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LMI based criterion for reinforced concrete frame structures

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Abstract. Due to the influence of nonlinearity and time-variation, it is difficult to establish an accurate model of concrete frame structures that adopt active controllers. Fuzzy theory is a relatively appropriate method but susceptible to human subjective experience to decrease the performance. To guarantee the stability of multi-time delays complex system with multi-interconnections, a delay-dependent criterion of evolved design is proposed in this paper. Based on this criterion, the sector nonlinearity which converts the nonlinear model to multiple rule base of the linear model and a new sufficient condition to guarantee the asymptotic stability via Lyapunov function is implemented in terms of linear matrix inequalities (LMI). A numerical simulation for a three-layer reinforced concrete frame structure subjected to earthquakes is demonstrated that the proposed criterion is feasible for practical applications.

Keywords: RC frame structure; fuzzy systems; multiple time delays; delay-dependent criterion

1. Introduction

Earthquakes seriously threaten the safety of civil engineering structures. The search for an effective control method to reduce the response of engineering structures under seismic action and improving the structural aseismic ability is always a significant research subject in the field of civil engineering (Adeli and Jiang 2006, Jiang and Adeli 2005, Zhou *et al*. 2015, Lee *et al.* 2017 , Kim *et al.* 2018, Chen 2019, Chen *et al.* 2020). The scientific models of numerous physical and building frameworks are habitually of high measurement, or having intuitive unique marvels. The data preparing and prerequisites to explore different avenues regarding these models for control reasons for existing are typically over the top. In addition, the presence of time delays is every now and again a wellspring of shakiness here and there. Thus, the issue of soundness investigation of time-defer frameworks has been one of the principle worries of specialists wishing to review the properties of such frameworks.

Stability criteria of the time-delay systems so far has been drawn nearer in two primary ways as indicated by the reliance upon the measure of postponement. One bearing is to devise dependability conditions that do exclude data on the postponement, while the other heading incorporates strategies which consider. The previous case is frequently alluded to as postponement free criteria and for the most part gives great mathematical conditions (Trinh and Aldeen 1995). Be that as it may, surrender of data on the measure of time delay fundamentally causes conservativeness of the criteria, particularly when the deferral is nearly little (Mori 1985).

In this paper, we consider a different time-defer extensive scale framework made out of *J* subsystems with interconnections and every subsystem is spoken to by the purported Takagi-Sugeno (T-S) model with various time delays. One basic property of control frameworks is steadiness and impressive reports have been issued in the writing on the soundness issue of unique frameworks (see Chen, 2014 and the references in that). Be that as it may, a writing overview shows that the soundness issue of frameworks with different time delays has not yet been settled. Thus, for the purpose of general application, a delay-dependent stability criterion in terms of Lyapunov's direct method is derived to guarantee the asymptotic stability of multiple time-delay fuzzy large-scale systems.

This paper proposes new evolved algorithms based on the LMI and evolutionary algorithm to optimize the rules and performs a numerical simulation on a three-layer reinforced concrete frame structure under excited earthquakes.

2. System description and stability analysis

Concrete frame structures are the most common type of modern building. Fig. 1 shows the model of a three three-layer reinforced concrete frame structure. It usually consists of a frame or a skeleton of concrete. Horizontal members are beams and vertical ones are the columns. Concrete Buildings structures also contain slabs which are used as base, as well as roof / ceiling. Among these, the column is the most important as it carries the primary load of the

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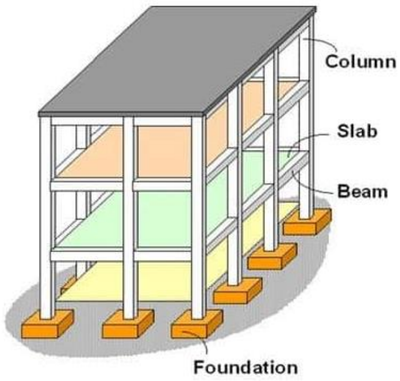

Fig. 1 The model of a three three-layer reinforced concrete frame structure

building.

