An observer-based fault tolerance control system with a static filter and its application to high-rise buildings

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Abstract
This article proposes a fault tolerance control (FTC) system that composes of a state observer and a static filter, which can eliminate the adverse effects of sensor failures on the active mass damper control system of high-rise buildings and realize fault detection and isolation. First, the accurate acceleration responses are obtained through a static filter that is used for minimizing the differences between the estimated and actual feedback signals. The key point is transformed into a gain optimization problem solved by a linear matrix inequality approach. Then, a state observer uses the detected and isolated acceleration responses as the feedback signals to estimate the whole states, which are used to calculate the control forces. Finally, a new observer-based FTC system is accomplished for high-rise buildings. To verify its effectiveness, the proposed methodology is applied to a numerical example and an experimental system. The results demonstrate that the fault tolerance controller has a good performance and stable control parameters, which provides good potential for structural vibration control of high-rise buildings.

KEYWORDS
active mass damper/driver, active structural control, fault tolerance control, high-rise buildings, linear matrix inequality, smart structure

1 INTRODUCTION

Active mass dampers (AMD),¹⁻³ active tuned mass dampers,⁴⁻⁷ and passive tuned mass dampers⁸⁻¹¹ have been used for controlling the dynamic responses of civil engineering structures under strong horizontal loads, for example, strong winds or moderate earthquakes. Theoretically, the performance of an AMD control system is more effective. However, different...
types of failures restrict the development of the AMD control system. These failures include four varieties, complete failure, fixed deviation, drift deviation, and accuracy decrease.

Various sensors are set up to measure the structural responses that are regarded as feedback signals to an AMD control system. Generally, the state vectors of each floor include its horizontal displacement and velocity responses that are too difficult to be measured directly. Therefore, a state observer is important for high-rise buildings with an AMD control system. References 14-17 showed that state observers were beneficial to linear uncertain systems and nonlinear systems. Compared with the horizontal displacement and velocity responses, the horizontal acceleration signals are easier to be measured. Therefore, the AMD control system based on acceleration feedback is more robust. However, accelerometers are easy to introduce fault signals which lead to a large estimation error and reduce the control performance. It is necessary to research deeply to improve the fault tolerance and robustness of observer-based systems. Such improved process is often based on a fault tolerance control (FTC) technology. The principal methods for establishing a FTC system includes an analytical and hardware redundancy method. The hardware redundancy method aims to provide backup hardware for the components that are prone to failure. Disadvantageously, it increases hardware costs and occupies too much available space. In order to be more appropriate in structural vibration control of high-rise buildings, the analytical redundancy method, which improves the system redundancy through the optimal design of its control gains, has attracted attentions.

A FTC system with an analytical redundancy method contains a passive system and an active system. The passive system is regarded as a traditional robust system without online fault identification. On the other hand, the active system utilizes a fault detection and isolation (FDI) technology to realize the online fault identification. A sensor fault compensation system was based on a FDI system and a model predictive control strategy in Reference 30. The results show the reliability of the method to detect and isolate the sensor failure and regulate the steam temperature. In Reference 31, multiple high-order sliding-mode observers with FDI problems were proposed for a certain class of nonlinear systems. A fully decentralized approach towards FDI of autonomous sensors was presented for wireless structural health monitoring systems in Reference 32. Then, a robust FDI scheme was proposed for linear discrete-time systems subject to faults, bounded additive disturbances and norm-bounded structured uncertainties in Reference 33. Similarly, a dynamic filter design method was developed and presented in Reference 34 to overcome the failures in sensors. Even with various fault signals, the control performances of a FTC system with the dynamic filter were stable. However, there are difficulties to achieve a fault-tolerance control process in engineering practices through hardware devices. Future efforts would be focused on a static FDI filter shown as a filter gain matrix to achieve the conversion between the measurement and real outputs. To solve the optimal filter gain easily, a linear matrix inequality (LMI) approach has been widely used. For instance, Reference 36 had a study on the robust fault detection filter design problem for linear time invariant systems with unknown inputs and modeling uncertainties. Besides, the optimal solution of a H∞ model-matching problem was then presented via a LMI formulation. Reference 37 proposed actuator fault diagnosis of neutral delayed systems with multiple time delays using an unknown input observer that was formulated in terms of linear matrix inequalities. In conclusion, the design problem of a static FDI filter can be transformed into a group of nonlinear matrix inequalities, which can be converted into a group of convex and easily solved linear matrix inequalities.

In this article, the state-space equation of an AMD control system with fault signals is derived first. Then based on a LMI approach, a static filter is built to detect and isolate fault signals through minimizing the difference between the estimated system and the actual system. The detected and isolated signals are regarded as the input of the designed state observer to estimate the whole states, which are used to calculate the control forces of the AMD system. Finally, an observer-based FTC system is completed for a numerical frame and an experimental frame. The control effects and the AMD parameters are used as the control indexes to verify the efficiency of the proposed method.

