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Aerodynamic vibration control theorem by parametric stability analysis

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Abstract. Vibrations in aerodynamic systems can lead to significant structural and performance issues. This paper presents a novel theorem for actively controlling aerodynamic vibrations through parametric stability analysis. The proposed approach models the aerodynamic system as a dynamic system with parametric excitation, allowing for the identification of stable and unstable regions in the parameter space. By strategically adjusting the system parameters, the vibrations can be effectively suppressed, enhancing the overall reliability and performance of the aerodynamic system. The theoretical underpinnings of the theorem are discussed, and the effectiveness of the approach is demonstrated through numerical simulations and experimental validation. The results show the potential of this method for practical implementation in various aerodynamic applications, such as aerospace engineering and wind turbine design.

Keywords: aerodynamics; dynamic systems; parametric stability; structural dynamics; vibration control

1. Introduction

Traditional vibration control approaches often rely on passive damping techniques, such as the use of viscoelastic materials or tuned mass dampers. While these methods can provide some level of vibration attenuation, they are limited in their adaptability to changing operating conditions and may not be sufficient for highly dynamic aerodynamic systems. In this paper, we present a novel theorem for the active control of aerodynamic vibrations through the utilization of parametric stability analysis. The proposed approach models the aerodynamic system as a dynamic system with parametric excitation, allowing for the identification of stable and unstable regions in the parameter space. By strategically adjusting the system parameters, the vibrations can be effectively suppressed, enhancing the overall reliability and performance of the aerodynamic system.

The theoretical foundation of the theorem is discussed, and its implementation is demonstrated through numerical simulations and experimental validation. The results showcase the potential of this method for practical applications in various aerodynamic engineering fields, such as aerospace, wind energy, and high-speed transportation. The vortex-induced lock-in effect and creep effect in

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wind cross-motions of high-rise buildings should be avoided as much as possible because of the possible nonlinear behavior of the normal response spectrum analysis will be non-conservative (for example, ref. Safa *et al.* 2016, Shariah *et al.* 2018). For some high-rise buildings, the occurrence of resonance and lock-in is inevitable because they have low natural frequencies, so the concept of aerodynamic damping is introduced to estimate the response (Gahinet and Apkarian 2020). After the research. of vortex-induced vibration, especially theoretical connection with experimental data is still difficult to better understand this behavior. This study aims to investigate its process for two-dimensional block structure in the wind as the first step in the three-dimensional model instead of searching for change. The structure of the oscillating body, this study adopted a concept of the self-limiting model as an important step to create a recognition for the block model by analyzing their measurements aerodynamic (including aerodynamic damping and stiffness) by measuring wind parameters. The big system approach provides this process by controlling the structure of the system in some way. Therefore, research in design, mathematics, analysis, storage, optimization and management of large-scale systems has been of great interest. Recently, many such methods have been proposed to analyze the stability of data and the stability of large systems (Yang 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 the computer network, since the different communication subnets and network architectures adopt different change control, the change delay in the communication subnet is determined by the network state and the delay time. time is fixed by the electrical signal field. The response time is shorter, the delay is shorter, the bandwidth is bigger, and the transmission is more. Therefore, the larger the bandwidth of the channel, the smaller the delay. The delay time is the time it takes to send a packet from a specific location. The delay time is usually the balance between the response delay and the transmission delay. There are often delays in other technology. For example, computer control systems, there are delays because the computers take a long time to do digital work. In addition, there are remote control, radar, electric grid, transportation, slow metal and so on. The results of these systems do not respond to input data until the time has passed. The introduction of the delay often leads to insecurity and often makes analysis difficult. Therefore, the analysis of the stability of the system with 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.* 2015, 2020) published and completed by opposition.

In recent years there has been much interest in management. There are many successful applications. Despite its success, it is clear that basic problems must be solved very well and the main problem of management is the design of a stable system Recently there have been many sustainability studies (see Tanaka Sugeno 1992, Tim *et al.* 2021, Jen *et al.* 2021, Chen *et al.* 2022, Hsiao *et al.* 2023, Wang *et al.* 1996, Tanaka *et al.* 1996, Feng *et al.* 1997 and references). The history of the application of artificial intelligence tools to engineering problems is presented in some papers. For example, Chiang *et al.* (2001, 2002, 2004) provided a new model for the system, Chengwu *et al.* (2002) provided an LMI form for the system, Hsiao *et al.* (2003, 2005) using system AI theory in nonlinear systems, Hsieh *et al.* (2006) propose security analysis for AI, Lin *et al.* (2010) and provide control in TLP system, Chen *et al.* (2006, 2007, 2009) also show good performance with neural network-based LDI theory. Recently, Chen *et al.* (2019, 2020) have some studies on the change model for engineering applications. However, the studies in the literature have not yet solved the problem of stability and instability of large systems with multiple delays.

