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Aviation stability analysis with coupled system criterion of theoretical solutions

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Abstract. In our research, we have proposed a solid solution for aviation analysis which can ensure the asymptotic stability of coupled nonlinear plants, according to the theoretical solutions and demonstrated method. Because this solution employed the scheme of specific novel theorem of control, the controllers are artificially combined by the parallel distribution computation to have a feasible solution given the random coupled systems with aviation stability analysis. Therefore, we empathize and manually derive the results which shows the utilized lemma and criterion are believed effective and efficient for aircraft structural analysis of composite and nonlinear scenarios. To be fair, the experiment by numerical computation and calculations were explained the perfectness of the methodology we provided in the research.

Keywords: aviation vehicles; inequality controlling & nonlinear stability analysis; linear matrix; spacecraft

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).

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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 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. However, studies in the literature have yet to solve the stability and non-stable problem of large systems with multiple delays.

Therefore, this study has a stability formula based directly on the Lyapunov method, which provides asymptotic stability for large systems with multiple delays. According to this statement and the limited control system, fuzzy control groups are involved to stabilize large systems in multi-delay systems that involve many interconnected systems. In addition, these subsystems are represented by a simple Takagi-Sugen model in multiple delays. In these models, each rule is represented by a linear model of the system, so the linear response of the control can be used as a stable response. Therefore, a type of compensation design based on a fuzzy model uses a parallel distributed compensation (PDC) scheme. The idea is that all linear local linear response models share the same assumptions. And we focus on the results that show the best efficiency of the proposed damage propagation theory for aerospace structural analysis of composite materials.

In summary, we will briefly introduce the Takagi Sugeno fuzzy model with some delays and describe the system. The stability measure is then derived and checked based on the Lyapunov method, to ensure the asymptotic stability of coupled systems with multiple delays. And we focus on the results that show the best efficiency of the proposed damage propagation theory for aerospace structural analysis of composite materials. Finally, descriptive results and conclusions are presented for numerical simulation models.

2. Coupled system description

The following we review a nonlinear aviation stability, that is to simplify the construction of the equation Eq. (2.1), we consider a nonlinear *J* as coupled subsystems F_j, The *j*th as isolated subsystems (without any interconnection) of $\boldsymbol{F}$ 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)

$$\text{Rule } i: \text{ IF any } x_{1j}(t) \text{ is } M_{i1j} \text{ and } \cdots \text{ and } x_{g\,j}(t) \text{ is } M_{ig\,j} \tag{2.1}$$

THEN $\dot{x}_j(t) = A_{ij}x_j(t) + \sum_{k=1}^{N_j} A_{i\rightleftarrows\rightleftarrows k\rightleftarrows j}x(t-\tau_{k\rightleftarrows j}) + B_{ij}u_j(t)$
where $x_j^T(t) = [x_{1j}(t), x_{2j}(t), \cdots, x_{g\,j}(t)]$, $u_j{}^T(t) = [u_{1j}(t), u_{2j}(t), \cdots, u_{mj}(t)]$

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

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

with

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

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

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

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

where C_{nj} is the interconnection.

3. Coupled system criterion of smart control

According to the decentralized fuzzy controllers using the parallel distributed compensation (PDC) method to stabilize the coupled system *F*, the option of the distributed compensation is each distributed control rule is designed in parallel. The fuzzy based controller shares the same fuzzy set with the fuzzy model in the spatial parameters with coupled aviation stability. Since each rule of the fuzzy model is described by a linear state equation, linear coupled control theory can be used to design the following aviation components of the fuzzy controller. The resulting overall fuzzy controller, usually non-linear, is obtained by combining each linear controller.