### 2 AN AMD CONTROL SYSTEM WITH FAULT SIGNALS

Fault signals are introduced into an AMD control system that are assumed to follow the form described in Reference 38. Focusing on a high-rise building \(n\) degrees of freedom, the force equilibrium of its AMD control system is

\[
M_0\ddot{X}(t) + C_0\dot{X}(t) + K_0X(t) = B_ww(t) + B_uu(t) + B_df(t)
\]

(1)
where \( M, C, \) and \( K \) are the mass matrix, the damping matrix and the stiffness matrix of a high-rise building with an AMD control system, respectively. \( u, w \) and \( f \) are the control forces, the external excitations and the fault signals, respectively. \( B_u, B_w, \) and \( B_e \) are the position matrices of the control forces, the external excitations and the fault signals, respectively. \( X \) is the displacement vectors.

The matrices \( M, C, K, B_u, B_w, \) and \( X \) are expressed as

\[
M = \begin{bmatrix} m_1 & 0 & 0 & 0 \\ 0 & \ddots & 0 & 0 \\ 0 & 0 & m_n & 0 \\ 0 & 0 & 0 & m_a \end{bmatrix}_{(n+1) \times (n+1)}, \quad C = \begin{bmatrix} c_1 + c_2 & -c_2 & 0 & 0 \\ -c_2 & \ddots & -c_n & 0 \\ 0 & \ddots & -c_n & c_n + c_a - c_d \\ 0 & 0 & -c_a & c_a \end{bmatrix}_{(n+1) \times (n+1)}, \quad K = \begin{bmatrix} k_1 + k_2 & -k_2 & 0 & 0 \\ -k_2 & \ddots & -k_n & 0 \\ 0 & \ddots & -k_n & k_n + k_a - k_a \\ 0 & 0 & -k_a & k_a \end{bmatrix}_{(n+1) \times (n+1)}.
\]

\[
X = \begin{bmatrix} x_{s1} \\ \vdots \\ x_{sn} \\ x_a \end{bmatrix}_{(n+1) \times 1}, \quad B_u = \begin{bmatrix} 0 \\ \vdots \\ 0 \\ -1 \\ 1 \end{bmatrix}_{(n+1) \times 1}, \quad B_w = -[1]_{(n+1) \times (n+1)} \]

where \( x_{si} \) is the absolute displacements of the \( i \)th floor and \( x_a \) is the relative displacements of the auxiliary mass. \( m_i, c_i, \) and \( k_a \) are the mass, the damping, and the stiffness of the auxiliary mass, respectively. \( m_l, k_l, \) and \( c_l \) are the mass, the interstorey stiffness, and the damping of the \( l \)th floor, respectively.

The state vectors \( Z \) of the system include the displacements and the velocities. The output vectors \( Y \) include the displacements, the velocities, and the accelerations. Specifically, the displacements and velocities are used to verify the control effect of an AMD system, and the accelerations are used to observe the whole states. Therefore, Equation (1) is expressed into the state-space equation as

\[
\begin{aligned}
Z(t) &= AZ(t) + B_1w(t) + B_2u(t) + Ef(t) \\
Y(t) &= CZ(t) + D_1w(t) + D_2u(t) + Ff(t)
\end{aligned}
\]  

(3)

where \( A, B_1, \) and \( B_2 \) are the state matrix, the excitation matrix, and the control matrix. \( C, D_1, \) and \( D_2 \) are the state output matrix, the direct transmission matrices of the control forces and the external excitations, respectively. \( E \) and \( F \) are the influence matrices of the fault signals on the state equation and the observation equation. These matrices are expressed as

\[
A = \begin{bmatrix} 0 & I \\ -M_0^{-1}K_0 & -M_0^{-1}C_0 \end{bmatrix}_{2(n+1) \times 2(n+1)}, \quad B_1 = \begin{bmatrix} 0 \\ M_0^{-1}B_u \end{bmatrix}_{2(n+1) \times (n+1)}, \quad B_2 = \begin{bmatrix} 0 \\ M_0^{-1}B_w \end{bmatrix}_{2(n+1) \times (n+1)}, \quad E = \begin{bmatrix} 0 \\ M_0^{-1}B_e \end{bmatrix}_{2(n+1) \times (n+1)}.
\]

\[
C = \begin{bmatrix} I \\ 0 \\ -M_0^{-1}K_0 & -M_0^{-1}C_0 \end{bmatrix}_{3(n+1) \times 2(n+1)}, \quad D_1 = \begin{bmatrix} 0 \\ 0 \\ M_0^{-1}B_w \end{bmatrix}_{3(n+1) \times (n+1)}, \quad D_2 = \begin{bmatrix} 0 \\ 0 \\ M_0^{-1}B_e \end{bmatrix}_{3(n+1) \times (n+1)}, \quad F = \begin{bmatrix} 0 \\ 0 \\ M_0^{-1}B_e \end{bmatrix}_{3(n+1) \times (n+1)}.
\]

(4)

The system (3) is reflected in Figure 1. \( P \) is its mathematical model, and \( C_0 \) is an original controller. The system is regarded as increasing a new input when a part of sensors fail to work. When the fault signals cannot be timely eliminated, the control forces are negatively impacted.

