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A new approach to deal with sensor errors in structural controls with MR damper

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Abstract. As commonly known, sensor errors and faulty signals may potentially lead structures in vibration to catastrophic failures. This paper presents a new approach to deal with sensor errors/faults in vibration control of structures by using the Fault detection and isolation (FDI) technique. To demonstrate the effectiveness of the approach, a space truss structure with semi-active devices such as Magneto-Rheological (MR) damper is used as an example. To address the problem, a Linear Matrix Inequality (LMI) based fixed-order H_∞ FDI filter is introduced and designed. Modeling errors are treated as uncertainties in the FDI filter design to verify the robustness of the proposed FDI filter. Furthermore, an innovative Fuzzy Fault Tolerant Controller (FFTC) has been developed for this space truss structure model to preserve the pre-specified performance in the presence of sensor errors or faults. Simulation results have demonstrated that the proposed FDI filter is capable of detecting and isolating sensor errors/faults and actuator faults e.g., accelerometers and MR dampers, and the proposed FFTC can maintain the structural vibration suppression in faulty conditions.

Keywords: space truss structure; sensor errors; fault detection and isolation; fault tolerant control

1. Introduction

Sensor technology and structural health monitoring has been emerging rapidly in the past several decades. An increasing amount of sensors with different types can be installed on structures for monitoring and control purposes. As the number increases, sensor errors and sensor faults become more frequent and critical comparing to structure's lifetime. A faulty sensor may not preserve its designed functionality and may potentially provide incorrect information leading to improper decisions/actions that can cause catastrophic failures of structures. Thus, fault detection and isolation (FDI) technique is necessary to detect and isolate errors/faults to preserve pre-specific performance.

An FDI system normally has three main tasks: detection, isolation, and identification of faults. First, a fault detection capability is necessary to monitor the proper functioning of a system. Since the isolation of the faulty component can result in more intelligent reconfiguration strategies and

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more economical maintenance, it is critical for many applications. Furthermore, identification will increase the capability of the system to preserve the proper action in the presence of faults, and hence most FDI systems include all three tasks as described by Chen and Patton (1999b), Isermann (1997) and Patton (1997a). Residuals, which are signals which become nonzero when abnormal behaviors are observed, are used in FDI systems to detect faults. An FDI system is simply a residual generator performed through hardware or analytical redundancy by Chiang *et al.* (2001). Most of current FDI systems are implemented by hardware redundancy, which is based on the use of multiple sensors, actuators or other components with the same function. The residual is generated by comparing the outputs from the hardware components performing the same task. The drawbacks of hardware redundancy are mainly in its cost, maintenance and potential unreliability. The other method is analytical redundancy, in which the residual is obtained by comparing the actual output measurement and the output of the corresponding mathematical model. In reality, it is seldom the case that a mathematical model perfectly matches the real system, and thus the residual can be obtained by comparing the output from mathematical model and the actual output from measurement. Thus, the difficulty of building a completely accurate model results in an issue of uncertainty that may corrupt the performance of the FDI system. Therefore, the robustness of FDI filters should be properly considered such that un-modeled uncertainties will be compensated and no critical degradation in performance will occur.

The first model-based fault diagnosis filters were developed by Beard (1971) and Jones (1973). In the 1980s, a more general theory based on geometric concepts stemming was presented by Massoumnia (1986). In the early 2000s, Linear Parameter Varying (LPV) theory has been applied by Balas and Bokor (2004) and also to nonlinear systems (Loocma 2001). The first frequency domain approaches in FDI were developed in the late 1980s, when residual generator designs based on the factorization of system transfer matrices were introduced by Viswanadham and Minto (1988). Based on the appropriate selection of performance indexes, Ding and Frank (1990) found solutions to the $H\infty$ method of robust fault detection. The application of robust residual evaluation was then studied to improve the robustness of the filter for $H\infty$ optimization (Frank and Ding 1994). Some algorithms were developed to solve the $H\infty$ filtering problem by Edelmayer *et al.* (1997) and Mangoubi *et al.* (1995), and further on uncertainty blocks and weighting matrices to specifically deal with disturbances and modeling errors in $H\infty$ frame (Neimann and Stoustrup, 1996). Solutions to the $H\infty$ FDI filter design using an LMI-based approach for both normal linear systems and linear parameter-varying systems were given recently (Grigoriadis and Watson 1997, Nobrega *et al.* 2000, Abdalla *et al.* 2001, Vanga 2004). Recently, this design method has been implemented to detect sensor faults of civil structures such as base isolation structures using a magneto-rheological damper (Wang and Song 2011). Also, as an emerging research topic, similar FDI technologies have been applied many areas including PWM rectifiers (Youssef *et al.* 2013), permanent-magnet motors (Foo *et al.* 2013), winding machine applications (Rodrigues *et al.* 2013) and aircrafts (Rosa and Silvestre 2013), etc.

