

Aircraft and spacecraft structural analysis with hybrid criterion of smart control

C.C. Hung^{*1,2} and T. Nguyễn³

¹Department of Mechanical Engineering, National Taiwan University, Taiwan

²Faculty of National Hsin Hua Senior High School, Tainan, Taiwan

³Ha Tinh University, Dai Nai Campus, No. 447, Street 26/3, Dai Nai Ward, Ha Tinh City, Vietnam

(Received April 22, 2022, Revised August 8, 2022, Accepted December 1, 2022)

Abstract. In this article, we propose a criterion for ensuring the asymptotic stability of large multiple delays, based on the direct Lyapunov method. Based on this criterion and distributed control scheme, the controllers are synthesized by the PDC to stabilize these large-scale systems with multiple delays. And we focus on the results which shows the high effective by the proposed theory utilized for damage propagation for aircraft structural analysis of composite materials. Finally, the numerical simulations confirmed the effectiveness of the method.

Keywords: aerospace vehicles; LMI; nonlinear systems; smart control; stability analysis

1. Introduction

Mathematics seems to be a guide, appearing by the physicist at the right time, bringing light to the gloomy world of physics. However, the mutual influence of mathematics and physics is far more complicated than the story told. In most recorded history, physics and mathematics are not even separate subjects. The mathematics of ancient Greece, Egypt, and Babylon believed that we live in a world where distance, time, and gravity all operate in a certain way. The mathematical and statistical models for many physical, nature and technical systems are generally large or contain dynamic interaction phenomena and the cost for testing these models of control purposes are often too high. Therefore, it is natural to find a technique that can reduce the calculation costs. The large systems methodology provides this technique by manipulating the structure of the system in some way. Therefore, research on modeling, math, analysis, collection, optimization and control of large-scale systems has generated great interest. Recently, many of these methods have been proposed to verify the stability of the literature and the stability of large systems (Yang and Chang 1996, Bedirhanoglu 2014, 2004, 2005, Chiang *et al.* 2007, Liu *et al.* 2009, Liu *et al.* 2010, Hung *et al.* 2019, Eswaran and Reddy 2016 and references included).

In a computer network, because different communication subnets and network architectures adopt different transfer control methods, the transfer delay in the communication subnet is determined by the network status. The delay time caused by the electrical signal response is fixed. The smaller the response time, the smaller the delay, the larger the bandwidth, and the higher the

*Corresponding author, E-mail: zykj_zywd@163.com

transmission rate. Therefore, the larger the channel bandwidth, the smaller the delay. Delay time is the time it takes to get a packet from a specific point. Delay time is generally the sum of response delay and transmission delay. Delays usually occur in other technological systems. Computer control systems, for example, experience delays because computers take a long time to perform digital tasks. Also, there are remote operations, radar, power grid, transportation, metal delay and so on. The outputs of these systems do not respond to the input data until a certain amount of time has passed. The introduction of a delay factor usually causes instability and often complicates the analysis. Therefore, the analysis of the delay stability of the system on research (Mori 1985, Trine Aldeen 1995, Tsai *et al.* 2012, 2015, Tim *et al.* 2019, Chen 2011, 2014, Tim *et al.* 2020, Chen *et al.* 2020) have published and executed by demonstrations.

In recent years, there has much been on the topic of a growing interest in system controls. There are already many successful applications. Despite that of its success, it is clear that a great of basic problems remain to be solved and the main problem with control systems is system design to ensure stability. Recently, there have been many studies on the stability (see Tanaka Sugeno 1992, Tim *et al.* 2021, Zhen *et al.* 2021, Chen *et al.* 2022, Hsiao *et al.*, Wang *et al.* 1996, Tanaka *et al.* 1996, Feng *et al.* 1997 and references). The history of applying the artificial intelligence tools into the the engineering problems has been presented in some papers. For example, Chiang *et al.* (2001, 2002, 2004) have provided the novel criterion for system, Chengwu *et al.* (2002) provided the LMI form for system, Hsiao *et al.* (2003, 2005) utilized the AI theory in nonlinear systems, Hsieh *et al.* (2006) proposed the stability analysis for AI, Lin *et al.* (2010) *et al.* provided the control application in TLP system, Chen *et al.* (2006, 2007, 2009) also demonstrated the performance by neural network based LDI theory. Recently Chen *et al.* (2019, 2020) had some research results of evolutionary models for engineering applications (Mori 1985 and Trine Aldeen 1995, Tsai *et al.* 2012, 2015, Tim *et al.* 2019, Chen 2011, 2014, Tim *et al.* 2020, Chen *et al.* 2020). However, studies in the literature have yet to solve the stability and non-stable problem of large systems with multiple delays.

Consequently, this study has a stability criterion based directly on the Lyapunov method to provide asymptotic stability to large systems with multiple delays. In accordance with this criterion and decentralized control schemes, fuzzy control groups are incorporated, stabilizing large-scale systems in multiple delays consisting of multiple interconnected subsystems. Furthermore, these subsystems are represented by a fuzzy Takagi-Sugeno model in multiple delays. In these models, each rule is represented by a linear system model, so linear feedback control can be used as feedback stability. Therefore, the kind of control design is based on the fuzzy model that uses a parallel distributed compensation (PDC) scheme. The ideas are those all linear local linear models control feedback share the same premises. And we focus on the results which shows the high effective by the proposed theory utilized for damage propagation for aircraft structural analysis of composite materials.

In summary, we briefly introduce Takagi Sugeno's fuzzy model with some delays and describe the system. The stability criterion is then derived and considered based on the Lyapunov method, ensuring asymptotic stability of systems with multiple delays. And we focus on the results which shows the high effective by the proposed theory utilized for damage propagation for aircraft structural analysis of composite materials. Finally, the results explain and draw conclusions for the numerical simulation examples they are referred to.

2. System description

The following we review a nonlinear parabolic PDE

To simplify the construction of the equation Eq. (2.1), we consider a nonlinear J as interconnected in subsystems $F_j, j=1,2,\dots,J$. The j th as isolated subsystems (without any interconnection) of F are represented by the technique of IF-THEN delay control model of Takagi-Sugeno. The main feature of the Takagi-Sugeno fuzzy model with multiple delays is the expression of each of rule by means of a linear equation of state, and the model is as follows (Chen 2014, Chen *et al.* 2019, Chen *et al.* 2020)

$$\text{Rule } i: \text{ IF any } x_{1j}(t) \text{ is } M_{i1j} \text{ and } \dots \text{ and } x_{gj}(t) \text{ is } M_{igj} \tag{2.1}$$

$$\text{THEN } \dot{x}_j(t) = A_{ij}x_j(t) + \sum_{k=1}^{N_j} A_{ikj}x(t-\tau_{kj}) + B_{ij}u_j(t)$$

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

r_j is the j th subsystem's IF-THEN rule umber. A_{ij}, A_{ikj} and B_{ij} are system matrices, state $x_j(t)$, input $u_j(t)$, delay τ_{kj} fuzzy set $M_{ipj}(p = 1, 2, \dots, g)$, and premise $x_{1j}(t) \sim x_{gj}(t)$ are used to infer the fuzzy dynamic model

$$\begin{aligned} \dot{x}_j(t) &= \frac{\sum_{i=1}^{r_j} w_{ij}(t) \left\{ A_{ij}x_j(t) + \sum_{k=1}^{N_j} A_{ikj}x(t-\tau_{kj}) + B_{ij}u_j(t) \right\}}{\sum_{i=1}^{r_j} w_{ij}(t)} \\ &= \sum_{i=1}^{r_j} h_{ij}(t) \left\{ A_{ij}x_j(t) + \sum_{k=1}^{N_j} A_{ikj}x(t-\tau_{kj}) + B_{ij}u_j(t) \right\} \end{aligned} \tag{2.2}$$

with

$$w_{ij}(t) = \prod_{p=1}^g M_{ipj}(x_{pj}(t)), \quad h_{ij}(t) = \frac{w_{ij}(t)}{\sum_{i=1}^{r_j} w_{ij}(t)} \tag{2.3}$$

in which $M_{ipj}(x_{pj}(t))$ is in the grade of any membership of $x_{pj}(t)$ in M_{ipj} if $w_{ij}(t) \geq 0, i = 1, 2, \dots, r_j$ and $\sum_{i=1}^{r_j} w_{ij}(t) > 0, h_{ij}(t) \geq 0, i = 1, 2, \dots, r_j, \sum_{i=1}^{r_j} h_{ij}(t) = 1$.

According to the above mentioned analysis, these j th F_j could be

$$\dot{x}_j(t) = \sum_{i=1}^{r_j} h_{ij}(t) \left\{ A_{ij}x_j(t) + \sum_{k=1}^{N_j} A_{ikj}x(t-\tau_{kj}) + B_{ij}u_j(t) \right\} + \sum_{\substack{n=1 \\ n \neq j}}^J C_{nj}x_n(t) \tag{2.4}$$

where C_{nj} is the interconnection.

