Fuzzy Model-Based Pitch Stabilization and Wing Vibration Suppression of Flexible Aircraft*

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Abstract— **This paper presents a fuzzy nonlinear controller to regulate the longitudinal dynamics of an aircraft and suppress the bending and torsional vibrations of its flexible wings. The fuzzy controller utilizes full-state feedback with input constraint. First, the Takagi-Sugeno fuzzy linear model is developed which approximates the coupled aeroelastic aircraft model. Then, based on the fuzzy linear model, a fuzzy controller is developed to utilize a full-state feedback and stabilize the system while it satisfies the control input constraint. Linear matrix inequality (LMI) techniques are employed to solve the fuzzy control problem. Finally, the performance of the proposed controller is demonstrated on the NASA Generic Transport Model (GTM).**

I. INTRODUCTION

Elastically shaped aircraft is a concept whereby highly flexible aerodynamic surfaces are elastically shaped in-flight by actively controlling the wing wash-out twist and wing bending deflection in order to change the local angle of attack in such a manner that can result in lower fuel burn by drag reduction during cruise. An earlier research study conducted by NASA has proven that overall aerodynamic efficiency can be improved by active control of wing aeroelasticity in-flight. As a result, the novel concept of Variable Camber Continuous Trailing Edge Flap (VCCTEF) system is proposed [1], [2]. Two sets of control actuators are employed in order to actuate the VCCTEF. The light-weight shaped memory alloy (SMA) is adapted for controlling the shape of the first two chordwise sections of the three-section VCCTEF. The third section is controlled by the electric drive motor (EDM) and provides the needed active wing shaping control in-flight. A preliminary static analysis has shown the potential efficacy of the VCCTEF system. In this paper, the NASA GTM platform configured with VCCTEF system is considered, see Figures 1 and 2.

The main challenge imposed by the control of coupled aeroelastic aircraft is the presence of low frequency flexible modes, which may lie within the range of aircraft rigid-body dynamics. An integrated modeling and control approach was studied in [3], in which an optimal covariance control algorithm was implemented with the goal to suppress the excessive wing vibrations. To extend the approach to full flight envelop, a covarinace control law needs to be developed at each flight condition and then gain scheduled for implementation. In [4], control of flexible wing aircraft, Body Freedom Flutter (BFF), using H_∞ and linear parameter varying (LPV) control design techniques was presented. The gain scheduling LPV plant representation was formulated in such a way that the quadratic stability problem is solvable when the corresponding parametric LMI has a feasible solution. In this paper, we propose to utilize fuzzy based modeling approach, from which a fuzzy control law can be derived.

Since the introduction of the Takagi-Sugeno (T-S) fuzzy model by Takagi and Sugeno [5] in 1985, there has been a tremendous progress on this type of fuzzy systems. The T-S model-based fuzzy system is based on using a set of fuzzy rules to describe a global nonlinear system in terms of a set of local linear models which are smoothly connected by fuzzy membership functions. The basic idea is to design a state feedback controller for each local model and then to construct a globally asymptotic stable controller from the local controllers. This technique is called Parallel Distributed Compensation or PDC and was introduced by Wang et. al. [6], [7]. An open-loop stability analysis of T-S fuzzy systems was first presented by Tanaka and Sugeno [8] in 1990. The stability of the global controller can be proven by formulating Lyapunov stability theory via linear matrix inequalities (LMIs). T-S fuzzy systems and PDC were expanded by generalization of linear control system theory. The work was expanded to developing T-S fuzzy observers and regulators [9], robust control [10], [11], optimal control [11], [12], [13] constraints on the input and output [14], and T-S control of nonlinear time-delayed systems [15]. Some performance criteria such as disturbance rejection [14], decay rate [16], and pole placement [17] have been incorporated in T-S fuzzy systems.