In recent years, magneto-rheological (MR) damper have been considered as new damping devices in various structures including vehicles, civil structures and space structures. The magneto-rheological fluid that responds to applied magnetic fields is used in MR dampers. The magneto-rheological fluid will change their viscosity according to the applied magnetic field and exhibit nonlinear properties like a typical Bingham fluid. The force generated by MR dampers can be controlled by adjusting the electric current supplied to the electromagnets. The advantage of this adaptive-passive system lies in its fail-safe design. Unlike the active control, which requires active energy for vibration suppression, the MR damper utilizes its passive properties in the event of energy loss. Because of their controllability and fast response, MR dampers have been developed as semi-active vibration suppression devices by Spenser *et al.* (1998) and applied on space truss structures in recent years (Oh and Onoda 2002, Huo *et al.* 2012). However, if faults occur on the feedback sensors or MR damper, the performance of semi-active controllers may be degraded. Thus, fault detection and isolation systems will be helpful to maintain the performance in the presence of faults.

To demonstrate the effectiveness of proposed methodology, this paper aims to equip a numerical space truss structure with a robust FDI filter for both sensor and actuator, and furthermore a nonlinear FFTC based semi-active control which can preserve structural performance in the presence of faulty feedback signals. Computer simulations of a space truss structure with an MR damper are shown to demonstrate the effectiveness of FDI filter and FFTC.

The remainder of the paper is organized as follows: in Section 2, an example of space truss structure is presented and properly modeled. The method to design a FDI filter using LMI is introduced in Section 3. This is followed by the design philosophy of FFTC in Section 4, which is applied to the MR damper in the space truss structure example. Numerical simulation results corresponding to previous sections are given and discussed in Section 5. In Section 6, conclusions are drawn with some comments.

2. Space truss structure example

A space truss structure model is used as a testing platform for the semi-active fuzzy logic controller, FDI filters, and FFTC. The details of the truss model are shown below:

This 8-bay planar aluminum truss structure consists of 109 rod elements connected at 36 nodes (Huo *et al.* 2012). The total length of the truss is 4m with each bay at 0.5 m long, and the rod elements having a Young's modulus of $E = 7.58\times 10^7 N / m^2$. All the members are 0.1 in. thick hollow tubes with an outer diameter of 0.5 in.

The truss can be simplified as a finite element model as shown in Fig. 1. This truss has an electromechanical shaker mounted for excitation at the node 4. Four identical accelerometers are mounted for the monitoring of vibrations on the truss at nodes 1, 9, 13 and 17, respectively. A Magneto-Rheological (MR) damper is installed between nodes 32 and 36 to minimize the vibration of the truss. In the numerical simulation, the MR damper is assumed to be a linear actuator in the space truss structure.

By using the finite element method, the space truss structure model can be represented by a state-space equation model (order of 108×108) and then simulated in MATLAB/Simulink. The first resonance frequency of the structural model is at 13.68 Hz (85.95 rad/sec).

3. Fault detection and isolation filter design

Consider a system plant P of order n_p with state-space representation as below

$$\begin{aligned} \dot{x}(t) &= A_p x(t) + B_p u(t) + Ed(t) + Ff(t) \\ y_p(t) &= C_p x(t) + D_p u(t) + Gd(t) + Hf(t) \end{aligned} \tag{1}$$

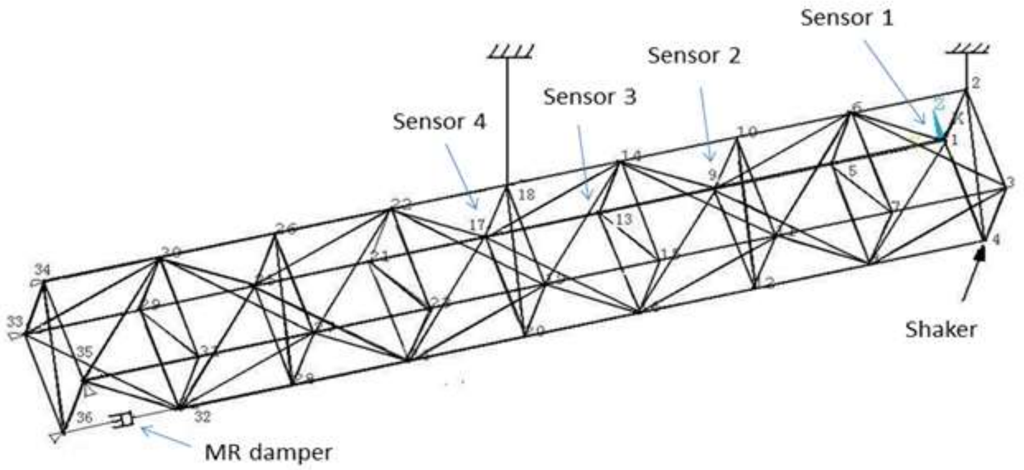

Fig. 1 Finite element model of the space truss structure

where $x(t)$ is the state vector, $u(t)$ is the control input, $d(t)$ is the disturbance, $f(t)$ is the fault vector, and A_p, B_p, C_p, D_p, E and G are real matrices of appropriate dimensions. F and H are distribution matrices that model sensor and actuator additive faults. A block diagram representing the proposed configuration is shown in Fig. 2.

In Fig. 2, Plant represents the base isolation to be monitored and FDI filter is the unknown filter which will be determined. The estimation error, e, is given by $e = r - f$, where r is the residual from the FDI filter. In summary, the main objective of this section is to design this unknown filter such that r can provide an estimation of fault vector f, and to minimize the estimation error e.