3. Parallel Distributed Compensation (PDC)

The fuzzy control, according to a distributed control system using PDC technology, is used to stabilize a large number of synthetic design. The concept of the PDC scheme is to provide a way to handle each distribution rule for the relevant rules of the Takagi Sugeno model with multiple delays. Each rule in the model is described linear, so you can use linear control theory to develop controllers.

The fuzzy controller of the j th subsystem of rule i is derived as follows.

$$\text{IF any of } x_{1j}(t) \text{ is } M_{i1j} \text{ and } \dots \text{ and } x_{r_jj}(t) \text{ is } M_{ir_jj}, \text{ THEN one } u_j(t) = -K_{ij}x_j(t), \quad (3.1)$$

in which $i=1, 2, \dots, r_j$. Hence, these final outputs of the fuzzy controllers are

$$u_j(t) = -\frac{\sum_{i=1}^{r_j} w_{ij}(t) K_{ij} x_j(t)}{\sum_{i=1}^{r_j} w_{ij}(t)} = -\sum_{i=1}^{r_j} h_{ij}(t) K_{ij} x_j(t). \quad (3.2)$$

Combine (3.2) and (2.4), the subsystem becomes

$$\dot{x}_j(t) = \sum_{i=1}^{r_j} \sum_{f=1}^{r_j} h_{ij}(t) h_{fj}(t) \left\{ (A_{ij} - B_{ij} K_{fj}) x_j(t) + \sum_{k=1}^{N_j} A_{ikj} x(t - \tau_{kj}) \right\} + \phi_j(t). \quad (3.3)$$

Theorem 1: These multiple time-delay fuzzy large-scale systems F are asymptotically regarded as stable condition, if the feedback gain (K_{ij}) is chosen in satisfying at least one of the following conditions, $j = 1, 2, \dots, J$

$$(I) \bar{\lambda}_j \equiv \max_k \lambda_M(\bar{Q}_{kj}) < 0 \text{ for } k = 1, 2, \dots, N_j \quad (3.4)$$

or

$$(II) \Lambda_j \equiv \begin{bmatrix} -\bar{\lambda}_j & 0 & 0 & \dots & 0 \\ 0 & \lambda_{1j} & 1/2\lambda_{12j} & \dots & 1/2\lambda_{1r_jj} \\ 0 & 1/2\lambda_{12j} & \lambda_{2j} & \dots & 1/2\lambda_{2r_jj} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 1/2\lambda_{1r_jj} & 1/2\lambda_{2r_jj} & \dots & \lambda_{r_jj} \end{bmatrix} > 0 \quad (3.5)$$

where

$$\bar{Q}_{kj} \equiv I - P_{kj}, \quad k = 1, 2, \dots, N_j \quad (3.6)$$

$$Q_{ij} = -\left\{ (A_{ij} - B_{ij} K_{ij})^T P_j + P_j (A_{ij} - B_{ij} K_{ij}) + \bar{P}_j + P_j \bar{A}_{ij} P_j + \sum_{n=1}^J \left[\left(\frac{J-1}{J} \right) I + P_j C_{nj} C_{nj}^T P_j \right] \right\} \quad (3.7)$$

with

$$\bar{P}_j = \sum_{k=1}^{N_j} P_{kj}, \quad \bar{A}_{ij} = \sum_{k=1}^{N_j} A_{ikj} A_{ikj}^T, \quad G_{ifj} = \frac{(A_{ij} - B_{ij} K_{fj}) + (A_{fj} - B_{fj} K_{ij})}{2}, \quad (3.8)$$

and $\lambda_M(\cdot)$ is the maximum eigenvalues, $\lambda_m(\cdot)$ is minimal eigenvalues.

Proof: See Appendix.

Remark 1: Both conditions are met by default. The stability of systems F with delays can be verified using the equations in (3.4) and (3.5). Therefore, it is advisable to check for asymptotic stability under certain conditions. If this fails, another condition is required.

An evolutionary bat algorithm (EBA) based on a complex system of bats in the wild is proposed. Unlike other cluster reconnaissance algorithms, the strength of EBA lies in the fact that only one of the parameter (called the environment) is determined. Therefore, it is necessary to use an algorithm to solve the problem (Yan *et al.* 1998, Tsai *et al.* 2015, Zandi *et al.* 2018). During the evolution, the choice of support determines the different phases of the study. In this study, we chose air because it is the original natural habitat in which bats live. The capabilities of the EBA could be summarized by four steps:

Initialization: random assignment of artificial reagents, diffusion in the solution area.

Movement: An artificial example is movement. Generate a random number and make sure it doesn't exceed a fixed heart rate intensity. If positive, a random walking process is used to move the artificial specimen. $x_i^t = x_i^{t-1} + D$,

in which these x_i^t indicate the coordinate in these i -th artificial agents in the t -th iteration, then x_i^{t-1} is the last iteration i -th artificial agents, and D moving distance as follows.

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

where $\gamma = 0.17$, $\Delta T \in [-1, 1]$ random number when the chosen mediums are air.

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

where random β , x_{best} is almost best solution are found so long throughout all of the artificial agents, and x_i^{tR} new coordinates in these artificial mean upon each walking movement.

Then we use the custom fitness function to calculate the artificial treatment fit and update it using the best stored solution.

4. Example

In this section, we will examine Fisher's equations and temperature control of high-speed aircraft cooling coils to demonstrate about this effectiveness of these proposed method in design. Fisher's equations have been used as the basis for various models of spatial gene spread of populations, chemical wave propagation, flame propagation, branched brown motion processes, and reactor theory. And we focus on the results which shows the high effective by the proposed theory utilized for damage propagation for aircraft structural analysis of composite materials.

The purpose of this example is to create the fuzzy controller based on the system stabilization model (4.1).

$J=1$, then

Rule No. 1: If $x_{11}(t)$ is about 4, Rule No. 2: If the $x_{11}(t)$ is about -4

Then we say $\dot{x}_1(t) = A_{11}x_1(t) + \sum_{k=1}^3 A_{1k1}x(t - \tau_{k1}) + B_{11}u_1(t)$, $\dot{x}_1(t) = A_{21}x_1(t) + \sum_{k=1}^3 A_{2k1}x(t - \tau_{k1}) + B_{21}u_1(t)$

$$\begin{aligned}
&\text{in } A_{11} = \begin{bmatrix} -9 & 1 \\ 3 & 2 \end{bmatrix}, A_{21} = \begin{bmatrix} -35 & -4 \\ 5 & -34 \end{bmatrix}, A_{111} = \begin{bmatrix} -6 & -3 \\ 2 & 2 \end{bmatrix}, A_{121} = \begin{bmatrix} -5 & -4 \\ 0.5 & 3 \end{bmatrix}, \\
A_{131} = \begin{bmatrix} -8 & -4 \\ 3 & 5 \end{bmatrix}, A_{211} = \begin{bmatrix} 7 & 3 \\ -2 & -1 \end{bmatrix}, A_{221} = \begin{bmatrix} 6 & 4 \\ -0.5 & -2 \end{bmatrix}, A_{231} = \begin{bmatrix} 9 & 4 \\ -3 & -4 \end{bmatrix}, \\
B_{11} = \begin{bmatrix} 0.55 \\ -2.1 \end{bmatrix}, B_{21} = \begin{bmatrix} 0.3 \\ 1.1 \end{bmatrix}, \tau_{11} = 1.2 \text{ (sec)}, \tau_{21} = 1.8 \text{ (sec)}, \tau_{31} = 2.5 \text{ (sec)} \quad (4.1)
\end{aligned}$$

and membership functions for 2 rules are $\frac{1}{1+\exp[-2x_{11}(t)]}$ and $1 - M_{111}(x_{11}(t))$.

$J=2$, then

Rule 1: If $x_{12}(t)$ is about 0, Rule 2: If $x_{12}(t)$ is about 4

Then $\dot{x}_2(t) = A_{12}x_2(t) + \sum_{k=1}^3 A_{1k2}x(t - \tau_{k2}) + B_{12}u_2(t)$, $\dot{x}_2(t) = A_{22}x_2(t) + \sum_{k=1}^3 A_{2k2}x(t - \tau_{k2}) + B_{22}u_2(t)$

$$\begin{aligned}
&\text{with } A_{12} = \begin{bmatrix} -10 & 1 \\ 1 & 3 \end{bmatrix}, A_{22} = \begin{bmatrix} -34 & -4 \\ 3 & -33 \end{bmatrix}, A_{112} = \begin{bmatrix} -2 & -3 \\ 1 & 2 \end{bmatrix}, A_{121} = \begin{bmatrix} -1.5 & -2 \\ 0.8 & 1.3 \end{bmatrix}, \\
A_{132} = \begin{bmatrix} -4 & -1 \\ 3.5 & 5 \end{bmatrix}, A_{132} = \begin{bmatrix} -4 & -1 \\ 3.5 & 5 \end{bmatrix}, A_{212} = \begin{bmatrix} 3 & 3 \\ -1 & -1 \end{bmatrix}, A_{222} = \begin{bmatrix} 2.5 & 2 \\ -0.8 & -0.3 \end{bmatrix}, \\
A_{232} = \begin{bmatrix} 5 & 1 \\ -3.5 & -4 \end{bmatrix}, B_{12} = \begin{bmatrix} 0.5 \\ -2 \end{bmatrix}, B_{22} = \begin{bmatrix} 0.36 \\ 1 \end{bmatrix}, \tau_{12} = 1.5 \text{ (sec)}, \tau_{22} = 2.2 \text{ (sec)}, \\
\tau_{32} = 3.1 \text{ (sec)} \quad (4.2)
\end{aligned}$$

and membership functions for 2 rules are $\exp[-x_{12}^2(t)]$ and $1 - M_{112}(x_{12}(t))$.