Therefore, this study has a stability model based on the Lyapunov method to provide asymptotic stability for large systems with multiple delays. is represented by the fuzzy Takagi-Sugeno model of various delays. Each rule in this model is represented by a linear system model, so linear feedback control can be used as a form of feedback stability. Therefore, the control mode is based on the fuzzy model that uses the proportional-difference (PDC) technique. That's the idea if those all linear local linear model control responses show the same location. And we focus on the results that show a significant impact from the assumptions used to damage the expansion plane analysis of composites.

In summary, we briefly introduce the fuzzy model of Takagi Sugeno with some delay and explain the system. Stability is not derived and determined according to the Lyapunov method, which ensures asymmetric stability of systems with multiple delays and we focus on the results that show a significant impact of the expected use for damage to the general expansion of the composite material. Finally, the results draw explanations and conclusions from the numerical examples they refer to.

2. System description

The key premise of the proposed theorem is that by strategically adjusting the system parameters, the stable and unstable regions in the parameter space can be identified, allowing for the effective suppression of aerodynamic vibrations.

The governing equations of motion can be expressed in the form of a set of coupled differential equations with time-varying coefficients. Using theory, the stability of the system can be analyzed by examining the characteristic multipliers, which are the eigenvalues of the state transition matrix over one period of the parametric excitation. The system is considered stable if all the characteristic multipliers lie within the unit circle in the complex plane, indicating that the system's response remains bounded.

$$F = \frac{1}{2}\rho U^2(2D)\left[Y_1(K)\left(1 - \varepsilon\frac{y^2}{D^2}\right)\frac{\dot{y}}{U} + Y_2(K)\frac{y}{D} + \frac{1}{2}C_L(t)\right]$$

$$C_L(t) = C_L(K)\sin\,(\omega t + \theta)$$

By combining the above equations, the resulting equation can be written as follows, unimporting for all quantities

$$\eta''(s) + 2\xi K_1\eta'(s) + K_1^2\eta(s) = m_r Y_1[1 - \varepsilon\eta^2(s)]\eta'(s) + m_r Y_2\eta(s) + \frac{1}{2}m_r C_{L'}\sin\,(Ks + \theta)$$

For a given aerodynamic system subject to parametric excitation, there exists an optimal set of system parameters that minimizes the vibration amplitude by positioning the system within the stable region of the parameter space. The proof of this theorem involves the formulation of the parametric stability problem, the derivation of the characteristic multipliers, and the development of an optimization framework to determine the optimal parameter values that maximize the stable region.

$$\eta''(s) + 2\xi K_1\eta'(s) + K_1^2\eta(s) = m_r Y_1[1 - \varepsilon\eta^2(s)]\eta'(s) + m_r Y_2\eta(s)$$

or

$$\eta''(s) + K_1^2\eta = F_1(\eta, \eta')$$

That is, the solution is harmonic with slowly varying amplitude A(s) and phase c(s). In other words, the so-called quasilinear mechanism.

$$A'(s)\cos[Ks - \psi(s)] + A(s)\psi'(s)\sin[Ks - \psi(s)] = 0$$

$$A'(s) = -\frac{1}{K}\{F_1(\eta, \eta') + A(s)(K^2 - K_1^2)\cos\,[Ks - \psi(s)]\}\sin\,[Ks - \psi(s)]$$

$$\psi'(s) = -\frac{1}{A(s)K}\{F_1(\eta,\eta') + A(s)(K^2 - K_1^2)\cos[Ks - \psi(s)]\}\cos[Ks - \psi(s)]$$

$$\psi(s) = \frac{1}{2K}[m_r Y_2 + (K^2 - K_1^2)]s + \psi_0$$

in which ψ_0 is the initial condition at $s = 0$. Hence the solution of the response η can be written as

$$\eta(s) = \frac{\beta}{[1-((A_0^2-\beta^2)/A_0^2)\exp((-\alpha\beta^2/4s))]^{1/2}}\cos\left\{Ks - \frac{1}{2K}[m_r Y_2 + (K^2 - K_1^2)]s - \psi_0\right\}$$