Based on the formulation above, the proposed H_∞ optimal filtering problem is to find an FDI dynamic filter to minimize the worst-case estimation error energy over all bounded energy generalized disturbances, $\omega^T = \begin{bmatrix} u^T & d^T & f^T \end{bmatrix}$, that is

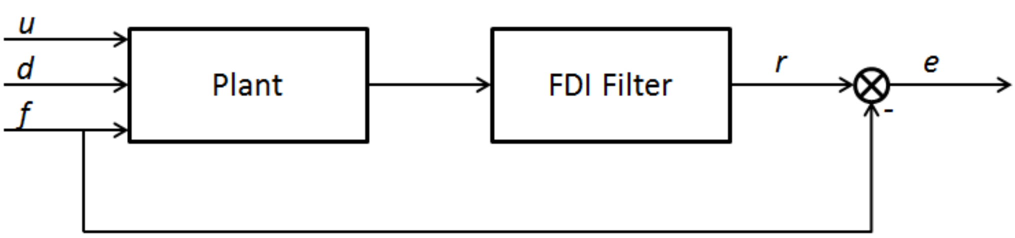

Fig. 2 Block diagram of the plant and FDI filter configuration

$$\min_{F} \sup_{\omega \in L_2 - \{0\}} \frac{\|e\|_{L2}}{\|\omega\|_{L2}} \tag{2}$$

where $L2$ denotes the vector norm.

Adopting the index in Eq. (1) is equivalent to minimizing the H$_\infty$ norm of the transfer function $T_{\omega e}$ between the generalized disturbance input and the error of the fault estimation. Therefore, the ã-suboptimal H$_\infty$ FDI filtering problem is to find, if it exists, a filter such that $\|T_{\omega e}\| < \gamma$, where γ is a given positive scalar.

The block diagram in Fig. 2 can be rearranged as in Fig. 3, where ω is the combined vector of system input, disturbances, and faults. Using the configuration in Fig. 2, the corresponding state-space linear fraction transformation is given by

$$\begin{aligned} \dot{x}_s &= A_p x_s + B_\omega \omega \\ e &= D_{e\omega}\omega + I_{nf} r \\ y &= C_y x_s + D_{y\omega}\omega \end{aligned} \tag{3}$$

where x_s is the state vector, $y^T = \begin{bmatrix} u^T & y_p^T \end{bmatrix}$ is the combined output vector, $\omega^T = \begin{bmatrix} u^T & d^T & f^T \end{bmatrix}$ is the combined vector of inputs, disturbance and faults, and $B_\omega = \begin{bmatrix} B_p & E & F \end{bmatrix}$, $D_{e\omega} = \begin{bmatrix} 0_{nf\times nu} & 0_{nf\times nd} & -I_{nf} \end{bmatrix}$, $C_y = \begin{bmatrix} 0_{nf\times nu} \\ C_p \end{bmatrix}$, $D_{e\omega} = \begin{bmatrix} I_{nu} & 0_{nu\times nd} & 0_{nu\times nf} \\ D_p & G & H \end{bmatrix}$. nu, nd, nf are the length of input vectors u, d, f, respectively.

The objective is to design a stable linear full-order filter with the following state-space representation

$$\begin{aligned} \dot{x}_f &= A_f x_f + B_f y \\ r &= C_f x_f + D_f y \end{aligned} \tag{4}$$

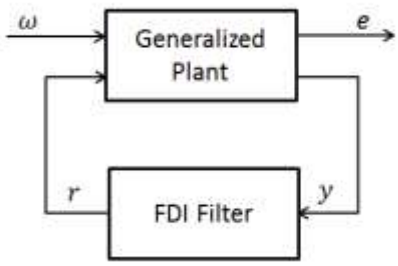

Fig. 3 Linear fraction transformation scheme of plant and filter

where the output r is the residual estimating faults, x_f is the filter state vector and A_f, B_f, C_f and D_f are real matrices of appropriate dimensions to be computed. The order of the filter, n_f, is equal to the order of the system, n_s. The unknown filter matrix is defined as $F = \begin{bmatrix} D_f & C_f \\ B_f & A_f \end{bmatrix}$.

An LMI-based approach is used to find a filter *F* based on the Bounded Real Lemma presented below:

LEMMA 1 (Bounded Real Lemma) (Nobrega *et al.* 2000) Consider a stable linear time invariant system with state space model

$$\begin{aligned} \dot{x}_c &= A_c x_c + B_c \varpi \\ y &= C_c x_c + D_c \varpi \end{aligned} \tag{5}$$

with transfer function $T_c(s) = C_c(sI - A)^{-1} B_c + D_c$ and let γ be a given positive scalar. Then $\|T_{\omega e}\|_\infty < \gamma$ if and only if there exists matrix $P > 0$ that satisfies

$$\begin{bmatrix} PA_c + A_c^T P & PB_c & C_c^T \\ B_c^T P & -\gamma^2 I & D_c^T \\ C_c & D_c & -I \end{bmatrix} < 0 \tag{6}$$

To find the solvability conditions of the LMI problem in Eq. (6), the Projection Lemma will be applied.