$J=3$, then

Rule No. 1: If $x_{13}(t)$ is about 3, Rule No. 2: If $x_{13}(t)$ is about -3

Then $\dot{x}_3(t) = A_{13}x_3(t) + \sum_{k=1}^3 A_{1k3}x(t - \tau_{k3}) + B_{13}u_3(t)$, $\dot{x}_3(t) = A_{23}x_3(t) + \sum_{k=1}^3 A_{2k3}x(t - \tau_{k3}) + B_{23}u_3(t)$.

$$\begin{aligned}
&\text{with } A_{13} = \begin{bmatrix} -12.5 & 1 \\ 3.2 & 2 \end{bmatrix}, A_{23} = \begin{bmatrix} -33 & -4 \\ 6.7 & -32 \end{bmatrix}, A_{113} = \begin{bmatrix} -6.3 & -3 \\ 3 & 2 \end{bmatrix}, A_{123} = \begin{bmatrix} -9 & -4.5 \\ 0.5 & 7 \end{bmatrix}, \\
A_{133} = \begin{bmatrix} -18 & -0.4 \\ 3 & 15 \end{bmatrix}, A_{213} = \begin{bmatrix} 7.3 & 3 \\ -3 & -1 \end{bmatrix}, A_{223} = \begin{bmatrix} 10 & 4.5 \\ -0.5 & -6 \end{bmatrix}, A_{233} = \begin{bmatrix} 19 & 0.4 \\ -3 & -14 \end{bmatrix}, \\
B_{13} = \begin{bmatrix} 0.5 \\ -2.2 \end{bmatrix}, B_{23} = \begin{bmatrix} 0.3 \\ 1.4 \end{bmatrix}, \tau_{13} = 1.3 \text{ (sec)}, \tau_{23} = 1.9 \text{ (sec)}, \tau_{33} = 3.4 \text{ (sec)} \quad (4.3)
\end{aligned}$$

and membership functions for 2 rules are $\frac{1}{1+\exp[-4x_{13}(t)]}$ and $1 - M_{113}(x_{13}(t))$.

In addition, the interconnection are described as

$$C_{21} = \begin{bmatrix} 2 & 0.1 \\ -0.2 & 4 \end{bmatrix}, C_{31} = \begin{bmatrix} 1.5 & 0.1 \\ 1.4 & 1.8 \end{bmatrix}, C_{12} = \begin{bmatrix} 2 & -2.4 \\ 1.6 & 3 \end{bmatrix},$$

$$C_{32} = \begin{bmatrix} 1.3 & 0.2 \\ 1.7 & -3.8 \end{bmatrix}, C_{13} = \begin{bmatrix} 2 & 0.1 \\ 0.3 & 3 \end{bmatrix}, C_{23} = \begin{bmatrix} 2.2 & 0.4 \\ 1.4 & 1.6 \end{bmatrix}. \tag{4.4}$$

Therefore, the multiple time-delay fuzzy large-scale system can be summarized as

$$F : \begin{cases} \dot{x}_1(t) = \sum_{i=1}^2 h_{i1}(t)[A_{i1}x_1(t) + B_{i1}u_1(t) + \sum_{k=1}^3 A_{ik1}x_1(t - \tau_{k1})] + \phi_1(t) & (4.5a) \\ \dot{x}_2(t) = \sum_{i=1}^2 h_{i2}(t)[A_{i2}x_2(t) + B_{i2}u_2(t) + \sum_{k=1}^3 A_{ik2}x_2(t - \tau_{k2})] + \phi_2(t) & (4.5b) \\ \dot{x}_3(t) = \sum_{i=1}^2 h_{i3}(t)[A_{i3}x_3(t) + B_{i3}u_3(t) + \sum_{k=1}^3 A_{ik3}x_3(t - \tau_{k3})] + \phi_3(t) & (4.5c) \\ \phi_j(t) = \sum_{\substack{n=1 \\ n \neq j}}^3 C_{nj}x_n(t), & (4.5d) \end{cases}$$

where $x_1^T(t)=[x_{11}(t) \ x_{21}(t)]$, $x_2^T(t)=[x_{12}(t) \ x_{22}(t)]$, $x_3^T(t)=[x_{13}(t) \ x_{23}(t)]$ are in and the matrices A_{ij} , B_{ij} and τ_{kj} are shown in Eqs. (4.1)-(4.3).

The pairs (A_{ij}, B_{ij}) , $i = 1, 2$, then $j=1, 2, 3$ are all locally controllable. Then we need to control (4.5) where three designed fuzzy controllers by these PDC schemes are described as the following.

Fuzzy controller j=1:

Rule No. 1: If $x_{11}(t)$ is about 4, Rule No. 2: If $x_{11}(t)$ is about -4

$$\text{Then one of } u_1(t) = -K_{11}x_1(t), \text{ or } u_1(t) = -K_{21}x_1(t) \tag{4.6}$$

Choosing these closed-loop eigenvalues $(-27.8, -8)$ for an $A_{11} - B_{11}K_{11}$ and these closed-loop eigenvalues at $(-17, -28)$ are $A_{21} - B_{21}K_{21}$, we would get $K_{11} = [-0.8848 \ -13.946]$ and then $K_{21} = [-27.153 \ -14.4128]$.

Fuzzy controller j=2:

Rule No. 1: If $x_{12}(t)$ is considered about 0, Rule No. 2: If $x_{12}(t)$ is considered about 4

$$\text{Then we get } u_2(t) = -K_{12}x_2(t), \text{ and we get } u_2(t) = -K_{22}x_2(t), \tag{4.7}$$

In another way, we choose these closed-loop eigenvalues $(-27.5, -8.5)$ in $A_{12} - B_{12}K_{12}$ and these closed-loop eigenvalues $(-16.5, -29)$ in $A_{22} - B_{22}K_{22}$, we have $K_{12} = [2.1493 \ -13.9627]$ and $K_{22} = [-20.7884 \ -14.0162]$.

Fuzzy controller j=3:

Rule No. 1: If $x_{13}(t)$ is about 3, Rule No. 2: If $x_{13}(t)$ is about -3

$$\text{Then the } u_3(t) = -K_{13}x_3(t), \text{ and Then } u_3(t) = -K_{23}x_3(t). \tag{4.8}$$

Choosing one of the closed-loop eigenvalues saying $(-28, -10)$ for $A_{13} - B_{13}K_{13}$ and one of these closed-loop eigenvalues $(-20, -23)$ for $A_{23} - B_{23}K_{23}$, then some get $K_{13} = [-1.7114 \ -12.1111]$ and $K_{23} = [-21.2908 \ -11.152]$.

The choice and dominance of an appropriate matrix to satisfy Theorem 1 will be key issues to

address. In this article, we will use EBA to find the right solution. The solution obtained in this case can be divided into two categories: possible and impossible. That said, developing an adaptive function with binary arithmetic is an easier way to meet the needs of this application. In this article, we use the Lyapunov function method to construct a fitness function according to stability criteria derived from the LMI state. The logical AND operation is used in the fit function to validate a solution and generate a binary classification result for the solution found. The formula for the training function is:

$$F = \begin{cases} 1, & \text{if } \Theta < 0 \text{ and } P = P^T > 0. \\ 0, & \text{otherwise.} \end{cases}$$

in which F is one of these fitness values and Θ is regarded as follows.

$$\Theta = (A_i - B_i K)^T P + P(A_i - B_i K)$$

If the elements of the array must always be symmetric, EBA is modified using the array. Also, the matrix and boundary conditions are used in the initialization process. Using the LMI optimization algorithm when the matrix is affected by the constraints of the same region, a workable solution is provided in Eq. (4.9).

$$P_1 = \begin{bmatrix} 0.78 & 0.22 \\ 0.22 & 0.25 \end{bmatrix}, P_2 = \begin{bmatrix} 0.7 & 0.22 \\ 0.22 & 0.3 \end{bmatrix}, P_3 = \begin{bmatrix} 0.86 & 0.22 \\ 0.22 & 0.27 \end{bmatrix}. \tag{4.9}$$