In order to develop fuzzy criterion for the three three-layer reinforced concrete frame structure, we consider a multiple time-delay fuzzy large-scale system $\boldsymbol{F}$ composed of J interconnected fuzzy subsystems F_j, j=1,2,…,J The jth isolated subsystem (without interconnection) of $\boldsymbol{F}$ is represented by a T-S fuzzy model with multiple time delays. All the reinforced concrete frame structures could be modeled as the fuzzy type controlled systems by selected fuzzy approximating variables. The main feature of T-S fuzzy model is to express each rule by a linear state equation, and the ith rule of this fuzzy model is of the following form

IF

$x_{1j}(t)$ is M_{i1j} and $\cdots$ and $x_{gj}(t)$ is M_{igj}

THEN

$$\dot{x}_j(t) = A_{ij}x_j(t) + \sum_{k=1}^{N_j} A_{ikj}x_j(t-\tau_{kj}) + \sum_{\substack{n=1\\ n\neq j}}^{J} \hat{A}_{inj}x_n(t), \tag{1}$$

where $x_j^T(t) = [x_{1j}(t), x_{2j}(t), \cdots, x_{gj}(t)]$

i=1,2,…,r_j and r_j is the number of IF-THEN rules of the jth subsystem; A_{ij} and A_{ikj} are constant matrices with appropriate dimensions, $x_j(t)$ is the state vector, τ_{kj} denotes the time delay, M_{ipj} (p=1,2,…,g) are the fuzzy sets and $x_{1j}(t)$~$x_{gj}(t)$ are the premise variables.

Based on the definition of above multiple layers RC structure and fuzzy type models, the final state of this fuzzy dynamic system is inferred as follows

$$\dot{x}_j(t) = \frac{\sum_{i=1}^{r_j} w_{ij}(t)[A_{ij}x_j(t) + \sum_{k=1}^{N_j} A_{ikj}x_j(t-\tau_{kj})]}{\sum_{i=1}^{r_j} w_{ij}(t)}$$

$$= \sum_{i=1}^{r_j} h_{ij}(t)[A_{ij}x_j(t) + \sum_{k=1}^{N_j} A_{ikj}x_j(t-\tau_{kj})] \tag{2}$$

with

$$w_{ij}(t) = \prod_{p=1}^{g} M_{ipj}(x_{pj}(t)), \quad h_{ij}(t) = \frac{w_{ij}(t)}{\sum_{i=1}^{r_j} w_{ij}(t)} \tag{3}$$

in which $M_{ipj}(x_{pj}(t))$ is the grade of membership of $x_{pj}(t)$ in M_{ipj}. In this paper, it is assumed that $w_{ij}(t)\geq 0$, i=1,2,…,r_j; j=1,2,…,J and $\sum_{i=1}^{r_j} w_{ij}(t) > 0$ for all t. Therefore, $h_{ij}(t)\geq 0$ and $\sum_{i=1}^{r_j} h_{ij}(t) = 1$ for all t. The fuzzy control force is used to guarantee the stability of the multiple layers RC structure, and thus the fuzzy Lyapunov of inequality will be considered and derived in the following section.

Based on the above analysis, the jth fuzzy subsystem F_j with interconnections can be described as follows

$$F_j: \begin{cases} \dot{x}_j(t) = \sum_{i=1}^{r_j} h_{ij}(t)(A_{ij}x_j(t) + \sum_{k=1}^{N_j} A_{ikj}x_j(t-\tau_{kj})) + \phi_j(t) & \text{(4a)} \\ \phi_j(t) = \sum_{\substack{n=1\\ n\neq j}}^{J} C_{nj}x_n(t), & \text{(4b)} \end{cases}$$

where C_{nj} is the interconnection matrix between the nth and jth subsystems.

The purpose of this paper is two-fold: to stabilize the closed-loop nonlinear system and to attenuate the influence of the external disturbance on the state variable. According to Chen (2014), the disturbance attenuation problem, which is characterized by means of the so-called L_2 gain of a nonlinear system, is defined as follows: Given a real number $\gamma > 0$, it is said that the exogenous input is locally attenuated by γ if there exists a neighborhood U of $\boldsymbol{x}$=0 such that for every positive integer N and for which the state trajectory of the closed-loop nonlinear system starting from $\boldsymbol{x}(0)$=0 remains in U

$$\sum_{j=1}^{J} \int_0^{t_f} \boldsymbol{x}_j^T(t) \boldsymbol{Q}_j \boldsymbol{x}_j(t) dt \leq$$

$$\boldsymbol{\eta}_j^2 \sum_{j=1}^{J} \int_0^{t_f} \boldsymbol{\phi}_j^T(t) \boldsymbol{\phi}_j(t) dt$$

where $\boldsymbol{Q}$ is a positive definite weighting matrix. The physical meaning is finding an L_2 gain less than or equal to a prescribed number γ (strictly less than 1).