3  |  INFLUENCE ANALYSIS OF AN OBSERVER-BASED FTC SYSTEM

3.1  |  Design principle

The static filter \( C_\xi \), which is shown as a gain matrix to achieve the conversion between the measurement and real outputs, is intended to estimate the actual states of the systems through a calculation model which is similar to the controlled structure. The difference \( r \) between the estimated and actual state vectors is regarded as the target outputs.
The static filter shown in Figure 2 is

\[
\begin{align*}
\dot{\hat{Z}}(t) &= A\hat{Z}(t) + B_2u(t) + K_f r(t) \\
\hat{Y}(t) &= C\hat{Z}(t) + D_2u(t) \\
r(t) &= \hat{Y}(t) - Y(t)
\end{align*}
\]  

(5)

where \( \hat{Z} \) and \( \hat{Y} \) are the estimated values of the state vectors and the output vector of the system, \( r \) is the detected fault signals, and \( K_f \) is the filter gain matrix of the static filter.

Equation (3) minus Equation (5), and then the residue equation of the state vectors is

\[
\begin{align*}
\ddot{\hat{Z}}(t) &= \tilde{\hat{A}}\hat{Z}(t) + \tilde{\hat{B}}W(t) \\
\hat{Y}(t) &= \tilde{\hat{C}}\hat{Z}(t) + \tilde{\hat{D}}W(t)
\end{align*}
\]

(6)

where

\[
\begin{align*}
\tilde{\hat{A}} &= A + K_f C, \tilde{\hat{B}} = \begin{bmatrix} B_1 + K_f D_1 & E + K_f F \end{bmatrix}, \tilde{\hat{C}} = -C, \tilde{\hat{D}} = -\begin{bmatrix} D_1 & F \end{bmatrix}, \\
\dot{Z}(t) &= Z(t) - \hat{Z}(t), \hat{Y}(t) = r(t), W(t) = \begin{bmatrix} w(t) & f(t) \end{bmatrix}^T, \\
Q &= \begin{bmatrix} \tilde{\hat{C}} \hat{A} & \tilde{\hat{C}}A^2 & \cdots & \tilde{\hat{C}}A^{m-1} \end{bmatrix}^T.
\end{align*}
\]  

(7)

From (7), the matrix \( Q \) is the observable matrix of the system (6) (\( m \) dimensions). The system (6) is regarded as a single-input system, so the observable matrix is an \( m \)-dimensional square matrix. The states of the system can be completely observable when its observable matrix \( Q \) satisfies that the rank is \( m \).

The static filter is completed for a control system, indicating that a relatively small error is obtained. The \( \text{H}_\infty \) norm of the transfer function between the interference inputs \( w_p \) (\( w_p = \begin{bmatrix} u & w^T \end{bmatrix} \)) and the target outputs is a given value, and its \( \text{H}_2 \) norm is minimized. The design process consists of the following two steps.

\( \gamma \) is a given positive scalar which represents the robust stability of the residue system. If and only if there exists a symmetric positive-definite matrix \( X_1 \) such that the following inequality holds.

\[
\begin{bmatrix}
\tilde{\hat{A}}X_1 + X_1\tilde{\hat{A}}^T & \tilde{\hat{B}} & X_1\tilde{\hat{C}}^T \\
\tilde{\hat{B}}^T & -I & \tilde{\hat{D}}^T \\
\tilde{\hat{C}}X_1 & \tilde{\hat{D}} & -\gamma^2I
\end{bmatrix} < 0
\]

(8)

The residue system (6) is stabilized with a \( \text{H}_\infty \) performance index according to Reference 39.

\( \eta \) is a positive scalar which represents the control performance of the residue system. If and only if there exists symmetric positive-definite matrices \( X_2 \) and \( Q \) such that the following inequalities hold.

\[
\begin{bmatrix}
\tilde{\hat{A}}X_2 + X_2\tilde{\hat{A}}^T + \tilde{\hat{B}}\tilde{\hat{D}}^T \\
-Q & \tilde{\hat{C}}X_2 \\
X_2\tilde{\hat{C}}^T & -X_2
\end{bmatrix} < 0
\]

\[
\text{trace}(Q) < \eta^2
\]

(9)

The residue system (6) is stabilized with a \( \text{H}_2 \) performance index according to Reference 40.
Owing to the filter gain matrix $K_f$ is coupling with the different matrices of $X_1$ and $X_2$, the variables $X_1$, $X_2$, and $Q$ are nonconvex and difficult to be solved. Therefore, a variable substitution method cannot be used to linearize these constraints. A public Lyapunov matrix is found to handle the problem.

$$X = X_1 = X_2$$ (10)

The optimization problem from inequalities (8) to (9) is summarized as

$$\min \eta$$ (11)

s.t. (1) Inequality (8); (2) Inequalities (9).