Combining (4.1–4.3, 4.9), (4.6–4.8) and (3.6–3.8) yields

$$\begin{aligned} Q_{11} &= \begin{bmatrix} 1.8532 & -1.9714 \\ -1.9714 & 2.6466 \end{bmatrix}, Q_{21} = \begin{bmatrix} 15.6251 & -1.8688 \\ -1.8688 & 1.7487 \end{bmatrix}, Q_{121} = \begin{bmatrix} 44.2194 & 15.9673 \\ 15.9673 & 5.0908 \end{bmatrix}, \\ Q_{12} &= \begin{bmatrix} 1.6302 & -2.2738 \\ -2.2738 & 3.3238 \end{bmatrix}, Q_{22} = \begin{bmatrix} 15.1128 & -0.8759 \\ -0.8759 & 2.8105 \end{bmatrix}, Q_{122} = \begin{bmatrix} 42.5249 & 16.8178 \\ 16.8178 & 6.2273 \end{bmatrix}, \\ Q_{13} &= \begin{bmatrix} 5.5364 & -3.3978 \\ -3.3978 & 2.9264 \end{bmatrix}, Q_{23} = \begin{bmatrix} 15.3401 & -3.6436 \\ -3.6436 & 1.8599 \end{bmatrix}, Q_{123} = \begin{bmatrix} 49.3992 & 13.7099 \\ 13.7099 & 3.0063 \end{bmatrix}, \bar{Q}_{11} = \begin{bmatrix} -0.1 & 0 \\ 0 & -0.1 \end{bmatrix}, \\ \bar{Q}_{21} &= \begin{bmatrix} -0.1 & 0 \\ 0 & -0.1 \end{bmatrix}, \bar{Q}_{31} = \begin{bmatrix} -0.1 & 0 \\ 0 & -0.1 \end{bmatrix}, \bar{Q}_{12} = \begin{bmatrix} -0.1 & 0 \\ 0 & -0.1 \end{bmatrix}, \bar{Q}_{22} = \begin{bmatrix} -0.1 & 0 \\ 0 & -0.1 \end{bmatrix}, \bar{Q}_{32} = \begin{bmatrix} -0.1 & 0 \\ 0 & -0.1 \end{bmatrix}, \\ \bar{Q}_{13} &= \begin{bmatrix} -0.1 & 0 \\ 0 & -0.1 \end{bmatrix}, \bar{Q}_{23} = \begin{bmatrix} -0.1 & 0 \\ 0 & -0.1 \end{bmatrix}, \bar{Q}_{33} = \begin{bmatrix} -0.1 & 0 \\ 0 & -0.1 \end{bmatrix} \end{aligned} \tag{4.10}$$

From Eq. (3.5), we have

$$\begin{aligned} \Lambda_1 &= \begin{bmatrix} 0.1 & 0 & 0 \\ 0 & 0.239 & -0.5979 \\ 0 & -0.5979 & 1.5014 \end{bmatrix}, \Lambda_2 = \begin{bmatrix} 0.1 & 0 & 0 \\ 0 & 0.0506 & -0.3669 \\ 0 & -0.3669 & 2.7485 \end{bmatrix}, \\ \Lambda_3 &= \begin{bmatrix} 0.1 & 0 & 0 \\ 0 & 0.5916 & -0.7423 \\ 0 & -0.7423 & 0.9381 \end{bmatrix} \end{aligned} \tag{4.11}$$

and the eigenvalues of them are given below

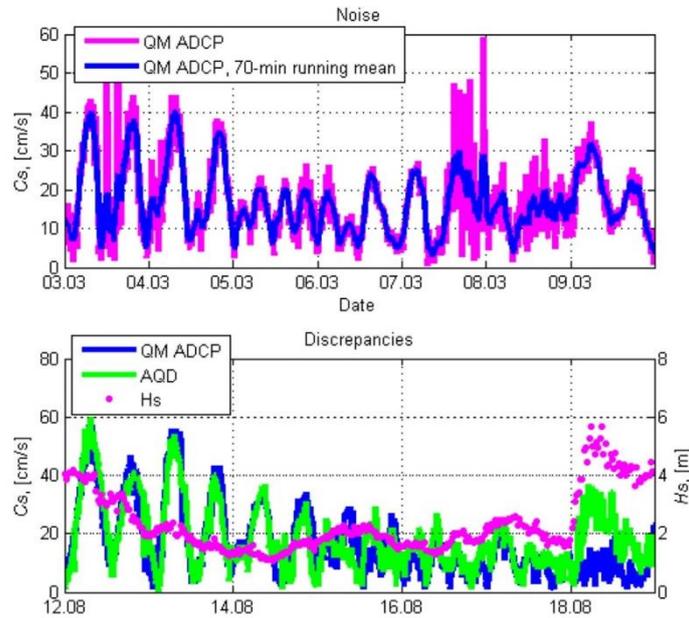


Fig. 1 The comparison of the numerical results

$$\lambda(\Lambda_1) = 0.1, 0.0008, 1.7396 > 0, \tag{4.12}$$

$$\lambda(\Lambda_2) = 0.1, 0.0016, 2.7975 > 0, \tag{4.13}$$

$$\lambda(\Lambda_3) = 0.1, 0.0026, 1.5272 > 0. \tag{4.14}$$

These math matrices in Λ_j ($j=1, 2, 3$) are considered with positive definite, which means Theorem 1 then let these fuzzy controllers (4.6-4.8) asymptotically in stabilization of the system (4.5). Simulation in results are all illustrated in Fig. 1 which shows the comparison of the numerical results.

5. Conclusions

A Modified fuzzy mechanical control of large-scale multiple time delayed dynamic systems in states is considered in this paper. To do this, at the first level, a two-step strategy is proposed to divide a large system into several interconnected subsystems. And we focus on the damage propagation for aircraft structural analysis of composite materials. As a modified fuzzy control command, the next was received as feedback theory based on the energetic function and the LMI optimal stability criteria which allow researchers to solve this problem and have the whole system in asymptotically stability. And we focus on the results which shows the high effective by the proposed theory utilized for damage propagation for aircraft structural analysis of composite materials.

References

- Bedirhanoglu, I. (2014), "A practical neuro-fuzzy model for estimating modulus of elasticity of concrete", *Struct. Eng. Mech.*, **51**(2), 249-265. <https://doi.org/10.12989/sem.2014.51.2.249>.
- Chen, C., Chen, P. and Chiang, W. (2011), "Stabilization of adaptive neural network controllers for nonlinear structural systems using a singular perturbation approach", *J. Vib. Control*, **17**, 1241-1252. <https://doi.org/10.1177/1077546309352827>.
- Chen, C.Y.J., Kuo, D., Hsieh, C. and Chen, T. (2020), "System simulation and synchronization for optimal evolutionary design of nonlinear controlled systems", *Smart Struct. Syst.*, **26**(6), 797-807. <https://doi.org/10.12989/sss.2020.26.6.797>.
- Chen, P.C., Chen, C. and Chiang, W. (2008), "GA-based fuzzy sliding mode controller for nonlinear systems", *Math. Prob. Eng.*, **2008**, Article ID 325859. <https://doi.org/10.1155/2008/325859>.
- Chen, P.C., Chen, C. and Chiang, W. (2009), "A novel stability condition and its application to GA-based fuzzy control for nonlinear systems with uncertainty", *J. Marine Sci. Technol.*, **17**, 293-299.
- Chen, P.C., Chen, C. and Chiang, W. (2009), "GA-based modified adaptive fuzzy sliding mode controller for nonlinear systems", *Exp. Syst. Appl.*, **36**, 5872-5879. <https://doi.org/10.1016/j.eswa.2008.07.003>.
- Chen, P.C., Chen, C., Chiang, W. and Lo, D.C. (2011), "GA-based decoupled adaptive FSMC for nonlinear systems by a singular perturbation scheme", *Exp. Syst. Appl.*, **3620**(4), 517-526. <https://doi.org/10.1007/s00521-011-0540-7>.
- Chen, T., M., Marto, A. and Chen, C. (2010), "Application of data mining to the spatial heterogeneity of foreclosed mortgages", *Exp. Syst. Appl.*, **37**, 993-997. <https://doi.org/10.1016/j.eswa.2009.05.076>.
- Chen, T., Yang, H.P. and Chen, C. (2008), "A mathematical tool for inference in logistic regression with small-sized data sets: A practical application on ISW-ridge relationships", *Math. Prob. Eng.*, **2008**, Article ID 186372. <https://doi.org/10.1155/2008/186372>.
- Chiang, W., Chen, C. and Hsiao, F. (2004), "Stability analysis of nonlinear interconnected systems via T-S fuzzy models", *Int. J. Comput. Intel. Appl.*, **4**, 41-55. <https://doi.org/10.1142/S1469026804001033>.
- Chiang, W., Chen, C. and Wu, D. (2007), "Modeling, H_∞ control and stability analysis for structural systems using Takagi-Sugeno fuzzy model", *J. Vib. Control*, **13**, 1519-1534. <https://doi.org/10.1177/1077546307073690>.
- Chiang, W., Chen, C., Lin, C., Tsai, C., Chen, C. and Yeh, K. (2007), "A novel delay-dependent criterion for time-delay T-S fuzzy systems using fuzzy Lyapunov method", *Int. J. Artif. Intell. Tool.*, **16**, 545-552. <https://doi.org/10.1142/S0218213007003400>.
- Chiang, W., Tsai, C., Chen, C. and Wang, M. (2007), "Fuzzy lyapunov method for stability conditions of nonlinear systems", *Int. J. Artif. Intell. Tool.*, **15**, 163-172. <https://doi.org/10.1142/S0218213006002618>.
- Chiang, W., Yeh, K., Chen, C. and Chen, C. (2007), "Robustness design of time-delay fuzzy systems using fuzzy Lyapunov method", *Appl. Math. Comput.*, **205**, 568-577. <https://doi.org/10.1016/j.amc.2008.05.104>.
- Chiang, W.L., Chen, T.W., Liu, M.Y. and Hsu, C.J. (2001), "Application and robust H control of PDC fuzzy controller for nonlinear systems with external disturbance", *J. Marine Sci. Technol.*, **9**(2), 84-90.
- Chiang, W.L., Yeh, K., Chen, C. and Chen, C. (2002), "A new approach to stability analysis for nonlinear time-delay systems", *Int. J. Fuzzy Syst.*, **4**(2), 735-738.
- Eswaran, M. and Reddy, G.R. (2016), "Numerical simulation of tuned liquid tank-structure systems through sigma-transformation based fluid-structure coupled solver", *Wind Struct*, **23**(5), 421-447. <https://doi.org/10.12989/was.2016.23.5.421>.
- Feng, G., Cao, S.G., Rees, N.W. and Chak, C.K. (1997), "Design of fuzzy control systems with guaranteed stability", *Fuzzy Set. Syst.*, **85**, 1-10. [https://doi.org/10.1016/0165-0114\(95\)00375-4](https://doi.org/10.1016/0165-0114(95)00375-4).
- Hsiao, F., Chen, C. and Tsai, K. (2005), "Stability conditions of fuzzy systems and its application to structural and mechanical systems", *Adv. Eng. Softw.*, **37**, 624-629. <https://doi.org/10.1016/j.advengsoft.2005.12.002>.
- Hsiao, F., Chen, C., Liang, Y., Xu, S. and Chiang, W. (2005), "T-S fuzzy controllers for nonlinear interconnected systems with multiple time delays", *IEEE Trans. Circuit. Syst. I: Regul. Paper.*, **52**(9),