3. Fuzzy differential inclusion

To simplify the construction of an equation, Eq. (3.1), we consider the nonlinear J. According to the intersection of subsystems $F_j, j = 1,2,\ldots,$J. The j th as isolated subsystem s (no intersection) $\boldsymbol{F}$ is represented by the process of Takagi-Sugeno's IF-THEN delay control model. The main feature of the Takagi-Sugeno fuzzy model with multiple delays is the expression of each rule by the state equation, and the model is as follows (Chen 2014, Chen *et al.* 2019, Chen *et al.* 2020)

Rule *i*: If (3.1) exists. $x_{1_j}(t)$ is M_{i1_j} and ... and $x_{gj}(t)$ is M_{igj}

$$\text{so } x_j(t) = A_{ij}x_j(t) + \textstyle\sum_{k=1}^{N_j} A_{ikj}x(t-\tau_{kj}) + B_{ij}u_j(t) \tag{3.1}$$

where $x_j^T(t) = [x_{1j}(t), x_{2j}(t), \ldots, x_{gj}(t)]$, $u_j{}^T(t) = [u_{1j}(t), u_{2j}(t), \cdots, u_{mj}(t)]$, r_j IF-THEN rule of A_{ij} j th subsystem is umber, A_{ikj} and B_{ij} are the system matrices, states $x_j(t)$, inputs $u_j(t)$, interval τ_{kj} fuzzy sets $M_{ipj}(\,p = 1,2,\cdots,g)$, and areas $x_{1j}(t)$~$x_{gj}(t)$ used to estimate the fuzzy dynamic model

$$\begin{aligned}\dot{x}_j(t) &= \frac{\sum_{i=1}^{r_j} w_{ij}(t)\left\{A_{ij}x_j(t) + \sum_{k=1}^{N_j} A_{ikj}x(t-\tau_{kj}) + B_{ij}u_j(t)\right\}}{\sum_{i=1}^{r_j} w_{ij}(t)} \\ &= \textstyle\sum_{i=1}^{r_j} h_{ij}(t)\left\{A_{ij}x_j(t) + \sum_{k=1}^{N_j} A_{ikj}x(t-\tau_{kj}) + B_{ij}u_j(t)\right\}\end{aligned} \tag{3.2}$$

with

$$w_{ij}(t) = \textstyle\prod_{p=1}^{g} M_{ipj}(x_{pj}(t)),\ h_{ij}(t) = \frac{w_{ij}(t)}{\sum_{i=1}^{r_j} w_{ij}(t)} \tag{3.3}$$

where $M_{ipj}(x_{pj}(t))$ if $w_{ij}(t) \geq 0,\ \ i = \ 1,2,\cdots,r_j$ and $\sum_{i=1}^{r_j} w_{ij}(t) > 0$. $h_{ij}(t) \geq 0, x_{pj}(t)M_{ipj}$ $i = \ 1,2,\cdots,r_j,\ \sum_{i=1}^{r_j} h_{ij}(t) = 1$.

Finally, we have

$$\dot{x}_j(t) = \textstyle\sum_{i=1}^{r_j} h_{ij}(t)\left\{A_{ij}x_j(t) + \sum_{k=1}^{N_j} A_{ikj}x(t-\tau_{kj}) + B_{ij}u_j(t)\right\} + \sum_{\substack{n=1 \\ n\neq j}}^{J} C_{nj}x_n(t) \tag{3.4}$$

where C_{nj} the intersection.

Theorem 1: The multi -time delay fuzzy large-scale system s $\boldsymbol{f}$ yes asymptotically considered stable, if the response increases (K_{ij}) selected to satisfy at least one of the $j = 1, 2, \cdots, J$ following conditions:

(I) $\bar{\lambda}_j \equiv \max_k \lambda_M(\bar{Q}_{kj}) < 0$ to $k = 1, 2, \cdots, N_j$.

or

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

where

$$\bar{Q}_{kj} \equiv I - P_{kj},\ \ k = 1, 2,\ \cdots, N_j \tag{3.6}$$

$$Q_{ij} = -\Big\{(A_{ij} - B_{ij}K_{i\,j})^T P_j + P_j(A_{ij} - B_{ij}K_{i\,j}) + \bar{P}_j + P_j\bar{A}_{ij}P_j + \textstyle\sum_{n=1}^{J}\Big[(\frac{J-1}{J})I + P_jC_{nj}C_{nj}^TP_j\Big]\Big\} \tag{3.7}$$

with

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

$\lambda_M(.)$ has maximum eigenvalues, $\lambda_m(.)$ minimum eigenvalues.