Both sides of the first inequality of inequalities (8) are pre- and postmultiplying $\text{diag}(X^{-1}, I, I)$. Defining $P = X^{-1}$, the matrix inequalities (11) are

$$\min \eta$$ (12)

s.t. \[
\begin{bmatrix}
\bar{A}^T P + P \bar{A} - I & \bar{C}

\bar{B}^T P & -\bar{D}^T

\bar{C} & \bar{D} - \gamma^2 I
\end{bmatrix} < 0
\]

$$\bar{A} P^{-1} + P^{-1} \bar{A}^T + \bar{B} \bar{B}^T < 0$$

$$\begin{bmatrix}
-Q & \bar{C} P^{-1}

P^{-1} \bar{C}^T & -P^{-1}
\end{bmatrix} < 0$$

$$\text{trace}(Q) < \eta^2$$

If and only if there exists symmetric positive-definite matrices $P$ and $Q$ such that the above inequalities hold, the system (3) has a $H_2/H_{\infty}$ filter. The second inequality of inequalities (12) can be satisfied by the first inequality.

By substituting Equation (7) into inequalities (12), then

$$\min \eta$$ (13)

s.t. \[
\begin{bmatrix}
(A + K_f C)^T P + P (A + K_f C)^T P [B_1 + K_f D_1] E + K_f F & \bar{C}^T

\bar{C}

[B_1 + K_f D_1] E + K_f P^T & -I & \bar{D}^T

\bar{C}

[\bar{D} & -\gamma^2 I]
\end{bmatrix} < 0
\]

$$\begin{bmatrix}
-Q & \bar{C} P^{-1}

P^{-1} \bar{C}^T & -P^{-1}
\end{bmatrix} < 0$$

$$\text{trace}(Q) < \eta^2$$

The above inequalities cannot be solved easily due to $P$ and $K_f$ are all unknown variables and coupled together. Therefore, a variable substitution method is now used for linearizing the constraint. Let $N = PK_f$, inequalities (13) is

$$\min \eta$$ (14)

s.t. \[
\begin{bmatrix}
A^T P + P A + N C + (N C)^T [P B_1 + N D_1] E + N F & \bar{C}^T

\bar{C}

[P B_1 + N D_1] E + N F^T & -I & \bar{D}^T

\bar{C}

[\bar{D} & -\gamma^2 I]
\end{bmatrix} < 0
\]
\[
\begin{bmatrix}
-Q & \tilde{C}P^{-1} \\
(P^{-1}\tilde{C})^T & -P^{-1}
\end{bmatrix} < 0
\]

\[\text{trace}(Q) < \eta^2\]

Inequalities (14) are changed as linear matrices. The optimal solutions of \(N\) and \(P\) are obtained by the solver “mincx” in LMI toolbox of Matlab. The optimal filter gain matrix of the static filter is

\[K_f = P^{-1}N\] (15)

The state-space equation of the static filter is

\[
\begin{align*}
\dot{\hat{Z}}(t) &= A\hat{Z}(t) + B_2u(t) + K_f(Y - \hat{Y}) \\
\hat{Y}(t) &= C\hat{Z}(t) + D_2u(t) \\
K_f &= P^{-1}N
\end{align*}
\] (16)

From the above deduction processes, the static filter shown as Equation (16) is designed by ensuring that the \(H_2\) norm of the residue Equation (6) has an upper bound. A state observer based on structural acceleration responses in Reference 42 is used in the article. The acceleration responses, which are detected and isolated through the static filter, are regarded as the inputs of the state observer. Finally, the estimated state vectors are used for calculating the control forces of the system. Therefore, the control feedback strategy of the system (3) is described as

\[u(t) = -G \cdot \hat{Y}_1\] (17)

where \(G\) is a closed-loop feedback gain matrix, and \(\hat{Y}_1\) is the estimated state vectors of the observer.

Depending on the deduction above, the rebuilding observer-based FTC system is illustrated in Figure 3. \(Y_2\) is the detected and isolated acceleration signals which are used for calculating the estimated state vectors. The symbol inside the dashed box in the figure represents the static filter.

**FIGURE 3** The simulink diagram of an observer-based FTC system
3.2 Numerical verification

In this study, a 10-storey frame has been established for the numerical analysis according to Reference 43. Based on Section 3.1, an observer-based FTC system is developed for the 10-storey frame. The accelerometer on the seventh floor is supposed to introduce into two comparatively significant types of artificially added fault signals, including complete failure and accuracy decrease. For instance, (1) Complete failure: a sine wave (the amplitude of 1 m/s², the period of 2 seconds). (2) Accuracy decrease: a white Gaussian noise (the power is 0.1 dBW, the load impedance is 0.1 Ω). These fault signals are shown in Figure 4.