If the initial condition is also considered, the inequality (3.1) can be modified as

where $\boldsymbol{P}$ are some positive definite matrices.

Prior to examination of asymptotic stability of the multi-time delay fuzzy complex system with multi-interconnections, a useful concept is given below.

In the following, a delay-dependent stability criterion is proposed to guarantee the asymptotic stability of the multiple time-delay fuzzy large-scale system $\boldsymbol{F}$. Prior to examination of asymptotic stability of $\boldsymbol{F}$, a useful concept is given below.

Lemma 1 (Tsai *et al.* 2015)**:** For any real matrices X and Y with appropriate dimensions, we have

$$X^TY + Y^TX \leq \kappa X^TX + \kappa^{-1}Y^TY$$

where κ is a positive constant.

Theorem 1: The multiple time-delay fuzzy large-scale system $\boldsymbol{F}$ is asymptotically stable, if there exist positive definite matrices $P_j = P_j^T > 0$, $R_{kj} = R_{kj}^T > 0$ and positive constants α_j>0, β>0 such that the following matrices Q_{ikj} and H_{ikj} are both negative definite for i=1,2,…,r_j;

j=1,2,…,J; k=1,2,…,N_j:

$$Q_{ikj} = \{ A_{ij}{}^T \tau_{kj} P_j + P_j \tau_{kj} A_{ij} + \alpha_j \tau_{kj}^2 N_j I + R_j + \sum_{n=1}^{J} [\frac{1}{N_j} \beta(\frac{J-1}{J}) \tau_n I + \beta^{-1} P_j C_{nj} C_{nj}^T P_j]\} < 0 \tag{5}$$

$$H_{ikj} = \alpha_j^{-1} N_j A_{ikj}^T P_j P_j A_{ikj} - R_{kj} < 0 \tag{6}$$

where $R_j \equiv \sum_{d=1}^{N_j} R_{dj}$ and $\tau_n \equiv \sum_{m=1}^{N_n} \tau_{mn}^2$.

Proof: Let the Lyapunov function for the multiple time-delay fuzzy large-scale system $\boldsymbol{F}$ be defined as

$$V(t) = \sum_{j=1}^{J} v_j(t) = \sum_{j=1}^{J} \{ \sum_{k=1}^{N_j} \tau_{kj} x_j^T(t) P_j x_j(t) + \sum_{k=1}^{N_j} \int_0^{\tau_{kj}} x_j^T(t-\tau) R_{kj} x_j(t-\tau) d\tau \} \tag{7}$$

where $P_j = P_j^T > 0$ and the weighting matrix $R_{kj} = R_{kj}^T > 0$. We then evaluate the time derivative of V on the trajectories of Eq. (4) to get