The fuzzy controller of the *j*th subsystem is in the following form

$$\text{Rule } i\text{: IF } x_{1j}(t) \text{ is } M_{i1j} \text{ and} \cdots \text{and } x_{gj}(t) \text{ is } M_{igj}$$
$$\text{THEN } u_j(t) = -K_{ij}x_j(t), \tag{3.1}$$

where $i = 1, 2, \cdots, r_j$. Hence, the final output of the fuzzy controller is

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

Substituting Eq. (3.2) into Eq. (2.4), we have the *j*th closed-loop subsystem

$$\dot{x}_j(t) = \sum_{i=1}^{r_j}\sum_{f=1}^{r_j} h_{ij}(t)h_{fj}(t)[A_{ij} - B_{ij}K_{fj}]x_j(t) + \phi_j(t). \tag{3.3}$$

A stability criterion is given below to guarantee the asymptotic stability of the fuzzy large-scale system ***F***.

Theorem 1: The fuzzy large-scale system ***F*** is asymptotically stable, if the feedback gains (K_{ij}) are chosen to satisfy

$$\textbf{(I)} \quad \hat{\lambda}_{ij} = \lambda_m(Q_{ij}) - \beta_j > 0 \quad \text{and} \quad \tilde{\lambda}_{ifj} = \lambda_m(Q_{ifj}) - \beta_j > 0 \tag{3.4}$$

for $i = 1, 2, \cdots, r_j$, $i < f \le r_j$, $j = 1, 2, \cdots, J$

or

$$\textbf{(II)} \quad \Lambda_j = \begin{bmatrix} \hat{\lambda}_{1j} & \tilde{\lambda}_{12j} & \cdots & \tilde{\lambda}_{1r_jj} \\ \tilde{\lambda}_{12j} & \hat{\lambda}_{2j} & \cdots & \tilde{\lambda}_{2r_jj} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{\lambda}_{1r_jj} & \tilde{\lambda}_{2r_jj} & \cdots & \hat{\lambda}_{r_jj} \end{bmatrix} > 0, \quad \text{for } j = 1, 2, \cdots, J \tag{3.5}$$

where

$$\beta_j = \sum_{\substack{n=1 \\ n \ne j}}^{J} (\|C_{nj}^T P_j\| + \|C_{jn}^T P_n\|),$$

$$Q_{ij} = -[(A_{ij} - B_{ij}K_{ij})^T P_j + P_j(A_{ij} - B_{ij}K_{ij})], \tag{3.6}$$

$$Q_{ifj} = -(G_{ifj}^T P_j + P_j G_{ifj}), \tag{3.7}$$

with $G_{ifj} = \dfrac{(A_{ij} - B_{ij}K_{fj}) + (A_{fj} - B_{fj}K_{ij})}{2}$, $P_j = P_j^T > 0$,

and $\lambda_m(Q_{ij})$ as well as $\lambda_m(Q_{ifj})$ denote the minimum eigenvalues of Q_{ij} and Q_{ifj}, respectively.

Let the Lyapunov function for the fuzzy large-scale system ***F*** be defined as

$$V = \sum_{j=1}^{J} v_j(t) = \sum_{j=1}^{J} x_j^T(t) P_j x_j(t) \tag{A1}$$

where $P_j = P_j^T > 0$. We then evaluate the time derivative of V on the trajectories of Eq. (3.3) to get

$$\begin{aligned}
\dot{V} &= \sum_{j=1}^{J} \dot{v}_j(t) = \sum_{j=1}^{J} [\dot{x}_j^T(t) P_j x_j(t) + x_j^T(t) P_j \dot{x}_j(t)] \\
&= \sum_{j=1}^{J} \{ [\sum_{i=1}^{r_j} \sum_{f=1}^{r_j} h_{ij}(t)\, h_{fj}(t)(A_{ij} - B_{ij} K_{fj}) x_j(t) + \phi_j(t)]^T P_j x_j(t) \\
&\quad + x_j^T(t) P_j [\sum_{i=1}^{r_j} \sum_{f=1}^{r_j} h_{ij}(t)\, h_{fj}(t)(A_{ij} - B_{ij} K_{fj}) + \phi_j(t)]\} \\
&= \sum_{j=1}^{J} \sum_{i=f=1}^{r_j} h_{ij}^2(t) x_j^T(t)[(A_{ij} - B_{ij} K_{ij})^T P_j + P_j (A_{ij} - B_{ij} K_{ij})] x_j(t) \\
&\quad + \sum_{j=1}^{J} \sum_{i \neq f}^{r_j} h_{ij}(t) h_{fj}(t) x_j^T(t)[(A_{ij} - B_{ij} K_{fj})^T P_j + P_j (A_{ij} - B_{ij} K_{fj})] x_j(t) \\
&\quad + \sum_{j=1}^{J} [\phi_j^T(t) P_j x_j(t) + x_j^T(t) P_j \phi_j(t)] \\
&= D_1 + D_2 + D_3,
\end{aligned} \tag{A2}$$

