| u \|_{2,\Omega}}, \quad u \neq 0 \tag{3}$$

$$\| \mathbf{G}(\rho) \|_{-,\Omega} = \inf_{\forall \rho \in \Theta, \forall u \in \mathcal{L}_{2,\Omega}} \frac{\| \mathbf{G}(\rho)u \|_{2,\Omega}}{\| u \|_{2,\Omega}}, \quad u \neq 0 \tag{4}$$

Remark 1.1. In the literature (see Ding et al., 2000; Henry & Zolghadri, 2005; Hou & Patton, 1996; Jaimoukha, Li, & Papakos, 2006; Liu, Wang, & Yang, 2005; Wang et al., 2007), the $\mathcal{H}_\infty$ performance and $\mathcal{H}_-$ index have been defined via using a singular value property to measure the sensitivity of the residual against faults corresponding to a given LTI system. The work in Wei and Verhaegen (2011) is extended in the study of Wang et al. (2007) to one compatible with parameter-varying systems. The $\mathcal{H}_-$ index over a finite frequency range is also denoted by $\|\cdot\|_e$ (Ding et al., 2000; Henry, 2012).

2. ADDSAFE benchmark

2.1. Benchmark problem

The ADDSAFE benchmark is highly representative of a generic twin engine civil commercial aircraft including the nonlinear rigid-body aircraft model with a full set of control surfaces, actuator models, sensor models, flight control laws and pilot inputs (Goupil & Puyou, 2011). The model is highly representative of the aircraft flight physics and handling qualities. Three fault scenarios are established within benchmark (Goupil, 2010a).

The Air Data and Inertial Reference System (ADIRS) Monitoring fault scenario defined within the ADDSAFE benchmark is selected as case studies in this paper. Fig. 1 shows that the ADIRS in the benchmark contains triplex dedicated sensor redundancy, i.e.