LEMMA 2 (Projection Lemma) (Nobrega *et al.* 2000) Let Γ , Λ and $\Theta = \Theta^T$ be given matrices. There exists a matrix F to solve the matrix inequality

$$\Theta + \Gamma F \Lambda + (\Gamma F \Lambda)^T < 0 \tag{7a}$$

if and only if the following conditions are satisfied

$$\begin{aligned} \Gamma^T \Theta \Gamma^{\perp T} &< 0 \\ \Lambda^{T\perp} \Theta \Lambda^{T\perp T} &< 0 \end{aligned} \tag{7b}$$

Lemma 1 and 2 may be applied for the FDI filter to provide the necessary and sufficient conditions for the existence of such filter and parameterization of all solutions. The following theorem gives the solution to the γ *-suboptimal* H_∞ FDI filtering problem.

THEOREM 1 (Grigoriadis and Watson 1997) *There exists an n_f-th order filter F to solve the γ-suboptimal H_∞ FDI filtering problem if and only if there exist matrices X and Y such that the following conditions are satisfied*

$$\begin{bmatrix} XA_s + A_s^T X & XB_\omega \\ B_\omega^T X & -\gamma^2 I \end{bmatrix} < 0 \tag{8a}$$

$$\begin{bmatrix} C_y^T \\ D_{y\omega}^T \end{bmatrix}^{\perp} \begin{bmatrix} YA_s + A_s^T Y & YB_\omega \\ B_\omega^T Y & D_{e\omega}^T D_{e\omega} - \gamma^2 I \end{bmatrix} \begin{bmatrix} C_y^T \\ D_{y\omega}^T \end{bmatrix} < 0 \tag{8b}$$

$$\begin{bmatrix} X & I \\ I & Y \end{bmatrix} \geq 0 \tag{8c}$$

$$rank(Y - X) \leq n_f \tag{8d}$$

Proof of the theorem is provided by Grigoriadis and Watson (1997).

The filtering error dynamics can be described by the following augmented system

$$\begin{aligned} \dot{\bar{x}} &= (\bar{A} + \bar{B}F\bar{M})\bar{x} + (\bar{D} + \bar{B}F\bar{E})\omega \\ e &= (\bar{C} + \bar{H}F\bar{M})\bar{x} + (\bar{G} + \bar{H}F\bar{E})\omega \end{aligned} \tag{9}$$

where $\bar{x}^T = \begin{bmatrix} x_s^T & x_f^T \end{bmatrix}$, $\bar{A} = \begin{bmatrix} A_p & 0 \\ 0 & 0 \end{bmatrix}$, $\bar{D} = \begin{bmatrix} B_\omega \\ 0 \end{bmatrix}$, $\bar{C} = 0$, $\bar{G} = D_{e\omega}$, $\bar{B} = \begin{bmatrix} 0 & 0 \\ 0 & I \end{bmatrix}$, $\bar{M} = \begin{bmatrix} I & 0 \\ 0 & C_y \end{bmatrix}$, $\bar{E} = \begin{bmatrix} D_{y\omega} \\ 0 \end{bmatrix}$, $\bar{H} = \begin{bmatrix} I & 0 \end{bmatrix}$.

According to Bounded Real Lemma 1, the error transfer functions has H_∞ norm less than γ if and only if there exists a matrix P>0 such that

$$\begin{bmatrix} P(\bar{A} + \bar{B}F\bar{M}) + (\bar{A} + \bar{B}F\bar{M})^T P & P(\bar{D} + \bar{B}F\bar{E}) & (\bar{C} + \bar{H}F\bar{M})^T \\ (\bar{D} + \bar{B}F\bar{E})^T P & -\gamma^2 I & (\bar{H}F\bar{E})^T \\ \bar{C} + \bar{H}F\bar{M} & \bar{H}F\bar{E} & -I \end{bmatrix} < 0 \tag{10}$$

Using Projection Lemma 2, this matrix inequality can be written in the general matrix inequality form Eq. (7(a))

$$\Gamma = \begin{bmatrix} P\bar{B} \\ 0 \\ \bar{H} \end{bmatrix}, \quad \Lambda^T = \begin{bmatrix} M^T \\ E^T \\ 0 \end{bmatrix}, \text{ and } \Theta = \begin{bmatrix} P\bar{A} + \bar{A}^T P & P\bar{B} & 0 \\ \bar{B}^T P & -\gamma^2 I & \bar{D}^T \\ 0 & \bar{D} & -I \end{bmatrix} \tag{11}$$

Define the following partitioning for P and P^{-1}

$$P = \begin{bmatrix} Y & Y_{12} \\ Y_{12}^T & Y_{22} \end{bmatrix}, P^{-1} = \begin{bmatrix} Z & Z_{12} \\ Z_{12}^T & Z_{22} \end{bmatrix} \tag{12}$$

Eq. (7(b)) of Lemma 2 results in

$$XA + A^T X + \frac{1}{\gamma^2} XBB^T X < 0 \tag{13}$$

where $X = Z^{-1}$, which provides Eq. (8(a)) of Theorem 1 and similarly the other condition in Eq. (7(b)) of Lemma 2 will result in Eq. (8(b)). Therefore, the 1-1 block equation of P and P^{-1} in Eq. (12) gives:

$$Y - Z^{-1} = Y - X = Y_{12} Y_{22}^{-1} Y_{12}^T \geq 0 \tag{14}$$

Since Y_{22} can be set in an $n \times n$ positive definite matrix, $Y \geq X$ and $rank(Y - X) \leq n_f$ are guaranteed.