- 1883-1893. <https://doi.org/10.1109/TCSI.2005.852492>.
- Hsiao, F., Chen, C., Wu, Y. and Chiang, W. (2005), "Fuzzy controllers for nonlinear interconnected tmd systems with external force", *J. Chin. Inst. Eng.*, **28**(1), 175-181. <https://doi.org/10.1080/02533839.2005.9670984>.
- Hsiao, F., Chiang, W. and Chen, C. (2004), "Stability analysis of T-S fuzzy models for nonlinear multiple time-delay interconnected systems", *Math. Comput. Simul.*, **66**, 523-537. <https://doi.org/10.1016/j.matcom.2004.04.001>.
- Hsiao, F., Chiang, W., Chen, C., Xu, S. and Wu, S. (2005), "Application and robustness design of fuzzy controller for resonant and chaotic systems with external disturbance", *Int. J. Uncertain. Fuzz. Knowl. Bas. Syst.*, **13**(3), 281-295. <https://doi.org/10.1142/S0218488505003461>.
- Hsiao, F., Chiang, W., Xu, S. and Wu, S. (2003), "Application and fuzzy H_∞ control via T-S fuzzy models for nonlinear time-delay systems", *Int. J. Artif. Intell. Tool.*, **12**(2), 117-137. <https://doi.org/10.1142/S0218213003001174>.
- Hsiao, F., Chiang, W., Xu, S. and Wu, S. (2005), "Fuzzy control for nonlinear systems via neural-network-based approach", *Int. J. Comput. Meth. Eng. Sci. Mech.*, **6**, 145-152. <https://doi.org/10.1080/15502280590923612>.
- Hsiao, F., Hwang, J., Chen, C. and Tsai, Z. (2005), "Robust stabilization of nonlinear multiple time-delay large-scale systems via decentralized fuzzy control", *IEEE Trans. Fuzzy Syst.*, **13**, 152-163. <https://doi.org/10.1109/TFUZZ.2004.836067>.
- Hsieh, T., Wang, M., Chen, C., Chen, C., Yu, S., Yang, H.P. and Chen, T. (2006), "A new viewpoint of s-curve regression model and its application to construction management", *Int. J. Artif. Intel. Tool.*, **15**, 131-142. <https://doi.org/10.1142/S021821300600259X>.
- Hung, C.C., Tim, C. and Abu, A.A. (2019), "Optimal fuzzy design of Chua's circuit system", *Int. J. Innov. Comput., Inform. Control*, **15**(6), 2355-2366. <https://doi.org/10.24507/ijicic.15.06.2355>.
- Lin, C., Wang, J.F., Chen, C., Chen, C. and Yen, C.V. (2009), "Improving the generalization performance of RBF neural networks using a linear regression technique", *Exp. Syst. Appl.*, **36**, 12049-12053. <https://doi.org/10.1016/j.eswa.2009.03.012>.
- Lin, J., Chen, C., Lee, W. (2010), "Modeling and fuzzy pdc control and its application to an oscillatory TLP structure", *Math. Prob. Eng.*, **2010**, Article ID 120403. <https://doi.org/10.1155/2010/120403>.
- Lin, J., Chen, C., Lee, W. and Chen, C. (2010), "Fuzzy control for an oceanic structure: A case study in time-delay TLP system", *J. Vib. Control*, **16**, 147-160. <https://doi.org/10.1177/1077546309339424>.
- Lin, J., Chen, C., Shen, C. and Cheng, M. (2010), "Application of fuzzy-model-based control to nonlinear structural systems with time delay: An LMI method", *J. Vib. Control*, **16**, 1651-1672. <https://doi.org/10.1177/1077546309104185>.
- Lin, J., Shen, C., Chen, C. and Cheng, M. (2010), "Stability analysis of an oceanic structure using the Lyapunov method", *Eng. Comput.*, **27**, 186-204. <https://doi.org/10.1108/02644401011022364>.
- Lin, M., Chen, C., Wang, Q., Cao, Y., Shih, J., Lee, Y., Chen, C. and Wang, S. (2009), "Fuzzy model-based assessment and monitoring of desertification using MODIS satellite imagery", *Eng. Comput.*, **26**, 745-760. <https://doi.org/10.1108/02644400910985152>.
- Lin, M.L. and Chen, C.W. (2010), "Application of fuzzy models for the monitoring of ecologically sensitive ecosystems in a dynamic semiarid landscape from satellite imagery", *Eng. Comput.*, **27**, 5-19. <https://doi.org/10.1108/02644401011008504>.
- Liu, K.F., Chen, C. and Cheng, M. (2009), "Modeling and control for nonlinear structural systems via a NN-based approach", *Exp. Syst. Appl.*, **36**, 4765-4772. <https://doi.org/10.1016/j.eswa.2008.06.062>.
- Liu, K.F., Chen, C., Shen, C., Chen, C. and Cheng, M. (2009), "A stability criterion for time-delay tension leg platform systems subjected to external force", *Chin. Ocean Eng.*, **23**, 49-57.
- Liu, K.F., Yeh, K. and Chen, C. (2009), "Adaptive fuzzy sliding mode control for seismically excited bridges with lead rubber bearing isolation", *Int. J. Uncertain. Fuzz. Knowl. Bas. Syst.*, **17**, 705-727. <https://doi.org/10.1142/S0218488509006224>.
- Liu, K.F., Yeh, K. and Chen, C. (2009), "The stability of an oceanic structure with T-S fuzzy models", *Math. Comput. Simul.*, **80**, 402-426. <https://doi.org/10.1016/j.matcom.2009.08.001>.