A numerical example of the above 10-storey frame is presented to verify the effectiveness of the observer-based FTC system. Specifically, its performance is verified by comparing with the system without fault signals (No fault signals). Sine wave stands for the system with the sine wave fault signals. White Gaussian noise stands for the system with the white Gaussian noise fault signals. A correlation coefficient \( r_{x,y} \) is used for showing the similarity between the estimated and actual states, which is expressed as

\[
r_{x,y} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \cdot \sum_{i=1}^{n}(y_i - \bar{y})^2}}
\]

where \( x \) and \( y \) are the real and estimated responses of the structure, respectively.

Under a 10-year return period wind load, the correlation coefficients between the estimated and actual states of the system with the sine wave fault signals are listed in Table 1. The structural responses and the AMD parameters of different control systems are shown in Figures 5 to 7, and its corresponding control effects and the AMD parameters are listed in Table 2. In this article, the control effect is quantified as the ratio between the dynamic responses of the structures with and without control.

From Tables 1 and 2, as the accelerometer on the seventh floor fails to work, the control effects of the system without fault tolerance are negative. Therefore, the negative effects of the fault signals need to be paid attentions to, and the filter is important for the FTC system. When the sine wave fault signals exist in the system, the correlation coefficients are nearly equivalent to one, meaning that the static filter estimates the structural responses accurately. After isolating the fault signals, the controller reduces the wind-induced vibration responses obviously, and the control effects and the AMD parameters of the system with the fault signals are close to the system without the fault signals. When the sine wave fault signals exist in the system,

| TABLE 1 | The correlation coefficients between the estimated and actual states |
|---------|-----------------|
| Index   | Correlation coefficient | Floor       |
|         |                  | The eighth | The ninth | The 10th |
| Acceleration (mm) |                  |            |           |           |
| The eighth floor | 0.997652 | 0.998155 | 0.998343 |
| The ninth floor   | 0.999855 | 0.999854 | 0.999851 |
| The 10th floor    | 0.999854 | 0.999851 | 0.999851 |

| TABLE 2 | The control effects of the numerical system with or without the FTC system |
|---------|-----------------|
| Index (mean square value) | Uncontrolled | No fault signals | With fault signals | With FTC (Sine wave) | With FTC (White Gaussian noise) |
| Displacement (mm)         | The eighth floor | 7.915 | 5.253 | 33.63 | Divergent | — | 5.255 | 33.61 | 5.254 | 33.62 |
| The ninth floor           | 8.388 | 5.569 | 33.61 | Divergent | — | 5.571 | 33.59 | 5.570 | 33.60 |
| The 10th floor            | 8.687 | 5.770 | 33.58 | Divergent | — | 5.771 | 33.56 | 5.770 | 33.57 |
| Acceleration (mm/s²)      | The eighth floor | 0.328 | 0.243 | 25.94 | Divergent | — | 0.244 | 25.62 | 0.243 | 25.94 |
| The ninth floor           | 0.356 | 0.266 | 25.43 | Divergent | — | 0.265 | 25.51 | 0.266 | 25.43 |
| The 10th floor            | 0.407 | 0.321 | 21.24 | Divergent | — | 0.322 | 20.83 | 0.321 | 21.24 |
| Control force (kN)        | — | 6.90 | — | Divergent | — | 6.97 | — | 6.94 | — |
| Stroke (cm)               | — | 9.25 | — | Divergent | — | 10.58 | — | 10.38 | — |
signals are considered, the maximum variations of the displacement and acceleration control effects are only 0.02% and 0.41%. The AMD parameters of the system only increase by 0.07 kN and 1.33 cm.

From Figures 5 to 7, the control system reduces the structural responses effectively when the accelerometer on the seventh floor is in normal working condition. The observer-based FTC system restrains structural responses accordingly, and its control performance is consistent with that of the system without the fault signals. The system not only detects and isolates the fault signals effectively, but also maintains the stability of the AMD parameters, which are consistent with the system without the fault signals. The same results are achieved when the fault signals are the white Gaussian noise.
FIGURE 6  The comparison of the accelerations to the eighth floor, (A) 0-120 seconds and (B) 50-70 seconds under uncontrolled and controlled without the fault signals, (C) 0-120 seconds and (D) 50-70 seconds considering the sine wave fault signals and controlled with the FTC system, (E) 0-120 seconds, and (F) 50-70 seconds considering the white Gaussian noise and controlled with the FTC system.

4 | EXPERIMENTAL VERIFICATION

The experimental system shown in Figure 8 consists of a four-storey frame with a servo motor installed on the fourth floor. Specifically, the acceleration signals on the second and fourth floors, which are collected by the controller, are used as the feedback signals to calculate the real-time control forces. A servo motor obtains the force signals from an EtherCAT bus system, and then is used for adding these forces to the experimental frame. The structural responses of each floor are used for verifying the control effectiveness.