Hence, the γ-suboptimal H_∞ FDI filtering problem becomes a feasibility problem to find a pair of positive definite matrices (X, Y) in the constraints of Eqs. (8(a)), (8(b)) and (8(d)). Furthermore, the optimal H_∞ FDI filter needs to minimize γ subject to the constraints of Eq. (8(a)), (8(b)) and (8(d)).

In summary, if faults are considered, by properly selecting matrices in Eq. (1) and applying the design procedure shown in this section, an FDI filter will be achieved to minimizing the H_∞ norm of the transfer function $T_{\omega e}$ between the generalized disturbance input and the error of the fault estimation.

4. Fuzzy fault tolerant controller design

Since an MR damper is used in the numerical example in Section 2, and due to its nonlinearity, it is not easy to obtain the nonlinear mathematical model to design the fault tolerant controller. Therefore, model based controllers shall not be applied in this paper. In order to design a suitable controller using MR damper, a fuzzy logic controller which is based on the expert experience rather than the system model, is chosen to drive the MR damper. Hence, by applying the FDI design procedure in previous section, an innovative fuzzy fault tolerant controller, as shown in Fig. 4, is developed to suppress the vibration of the space truss structure in the presence of faulty sensor and actuator signals.

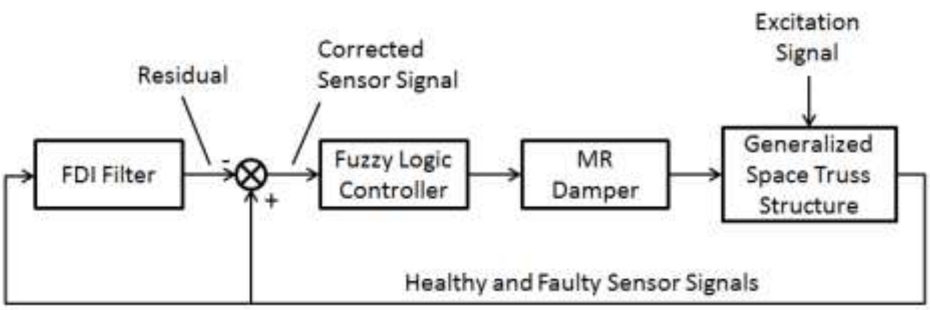

Fig. 4 Block diagram of FFTC with base isolation system

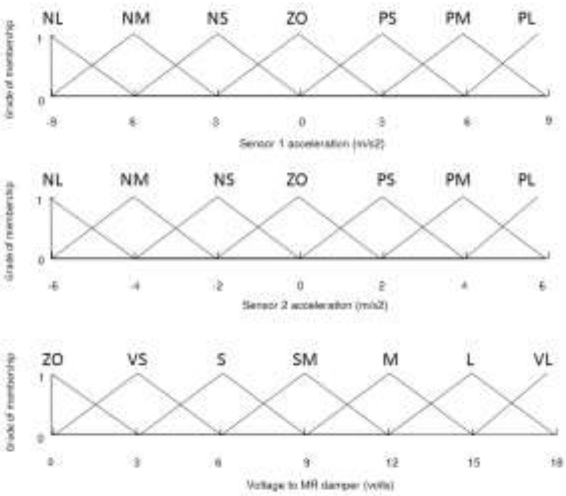

Fig. 5 Membership functions of the fuzzy logic controller for space truss structure

The FDI filter design, shown in Section 3, is implemented on each sensor (accelerometer) and the MR damper accordingly to detect and isolate the unknown faults. Due to the nonlinearity of MR dampers, a fuzzy logic controller was chosen as a semi-active control algorithm to control the voltage to the MR damper with the feedback of accelerations of sensor 1 and sensor 2; all membership functions, shown in Fig. 5, and rules, shown in Table 1, are designed and adjusted based on system performance. If faults and an FDI filter are introduced into the fuzzy logic controller, combining the fault detection and isolation filter design, then the space truss structure with FFTC should behave according to the diagram as shown in Fig. 4.

When the accelerations of sensor 1 and sensor 2 are both Positive Large (PL), or both Negative Large (NL), or one of each, the voltage of the MR damper should be Very Large (VL) to generate a large damping force. Otherwise, the voltage should be small. The rule-base of the fuzzy logic controller is shown in Table 1.