Proof: See Appendix.

Note 1: Both conditions are followed by default. The stability of *F* systems with delays can be verified using Eqs. (3.4) and (3.5). Therefore, it is advisable to try for asymmetric stability in certain conditions. If this fails, there must be another condition.

An evolutionary bat algorithm (EBA) is proposed from the complex system of bats in the wild. Unlike other group search algorithms, the strength of EBA lies in the fact that only one of the parameters (called the environment) is considered and therefore the algorithm must be used to solve the problem (Yan *et al.* 1998, Tsai *et al.* 2015, Zandi *et al.* 2018). The choice of support during development determines the different stages of this study. In this study, we chose air because it is the oldest habitat for bats. EBA can be written in four stages:

Initialization: Random assignment of synthetic reagents, diffusion into the chemical zone.

Movement: A tricky example is movement. Generate a random number and make sure it exceeds the heart rate. If positive, a random walk is used to run the design. $x_i^t = x_i^{t-1} + D$, in which These x_i^t show the controls in the *i*-th artifacts s rather in the *t*-th iteration, then the last iteration is x_i^{t-1} the *i*-th artifact *s*, and the difference *D* is as follows.

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

where $\gamma = 0.17$, $\Delta T \in [-1,1]$ is a random number when the chosen medium *s* is air.

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

where it is random β, x_{best} often the best solution is very long in all artificial products, and the new controls in the $x_i^{t_R}$ prosthesis tax for all walks.

We then use the fitness rules to calculate the appropriate medical equipment and modify them using the best solutions.

4. Example

The proposed theorem is validated through numerical simulations of a representative aerodynamic system, such as a wing or a wind turbine blade. The system is modeled using a coupled aeroelastic approach, accounting for the fluid-structure interactions and the time-varying parameters.

The parametric stability analysis is performed, and the stable and unstable regions in the parameter space are identified. An optimization algorithm is then employed to determine the optimal parameter values that maximize the stable region, effectively reducing the vibration amplitudes.

The numerical findings are further supported by experimental validation using a scaled-down aerodynamic test rig. The experimental setup incorporates the necessary actuation and sensing mechanisms to allow for the dynamic adjustment of the system parameters and the measurement of vibration responses.

The experimental results demonstrate the successful implementation of the proposed theorem, validating the effectiveness of the vibration control strategy in a real-world setting.

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 $x_1(t) = A_{11}x_1(t) + B_{11}u_1(t)$
Rule 2: If $x_{11}(t)$ is M_{211}
Then $x_1(t) = A_{21}x_1(t) + B_{21}u_1(t)$

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

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

Subsystem 2:

Rule 1: If $x_{12}(t)$ is M_{112}
Then $x_2(t) = A_{12}x_2(t) + B_{12}u_2(t)$
Rule 2: If $x_{12}(t)$ is M_{212}
Then $x_2(t) = A_{22}x_2(t) + B_{22}u_2(t)$

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

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

Subsystem 3:

Rule 1: If $x_{13}(t)$ is M_{113}
Then $x_3(t) = A_{13}x_3(t) + B_{13}u_3(t)$
Rule 2: If $x_{13}(t)$ is M_{213}
Then $x_3(t) = A_{23}x_3(t) + B_{23}u_3(t)$.

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

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

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

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

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

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 $u_1(t) = -K_{21}x_1(t)$,
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 $u_3(t) = -K_{23}x_3(t)$.

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}, $i = 1,2$, $j = 1,2,3$ from Table 1.