The observer-based FTC system is applied to the experimental system. Assuming that the accelerometer on the second floor fails to work, and the artificially added fault signals are shown in Figure 4. In these figures, a period of 30 seconds is merely given. The original signals, which include the acceleration responses of the second and fourth floors, are processed by the static filter.

Under a sinusoidal excitation load that has a 1 Hz loading frequency and a 45.89 N peak value, the structural responses of different control systems are shown in Figures 9 and 10, and the corresponding control effects and the AMD parameters are listed in Table 3.

From Table 3, when one of the accelerometers fails to work, the system increases the structural responses and has a negative impact on vibration control. Specifically, the structural response control effects of these systems with the fault signals are negative. For the sine wave fault signals, the control effects and the AMD parameters of the FTC system are nearly equal to the system without the fault signals. Comparing the two different systems, the maximum variations in displacements and acceleration control effects are 2.76% and 9.94%, respectively. At the same time, the AMD parameters of the FTC system are reduced by 0.50 N and increased by 1.25 cm, respectively. For white Gaussian noise signals, the
maximum variations in different control effects between the two systems are 4.33% and 10.79%, respectively, and the AMD parameters are reduced by 3.18 N and increased by 1.33 cm, respectively.

From Figures 9 and 10, the observer-based FTC system restrains structural responses available. Besides, the peak values of different dynamic responses of the system with the fault signals are consistent with that of the system without the fault signals. It means the FTC system detects and isolates the fault signals with different types effectively, and it restrains the structural responses obviously and maintains the AMD parameters in an appropriate range. For the experimental curves, the structural responses disobey the sine law completely. This phenomenon is caused by the interaction between the control system, the experimental frame and the coupling between horizontal and vertical structural vibrations. Due to the acceleration control needs high-frequency control forces that mitigate the high-order modes of the experimental frame, the control effects of the third floor, which have an opposite high-order phase with the fourth floor, is significantly less than those of the second and fourth floors.

5 | CONCLUSIONS

In this article, an observer-based FTC system with a state observer and a static filter is proposed for high-rise buildings. The state observer based on structural accelerations is designed for estimating the state vectors of an AMD control system, and the static filter is presented to mitigate the negative effect of fault signals in accelerometers. A numerical example and an experimental frame are presented to verify the effectiveness of the proposed method. The main conclusions are as follows.

(1) When several accelerometers fail to work, the control system is introduced into new input signals which bring harmful interferences. An AMD control system with fault signals increases structural responses and has a negative impact on vibration control.

(2) A well-designed static filter is used to isolate fault signals and obtain the accurate acceleration responses which are regarded as the feedback signals to calculate the control forces.

(3) The observer-based FTC system restrains structural responses available, and the system not only detects and isolates the fault signals effectively, but also maintains the stability of the AMD parameters, which are consistent with the system without the fault signals.

(4) The same results are obtained in the experimental system. The control effects and the AMD parameters of the FTC system are consistent with the system without fault signals, indicating that its robustness is improved.

In conclusion, the observer-based FTC system is a suitable robust control method for high-rise buildings. The filter of the observer-based FTC system is presented as the form of a gain matrix, which presents a static characteristic. It is convenient for implementing the FTC system with hardware devices and achieving the conversion between the measurement outputs and the real outputs quickly. On the other hand, a convergence problem may exist in the solution of a local optimal gain since the stability of the filter is not well controlled. In result, it cannot be applied widely to achieve the complex situation of fault-tolerance control in engineering practices. Thus, future efforts could be focused on a dynamic FDI filter which is easy to converge and widely applied to accomplish online fault identification in structural vibration control of high-rise buildings. Moreover, future investigations should also include a designed reduced-order controller to reduce the calculation time of the control system and a robust controller applied to high-rise buildings with parametric uncertainties.
**Figure 8**  The pictures of the steel frame structure, (A) the practicality, (B) the exhibition

**Figure 9**  The comparison of the structural responses to the fourth floor of the experimental system, (A), (B) under uncontrolled and controlled without the fault signals, (C), (D) considering the sine wave fault signals and controlled with the FTC system, (E), (F) considering the white Gaussian noise and controlled with the FTC system
| Index (mean square value) | No fault signals | Without FTC (Sine wave) | With FTC (Sine wave) | Without FTC (White Gaussian noise) | With FTC (White Gaussian noise) |
|--------------------------|------------------|-------------------------|----------------------|------------------------------------|-------------------------------|
|                          | Uncontrolled     | Responses               | Effect (%)           | Responses                           | Effect (%)                   |
|                          |                  |                        |                      |                                    |                               |
| Displacement (cm)        |                  |                        |                      |                                    |                               |
| The second floor         | 3.782            | 2.758                   | 27.06                | 3.967                              | -4.90                       |
| The third floor          | 3.873            | 2.789                   | 27.98                | 4.056                              | -4.74                       |
| The fourth floor         | 3.932            | 2.826                   | 28.12                | 4.118                              | -4.74                       |
|                          |                  |                        |                      |                                    |                               |
| Acceleration (cm/s²)     |                  |                        |                      |                                    |                               |
| The second floor         | 26.400           | 6.216                   | 76.45                | 29.094                             | -10.20                      |
| The third floor          | 27.534           | 16.314                  | 40.75                | 29.616                             | -7.56                       |
| The fourth floor         | 29.559           | 7.761                   | 73.74                | 32.943                             | -11.45                      |
|                          |                  |                        |                      |                                    |                               |
| Control force (N)        |                  | 32.22                   |                      | 31.41                              | -11.72                      |
|                          |                  |                        |                      | 31.72                              | -                            |
| Stroke (cm)              |                  | 16.92                   |                      | 18.78                              | -18.17                      |
|                          |                  |                        |                      | 16.71                              | -18.25                      |
FIGURE 10  The comparison of the AMD parameters, (A) the control forces, (B) the strokes

