Mechanical Systems and Signal Processing 60-61 (2015) 678–694

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Bank of $\mathcal{H}_\infty$ filters for sensor fault isolation in active controlled flexible structures

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ARTICLE INFO

Article history:
Received 2 September 2013
Received in revised form 23 January 2015
Accepted 30 January 2015
Available online 19 February 2015

Keywords:
Sensor validation
Sensor fault
Fault detection
Vibration control
Bank of filters
$\mathcal{H}_\infty$ control

ABSTRACT

In this paper a scheme based on a bank of $\mathcal{H}_\infty$ filters for sensor validation in closed-loop with the aid of a specialized indicator for quantitative analysis of residues is proposed. The residues are generated by a bank of $\mathcal{H}_\infty$ estimators. The indicator applied to the residues is the product of three other ones, namely sum of the modulus of the residue, quadratic sum of the residue, modal assurance criterion between measures and estimated outputs. The technique is validated in simulations with a model of an identified aluminum plate structure under active vibration control. Experiments were also performed.

1. Introduction

Structural Health Monitoring (SHM) in flexible structures can be accomplished by the aid of piezoelectric sensors and actuators. Active Vibration Control (AVC) can also be conducted with the support of this type of instrumentation. However, if any of these transducers fail, a very reasonable hypothesis, the SHM or the AVC will not be useful. Then, some sorts of techniques to monitor the sensors and actuators should be applied.

Sensor monitoring has received attention in SHM community in the last years, especially under the subject Sensor Validation [1–3]. In control and chemical engineering communities the monitoring of faults has been approached under the subject Fault Detection and Isolation (FDI) [4,5], where the applications generally involve closed loop systems.

One possibility to achieve Sensor Validation is to use a model based technique to predict the measured outputs and then accomplish a post-processing step in which an indicator, or index, is applied [3]. The Sensor Validation can also be performed by data driven methods, without the need of a structural model of the system. In this case, Principal Component Analysis (PCA) is a usual possibility [2]. A limitation of these works for the point of view of the Active Vibration Control community is that they did not perform tests in closed loop, which makes the fault detection a more challenging task.

There are few works with FDI techniques applied to SHM, specially in closed loop. Some adopted methods involving closed-loop are model-based, based on Fault Detection Filters [6] and $\mathcal{H}_\infty$ theory [7]. The former one does not deal with the case of sensor fault and the latter considers just the SISO case.

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http://dx.doi.org/10.1016/j.ymssp.2015.01.036
0888-3270/

Hereupon, the aim of this work is the development, inspired on the FDI techniques, of a sensor validation procedure suitable for actively controlled flexible structures. The FDI technique selected is an observer-based residual generation scheme with $\mathcal{H}_\infty$ filters performing output estimatives and a bank of filters dealing with the fault isolation problem. A proposed indicator is applied to the residues for quantitative analysis. This new indicator is the product of three other ones, namely sum of the modulus of the residue, quadratic sum of the residue, modal assurance criterion between measures and estimated outputs. This sensor validation procedure is tested by simulations on a model of an identified aluminum plate structure subjected to active vibration control. Multiplicative and additive faults are considered. The verification for an experimental case is also performed in this work.

2. $\mathcal{H}_\infty$ filters for output estimation

2.1. Introduction

FDI is a problem widely treated in chemical engineering, nuclear engineering, aerospace engineering and automotive systems [4]. However, techniques arising from these disciplines are not commonly applied either in vibration control or in structural monitoring. The FDI problem consists of making a decision about a fault occurrence and determining its location. In general, the concept of analytical redundancy, which requires a mathematical model of the system and estimation techniques, is utilized.

Two steps should appear in FDI techniques: residual generation and residual evaluation. The residuals are signals ideally zero under non-faulty conditions, desirably insensitive to noises, to disturbances and to model uncertainties while maximally sensitive to faults. One approach for residual generation, the first step in FDI, is to design a robust filter or estimator that generates output estimatives used to determine the residuals. Widely treated examples of this approach are the fault detection filters, the observer-based methods, the parity relation methods, the parameter estimation methods and Kalman filter-based methods [8,9]. For the second step, residual evaluation, the simplest decision rule is to declare that a fault occurs when the instantaneous value of a residual exceeds a constant threshold. More sophisticated decision rules may consist of adaptive thresholds.

2.2. Output estimator

Fault detection can be accomplished by the usage of output estimators in order to compare estimated signals with the measured ones. This idea is schematically represented in Fig. 1, where unknown inputs w, known inputs u, measured output y, estimated output $\hat{y}$, the plant P and the output estimator filter F can be seen. The subtraction of the measured and estimated signals generates error signals which characterizes the residue. This is the residual generation step.

A possible output estimator is the $\mathcal{H}_\infty$ filter [10]. The design is formulated as an optimization problem to minimize the interference of disturbances on the estimation error. A standard scheme of the $\mathcal{H}_\infty$ design is shown in Fig. 2(a), where K is the controller or filter and P is the plant with disturbance input w, control input u, performance output z and measured output y. The purpose of the $\mathcal{H}_\infty$ problem is to design a controller that minimizes the influence of the disturbance input w in the performance output z [11,12].

The output estimation scheme of Fig. 1 can be converted into the standard $\mathcal{H}_\infty$ scheme of Fig. 2(a), as shown in Fig. 2(b) with $\hat{y}$ being the estimated output and e the estimation error, which is the performance signal. Weighting functions can be used to enhance the performance [12].

There are several ways to solve the $\mathcal{H}_\infty$ problem: direct search, where the optimization problem is solved; solution of the corresponding Riccati equations; employment of techniques based on Linear Matrix Inequalities (LMI). A numerical solution can be obtained from several computer packages, highlighting the Robust Control Toolbox of MATLAB [13], which was used in this work.

3. $\mathcal{H}_\infty$ problem formulation

Let a linear system be described by the state-space equations:

$$\dot{x}(t) = Ax(t) + B_1 w(t) + B_2 u(t) \tag{1}$$

$$z(t) = C_1 x(t) + D_{11} w(t) + D_{12} u(t) \tag{2}$$

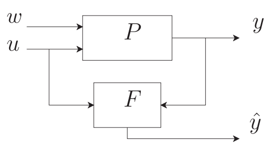

Fig. 1. Output estimation scheme.