In the last two decades, a number of researchers have considered T-S fuzzy control for attitude stabilization of rigid spacecraft with input constraints. For instance, Park et al. [13] proposed an optimal T-S fuzzy system based on the inverse optimal approach with input constraints [18]. Zhang et al. proposed a T-S fuzzy model with output feedback [19], decay rate [20], and H_∞ control [21], for a rigid spacecraft. Butler et al. [22] introduced a T-S fuzzy model-based PDC flight control for controlling a damaged rigid aircraft. Recently, Ayoubi and Sendi [23] presented a T-S fuzzy model controller with optimal H_∞ robustness performance to stabilize the position and attitude, and attenuate the

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vibration in the flexible appendage of a spacecraft during a slew maneuver. In this paper, we propose a T-S model-based fuzzy control for angle-of-attack and pitch rate stabilization and vibration suppression in a flexible aircraft with control input constraint. The controller design problem is formulated in terms of linear matrix inequalities (LMIs). Though the resulting stabilizing T-S fuzzy controller is nonlinear, its structure is simple hence easy to implement.

This paper is organized as follows: In Section II, we briefly review the longitudinal equation of motion of a flexible aircraft in the state-space form. The first part of section III presents the concept of T-S modeling via local approximation in fuzzy partition space and the second part of Section III overviews the Tagagi-Sugeno fuzzy control or PDC control technique. Section IV presents the open-loop and closed-loop simulations and shows the performance of the proposed fuzzy controller. Finally, concluding remarks and suggestions for future works are made in Section V. Throughout this paper, we use bold and lower case letters to denote the vector quantities.

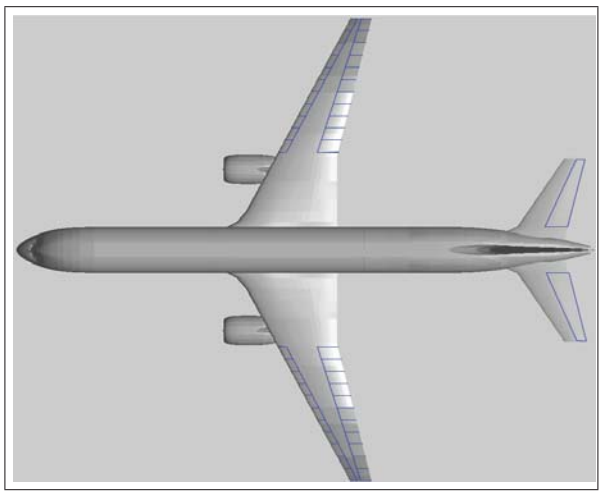

Fig. 1. NASA Generic Transport Model

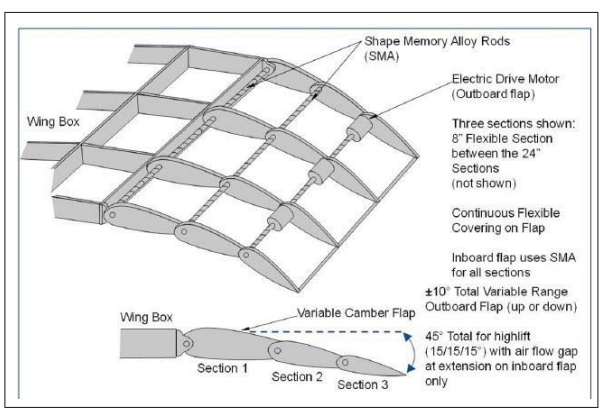

Fig. 2. The concept and structure of VCCTEF.

II. Aircraft Longitudinal Model

Figure 1 shows NASA GTM which is used in this study. The aircraft has 23 control surfaces including 11 VCCTE flaps, 11 slats, and one elevator. As described earlier, only the third section of VCCTEF is used for wing shape control. The equations of motion for coupled aircraft longitudinal rigid-body dynamics with flexible aeroelastic wing modes at cruise conditions can be described in the following state-space form,

$$\dot{\mathbf{x}} = A\mathbf{x} + B\mathbf{u} \tag{1}$$

or

$$\underbrace{\begin{bmatrix} \dot{\mathbf{x}}_a \\ \dot{\mathbf{x}}_e \end{bmatrix}}_{\dot{\mathbf{x}}} = \underbrace{\begin{bmatrix} A_{aa} & A_{ae} \\ A_{ea} & A_{ee} \end{bmatrix}}_{A} \underbrace{\begin{bmatrix} \mathbf{x}_a \\ \mathbf{x}_e \end{bmatrix}}_{\mathbf{x}} + \underbrace{\begin{bmatrix} B_{aa} & B_{ae} \\ B_{ea} & B_{ee} \end{bmatrix}}_{B} \underbrace{\begin{bmatrix} \delta_a \\ \delta_f \end{bmatrix}}_{\mathbf{u}}$$