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CONFLICT OF INTEREST
The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS
Chaojun Chen wrote the article and summarized the results. Zuohua Li and Jun Teng participated in the data analysis and conceived the study. Qinggui Wu and Beichun Lin reviewed the study plan and corrected the grammatical mistakes.

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REFERENCES
1. Zhang CW, Ou JP. Modeling and dynamical performance of the electromagnetic mass driver system for structural vibration control. Eng Struct. 2015;82:93-103.
2. Xu HB, Zhang CW, Li H, Ou JP. Real-time hybrid simulation approach for performance validation of structural active control systems: a linear motor actuator based active mass driver case study. Struct Control Health. 2014;21:574-589.
3. Li ZH, Chen CJ, Teng J. A multi-time-delay compensation controller using a Takagi-Sugen fuzzy neural network method for high-rise buildings with an active mass damper/driving system. Struct des Tall Spec. 2019;28:e1631.
4. Li CX, Li JH, Qu Y. An optimum design methodology of active tuned mass damper for asymmetric structures. Mech Syst Signal Pr. 2010;24:746-765.
5. Lu XL, Li PZ, Guo XQ, Shi WX, Liu J. Vibration control using ATMD and site measurements on the Shanghai world financial center tower. Struct des Tall Spec. 2014;23:105-123.
6. Li CX. Effectiveness of active multiple-tuned mass dampers for asymmetric structures considering soil-structure interaction effects. Struct des Tall Spec. 2012;21:543-565.
7. Ferreira F, Moutinho C, Cunha A, Caetano E. Use of semi-active tuned mass dampers to control footbridges subjected to synchronous lateral excitation. J Sound Vib. 2019;446:176-194.
8. Jiang JW, Zhang P, Patil D, Li HN, Song GB. Experimental studies on the effectiveness and robustness of a pounding tuned mass damper for vibration suppression of a submerged cylindrical pipe. Struct Control Health. 2017;24:e202712.
9. Zhang P, Song GB, Li HN, Lin YX. Seismic control of power transmission tower using pounding TMD. J Eng Mech. 2013;139:1395-1406.
10. Eason RP, Sun C, Dick AJ, Nagarajaiah S. Attenuation of a linear oscillator using a nonlinear and a semi-active tuned mass damper in series. J Sound Vib. 2013;332:154-166.
11. Hu Y, He E. Active structural control of a floating wind turbine with a stroke-limited hybrid mass damper. J Sound Vib. 2017;410:447-472.
12. Teng J, Xing HB, Xiao YQ, Liu CY, Li H, Ou JP. Design and implementation of AMD system for response control in tall buildings. Smart Struct Syst. 2014;13:235-255.
13. Teng J, Xing HB, Lu W, Li ZH, Chen CJ. Influence analysis of time delay to active mass damper control system using pole assignment method. Mech Syst Signal Pr. 2016;80:99-116.

14. Farza M, M’Saad M, Maatoug T, Kamoun M. Adaptive observers for nonlinearity parameterized class of nonlinear systems. Automatica. 2009;45:2292-2299.

15. Liu DR, Huang YZ, Wang D, Wei QL. Neural-network-observer-based optimal control for unknown nonlinear systems using adaptive dynamic programming. Int J Control. 2013;86:1554-1566.

16. Boizot N, Busvelle E, Gauthier JP. An adaptive high-gain observer for nonlinear systems. Automatica. 2010;46:1483-1488.

17. Wang C, Zuo Z, Qi Z, Ding Z. Predictor-based extended-state-observer design for consensus of mass with delays and disturbances. IEEE T Cybern. 2019;49:1259-1269.

18. Jeon S, Tomizuka M. Benefits of acceleration measurement in velocity estimation and motion control. Control Eng Pract. 2007;15:325-332.

19. Zhang B, Feng A, Li J. Observer-based optimal fault-tolerant control for offshore platforms. Comput Electr Eng. 2014;40:2204-2215.

20. Qu CX, Huo LS, Li HN. Fault tolerant control for civil structures based on LMI approach. Math Probl Eng. 2013;2013:1-8.