$$\begin{aligned}
\dot{V} &= \sum_{j=1}^{J} \dot{v}_j(t) = \sum_{j=1}^{J}\sum_{k=1}^{N_j} [\tau_{kj} (\dot{x}_j^T(t) P_j x_j(t) + x_j^T(t) P_j \dot{x}_j(t))] \\
&\quad + \sum_{j=1}^{J}\sum_{k=1}^{N_j} [x_j^T(t) R_{kj} x_j(t) - x_j^T(t-\tau_{kj}) R_{kj} x_j(t-\tau_{kj})] \\
&= \sum_{j=1}^{J}\sum_{k=1}^{N_j} \tau_{kj} \{ [\sum_{i=1}^{r_j} h_{ij}(t)(A_{ij} x_j(t) + \sum_{d=1}^{N_j} A_{idj} x_j(t-\tau_{dj})) + \phi_j(t)]^T P_j x_j(t) \\
&\quad + x_j^T(t) P_j [\sum_{i=1}^{r_j} h_{ij}(t)(A_{ij} x_j(t) + \sum_{d=1}^{N_j} A_{idj} x_j(t-\tau_{dj})) + \phi_j(t)] \} \\
&\quad + \sum_{j=1}^{J}\sum_{k=1}^{N_j} (x_j^T(t) R_{kj} x_j(t) - x_j^T(t-\tau_{kj}) R_{kj} x_j(t-\tau_{kj})) \\
&= \sum_{j=1}^{J}\sum_{k=1}^{N_j}\sum_{i=1}^{r_j} h_{ij}(t) x_j^T(t)(A_{ij}{}^T \tau_{kj} P_j + P_j \tau_{kj} A_{ij}) x_j(t) + \\
&\quad \sum_{j=1}^{J}\sum_{k=1}^{N_j} [\phi_j^T(t) P_j \tau_{kj} x_j(t) + x_j^T(t) P_j \tau_{kj} \phi_j(t)] \\
&\quad + \sum_{j=1}^{J}\sum_{k=1}^{N_j}\sum_{i=1}^{r_j} h_{ij}(t) \sum_{d=1}^{N_j} [x_j^T(t-\tau_{dj}) A_{idj}^T P_j \tau_{kj} x_j(t) \\
&\quad + x_j^T(t) \tau_{kj} P_j A_{idj} x_j(t-\tau_{dj})] \\
&\quad + \sum_{j=1}^{J}\sum_{i=1}^{r_j} h_{ij}(t) \sum_{d=1}^{N_j} [x_j^T(t) R_{dj} x_j(t) - x_j^T(t-\tau_{dj}) R_{dj} x_j(t-\tau_{dj})] \\
&\le \sum_{j=1}^{J}\sum_{k=1}^{N_j}\sum_{i=1}^{r_j} h_{ij}(t) x_j^T(t)(A_{ij}{}^T \tau_{kj} P_j + P_j \tau_{kj} A_{ij}) x_j(\mathrm{t}) + \\
&\quad \sum_{j=1}^{J}\sum_{k=1}^{N_j} [\phi_j^T(t) P_j \tau_{kj} x_j(t) + x_j^T(t) P_j \tau_{kj} \phi_j(t)] \\
&\quad + \sum_{j=1}^{J}\sum_{k=1}^{N_j}\sum_{i=1}^{r_j} h_{ij}(t) \sum_{d=1}^{N_j} [\alpha_j x_j^T(t) \tau_{kj}^2 x_j(t) + \\
&\quad \alpha_j^{-1} x_j^T(t-\tau_{dj}) A_{idj}^T P_j P_j A_{idj} x_j(t-\tau_{dj})]
\end{aligned}$$

(by Lemma 1)

$$\begin{aligned}
&+ \sum_{j=1}^{J}\sum_{i=1}^{r_j}\sum_{d=1}^{N_j} h_{ij}(t)[x_j^T(t) R_{dj} x_j(t) - x_j^T(t-\tau_{dj}) R_{dj} x_j(t-\tau_{dj})] \\
&\le \sum_{j=1}^{J}\sum_{k=1}^{N_j}\sum_{i=1}^{r_j} h_{ij}(t) x_j^T(t)(A_{ij}{}^T \tau_{kj} P_j + \\
&\quad P_j \tau_{kj} A_{ij} + \alpha_j \tau_{kj}^2 N_j I + \sum_{d=1}^{N_j} R_{dj}) x_j(t) \\
&+ \sum_{j=1}^{J}\sum_{k=1}^{N_j}\sum_{n=1}^{J} [\beta(\frac{J-1}{J}) \tau_{kj}^2 x_n^T(t) x_n(t) + \beta^{-1} x_j^T(t) P_j C_{nj} C_{nj}^T P_j x_j(t)]
\end{aligned}$$

(by Lemma 1)