Table 1: Rules-base of fuzzy logic controller for the space truss structure
(Row: Sensor 1 feedback; column: Sensor 2 feedback)

	NL	NM	NS	ZO	PS	PM	PL
NL	VL	L	M	SM	M	L	VL
NM	L	M	SM	S	SM	M	B
NS	M	SM	S	VS	S	SM	M
ZO	SM	S	VS	ZO	VS	S	SM
PS	M	SM	S	VS	S	SM	M
PM	L	M	SM	S	SM	M	L
PL	VL	L	M	SM	M	L	VL

5. Numerical simulation

In order to reduce the calculation in the FDI filter design, the finite element method model (state-space model with order of 108×108) described in Section 2 is reduced to a 12×12 state-space model as shown in Eq. (15) using model decomposition, and then the FDI design method of Section 3 is applied to achieve the FDI filters.

$$\begin{aligned}\dot{x}(t) &= \underbrace{\begin{bmatrix} \underset{6\times6}{0} & \underset{6\times6}{I} \\ A_1 & A_2 \end{bmatrix}}_{A_p} x(t) + \underbrace{\begin{bmatrix} \underset{6\times1}{0} \\ B_1 \end{bmatrix}}_{B_p} u(t) \\ y(t) &= \underbrace{\begin{bmatrix} \underset{6\times6}{I} \end{bmatrix}}_{C_p} x(t) + \underbrace{\begin{bmatrix} \underset{6\times1}{0} \end{bmatrix}}_{D_p} u(t)\end{aligned} \tag{15}$$

where

$A_1 = diag(7.31e3, -5.81e4, -1.73e5, -4.75e5, -5.05e5, -5.87e5)$ is a 6×6 diagonal matrix,

$A_2 = diag(-1.71, -4.82, -11.84, -30.35, -30.21, -37.20)$ is a 6×6 diagonal matrix,

$B_1 = \begin{bmatrix} -0.45 & -0.21 & 0.34 & -0.22 & -0.02 & -0.03 \end{bmatrix}^T$.

Therefore, the model simplification is introduced to the system as model uncertainties, which can be further used to prove the robustness of the proposed FDI approach. To simulate both high and low frequency faults for the space truss structures, the residuals to two types of faulty inputs are examined: band-limited white noise faults and single frequency sinusoid faults, respectively.

Since the fault detection and isolation results of all sensors are fairly similar, only the results on sensor 1 will be shown as an example. By applying the FDI filter to sensor 1, Fig. 6 shows the FDI filter detection result with band-limited white noise fault and Fig. 7 shows the result with sinusoid fault.

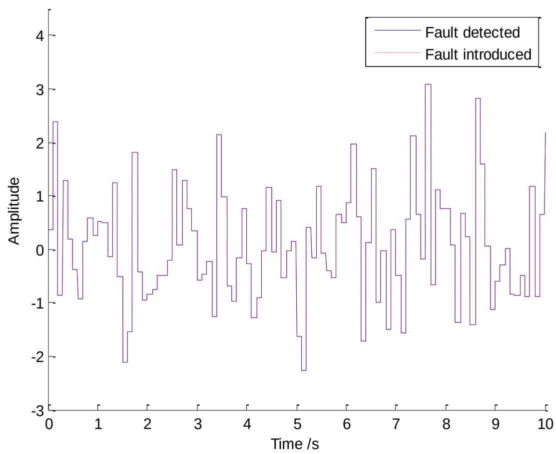

Fig. 6 FDI filter result on sensor1 with band-limited white noise fault

Therefore, as shown above, the calculated residual can successfully track various types of introduced sensor faults with model uncertainties. Difference between introduced fault and residual (detected fault) is nearly invisible in Figs. 6 and 7, and thus, a zoom in picture of Fig. 6 is shown in Fig. 8. As observed in Fig. 8, the isolating errors between the residual and the fault with a mean square error of 1.8e-5 m/s^2 can be observed but should be tolerable in most applications.

By applying the FDI filter for the faults of the MR damper, Fig. 9 shows the FDI filter detection result with band-limited white noise fault and Fig. 10 shows the result with sinusoid fault.

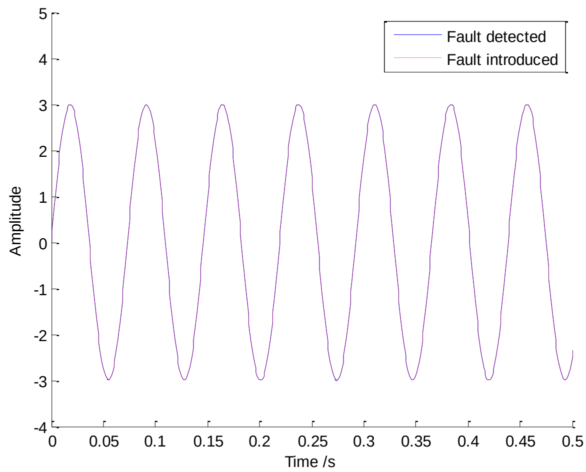

Fig. 7 FDI filter result on sensor1 with sinusoid fault

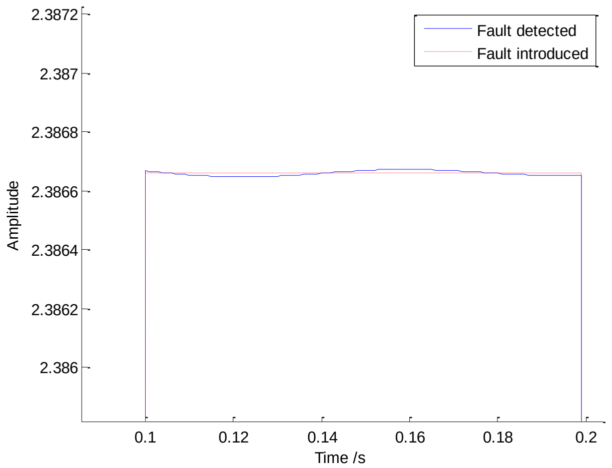

Fig. 8 Zoom-in of FDI filter result on sensor1 with band-limited white noise fault