21. Alegría-Zamudio M, Escobar-Jiménez RF, Gómez-Aguilar JF. Fault tolerant system based on non-integers order observers: application in a heat exchanger. Isa T. 2018;28:286-296.

22. Escobar RF, Carbot-Rojas DA, Gómez-Aguilar JF, Martínez VMA, Hernández JA. Actuator fault tolerant control based on a MIMO-MPC: application in a double-pipe heat exchanger. Chem Eng Commun. 2016;204:1-17.

23. Carbot-Rojas DA, Escobar RF, Gómez-Aguilar JF, López-López G, Olivares-Peregrino VH. Experimental validation of an actuator fault tolerant control system using virtual sensor: application in a double pipe heat exchanger. Chem Eng Res des. 2015;104:400-408.

24. Yu X, Jiang J. A survey of fault-tolerant controllers based on safety-related issues. Annu Rev Control. 2015;39:46-57.

25. Sloth C, Esbensen T, Stoustrup J. Robust and fault-tolerant linear parameter-varying control of wind turbines. Mechatronics. 2011;21:645-659.

26. Palleti VR, Chong TY, Samavedham L. A mechanistic fault detection and isolation approach using Kalman filter to improve the security of cyber physical systems. J Process Contr. 2018;68:160-170.

27. Namigtle-Jiménez A, Escobar-Jiménez RF, Gómez-Aguilar JF, García-Beltrán CD, Téllez-Anguiano AC. Online ANN-based fault diagnosis implementation using an FPGA: application in the EFI system of a vehicle. Isa T. 2019. https://doi.org/10.1016/j.isatra.2019.11.003.

28. Carbot-Rojas DA, Besancon G, Escobar-Jiménez RF. EKF based sensor fault diagnosis for an internal combustion engine. Paper presented at: Proceedings of the 23rd International Conference on System Theory, Control and Computing; 2019.

29. Escobar-Jiménez RF, Astorga-Zaragoza CM, Téllez-Anguiano AC, Juárez-Romero D, Hernández JA, Guerrero-Ramírez GV. Sensor fault detection and isolation via high-gain observers: application to a double-pipe heat exchanger. Isa T. 2011;50:480-486.

30. Escobar-Jiménez RF, Astorga-Zaragoza CM, Hernández JA, Juárez-Romero D, García-Beltrán CD. Sensor fault compensation via software sensors: application in a heat pump’s helical evaporator. Chem Eng Res des. 2015;93:473-482.

31. Rios H, Davila J, Fridman L, Edwards C. Fault detection and isolation for nonlinear systems via high-order-sliding-mode multiple-observer. Int J Robust Nonlin. 2015;25:2871-2893.

32. Smarsly K, Law KH. Decentralized fault detection and isolation in wireless structural health monitoring systems using analytical redundancy. Adv Eng Softw. 2014;73:1-10.

33. Zhang Z, Jaimoukha IM. On-line fault detection and isolation for linear discrete-time uncertain systems. Automatica. 2014;50:513-518.

34. Chen CJ, Li ZH, Teng J, Wang Y. An observer-based fault-tolerant controller for flexible buildings-based on linear matrix inequality approach. Curr Sci India. 2018;114:341-354.

35. Boyd S, Ghaoui LE, Feron E, Balakrishnan V. Linear matrix inequalities in system and control theory. Society for Industrial and Applied Mathematics (SIAM). Philadelphia, PA: SIAM Publications; 1994.

36. Guo J, Huang X, Cui Y. Design and analysis of robust fault detection filter using LMI tools. Comput Math Appl. 2009;57:1743-1747.

37. Elhsoumi A, Ali SBH, El Harabi R, Abdelkrim MN. Unknown input fault detection and isolation observer design for neutral systems. Asian J Control. 2016;18:1825-1835.

38. Gao Z, Ding SX. State and disturbance estimation for time-delay systems with application to fault estimation and signal compensation. IEEE T Signal Proces. 2007;55:5541-5551.

39. Palacios-Quinonero F, Rubio-Massegu J, Rossell JM, Karimi HR. An effective computational design strategy for H-infinity vibration control of large structures with information constraints. Eng Struct. 2018;171:298-308.

40. Deaecto GS, Geromel JC. H-2 state feedback control design of continuous-time positive linear systems. IEEE T Automat Contr. 2017;62:5844-5849.

41. Yu L. Robust Control-Linear Matrix Inequalities Approach. China: Tsinghua University Press; 2002.

42. Chen CJ, Li ZH, Teng J, Hu WH, Wang Y. An observer-based controller with a LMI-based filter against wind-induced motion for high-rise buildings. Shock Vib. 2017;2017:1-18.

43. Li ZH, Chen CJ, Teng J, Wang Y. A compensation controller based on a regional pole-assignment method for AMD control systems with a time-varying delay. J Sound Vib. 2018;419:18-32.
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