- Meng, Y.Z., Fu, Q. and Chen, T. (2022), “Grey FNN control and robustness design for practical nonlinear systems”, *J. Eng. Res.*, <https://doi.org/10.36909/jer.11273>.
- Meng, Y.Z., Fu, Q. and Chen, T. (2022), “Stochastic intelligent GA-NN controller design for active TMD shear building”, *Struct. Eng. Mech.*, **81**(1), 51-57. <https://doi.org/10.12989/sem.2022.81.1.051>.
- Meng, Y.Z., Fu, Q. and Chen, T. (2022), “Systematic fuzzy Navier-Stokes equations for aerospace vehicles”, *Aircraft Eng. Aerosp. Technol.*, **94**(3), 351-359. <https://doi.org/10.1108/AEAT-06-2020-0109>.
- Meng, Y.Z., M., Marto, A. and Chen, T. (2022), “NN model-based evolved control by DGM model for practical nonlinear systems”, *Exp. Syst. Appl.*, **193**, 115873. <https://doi.org/10.1016/j.eswa.2021.115873>.
- Meng, Y.Z., Wang, R., Fu, Q. and Chen, T. (2022), “Composite components damage tracking and dynamic structural behaviour with AI algorithm”, *Steel Compos. Struct.*, **42**(2) 151-159. <https://doi.org/10.12989/scs.2022.42.2.151>.
- Mori, T. (1985), “Criteria for asymptotic stability of linear time delay systems”, *IEEE Trans. Automat. Contr.*, **30**, 158-162. <https://doi.org/10.1109/TAC.1985.1103901>.
- Razavi, A. and Sarkar, P.P. (2018), “Laboratory investigation of the effects of translation on the near-ground tornado flow field”, *Wind Struct.*, **26**(3), 179-190. <https://doi.org/10.12989/was.2018.26.3.179>.
- Tanaka, K. and Sugeno, M. (1992), “Stability analysis and design of fuzzy control system”, *Fuzzy Set. Syst.*, **45**, 135-156. [https://doi.org/10.1016/0165-0114\(92\)90113-I](https://doi.org/10.1016/0165-0114(92)90113-I).
- Tanaka, K., Ikeda, T. and Wang, H.O. (1996), “Robust stabilization of a class of uncertain nonlinear systems via fuzzy control: Quadratic stabilizability, H^∞ control theory, and linear matrix inequalities”, *IEEE Trans. Fuzzy Syst.*, **4**, 1-13. <https://doi.org/10.1109/91.481840>.
- Tim, C. and Chen, C. (2020), “Intelligent fuzzy algorithm for nonlinear discrete-time systems”, *Trans. Inst. Measure. Control*, **42**(7), 1358-1374. <https://doi.org/10.1177/0142331219891383>.
- Tim, C. and Chen, C. (2021), “Evolved auxiliary controller with applications to aerospace”, *Aircraft Eng. Aerosp. Technol.*, **93**(4), 529-543. <https://doi.org/10.1108/AEAT-12-2019-0233>
- Tim, C. and Chen, C.Y.J. (2019), “Meteorological tidal predictions in the mekong estuary using an evolved ANN time series”, *Marine Technol. Soc. J.*, **53**(6), 27-34. <https://doi.org/10.4031/MTSJ.53.6.3>.
- Tim, C. and Chen, J.C. (2019), “Decentralized fuzzy C-Means robust algorithm for continuous systems”, *Aircraft Eng. Aerosp. Technol.*, **92**(2), 222-228. <https://doi.org/10.1108/AEAT-04-2019-0082>.
- Tim, C. and Cheng, C. (2019), “Modelling and verification of an automatic controller for a water treatment mixing tank”, *Desalin. Water Treat.*, **159**, 318-326. <https://doi.org/10.5004/dwt.2019.24143>.
- Tim, C., Dkuo, N.J. and Chen, C. (2020), “A composite control for UAV systems with time delays”, *Aircraft Eng. Aerosp. Technol.*, **92**(7), 949-954. <https://doi.org/10.1108/AEAT-11-2019-0219>.
- Tim, C., Huang, Y., Hung, C.C., Frias, S., Muhammad, J.A. and Chen, C. (2021), “Smart structural stability and NN based intelligent control for nonlinear systems”, *Smart Struct. Syst.*, **27**(6), 917-926. <https://doi.org/10.12989/sss.2021.27.6.917>.
- Tim, C., Hung, C.C., Huang, Y.C., Chen, J.C., Rahman, S. and Islam Mozumder, T. (2021), “Grey signal predictor and fuzzy controls for active vehicle suspension systems via Lyapunov theory”, *Int. J. Comput. Commun. Control*, **16**(3), 3991, 2021. <https://doi.org/10.15837/ijccc.2021.3.3991>.
- Tim, C., Kapron, N. and Chen, J.C. (2020), “Using evolving ANN-Based algorithm models for accurate meteorological forecasting applications in Vietnam”, *Math. Prob. Eng.*, **2020**, Article ID 8179652. <https://doi.org/10.1155/2020/8179652>.
- Tim, C., Kuo, D., Huiwi, M., Gong-yo, T. and Chen, J. (2021), “Evolved predictive vibration control for offshore platforms based on the Lyapunov stability criterion”, *Ship. Offshore Struct.*, **16**(7), 700-713. <https://doi.org/10.1080/17445302.2020.1776548>.
- Tim, C., Lohnash, M., Owens, E. and Chen, C. (2020), “PDC Intelligent control-based theory for structure system dynamics”, *Smart Struct. Syst.*, **25**(4), 401-408. <https://doi.org/10.12989/sss.2020.25.4.401>.
- Tim, C., Morozov, S.N. and Chen, C.Y.J. (2019), “Hazard data analysis for underwater vehicles by submarine casualties”, *Marine Technol. Soc. J.*, **53**(6), 21-26. <https://doi.org/10.4031/MTSJ.53.6.2>.
- Trinh H. and Aldeen, (1995), “A comment on ‘Decentralized stabilization of the large scale interconnected systems with delays’”, *IEEE Trans. Automat. Contr.*, **40**, 914-916.
- Tsai, P.W., Hayat, T., Ahmad, B. and Chen, C.W. (2015), “Structural system simulation and control via NN

- based fuzzy model”, *Struct. Eng. Mech.*, **56**(3), 385-407. <https://doi.org/10.12989/sem.2015.56.3.385>.
- Tsai, P.W., Pan, J.S., Liao, B.Y., Tsai, M.J. and Istanda, V. (2012), “Bat algorithm inspired algorithm for solving numerical optimization problems”, *Appl. Mech. Mater.*, **148**, 134-137. <https://doi.org/10.4028/www.scientific.net/AMM.148-149.134>.
- Tsai, P.W., Tseng, C.P., Hsu, W. and Chiang, W. (2012), “A novel strategy to determine insurance and risk control plan for natural disaster risk management”, *Nat. Hazard.*, **64**, 1391-1403. <https://doi.org/10.1007/s11069-012-0305-3>.
- Wang H.O., Tanaka, K. and Griffin, M.F. (1996), “An approach to fuzzy control of nonlinear systems: stability and design issues”, *IEEE Trans. Fuzzy Syst.*, **4**, 14-23.
- Wang, R., Zhen, C., Meng, Y.Z., Fu, Q. and Chen, T. (2021), “Active TMD systematic design of fuzzy control and the application in high-rise buildings”, *Earthq. Struct.*, **21**(6), 577-585. <https://doi.org/10.12989/eas.2021.21.6.577>.
- Wang, R., Zhen, C., Meng, Y.Z., Fu, Q. and Chen, T. (2021), “Apply a robust fuzzy LMI control scheme with AI algorithm to civil frame building dynamic analysis”, *Comput. Concrete*, **28**(4), 433-440. <https://doi.org/10.12989/cac.2021.28.4.433>.
- Wang, R., Zhen, C., Meng, Y.Z., Fu, Q. and Chen, T. (2021), “Grey signal predictor and evolved control for practical nonlinear mechanical systems”, *J. Grey Syst.*, **33**(1), 156-170.
- Wang, R., Zhen, C., Meng, Y.Z., Fu, Q. and Chen, T. (2021), “Smart structural control and analysis for earthquake”, *Struct. Eng. Mech.*, **79**(2), 131-139. <https://doi.org/10.12989/sem.2021.79.2.131>.
- Wu, C. (2006), “Fuzzy Lyapunov method for stability conditions of nonlinear systems”, *Int. J. Artif. Intell. Tool.*, **15**, 163-171. <https://doi.org/10.1142/S0218213006002618>.
- Wu, C. (2007), “A novel delay-dependent criterion for time-delay T-S fuzzy systems using fuzzy Lyapunov method”, *Int. J. Artif. Intell. Tool.*, **16**, 545-552. <https://doi.org/10.1142/S0218213007003400>.
- Wu, C. (2007), “Modeling, control and stability analysis for structural systems using Takagi-Sugeno Fuzzy model”, *J. Vib. Control*, **13**, 1519-1534. <https://doi.org/10.1177/1077546307073690>.
- Wu, C. (2010), “Modeling and fuzzy PDC control and its application to an oscillatory TLP structure”, *Math. Prob. Eng.*, **2010**, Article ID 120403. <https://doi.org/10.1155/2010/120403>.
- Wu, C., Weiling, C., Ken, Y., Zhenyuan, C. and Liteh, L. (2002), “A stability criterion of time-delay fuzzy systems”, *J. Marine Sci. Technol.*, **10**, 33-35.
- Yan, X.G. and Dai, G.Z. (1998), “Decentralized output feedback robust control for nonlinear large-scale systems”, *Automatica*, **34**(11), 1469-1472. [https://doi.org/10.1016/S0005-1098\(98\)00090-9](https://doi.org/10.1016/S0005-1098(98)00090-9).
- Yang, G.H. and Zhang, S.Y. (1996), “Decentralized control of a class of large-scale systems with symmetrically interconnected subsystems”, *IEEE Trans. Automat. Contr.*, **41**, 710-713.
- Yuan, C.C. (2007), “An experimental study of stratified mixing caused by internal solitary waves in a two-layered fluid system over variable seabed topography”, *Ocean Eng.*, **34**, 1995-2008. <https://doi.org/10.1016/j.oceaneng.2007.02.014>.
- Yuan, C.C. and Hsu, J.R. (2006), “Numerical model of an internal solitary wave evolution on impermeable variable seabed in a stratified two-layer fluid system”, *China Ocean Eng.*, **20**, 303-313.
- Yuan, C.C. and Hsu, J.R. (2009), “A stability criterion for time-delay tension leg platform systems subjected to external force”, *China Ocean Engineering* **23**, 49-57.
- Yuan, C.C., Cheng, M.H. and Hsu, J.R. (2011), “Laboratory experiments on waveform inversion of an internal solitary wave over a slope-shelf”, *Environ. Fluid Mech.*, **11**, 353-384. <https://doi.org/10.1007/s10652-010-9204-x>.
- Yuan, C.C., Hsu, J.R. and Chen, C. (2005), “fuzzy logic derivation of neural network models with time delays in subsystems”, *Int. J. Artif. Intel. Tool.*, **14**, 967-974. <https://doi.org/10.1142/S021821300500248X>.
- Yuan, C.C., Hsu, J.R., Chen, H., Kuo, C. and Cheng, M. (2007), “Laboratory observations on internal solitary wave evolution on steep and inverse uniform slopes”, *Ocean Eng.*, **34**, 157-170. <http://doi.org/10.1016/j.oceaneng.2005.11.019>.
- Yuan, C.C., Hsu, J.R., Cheng, M., Chen, H. and Kuo, C. (2007), “An investigation on internal solitary waves in a two-layer fluid: Propagation and reflection from steep slopes”, *Ocean Eng.*, **34**, 171-184.