where $\mathbf{x}_a = [\alpha, q]^T$ denotes the longitudinal rigid-body state vector; α is the angle of attack and q the pitch rate, $\mathbf{x}_e$ consists of displacement and velocity of aeroelastic wing at generalized coordinates, δ_a denotes the elevator deflection, and δ_f denotes the slat and VCCTEF 3rd segment deflection vector. The matrices A_{aa} and A_{ee} contain aircraft rigid-body and aeroelastic characteristics, whereas A_{ae} and A_{ea} correspond to aeroelastic coupling and aircraft rigid-body coupling, respectively. Similarly, B_{ae} and B_{ea} represent coupling effect between the control surface and slat/VCCTEF. Note that the dimension of overall system depends on the number of aeroelastic modes included in the problem setup. In this study, we consider 20 bending modes and 20 torsional modes, hence $\mathbf{x} \in \mathbb{R}^{82\times 1}$, $\mathbf{u} \in \mathbb{R}^{23\times 1}$, $A \in \mathbb{R}^{82\times 82}$, and $B \in \mathbb{R}^{82\times 23}$.The detail derivations and physical interpretations of Eq. (1) can be found in Nguyen et al. [24]. A number of aircraft cruise models at varying airspeed can be generated, which are in the form of Eq. (1), and a novel vibration suppression control concept will be developed by utilizing the Takagi-Sugeno fuzzy modeling approach.

III. Takagi-Sugeno Fuzzy Modeling and Control

A. Takagi-Sugeno Fuzzy Modeling

There are three methods to build a T-S fuzzy model approximation: 1) Sector nonlinearity, 2) local approximation in fuzzy partition spaces or simply "local approximation", and 3) the combination of sector nonlinearity and local approximation. In this study, we use the second method, "local approximation". The main idea behind this approach is to approximate a nonlinear system by choosing an appropriate parameter in the system and approximating the nonlinear system around the selected parameter values (or premise variables), building membership functions in the universe of discourse of each premise variable, and creating model rules corresponding to each point. If there are p premise variables, $\mathbf{s}(t) = [s_1(t), s_2(t), \ldots, s_p(t)]$, then the number of model rules, r, is 2^p.

Model Rule i:
IF $s_1(t)$ is about $\mu_{i1}(s_1)$, $\cdots$, $s_p(t)$ is about $\mu_{ip}(s_p)$.
THEN

$$\begin{cases} \dot{\mathbf{x}}(t) = A_i\mathbf{x}(t) + B_i\mathbf{u}(t) \\ \mathbf{y}(t) = C_i\mathbf{x}(t); \qquad (i = 1, 2, \ldots, r) \end{cases} \tag{2}$$

where $\mu_{ij}(s_j)$ is the fuzzy membership function corresponding to s_j. The firing strength of each rule can be determined using $T-norm$ product as follows,

$$w_i(\mathbf{s}(t)) = \prod_{j=1}^{p} \mu_{ij}(\mathbf{s}(t)) \tag{3}$$

and the fuzzy basis functions are determined from

$$h_i(\mathbf{s}(t)) = \frac{w_i(\mathbf{s}(t))}{\sum_{i=1}^{r} w_i(\mathbf{s}(t))}, \ \forall t \ \geq 0. \tag{4}$$

After combining all the rules of T-S models, the overall system can be approximated as

$$\begin{cases} \dot{\mathbf{x}}(t) = \sum_{i=1}^{r} h_i\{A_i\mathbf{x}(t) + B_i\mathbf{u}(t)\} \\ \mathbf{y}(t) = \sum_{i=1}^{r} h_i C_i \mathbf{x}(t) \end{cases} \tag{5}$$

B. Parallel Distributed Compensation Control

The Parallel Distributed Compensation (PDC) control technique which was introduced by Wang et al. [6] is based on the Takagi-Sugeno fuzzy model approximation. We design a full state-feedback control law for each model rule. Therefore, each control rule has the same premise variables, i.e. "IF" statement, but different consequent, i.e. "THEN" statement. The general structure of each control rule is as follows:

Control Rule i:
IF $s_1(t)$ is about $\mu_{i1}(s_1)$, $\cdots$, $s_p(t)$ is about $\mu_{ip}(s_p)$.
THEN

$$\mathbf{u}_i(t) = -\mathbf{F}_i\mathbf{x}(\mathbf{t}), \ i = 1, 2, \ldots, r, \tag{6}$$

where $\mathbf{F}_i$ is the feedback gain matrix for ith T-S fuzzy model. The overall control input with fuzzy basis functions becomes

$$\mathbf{u}(t) = -\sum_{i=1}^{r} \frac{w_i(\mathbf{s}(t))\mathbf{F}_i\mathbf{x}(t)}{\sum_{j=1}^{r} w_j(\mathbf{s}(t))} = -\sum_{i=1}^{r} h_i\mathbf{F}_i\mathbf{x}(t) \tag{7}$$

We use the following theorems to formulate the T-S model-based fuzzy control problem in the form of linear matrix inequalities (LMIs). The first two theorems are used to include the input control constraint into the design process.

Theorem 1: Assume the initial condition $\mathbf{x}(\mathbf{0})$ is known. The constraint $||\mathbf{u}(t)||_2 \leq \rho$ is enforced at all times if the following LMIs hold [16]:

$$\begin{bmatrix} I & x(0)^T \\ x(0) & X \end{bmatrix} \geq 0 \tag{8}$$

and

$$\begin{bmatrix} X & \mathbf{M}_i^T \\ \mathbf{M}_i & \rho^2 I \end{bmatrix} \geq 0 \tag{9}$$

where $X = X^T > 0$ and $\mathbf{M}_i = \mathbf{F}_i X$.

Theorem 2: Assume that $||\mathbf{x}(\mathbf{0})|| \leq \beta$ where $\mathbf{x}(\mathbf{0})$ is unknown but the upper bound $\beta > 0$ is known. Then the condition

$$X \geq \beta^2 I \tag{10}$$

is equivalent to the following LMI [16]

$$\begin{bmatrix} I & x(0)^T \\ x(0) & X \end{bmatrix} \geq 0. \tag{11}$$

Theorem 3: The equilibrium point of the T-S fuzzy system given by Eq. (5) with the feedback control law given by Eq. (6) is globally asymptotically stable if there are matrices X and $\mathbf{M}_i$ which satisfy the following LMIs [16]

$$\begin{bmatrix} X & (XA_i^T - M_i^T B_i^T) \\ (A_i X - B_i M_i) & X \end{bmatrix} > 0 \tag{12}$$

and

$$\begin{bmatrix} X & \left(\frac{A_i X + A_j X - B_i M_j - B_j M_i}{2}\right)^T \\ \left(\frac{A_i X + A_j X - B_i M_j - B_j M_i}{2}\right) & X \end{bmatrix} \geq 0 \tag{13}$$

where $i, j = 1, 2, \ldots, r$ and $i < j$ such that $h_i \cap h_j \neq \emptyset$. Therefore, the problem of stabilizing T-S fuzzy model using full-state feedback with control input constraint, and independent of initial conditions, is equivalent to solving the system of convex LMIs given by Eqs. (9)–(10) and (12)–(13). The solution of this set of LMIs, i.e. X and $\mathbf{M}_i$, will be used to find the feedback gain matrix $\mathbf{F}_i = \mathbf{M}_i X^{-1}$. We can reformulate this problem as the convex optimization problem as follows:
Given: A_i, B_i; $(i = 1, 2, \ldots, r)$, and β
Minimize: ρ^2
Subject to: Eqs. (9)–(10) and (12)–(13)

The control objective is to design a stabilizing fuzzy controller to control the angle of attack and pitch rate, and suppress the wing vibration. Note that the control inputs are norm bounded. In the next section, we show the performance of the T-S fuzzy model approximation and PDC controller on NASA GTM.

IV. Numerical Simulation

In this section, we first develop a T-S fuzzy model (TSFM) for NASA GTM and compare the open-loop response of the proposed TSFM with an arbitrary initial condition. Then, we present a PDC controller and the performance of the closed-loop system. Finally, we investigate the performance of the controller in the presence of uncertainties.