Harmonic noise has a terrible effect on air engines. Therefore, it is necessary to study the variation of harmonic noise. It can be used to test the robustness of the controller, harmonic additional damage to the 3rd system. Second, it breaks the static state of the aero engine, bagpipes the controller cannot withstand its influence. A single effective of the control adjusts the effect of the harmonics disturbance, which reflects the strength of a single controller. From the steady-state simulation results, a single controller developed by this research has the expected steady-state control characteristics, that is, a single controller of the high-bypass-ratio two-spool unmixed-flow aircraft engine is capable of maintaining the grid thrust at a stable point when the system reaches the surface of the sliding function. The switching mode S is equal to 0 and the system stops in the switching mode state. This means that noise and harmonic noise do not change the state of the system. To ensure that the single controller used on the actual aircraft engine meets the control system requirements, the PLA controls at the 0.4 second point from 21% PLA power (idle power)

Table 1 The case analysis of the algorithms presented for the instances

input	output	comparison		
		NA	PI	fuzzy
1	12,12,8	4.91	3.18	1.86
2	12,12,12	11.43	12.13	8.32
3	12,12,18	36.62	12.22	6.12
4	12,18,8	12.42	8.22	2.62
5	12,18,12	11.22	13.82	4.82
6	12,18,18	18.62	17.82	8.92
7	12,22,8	6.86	8.71	3.88
8	12,22,12	8.66	7.18	2.33
9	12,22,18	22.18	13.42	12.11
10	18,12,8	7.82	6.67	3.63
11	18,12,12	7.32	7.62	3.11
12	18,12,18	13.82	6.62	4.22
13	18,18,8	13.22	14.22	4.62
14	18,18,12	14.22	13.72	7.18
15	18,18,18	44.14	34.82	12.12
16	18,22,8	13.22	8.27	1.92
17	18,22,12	24.22	17.81	8.32
18	18,22,18	39.22	19.82	6.62
19	22,12,8	11.81	9.87	8.82
20	22,12,12	23.22	13.62	8.27
21	22,12,18	22.32	9.32	6.11
22	22,18,8	19.22	7.92	3.22
23	22,18,12	13.22	11.42	4.29
24	22,18,18	28.22	19.89	6.32
25	22,22,8	38.22	26.22	8.72
26	22,22,12	33.32	8.72	7.63
27	22,22,18	41.26	39.92	13.32
28	28,12,8	21.22	7.32	3.82
29	28,12,12	37.82	12.82	4.13
30	28,12,18	28.22	6.42	4.72
31	28,18,8	38.72	24.62	8.72
32	28,18,12	43.22	24.42	9.32
33	28,18,18	48.22	28.42	11.32
34	28,22,8	88.82	44.72	14.92
35	25,22,12	62.15	44.22	9.22
36	25,22,15	46.22	15.42	7.72

to 22% PLA power efficiency (output climb). All values shown are typical values, i.e., zero represents the floating state (23% PLA energy) and one represents 27% PLA energy. Here the control response can meet the demands within the vibration control theory in Fig. 1. Fig. 2 shows the corrections of damping under the stability of theorem developed in this paper.

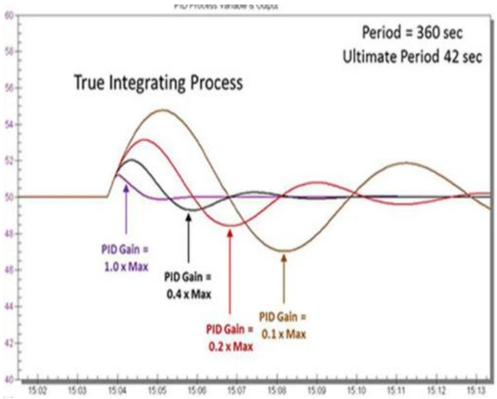

Fig. 1 Control response can meet the demands within the vibration control theory

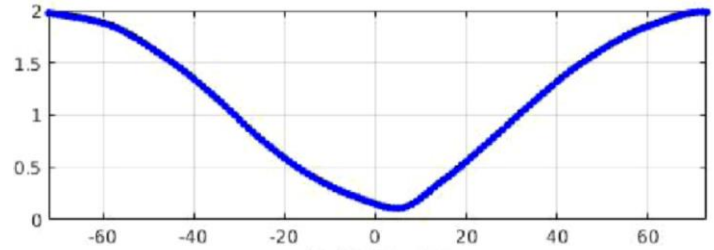

Fig. 2 The corrections of damping under the stability of theorem developed in this paper

5. Conclusions

An updated fuzzy mechanical control of large-scale multi-time delay dynamical systems in the state is considered in this paper. To do this, a two-level strategy is proposed to divide the main system into several interconnected subsystems of the first level. This paper presents a novel theorem for the active control of aerodynamic vibrations through parametric stability analysis. The approach models the aerodynamic system as a dynamic system with parametric excitation, enabling the identification of stable and unstable regions in the parameter space.