- <http://doi.org/10.1016/j.oceaneng.2005.11.020>.
- Yuan, C.C., Yang, Y., Chen, C., Chen, L. and Chen, T. (2010), "Linking the balanced scorecard (BSC) to business management performance: A preliminary concept of fit theory for navigation science and management", *Int. J. Phys. Sci.*, **5**, 1296-1305.
- Zandi, Y., Shariati, M., Marto, A., Wei, X., Karaca, Z., Dao, D., Toghroli, A., Hashemi, M.H., Sedghi, Y., Wakil, K. and Khorami, M. (2018), "Computational investigation of the comparative analysis of cylindrical barns subjected to earthquake", *Steel Compos. Struct.*, **28**(4), 439-447. <http://doi.org/10.12989/scs.2018.28.4.439>.
- Zhang, Y. (2015), "A fuzzy residual strength based fatigue life prediction method", *Struct. Eng. Mech.*, **56**(2), 201-221. <https://doi.org/10.12989/sem.2015.56.2.201>.
- Zhen, C. (2014), "Stability analysis and robustness design of nonlinear systems: An NN-based approach", *Appl. Soft Comput.*, **11**, 2735-2742. <https://doi.org/10.1016/j.asoc.2010.11.004>.
- Zhen, C. (2014), "Modeling, control, and stability analysis for time-delay TLP systems using the fuzzy Lyapunov method", *Neur. Comput. Appl.*, **20**, 527-534. <https://doi.org/10.1007/s00521-011-0576-8>.
- Zhen, C.W. (2014), "A criterion of robustness intelligent nonlinear control for multiple time-delay systems based on fuzzy Lyapunov methods", *Nonlin. Dyn.*, **76**(1), 23-31. <https://doi.org/10.1007/s11071-013-0869-9>.
- Zhen, C.W. (2014), "Interconnected TS fuzzy technique for nonlinear time-delay structural systems", *Nonlin. Dyn.*, **76**(1), 13-22. <https://doi.org/10.1007/s11071-013-0841-8>.
- Zhen, C.Y., Ya, M.H., Rai, W.Y. and Timothy, C. (2020a), "Neural ordinary differential gray algorithm to forecasting nonlinear systems", *Adv. Eng. Softw.*, **173**, 103199. <https://doi.org/10.1016/j.advengsoft.2022.103199>.
- Zhen, C.Y., Ya, M.H., Rai, W.Y. and Timothy, C. (2020b), "LQG modeling and GA control of structures subjected to earthquakes", *Earthq. Struct.*, **22**(4), 421-430 <https://doi.org/10.12989/eas.2022.22.4.421>.
- Zhen, C.Y., Ya, M.H., Rai, W.Y. and Timothy, C. (2020c), "Fuzzy neural network controller of interconnected method for civil structures", *Adv. Concrete Constr.*, **13**(5), 385-394 <https://doi.org/10.12989/acc.2022.13.5.385>.
- Zhen, C.Y., Ya, M.H., Rai, W.Y. and Timothy, C. (2020d), "Bridges dynamic analysis under earthquakes using a smart algorithm", *Earthq. Struct.*, **23**(4), 329-338 <https://doi.org/10.12989/eas.2022.23.4.329>.
- Zhen, C.Y., Ya, M.H., Rai, W.Y. and Timothy, C. (2020e), "Composite components damage tracking and dynamic structural behaviour with AI algorithm", *Steel Compos. Struct.*, **42**(2), 151-159 <https://doi.org/10.12989/scs.2022.42.2.151>.
- Zhen, C.Y., Ya, M.H., Rai, W.Y. and Timothy, C. (2020f), "Dynamic intelligent control of composite buildings by using M-TMD and evolutionary algorithm", *Steel Compos. Struct.*, **42**(5), 591-598 <https://doi.org/10.12989/scs.2022.42.5.591>.
- Zhen, C.Y., Ya, M.H., Rai, W.Y. and Timothy, C. (2020g), "NNDI decentralized evolved intelligent stabilization of large-scale systems", *Smart Struct. Syst.*, **30**(1), 1-15 <https://doi.org/10.12989/sss.2022.30.1.001>.
- Zhen, C.Y., Ya, M.H., Rai, W.Y. and Timothy, C. (2020h), "Intelligent algorithm and optimum design of fuzzy theory for structural control", *Smart Struct. Syst.*, **30**(5), 537-544 <https://doi.org/10.12989/sss.2022.30.5.537>.
- Zhou, X., Lin, Y. and Gu, M. (2015), "Optimization of multiple tuned mass dampers for large-span roof structures subjected to wind loads", *Wind Struct.*, **20**(3), 363-388. <https://doi.org/10.12989/was.2015.20.3.363>.

Appendix: Proof of theorem 1

(I): Let these Lyapunov function in these multiple time-delay fuzzy large-scale systems F are defined as

$$V = \sum_{j=1}^J v_j(t) = \sum_{j=1}^J \left\{ x_j^T(t) P_j x_j(t) + \sum_{k=1}^{N_j} \int_0^{\tau_{kj}} x_j^T(t-\tau) P_{kj} x_j(t-\tau) d\tau \right\} \quad (A1)$$

where $P_j = P_j^T > 0$ and $P_{kj} = P_{kj}^T > 0$, $k = 1, 2, \dots, N_j$. We therefore evaluate these time derivatives of V in the trajectories of Eq. (3.3), so we have

$$\begin{aligned} \dot{V} &= \sum_{j=1}^J \dot{v}_j(t) \\ &= \sum_{j=1}^J [\dot{x}_j^T(t) P_j x_j(t) + x_j^T(t) P_j \dot{x}_j(t) + \sum_{k=1}^{N_j} (x_j^T(t) P_{kj} x_j(t) - x_j^T(t - \tau_{kj}) P_{kj} x_j(t - \tau_{kj}))] \\ &= \sum_{j=1}^J \left\{ \left[\sum_{i=1}^{r_j} \sum_{f=1}^{r_j} h_{ij}(t) h_{fj}(t) ((A_{ij} - B_{ij} K_{fj}) x_j(t) + \sum_{k=1}^{N_j} A_{ikj} x(t - \tau_{kj}) + \phi_j(t)) \right]^T P_j x_j(t) \right. \\ &\quad \left. + x_j^T(t) P_j \left[\sum_{i=1}^{r_j} \sum_{f=1}^{r_j} h_{ij}(t) h_{fj}(t) ((A_{ij} - B_{ij} K_{fj}) x_j(t) + \sum_{k=1}^{N_j} A_{ikj} x(t - \tau_{kj}) + \phi_j(t)) \right] \right. \\ &\quad \left. + \sum_{k=1}^{N_j} (x_j^T(t) P_{kj} x_j(t) - x_j^T(t - \tau_{kj}) P_{kj} x_j(t - \tau_{kj})) \right\} \\ &= \sum_{j=1}^J \sum_{i=f=1}^{r_j} h_{ij}^2(t) x_j^T(t) [(A_{ij} - B_{ij} K_{ij})^T P_j + P_j (A_{ij} - B_{ij} K_{ij}) + \bar{P}_j] x_j(t) \\ &\quad + \sum_{j=1}^J \sum_{i \neq f}^{r_j} h_{ij}(t) h_{fj}(t) x_j^T(t) [(A_{ij} - B_{ij} K_{fj})^T P_j + P_j (A_{ij} - B_{ij} K_{fj}) + \bar{P}_j] x_j(t) \\ &\quad + \sum_{j=1}^J [\phi_j^T(t) P_j x_j(t) + x_j^T(t) P_j \phi_j(t)] - \sum_{j=1}^J \sum_{k=1}^{N_j} [x_j^T(t - \tau_{kj}) P_{kj} x_j(t - \tau_{kj})] \\ &\quad + \sum_{j=1}^J \sum_{i=1}^{r_j} \sum_{f=1}^{r_j} h_{fj}(t) \sum_{k=1}^{N_j} h_{ij}(t) [x_j^T(t) P_j A_{ikj} A_{ikj}^T P_j x_j(t) + x_j^T(t - \tau_{kj}) x_j(t - \tau_{kj})] \\ &= \sum_{j=1}^J \sum_{i=f=1}^{r_j} h_{ij}^2(t) x_j^T(t) [(A_{ij} - B_{ij} K_{ij})^T P_j + P_j (A_{ij} - B_{ij} K_{ij}) + \bar{P}_j] x_j(t) \\ &\quad + \sum_{j=1}^J \sum_{i \neq f}^{r_j} h_{ij}(t) h_{fj}(t) x_j^T(t) [(A_{ij} - B_{ij} K_{fj})^T P_j + P_j (A_{ij} - B_{ij} K_{fj}) + \bar{P}_j] x_j(t) \\ &\quad + \sum_{j=1}^J [\phi_j^T(t) P_j x_j(t) + x_j^T(t) P_j \phi_j(t)] - \sum_{j=1}^J \sum_{k=1}^{N_j} [x_j^T(t - \tau_{kj}) P_{kj} x_j(t - \tau_{kj})] \\ &\quad + \sum_{j=1}^J \sum_{i=f=1}^{r_j} h_{ij}^2(t) [x_j^T(t) P_j \bar{A}_{ij} P_j x_j(t)] \end{aligned}$$