A. Open Loop Response

The local approximation method is employed to develop TSFM. We choose Mach number as a premise variable and consider two flight speeds at $M = 0.5$ and $M = 0.8$, and we define the simplest form of membership function, which is triangular, to fuzzify the Mach number. The membership functions corresponding to two flight speeds are shown in Fig. 3.

We simulate the open loop response of the TSFM when $M = 0.7$, $\alpha(0) = 1$ deg, and $q(0) = 0.1$ rad/s. We assume all other initial conditions are zero. The open-loop response of TSFM for angle of attack and pitch rate are shown in Fig. 4.

Similarly, the bending and torsional deflections at the flexible wing-tip are shown in Fig. 5. It can be seen from the plots that the TSFM closely follows the GTM.

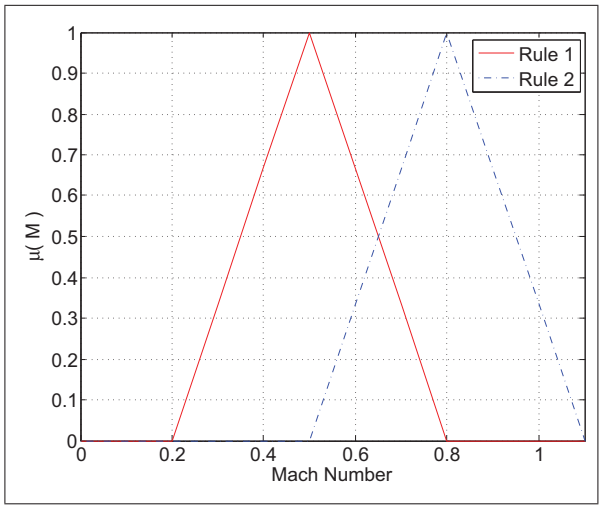

Fig. 3. Mach number membership functions.

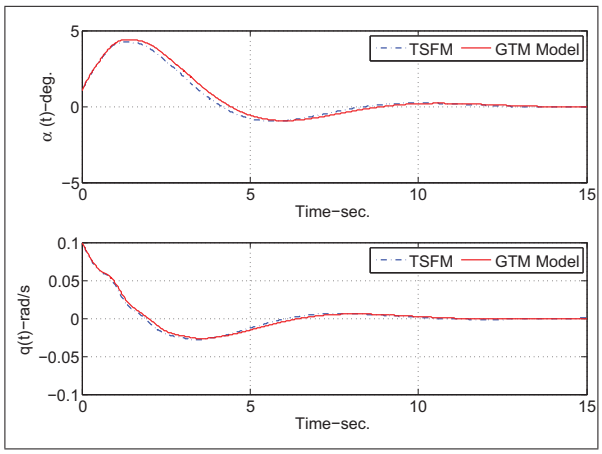

Fig. 4. The open-loop response of angle of attack and pitch rate at $M = 0.7$.

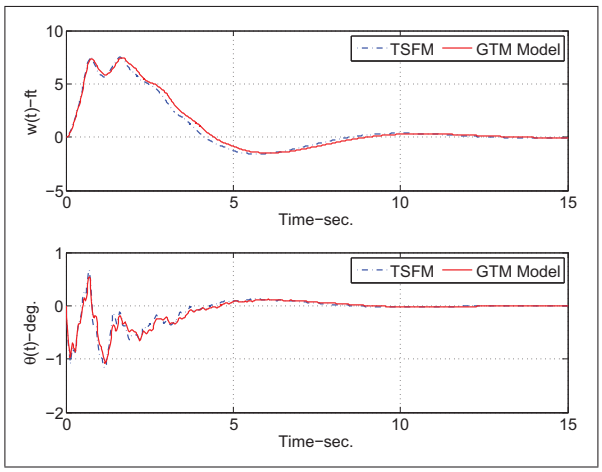

Fig. 5. The open-loop response of bending and torsional deflections of the wing-tip at $M = 0.7$.