where

$$\begin{aligned}
D_1 &\equiv \sum_{j=1}^{J} \sum_{i=f=1}^{r_j} h_{ij}^2(t) x_j^T(t)[(A_{ij} - B_{ij} K_{ij})^T P_j + P_j (A_{ij} - B_{ij} K_{ij})] x_j(t) \\
&= -\sum_{j=1}^{J} \sum_{i=1}^{r_j} h_{ij}^2(t) x_j^T(t) Q_{ij} x_j(t) \le -\sum_{j=1}^{J} \sum_{i=1}^{r_j} h_{ij}^2(t) \lambda_m(Q_{ij}) \| x_j(t) \|^2,
\end{aligned} \tag{A3}$$

$$\begin{aligned}
D_2 &\equiv \sum_{j=1}^{J} \sum_{i \neq f}^{r_j} h_{ij}(t) h_{fj}(t) x_j^T(t)[(A_{ij} - B_{ij} K_{fj})^T P_j + P_j (A_{ij} - B_{ij} K_{fj})] x_j(t) \\
&= 2\sum_{j=1}^{J} \sum_{i<f}^{r_j} h_{ij}(t) h_{fj}(t) x_j^T(t)(G_{ifj}^T P_j + P_j G_{ifj}) x_j(t) \\
&\le -2\sum_{j=1}^{J} \sum_{i<f}^{r_j} h_{ij}(t) h_{fj}(t) \lambda_m(Q_{ifj}) \| x_j(t) \|^2,
\end{aligned} \tag{A4}$$

$$\begin{aligned}
D_3 &\equiv \sum_{j=1}^{J} [\phi_j^T(t) P_j x_j(t) + x_j^T(t) P_j \phi_j(t)] \\
&= \sum_{j=1}^{J} \sum_{n \neq j}^{J} [x_n^T(t) C_{nj}^T P_j x_j(t) + x_j^T(t) P_j C_{nj} x_n(t)] \le 2\sum_{j=1}^{J} \sum_{n \neq j}^{J} \| x_n^T(t) C_{nj}^T P_j x_j(t) \| \\
&\le 2\sum_{j=1}^{J} \sum_{n \neq j}^{J} \| x_n(t) \| \| C_{nj}^T P_j \| \| x_j(t) \| \le \sum_{j=1}^{J} \sum_{n \neq j}^{J} \| C_{nj}^T P_j \| (\| x_n(t) \|^2 + \| x_j(t) \|^2)
\end{aligned}$$

$$=\sum_{j=1}^{J}\sum_{n\neq j}^{J}(\|C_{nj}^{T}P_j\|+\|C_{jn}^{T}P_n\|)\|x_j(t)\|^2=\sum_{j=1}^{J}\beta_j\|x_j(t)\|^2 . \tag{A5}$$