$$\begin{aligned}
& + \sum_{j=1}^J \sum_{\substack{i=1 \\ i \neq f}}^{r_j} h_{ij}(t) h_{if}(t) [x_j^T(t) P_j \bar{A}_{ij} P_j x_j(t)] + \sum_{j=1}^J \sum_{k=1}^{N_j} x_j^T(t - \tau_{kj}) I x_j(t - \tau_{kj}) \\
= & \sum_{j=1}^J \sum_{i=f=1}^{r_j} h_{ij}^2(t) x_j^T(t) [(A_{ij} - B_{ij} K_{ij})^T P_j + P_j (A_{ij} - B_{ij} K_{ij}) + \bar{P}_j + P_j \bar{A}_{ij} P_j] x_j(t) \\
& + \sum_{j=1}^J \sum_{i < f}^{r_j} h_{ij}(t) h_{if}(t) x_j^T(t) [2(G_{ifj}^T P_j + P_j G_{ifj} + \bar{P}_j + P_j \bar{A}_{ij} P_j)] x_j(t) \\
& + \sum_{j=1}^J [\phi_j^T(t) P_j x_j(t) + x_j^T(t) P_j \phi_j(t)] + \sum_{j=1}^J \sum_{k=1}^{N_j} \{x_j^T(t - \tau_{kj}) [I - P_{kj}] x_j(t - \tau_{kj})\} \\
= & D_1 + D_2 + D_3 + D_4, \tag{A2}
\end{aligned}$$

where

$$D_1 \equiv \sum_{j=1}^J \sum_{i=f=1}^{r_j} h_{ij}^2(t) x_j^T(t) [(A_{ij} - B_{ij} K_{ij})^T P_j + P_j (A_{ij} - B_{ij} K_{ij}) + \bar{P}_j + P_j \bar{A}_{ij} P_j] x_j(t), \tag{A3}$$

$$D_2 \equiv \sum_{j=1}^J \sum_{i < f}^{r_j} h_{ij}(t) h_{if}(t) x_j^T(t) [2(G_{ifj}^T P_j + P_j G_{ifj} + \bar{P}_j + P_j \bar{A}_{ij} P_j)] x_j(t), \tag{A4}$$

$$D_3 \equiv \sum_{j=1}^J [\phi_j^T(t) P_j x_j(t) + x_j^T(t) P_j \phi_j(t)]$$

$$\begin{aligned}
= & \sum_{j=1}^J \sum_{n \neq j}^J [x_n^T(t) C_{nj}^T P_j x_j(t) + x_j^T(t) P_j C_{nj} x_n(t)] \leq \sum_{j=1}^J \sum_{n \neq j}^J [x_n^T(t) x_n(t) + x_j^T(t) P_j C_{nj} C_{nj}^T P_j x_j(t)] \\
& + \sum_{j=1}^J \sum_{i \neq f}^{r_j} \sum_{n=1}^J h_{ij}(t) h_{if}(t) x_j^T(t) \left[\left(\frac{J-1}{J} \right) I + P_j C_{nj} C_{nj}^T P_j \right] x_j(t), \tag{A5}
\end{aligned}$$

$$D_4 \equiv \sum_{j=1}^J \sum_{k=1}^{N_j} \{x_j^T(t - \tau_{kj}) [I - P_{kj}] x_j(t - \tau_{kj})\} \leq \sum_{j=1}^J \sum_{k=1}^{N_j} \lambda_M(I - P_{kj}) \|x_j(t - \tau_{kj})\|^2. \tag{A6}$$

Substituting Eqs. (A3-A6) into Eq. (A2) yields

$$\begin{aligned}
\dot{V} \leq & \sum_{j=1}^J \sum_{i=f=1}^{r_j} h_{ij}^2(t) x_j^T(t) [(A_{ij} - B_{ij} K_{ij})^T P_j + P_j (A_{ij} - B_{ij} K_{ij}) + \bar{P}_j + P_j \bar{A}_{ij} P_j] x_j(t) \\
& + \sum_{j=1}^J \sum_{i < f}^{r_j} h_{ij}(t) h_{if}(t) x_j^T(t) [2(G_{ifj}^T P_j + P_j G_{ifj} + \bar{P}_j + P_j \bar{A}_{ij} P_j)] x_j(t) \\
& + 2 \sum_{n=1}^J \left[\left(\frac{J-1}{J} \right) I + P_j C_{nj} C_{nj}^T P_j \right] x_j(t) + \sum_{j=1}^J \sum_{k=1}^{N_j} \lambda_M(I - P_{kj}) \|x_j(t - \tau_{kj})\|^2 \\
= & - \sum_{j=1}^J \left\{ \sum_{i=f=1}^{r_j} h_{ij}^2(t) x_j^T(t) Q_{ij} x_j(t) + \sum_{i < f}^{r_j} h_{ij}(t) h_{if}(t) x_j^T(t) Q_{ifj} x_j(t) - \sum_{k=1}^{N_j} \lambda_M(I - P_{kj}) \|x_j(t - \tau_{kj})\|^2 \right\}
\end{aligned}$$

$$\leq -\sum_{j=1}^J \left\{ \left[\sum_{i=1}^{r_j} h_{ij}^2(t) \lambda_m(Q_{ij}) + \sum_{i < f}^{r_j} h_{ij}(t) h_{fj}(t) \lambda_m(Q_{ifj}) \right] \|x_j(t)\|^2 - \bar{\lambda}_j \sum_{k=1}^{N_j} \|x_j(t - \tau_{kj})\|^2 \right\} \quad (\text{A.7})$$

According to these Eq. (3.4), we therefore get $\dot{V} < 0$ as well as the proof in condition (I) is then satisfied.

(II): Based in Eq. (A.7), we then get

$$\begin{aligned} \dot{V} &\leq -\sum_{j=1}^J \left\{ \left[\sum_{i=1}^{r_j} h_{ij}^2(t) \lambda_m(Q_{ij}) + \sum_{i < f}^{r_j} h_{ij}(t) h_{fj}(t) \lambda_m(Q_{ifj}) \right] \|x_j(t)\|^2 - \bar{\lambda}_j \sum_{k=1}^{N_j} \|x_j(t - \tau_{kj})\|^2 \right\} \\ &= -\sum_{j=1}^J \left\{ \left[\sqrt{\sum_{k=1}^{N_j} \|x_j(t - \tau_{kj})\|^2} \quad h_{1j}(t) \|x_j(t)\| \quad h_{2j}(t) \|x_j(t)\| \quad \cdots \quad h_{r_jj}(t) \|x_j(t)\| \right] \right. \\ &\quad \cdot \left. \begin{bmatrix} -\bar{\lambda}_j & 0 & 0 & \cdots & 0 \\ 0 & \lambda_{1j} & 1/2\lambda_{12j} & \cdots & 1/2\lambda_{1r_jj} \\ 0 & 1/2\lambda_{12j} & \lambda_{2j} & \cdots & 1/2\lambda_{2r_jj} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 1/2\lambda_{1r_jj} & 1/2\lambda_{2r_jj} & \cdots & \lambda_{r_jj} \end{bmatrix} \cdot \begin{bmatrix} \sqrt{\sum_{k=1}^{N_j} \|x_j(t - \tau_{kj})\|^2} \\ h_{1j}(t) \|x_j(t)\| \\ h_{2j}(t) \|x_j(t)\| \\ \vdots \\ h_{r_jj}(t) \|x_j(t)\| \end{bmatrix} \right\} \\ &= -\sum_{j=1}^J H_j^T \Lambda_j H_j, \end{aligned}$$

in which $H_j^T \equiv \left[\sqrt{\sum_{k=1}^{N_j} \|x_j(t - \tau_{kj})\|^2} \quad h_{1j}(t) \|x_j(t)\| \quad h_{2j}(t) \|x_j(t)\| \quad \cdots \quad h_{r_jj}(t) \|x_j(t)\| \right]$. The Lyapunov math derivatives are negative if one of these matrices Λ_j ($j=1, 2, \dots, J$) is positive digit, which accomplish one of the proof in condition (II).