$$\begin{aligned}
&+ \sum_{j=1}^{J}\sum_{i=1}^{r_j}\sum_{d=1}^{N_j} h_{ij}(t) x_j^T(t-\tau_{dj})(\alpha_j^{-1} N_j A_{idj}^T P_j P_j A_{idj} - R_{dj}) x_j(t-\tau_{dj}) \\
&= \sum_{j=1}^{J}\sum_{k=1}^{N_j}\sum_{i=1}^{r_j} h_{ij}(t) x_j^T(t)(A_{ij}{}^T \tau_{kj} P_j + P_j \tau_{kj} A_{ij} \\
&\quad + \alpha_j \tau_{kj}^2 N_j I + \sum_{d=1}^{N_j} R_{dj}) x_j(t) \\
&\quad + \sum_{j=1}^{J}\sum_{n=1}^{J}\sum_{m=1}^{N_n} \beta(\frac{J-1}{J}) \tau_{mn}^2 x_j^T(t) x_j(t) \\
&+ \sum_{j=1}^{J}\sum_{k=1}^{N_j}\sum_{i=1}^{r_j}\sum_{n=1}^{J} h_{ij}(t) \beta^{-1} x_j^T(t) P_j C_{nj} C_{nj}^T P_j x_j(t) \\
&+ \sum_{j=1}^{J}\sum_{i=1}^{r_j}\sum_{k=1}^{N_j} h_{ij}(t) x_j^T(t-\tau_{kj})(\alpha_j^{-1} N_j A_{ikj}^T P_j P_j A_{ikj} \\
&\quad - R_{kj}) x_j(t-\tau_{kj}) \\
&= \sum_{j=1}^{J}\sum_{k=1}^{N_j}\sum_{i=1}^{r_j} h_{ij}(t) x_j^T(t)(A_{ij}{}^T \tau_{kj} P_j + P_j \tau_{kj} A_{ij} \\
&\quad + \alpha_j \tau_{kj}^2 N_j I + \sum_{d=1}^{N_j} R_{dj}) x_j(t) \\
&+ \sum_{j=1}^{J}\sum_{k=1}^{N_j}\sum_{i=1}^{r_j}\sum_{n=1}^{J}\sum_{m=1}^{N_n} h_{ij}(t) x_j^T(t)[\frac{1}{N_j} \beta(\frac{J-1}{J}) \tau_{mn}^2 I \\
&\quad + \frac{1}{N_n} \beta^{-1} P_j C_{nj} C_{nj}^T P_j] x_j(t) \\
&+ \sum_{j=1}^{J}\sum_{i=1}^{r_j}\sum_{k=1}^{N_j} h_{ij}(t) x_j^T(t-\tau_{kj})(\alpha_j^{-1} N_j A_{ikj}^T P_j P_j A_{ikj} \\
&\quad - R_{kj}) x_j(t-\tau_{kj}) \\
&= \sum_{j=1}^{J}\sum_{k=1}^{N_j}\sum_{i=1}^{r_j} h_{ij}(t) x_j^T(t) \{ (A_{ij}{}^T \tau_{kj} P_j \\
&\quad + P_j \tau_{kj} A_{ij} + \alpha_j \tau_{kj}^2 N_j I + R_j) \\
&+ \sum_{n=1}^{J} [\frac{1}{N_j} \beta(\frac{J-1}{J}) \tau_n I + \beta^{-1} P_j C_{nj} C_{nj}^T P_j]\} x_j(t) \\
&+ \sum_{j=1}^{J}\sum_{i=1}^{r_j}\sum_{k=1}^{N_j} h_{ij}(t)[x_j^T(t-\tau_{kj}) H_{ikj} x_j(t-\tau_{kj})] \\
&= \sum_{j=1}^{J}\sum_{k=1}^{N_j}\sum_{i=1}^{r_j} h_{ij}(t) x_j^T(t) Q_{ikj} x_j(t) \\
&+ \sum_{j=1}^{J}\sum_{i=1}^{r_j}\sum_{k=1}^{N_j} h_{ij}(t)[x_j^T(t-\tau_{kj}) H_{ikj} x_j(t-\tau_{kj})].
\end{aligned} \tag{8}$$

The Lyapunov derivative is negative if the matrices Q_{ikj} and H_{ikj} (j=1,2,…,J; i=1,2,…,r_j; k=1,2,…,N_j) are negative definite, which completes the proof.

Evolved Bat Algorithm (EBA) is proposed based on the bat echolocation fuzzy complex system in the natural world. Unlike other swarm intelligence algorithms, the strong point

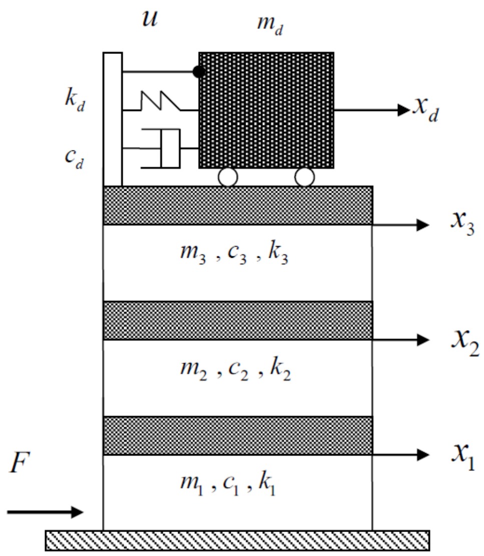

Fig. 2 Four-DOF structure-ATMD system

of EBA is that it only has one parameter, which is called the medium, needs to be determined before employing the algorithms to solve problems. Choosing different medium determines different searching step size in the evolutionary process. In this study, we choose the air to be the medium because it is the original existence medium in the natural environment where bats live. The operation of EBA can be summarized in following steps:

Initialization: the artificial agents are spread into the solution space by randomly assigning coordinates to them.