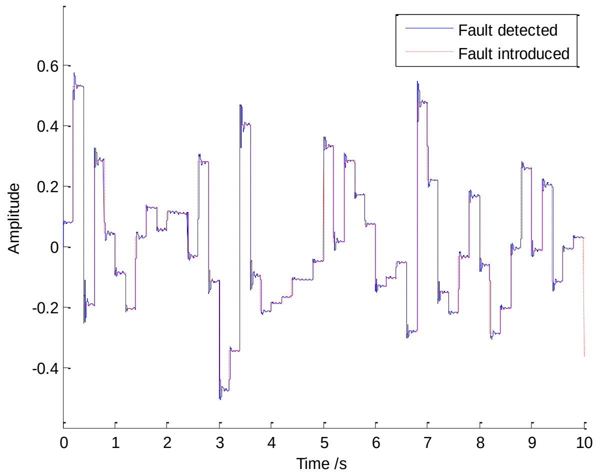

Fig. 9 FDI filter result of MR damper with band-limited white noise fault

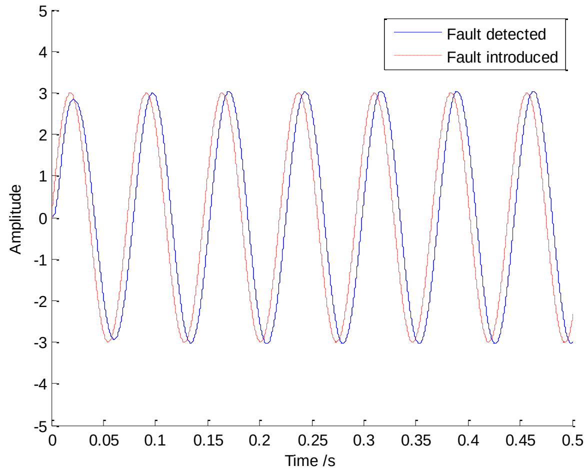

Fig. 10 FDI filter result of MR damper with sinusoid fault

Similarly, it is clear that the residuals identify various types of faults that occur on the MR damper. Small delays and oscillations can be found in the Figs. 9 and 10. Most importantly, the FDI filter still tracks the faults with limited errors. Therefore, it is proven that the designed FDI filters can detect the unknown faults from both the sensors and MR damper of the space truss structure with model uncertainties and faults from both sensors and actuators.

As introduced in Section 1, faulty signals in the feedback loop may dramatically impair the controller performance. In the numerical simulation, two types of input are applied to the space truss model to validate the performance of the proposed FFTC. One is a sinusoid wave with a frequency of 85.95 rad/sec, which is the first modal excitation, and the other input is a chirp signal with a frequency range from 0.63 rad/sec to 125 rad/sec. Thus, a comparison of fuzzy logic controller and FFTC performance is conducted to demonstrate the effectiveness of the FFTC in the presence of the sinusoid fault on MR damper as shown in Fig. 10. Fig. 11 presents the vibration performance of the fuzzy logic controller with and without the MR damper fault under the sinusoid wave input.

As shown in Fig. 11, considering no fault is presented, the red solid curve represents the performance of the fuzzy logic controller, and the blue dash curve represents no control actions. By introducing the fuzzy logic controller, the vibration (maximum amplitude) has been reduced by around 60%, which proves the effectiveness of the fuzzy logic controller on the space truss structure. However, when the MR damper fault is introduced, the black dot curve shows the faulty fuzzy logic controller performance with faulty feedback signals. Obviously the controller is degraded and incapable to preserve the performance as effectively.

Thus, the FFTC is applied to isolate the MR damper fault, and to suppress the vibration and compare with faulty fuzzy logic controller performance as shown in Fig. 12.

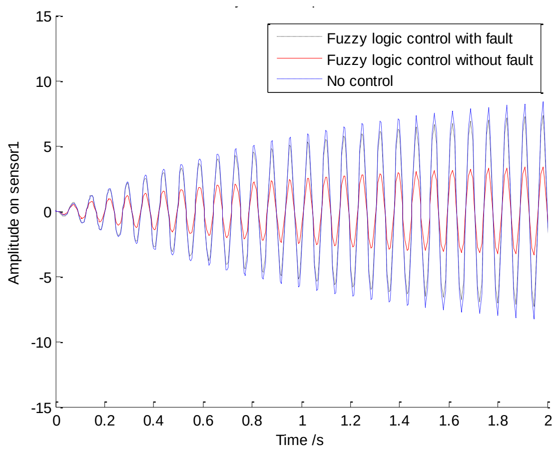

Fig. 11 Fuzzy logic controller simulation performance on space truss structure (sinusoid wave input)