Substituting Eqs. (A3)-(A5) into Eq. (A2) yields

$$\dot V\le-\sum_{j=1}^{J}\{\sum_{i=1}^{r_j}h_{ij}^2(t)\lambda_m(Q_{ij})+2\sum_{i<f}^{r_j}h_{ij}(t)h_{fj}(t)\lambda_m(Q_{ifj})-\sum_{i=1}^{r_j}\sum_{f=1}^{r_j}h_{ij}(t)h_{fj}(t)\beta_j\}\|x_j(t)\|^2$$

$$=-\sum_{j=1}^{J}\{\sum_{i=1}^{r_j}h_{ij}^2(t)\lambda_m(Q_{ij})+2\sum_{i<f}^{r_j}h_{ij}(t)h_{fj}(t)\lambda_m(Q_{ifj})-\sum_{i=1}^{r_j}h_{ij}{}^2(t)\beta_j-2\sum_{i<f}^{r_j}h_{ij}(t)h_{fj}(t)\beta_j\}\|x_j(t)\|^2$$

$$=-\sum_{j=1}^{J}\{\sum_{i=1}^{r_j}h_{ij}^2(t)\hat\lambda_{ij}+2\sum_{i<f}^{r_j}h_{ij}(t)h_{fj}(t)\tilde\lambda_{ifj}\}\|x_j(t)\|^2 . \tag{A6}$$

Based on Eq. (3.4), we have $\dot V<0$ and the proof of condition (I) is thereby completed.

(II): According to Eq. (A6), we get

$$\dot V\le-\sum_{j=1}^{J}\{\sum_{i=1}^{r_j}h_{ij}^2(t)\hat\lambda_{ij}+2\sum_{i<f}^{r_j}h_{ij}(t)h_{fj}(t)\tilde\lambda_{ifj}\}\|x_j(t)\|^2$$

$$=-\sum_{j=1}^{J}\{\begin{bmatrix}h_{1j}(t) & h_{2j}(t) & \cdots & h_{r_jj}(t)\end{bmatrix}\begin{bmatrix}\hat\lambda_{1j} & \tilde\lambda_{12j} & \cdots & \tilde\lambda_{1r_jj}\\ \tilde\lambda_{12j} & \hat\lambda_{2j} & \cdots & \tilde\lambda_{2r_jj}\\ \vdots & \vdots & \vdots & \vdots\\ \tilde\lambda_{1r_jj} & \tilde\lambda_{2r_jj} & \cdots & \hat\lambda_{r_jj}\end{bmatrix}\begin{bmatrix}h_{1j}(t)\\ h_{2j}(t)\\ \vdots\\ h_{r_jj}(t)\end{bmatrix}\}\|x_j(t)\|^2$$

$$=-\sum_{j=1}^{J}H_j^T\Lambda_jH_j\ \|x_j(t)\|^2, \tag{A7}$$

in which $H_j^T\equiv[h_{1j}(t)\quad h_{2j}(t)\quad\cdots\quad h_{r_jj}(t)]$.

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. Consider a aviation stability from the coupled system composed of three linking in and out states which are described as follows.

Subsystem 1:

Rule 1: If $x_{11}(t)$ is M_{111}

Then $\dot x_1(t)=A_{11}x_1(t)+B_{11}u_1(t)$

Rule 2: If $x_{11}(t)$ is M_{211}

Then $\dot x_1(t)=A_{21}x_1(t)+B_{21}u_1(t)$

$$\text{with } A_{11}=\begin{bmatrix} -29 & 1 \\ 3 & -12 \end{bmatrix}, A_{21}=\begin{bmatrix} -25 & -4 \\ 5 & -14 \end{bmatrix}, B_{11}=\begin{bmatrix} 0.5 \\ -2 \end{bmatrix}, B_{21}=\begin{bmatrix} 0.3 \\ 1 \end{bmatrix} \tag{4.1}$$

and membership functions for Rule 1 and Rule 2 are

$$M_{111}(x_{11}(t))=\frac{1}{1+\exp[-2x_{11}(t)]},\ M_{211}(x_{11}(t))=1-M_{111}(x_{11}(t)).$$

Subsystem 2:

Rule 1: If $x_{12}(t)$ is M_{112}

Then $\dot{x}_2(t)=A_{12}x_2(t)+B_{12}u_2(t)$

Rule 2: If $x_{12}(t)$ is M_{212}

Then $\dot{x}_2(t)=A_{22}x_2(t)+B_{22}u_2(t)$

$$\text{with } A_{12}=\begin{bmatrix} -30 & 1 \\ -5 & -16 \end{bmatrix}, A_{22}=\begin{bmatrix} -25 & 1 \\ -6 & -13 \end{bmatrix}, B_{12}=\begin{bmatrix} 0.2 \\ 2 \end{bmatrix}, B_{22}=\begin{bmatrix} 0.6 \\ -3 \end{bmatrix} \tag{4.2}$$

and membership functions for Rule 1 and Rule 2 are

$$M_{112}(x_{12}(t))=\exp[-x_{12}^2(t)],\ M_{212}(x_{12}(t))=1-M_{112}(x_{12}(t)).$$

Subsystem 3:

Rule 1: If $x_{13}(t)$ is M_{113}

Then $\dot{x}_3(t)=A_{13}x_3(t)+B_{13}u_3(t)$

Rule 2: If $x_{13}(t)$ is M_{213}

Then $\dot{x}_3(t)=A_{23}x_3(t)+B_{23}u_3(t)$.

$$\text{with } A_{13}=\begin{bmatrix} -37 & 2 \\ 2 & -13 \end{bmatrix}, A_{23}=\begin{bmatrix} -34 & -3 \\ 3 & -14 \end{bmatrix}, B_{13}=\begin{bmatrix} 0.8 \\ -2 \end{bmatrix}, B_{23}=\begin{bmatrix} 0.9 \\ 1 \end{bmatrix} \tag{4.3}$$

and membership functions for Rule 1 and Rule 2 are

$$M_{113}(x_{13}(t))=\frac{1}{1+\exp[-4x_{13}(t)]},\ M_{213}(x_{13}(t))=1-M_{113}(x_{13}(t)).$$

Moreover, the coupled in and out states matrices among three aviation stability are

$$C_{21}=\begin{bmatrix} 1.5 & -2.1 \\ -1 & 3 \end{bmatrix},\quad C_{31}=\begin{bmatrix} 5 & 4.5 \\ 3 & 2.5 \end{bmatrix},\quad C_{12}=\begin{bmatrix} 2 & -3 \\ -1.4 & 1.5 \end{bmatrix},$$

$$C_{32}=\begin{bmatrix} 1 & -2.4 \\ -1.4 & 1.2 \end{bmatrix},\quad C_{13}=\begin{bmatrix} 2 & -0.5 \\ -0.6 & 0.5 \end{bmatrix},\quad C_{23}=\begin{bmatrix} 1 & -1.4 \\ 1.2 & -0.3 \end{bmatrix}. \tag{4.4}$$

Therefore, aviation stability from coupled systems have the states matrices A_{ij} and B_{ij} shown in Eqs. (4.1)-(4.3).

Since the pairs (A_{ij}, B_{ij}), i=1,2, j=1,2,3 are all given, we analyze controlled coupled structures as

Rule 1: If $x_{11}(t)$ is M_{111} Then $u_1(t)=-K_{11}x_1(t)$, Rule 2: If $x_{11}(t)$ is M_{211} Then $u_1(t) = -K_{21}x_1(t)$.

$K_{11} = [-11.4815 \quad -0.3704]$ and $K_{21} = [-0.5161 \quad 0.1548]$.

Rule 1: If $x_{12}(t)$ is M_{112} Then $u_2(t) = -K_{12}x_2(t)$,

Rule 2: If $x_{12}(t)$ is M_{212} Then $u_2(t) = -K_{22}x_2(t)$,

$K_{12} = [-14.2857 \quad -0.5714]$ and $K_{22} = [0.5495 \quad -1.5568]$.

Rule 1: If $x_{13}(t)$ is M_{113} Then $u_3(t) = -K_{13}x_3(t)$,

Rule 2: If $x_{13}(t)$ is M_{213} Then $u_3(t) = -K_{23}x_3(t)$.

$K_{13} = [-4.0426 \quad -3.6170]$ and $K_{23} = [-11.7542 \quad -1.4213]$.