Movement: the artificial agents are moved. A random number is generated and then it is checked whether it is larger than the fixed pulse emission rate. If the result is positive, the artificial agent is moved using the random walk process.

$$x_i^t = x_i^{t-1} + D,$$

where x_i^t indicates the coordinate of the i-th artificial agent at the t-th iteration, x_i^{t-1} represents the coordinate of the i-th artificial agent at the last iteration, and D is the moving distance that the artificial agent goes in this iteration.

$$D = \gamma \cdot \Delta T$$

where γ is a constant corresponding to the medium chosen in the experiment, and $\Delta T \in [-1, 1]$ is a random number. γ=0.17 is used in our experiment because the chosen medium is air.

$$x_i^{tR} = \beta\left(x_{\text{best}} - x_i^t\right), \quad \beta \in [0, 1]$$

where β is a random number; x_{best} indicates the coordinate of the near best solution found so far throughout all artificial agents; and x_t^{tR} represents the new coordinates of the artificial agent after the operation of the random walk process.

Remark 1: The proposed delay-dependent stability conditions for the larger delays τ_{kj} of the multiple time-delay fuzzy large-scale system $\boldsymbol{F}$ are more difficult to be satisfied in this paper.

Remark 2: From Eq. (5), it is obvious that the larger delay τ_{kj} the multiple time-delay fuzzy large-scale system $\boldsymbol{F}$ has, the more difficult to ensure the stability of the system.

3. Numerical simulation and results

In this section, the proposed fuzzy criterion is demonstrated in reinforced concrete frame structures with an example of ATMD System shown in Fig. 2. To reflect the real working state of the reinforced concrete structure, the random seismic waves (El Centro wave is chosen, so that the domain of the seismic acceleration may be determined as 0~0.2 m/s2. For the structure, the basic domain of the structure displacement response is 0~h/200 under a basic fortification intensity, where h is the layer height. The duration and time step are set to 15 s.

The active TMD mounted on a shear structure is modeled as a Four-degree-of freedom structure-ATMD system as shown in Fig. 2. The parameters m_d=50 (kg), c_d=14.05 (N-s/m), and k_d=9875.18 (N/m) represent mass, damping, and stiffness in the ATMD and the following parameter vectors: M (kg), C (N-s/m), and K (N/m), represent mass, damping, and stiffness vector (t=t+Δt, Δt=0.02 sec) of this nonlinear time-varying dilapidated-simulation structure with ATMD; F and u represent the external force and control input. The dynamic equations of motion of the pendulum are given below.

$$\begin{bmatrix}\ddot{x}_1\\ \ddot{x}_2\\ \ddot{x}_3\\ \ddot{x}_d\end{bmatrix} = \left[(-M^{-1}K)_{4\times4} \quad (-M^{-1}C)_{4\times4}\right]\begin{bmatrix}x_1\\ x_2\\ x_3\\ x_d\\ \dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\\ \dot{x}_d\end{bmatrix} + \begin{bmatrix}0\\ 0\\ -1/m_3\\ -1/m_d\end{bmatrix}\cdot u + \begin{bmatrix}-1/m_1\\ -1/m_2\\ -1/m_3\\ -1/m_d\end{bmatrix}\cdot F,$$

where $M = \begin{bmatrix}980.71 & 0 & 0 & 0\\ 0 & 980.71 & 0 & 0\\ 0 & 0 & 980.71 & 0\\ 0 & 0 & 0 & 50\end{bmatrix}$,

$$K = \begin{bmatrix}2740599(1-0.3t) & -1640938(1-0.3t) & 368992(1-0.3t) & 0\\ -1640938(1-0.3t) & 3020937(1-0.3t) & -1624126(1-0.3t) & 0\\ 368992(1-0.3t) & -1624126(1-0.3t) & 1333065(1-0.3t)+9875.2 & -9875.2\\ 0 & 0 & -9875.2 & 9875.2\end{bmatrix},$$

$$C = \begin{bmatrix}382.65(1+0.1t) & -57.27(1+0.1t) & 61.64(1+0.1t) & 0\\ -57.27(1+0.1t) & 456.73(1+0.1t) & -2.63(1+0.1t) & 0\\ 61.64(1+0.1t) & -2.63(1+0.1t) & 437.29(1+0.1t)+14.05 & -14.05\\ 0 & 0 & -14.05 & 14.05\end{bmatrix}.$$