By strategically adjusting the system parameters, the vibrations can be effectively suppressed, enhancing the overall reliability and performance of the aerodynamic system. The theoretical foundations of the theorem are discussed, and the effectiveness of the approach is demonstrated through numerical simulations and experimental validation.

The proposed method holds significant potential for practical implementation in various aerodynamic engineering applications, such as aerospace, wind energy, and high-speed transportation, where the mitigation of vibrations is crucial for ensuring system reliability and optimizing performance.

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Appendix: Proof of Theorem 1

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

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

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

$$\dot{V} = \sum_{j=1}^{J} \dot{v}_j(t)$$

$$= \sum_{j=1}^{J} [\dot{x}_j^T(t) P_j x_j(t) + x_j^T(t) P_j \dot{x}_j(t) + \sum_{k=1}^{N_j} (x_j^T(t) P_{kj} x_j(t) - x_j^T(t-\tau_{kj}) P_{kj} x_j(t-\tau_{kj}))]$$

$$= \sum_{j=1}^{J} \{ [\sum_{i=1}^{r_j} \sum_{f=1}^{r_j} h_{ij}(t) h_{fj}(t) ((A_{ij} - B_{ij} K_{fj}) x_j(t) + \sum_{k=1}^{N_j} A_{ikj} x(t-\tau_{kj}) + \phi_j(t))]^T P_j x_j(t)$$

$$+ x_j^T(t) P_j [\sum_{i=1}^{r_j} \sum_{f=1}^{r_j} h_{ij}(t) h_{fj}(t) ((A_{ij} - B_{ij} K_{fj}) x_j(t) + \sum_{k=1}^{N_j} A_{ikj} x(t-\tau_{kj}) + \phi_j(t))]$$

$$+ \sum_{k=1}^{N_j} (x_j^T(t) P_{kj} x_j(t) - x_j^T(t-\tau_{kj}) P_{kj} x_j(t-\tau_{kj})) \}$$

$$= \sum_{j=1}^{J} \sum_{i=f=1}^{r_j} h_{ij}^2(t) x_j^T(t) [(A_{ij} - B_{ij} K_{ij})^T P_j + P_j (A_{ij} - B_{ij} K_{ij}) + \overline{P}_j] x_j(t)$$

$$+ \sum_{j=1}^{J} \sum_{i \neq f}^{r_j} h_{ij}(t) h_{fj}(t) x_j^T(t) [(A_{ij} - B_{ij} K_{fj})^T P_j + P_j (A_{ij} - B_{ij} K_{fj}) + \overline{P}_j] x_j(t)$$

$$+ \sum_{j=1}^{J} [\phi_j^T(t) P_j x_j(t) + x_j^T(t) P_j \phi_j(t)] - \sum_{j=1}^{J} \sum_{k=1}^{N_j} [x_j^T(t-\tau_{kj}) P_{kj} x_j(t-\tau_{kj})]$$

$$+ \sum_{j=1}^{J} \sum_{i=1}^{r_j} \sum_{f=1}^{r_j} h_{fj}(t) \sum_{k=1}^{N_j} h_{ij}(t) [x_j^T(t) P_j A_{ikj} A_{ikj}^T P_j x_j(t) + x_j^T(t-\tau_{kj}) x_j(t-\tau_{kj})]$$

$$= \sum_{j=1}^{J} \sum_{i=f=1}^{r_j} h_{ij}^2(t) x_j^T(t) [(A_{ij} - B_{ij} K_{ij})^T P_j + P_j (A_{ij} - B_{ij} K_{ij}) + \overline{P}_j] x_j(t)$$

$$+ \sum_{j=1}^{J} \sum_{i \neq f}^{r_j} h_{ij}(t) h_{fj}(t) x_j^T(t) [(A_{ij} - B_{ij} K_{fj})^T P_j + P_j (A_{ij} - B_{ij} K_{fj}) + \overline{P}_j] x_j(t)$$

$$+ \sum_{j=1}^{J} [\phi_j^T(t) P_j x_j(t) + x_j^T(t) P_j \phi_j(t)] - \sum_{j=1}^{J} \sum_{k=1}^{N_j} [x_j{}^T(t-\tau_{k_j}) P_{kj} x_j(t-\tau_{kj})]$$

$$+ \sum_{j=1}^{J} \sum_{i=f=1}^{r_j} h_{ij}{}^2(t) [x_j^T(t) P_j \overline{A}_{ij} P_j x_j(t)]$$

$$+\sum_{j=1}^{J}\sum_{\substack{i=1\\ i\neq f}}^{r_j} h_{ij}(t)h_{fj}(t)[x_j^T(t)P_j\bar{A}_{ij}P_jx_j(t)] + \sum_{j=1}^{J}\sum_{k=1}^{N_j} x_j^T(t-\tau_{kj})Ix_j(t-\tau_{kj})$$