In order to satisfy the aviation stability conditions from coupled system of Theorem 1, Eq. (3.6) must be positive we can obtain Q_{ij}, $i = 1, 2$, $j = 1, 2, 3$ positive definite:

$$P_1 = \begin{bmatrix} 1.5062 & -0.2794 \\ -0.2794 & 1.7619 \end{bmatrix},\ P_2 = \begin{bmatrix} 1.3865 & 0.3153 \\ 0.3153 & 1.4738 \end{bmatrix},\ P_3 = \begin{bmatrix} 1.3662 & 0.0876 \\ 0.0876 & 1.9350 \end{bmatrix}.$$

$$Q_{11} = \begin{bmatrix} 58.9131 & 23.3305 \\ 23.3305 & 45.5584 \end{bmatrix}, Q_{21} = \begin{bmatrix} 77.9267 & -14.5195 \\ -14.5195 & 47.6183 \end{bmatrix},\ Q_{121} = \begin{bmatrix} 80.9133 & -24.5816 \\ -24.5816 & 43.7829 \end{bmatrix},$$

$$Q_{12} = \begin{bmatrix} 60.4030 & -23.0437 \\ -23.0437 & 43.0915 \end{bmatrix},\ Q_{22} = \begin{bmatrix} 72.9823 & 17.2892 \\ 17.2892 & 50.8670 \end{bmatrix},\ Q_{122} = \begin{bmatrix} 81.8514 & 50.3456 \\ 50.3456 & 39.8423 \end{bmatrix},$$

$$Q_{13} = \begin{bmatrix} 93.3250 & 9.8202 \\ 9.8202 & 77.4496 \end{bmatrix},\ Q_{23} = \begin{bmatrix} 61.4088 & -23.0449 \\ -23.0449 & 48.9820 \end{bmatrix},\ Q_{123} = \begin{bmatrix} 80.4472 & 15.3662 \\ 15.3662 & 50.4499 \end{bmatrix}.$$

From Eq. (3.5), we have†

$$\Lambda_1 = \begin{bmatrix} 2.0797 & 5.6548 \\ 5.6548 & 15.8965 \end{bmatrix},\ \Lambda_2 = \begin{bmatrix} 7.7627 & -13.0736 \\ -13.0736 & 22.0329 \end{bmatrix},\ \Lambda_3 = \begin{bmatrix} 52.6056 & 23.8213 \\ 23.8213 & 11.1730 \end{bmatrix} \tag{4.11}$$

and the eigenvalues of them are given below:

$\lambda(\Lambda_1) = 0.0605,\ 17.9157 > 0,\ \ \lambda(\Lambda_2) = 0.0039,\ 29.7917 > 0,\ \lambda(\Lambda_3) = 0.3201,\ 63.4586 > 0$.

From Table 1 and Figs. 1-4, we see the feasibility of proposed control results.

5. Conclusions

In this paper, the modulated complex mechanical control of dynamically coupled systems with aviation stability is considered. To do this, a two-step strategy is proposed to first divide a large integrated system into several interrelated subsystems. We focus on damage propagation for in-plane structural analysis of composite materials. As a modified fuzzy control order, the following has been adopted as a feedback theory based on the energy function and LMI optimal stability

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†In this example, the Euclidean norm is considered.