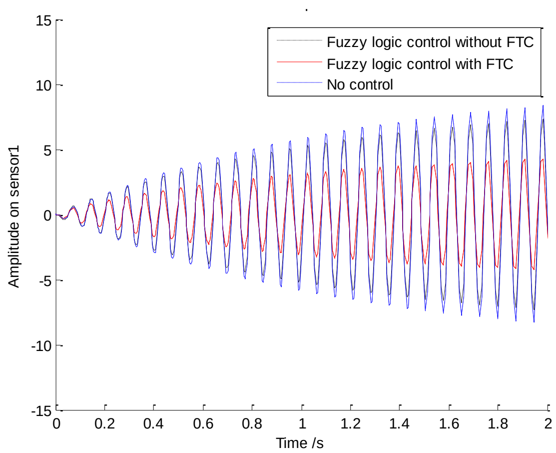

Fig. 12 FFTC simulation performance on space truss structure (sinusoid wave input)

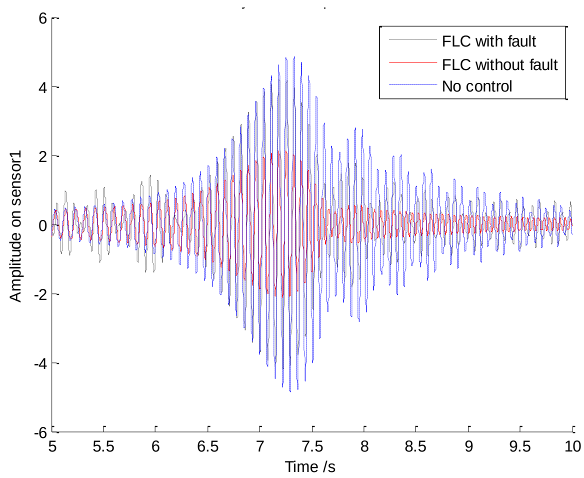

Fig. 13 Fuzzy logic controller simulation performance on space truss structure (chirp signal input)

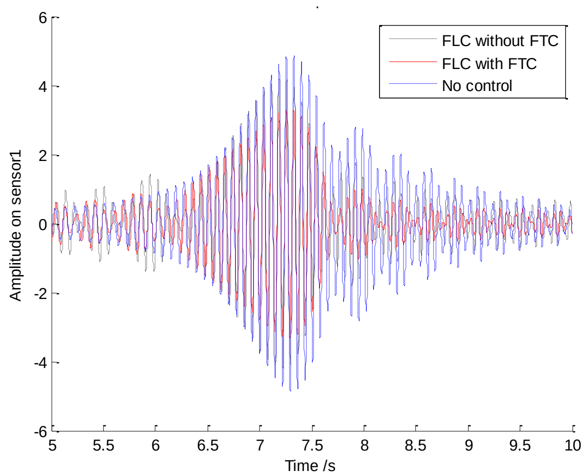

Fig. 14 FFTC simulation performance on space truss structure (chirp signal input)

In Fig. 12, the red solid curve represents the performance of FFTC. Although the vibration suppression is around 50% and does not perfectly match the fuzzy logic controller performance without fault in Fig. 11, the FFTC still significantly reduces the consequence of the faulty signals on the controller.

The second input of a chirp signal with a frequency range from 0.6 rad/sec to 125 rad/sec is also applied to exam the FFTC performance for non-single frequency response. Since the vibration in low frequency part is relatively limited, only high frequency part is shown in the Figs. 13 and 14 below. Similar to the sinusoid wave input, Fig. 13 presents the performance of the fuzzy logic controller (FLC).

When fault is not presented, with the utilization of the fuzzy logic controller, the structural vibration (maximum amplitude) has been significantly reduced by 60% comparing the red solid curve and the blue dash curve. When the MR damper fault is introduced, the fuzzy logic controller is not capable to preserve its performance as designed. For some ranges, the controller is behaving even worse than no control actions. Hence, Fig. 14 shows the effect of the FFTC.

With the utilization of the FFTC, the structural vibration has been reduced by about 30% in the presence of the sensor fault. Because the detection errors and delays as shown in Fig. 10, the FFTC performance cannot competing with the fuzzy logic controller without fault but still present a decent result comparing with non-fault tolerant controller. If only consider sensor faults, the results of FFTC shall be better.

In summary, despite the fault types of white noise or sinusoid signals, the fault locations on sensors or MR dampers, the excitation input to the structure either a sinusoid excitation or a chirp excitation, FDI filter can always detect the introduced fault and FFTC can preserve the controller performance in a reasonable manner.

6. Conclusions

In this paper, a new approach to deal with sensor errors in structural vibration control was presented. A model-based fault detection and isolation (FDI) filter and fuzzy fault tolerant controller (FFTC) based on $H\infty$ technique was developed for the advanced vibration control. By using Linear Matrix Inequalities, the FDI filter was designed to detect various types of faulty signals from the sensors and the MR damper with modeling uncertainties and measurement noise. Furthermore, to tolerate faulty feedback signals, an FFTC based semi-active control was applied to preserve the structural performance in the presence of faults. To validate the effectiveness of the proposed methodology, a numerical space truss structure using a semi-active MR damper was built and used. Through numerical simulation, the residuals obtained from the FDI filter successfully followed the introduced various types of faulty signals and thus the $H\infty$ FDI design solved the problem of bounded model uncertainties. Given various input signals, the designed FFTC achieved reasonable vibration suppression, and reduced the consequence of the faulty signals of the MR damper.

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