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

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

$$+\sum_{j=1}^{J}[\phi_j^T(t)P_jx_j(t) + x_j^T(t)P_j\phi_j(t)] + \sum_{j=1}^{J}\sum_{k=1}^{N_j}\left\{x_j^T(t-\tau_{kj})[I-P_{kj}]x_j(t-\tau_{kj})\right\}$$

$$= D_1 + D_2 + D_3 + D_4\,, \tag{A2}$$

where

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

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

$$\begin{aligned} D_3 &\equiv \sum_{j=1}^{J}[\phi_j^T(t)P_jx_j(t) + x_j^T(t)P_j\phi_j(t)] \\ &= \sum_{j=1}^{J}\sum_{n\neq j}^{J}[x_n^T(t)C_{nj}^T P_jx_j(t) + x_j^T(t)P_jC_{nj}x_n(t)] \\ &\leq \sum_{j=1}^{J}\sum_{n\neq j}^{J}[x_n^T(t)x_n(t) + x_j^T(t)P_jC_{nj}C_{nj}^T P_jx_j(t)] \\ &+\sum_{j=1}^{J}\sum_{i\neq f}^{r_j}\sum_{n=1}^{J} h_{ij}(t)h_{fj}(t)x_j^T(t)\left[(\frac{J-1}{J})I + P_jC_{nj}C_{nj}^T P_j\right]x_j(t)\,, \end{aligned} \tag{A5}$$

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

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

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

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

$$+2\sum_{n=1}^{J}\left[(\frac{J-1}{J})I + P_jC_{nj}C_{nj}^T P_j\right]\Bigg\}x_j(t) + \sum_{j=1}^{J}\sum_{k=1}^{N_j}\lambda_M(I-P_{kj})\left\|x_j(t-\tau_{kj})\right\|^2$$

$$= -\sum_{j=1}^{J}\left\{\sum_{i=f=1}^{r_j} h_{ij}^2(t)x_j^T(t)Q_{ij}x_j(t) + \sum_{i<f}^{r_j} h_{ij}(t)h_{fj}(t)x_j^T(t)Q_{ifj}x_j(t) - \sum_{k=1}^{N_j}\lambda_M(I-P_{kj})\left\|x_j(t-\tau_{kj})\right\|^2\right\}$$

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

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

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

$$= -\sum_{j=1}^{J}\{\begin{bmatrix}\sqrt{\sum_{k=1}^{N_j}\left\|x_j(t-\tau_{kj})\right\|^2} & h_{1j}(t)\left\|x_j(t)\right\| & h_{2j}(t)\left\|x_j(t)\right\| & \cdots & h_{r_j j}(t)\left\|x_j(t)\right\|\end{bmatrix}$$

$$\cdot\begin{bmatrix}-\bar{\lambda}_j & 0 & 0 & \cdots & 0\\ 0 & \lambda_{1j} & 1/2\lambda_{12j} & \cdots & 1/2\lambda_{1r_j j}\\ 0 & 1/2\lambda_{12j} & \lambda_{2j} & \cdots & 1/2\lambda_{2r_j j}\\ \vdots & \vdots & \vdots & \vdots & \vdots\\ 0 & 1/2\lambda_{1r_j j} & 1/2\lambda_{2r_j j} & \cdots & \lambda_{r_j j}\end{bmatrix}\cdot\begin{bmatrix}\sqrt{\sum_{k=1}^{N_j}\left\|x_j(t-\tau_{kj})\right\|^2}\\ h_{1j}(t)\left\|x_j(t)\right\|\\ h_{2j}(t)\left\|x_j(t)\right\|\\ \vdots\\ h_{r_j j}(t)\left\|x_j(t)\right\|\end{bmatrix}\}$$

$$= -\sum_{j=1}^{J} H_j^T\Lambda_j H_j\,,$$

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