Table 1 Basic data for test sets

State No.	number/meshes	State No.	number/meshes	State No.	number/meshes	State No.	number/meshes
1	784.59	26	275.92	51	289.27	76	222.87
2	748.7	27	253.44	52	293.53	77	255.93
3	72.09	28	247.99	53	288.4	78	272.07
4	778.94	29	247.78	54	409.4	79	285.74
5	89.48	40	792.07	55	405.54	80	247.47
6	98.84	41	798.8	56	287.4	81	244.74
7	727.74	42	258.54	57	404.27	82	229.74
8	785.59	44	287	58	279.07	84	245.87
9	749.44	44	427.2	59	797.74	84	224.74
10	728.45	45	274.47	80	258.8	85	225.47
17	747.9	46	282.94	61	228.74	88	798.47
12	729.07	47	482.8	62	248.4	87	729.74
14	727.92	48	478.2	64	278.94	88	797.48
14	754.89	49	449.47	64	285.4	89	777.82
15	745.8	40	445.27	65	297.27	90	784.49
16	728.77	41	489.8	66	278.2	91	781.94
17	92.78	42	452.94	67	275.8	92	770.77
18	744.42	44	284	68	278.4	94	788.27
19	749.07	44	248.2	69	288.2	94	784.28
20	747.79	45	248.44	70	295.8	95	788.47
21	149.58	46	272.94	71	289.74	96	208.49
22	145.79	47	274.54	72	255.27	97	424.8
24	140.57	48	259.27	74	185.07	98	411.14
24	155.88	49	258.47	74	204.27	99	274.47
25	194.09	50	280	75	214.74	100	207.73

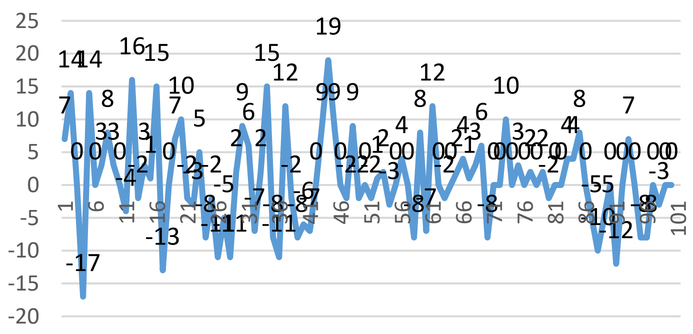

Fig. 1 The coupled system model 1 prediction results and prediction error

criteria, which allows researchers to solve this problem and ensure the entire integrated system is in asymptotic stability. We focus on results that demonstrate the high efficiency of the proposed theory applied to damage propagation for in-plane structural analysis of composite materials.

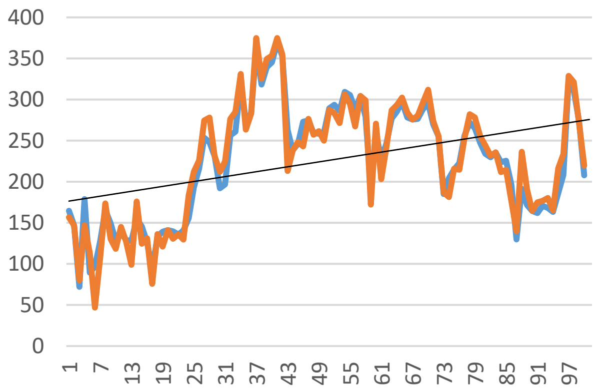

Fig. 2 The nonlinear coupled system 2 prediction results and prediction error

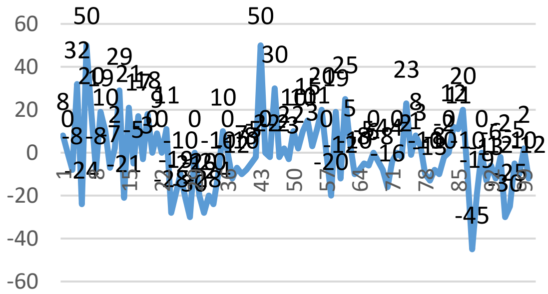

Fig. 3 The nonlinear coupled system 3 prediction results and prediction error

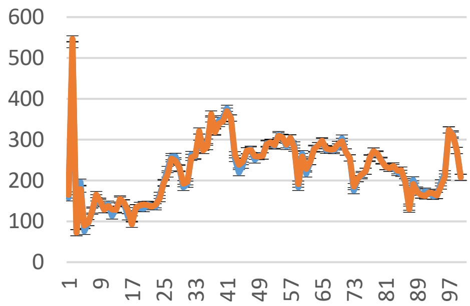

Fig. 4 The nonlinear coupled system summation results

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