We set the sensor on the top floor of the dilapidated-simulation structure. Using the procedure discussed above, we specify the response by defining a suitable surface $S = c^T e_m = 30e_3 - 0.2e_d + \dot{e}_3 - 0.4\dot{e}_d$. Then, we construct

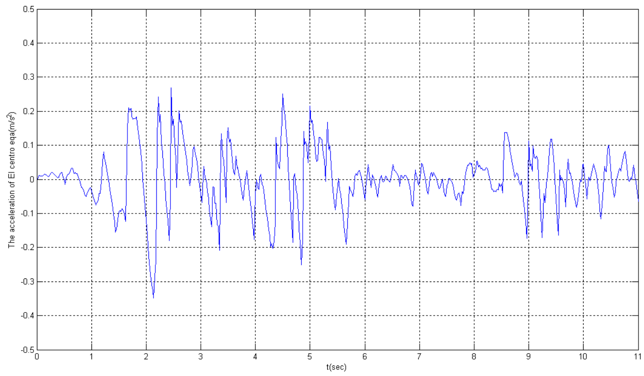

Fig. 3 Acceleration of the random earthquake

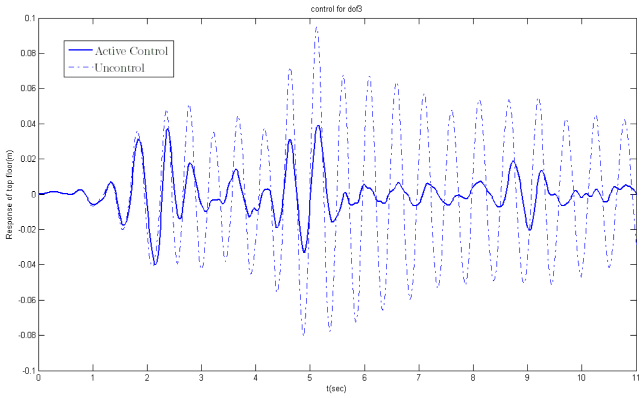

Fig. 4 Top floor response of the structure in the random earthquake

the structure on the evolved algorithm and the initial values of the consequent parameter vector $\hat{w}$ can be chosen as follows: [1 0.88 0.60 0.25 0.05 0 -0.06 -0.25 -0.36 -0.72 -0.95]'. Then, let η=10, Φ=0.2, and adjust $\hat{w}$ by the adaptive law.

The simulation results in the random earthquake disturbances are illustrated in Figs. 3-5. It is shown to improve the performance of the system in all respects while retaining the advantage of assuring robustness in the presence of bounded disturbances. The dilapidated simulated structure rapidly becomes asymptotically stable and the modified fuzzy criterion can be derived to guarantee the stability of the three-layer reinforced concrete frame structure.

4. Conclusions

This paper is concerned with the stability problem of a multiple time-delay fuzzy large-scale system which consists of a few interconnected subsystems. Each subsystem is represented by a T-S fuzzy models with multiple time delays. Next, a delay-dependent stability criterion in terms of Lyapunov's direct method is proposed to guarantee the asymptotic stability of multiple time-delay fuzzy large-scale systems. A numerical simulation for a three-layer reinforced concrete frame structure subjected to earthquakes is demonstrated that the proposed criterion is feasible for practical applications.

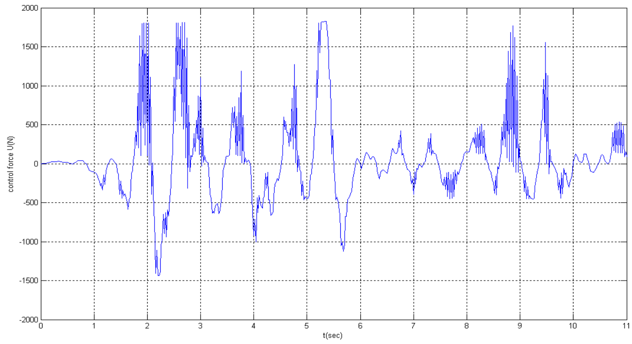

Fig. 5 Control force of the ATMD system in the random earthquake

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