B. Closed-Loop Response

We use CVX, a package for specifying and solving convex programs [25], [26] to find the lower bound of control inputs subject to Eqs. (9)–(10) and (12)–(13). The obtained fuzzy control law is used to simulate the behavior of TSFM and GTM at $M = 0.7$ with the same initial conditions which is used in the open-loop analysis. The time history of the aircraft angle of attack and pitch rate are shown in Fig. 6. The time history of the bending and torsional deflections of the wing-tip are plotted in Fig. 7. The plots show that the angle of attack and pitch rates are stabilized and the wing-tip vibration suppressed around 3 seconds. The open and closed-loop responses of both models, TSFM and GTM, are examined at M=0.5, 0.6, 0.8, and 0.88, but for the sake of brevity, the results are omitted here. We noticed that the proposed fuzzy controller could stabilize the unstable aircraft at $M = 0.88$.

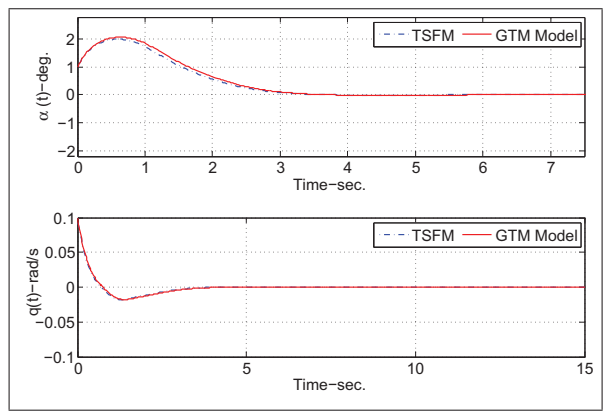

Fig. 6. The closed-loop response of the angle of attack and pitch rate at $M = 0.7$.

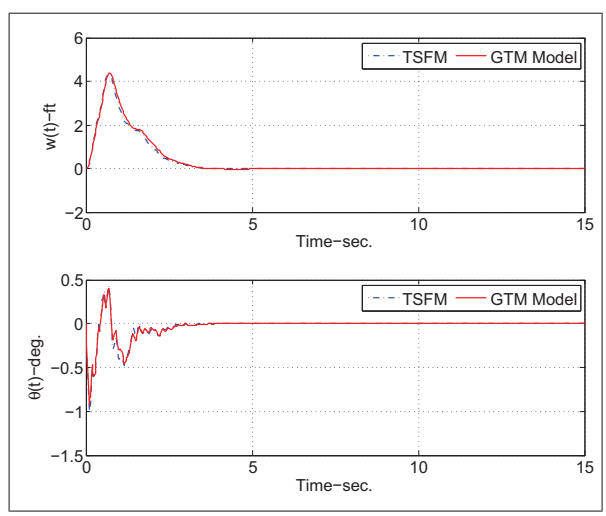

Fig. 7. The closed-loop response of bending and torsional deflections of the wing-tip at $M = 0.7$.

The maximum control deflections of each control surface are plotted in Fig. 8. It can be seen that the control system uses the outer control surfaces (close to the wing-tip) for attitude stabilization and vibration attenuation.

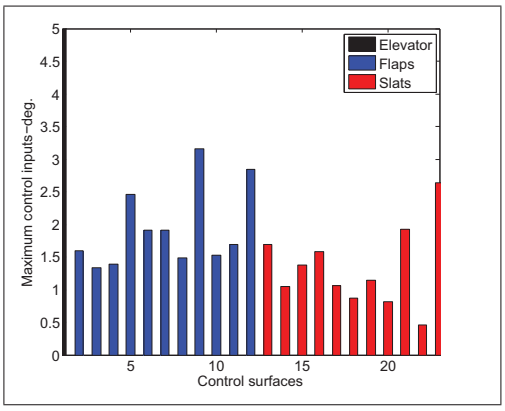

Fig. 8. Maximum control surface deflections at $M = 0.7$

C. Controller Robustness Test

We examine the robustness of the proposed fuzzy model-based controller due to uncertainties in the system matrix, A, and in the input matrix, B, of the GTM model. Figure 9 shows the time responses of the angle of attack and pitch rate of the closed-loop system in the presence of input uncertainty. The time responses of the bending and torsional motion at the wing-tip are shown in Fig. 10. The simulation results show that a good closed-loop performance is maintained when input uncertainty satisfies $\frac{\Delta B}{B} \leq 0.5$.

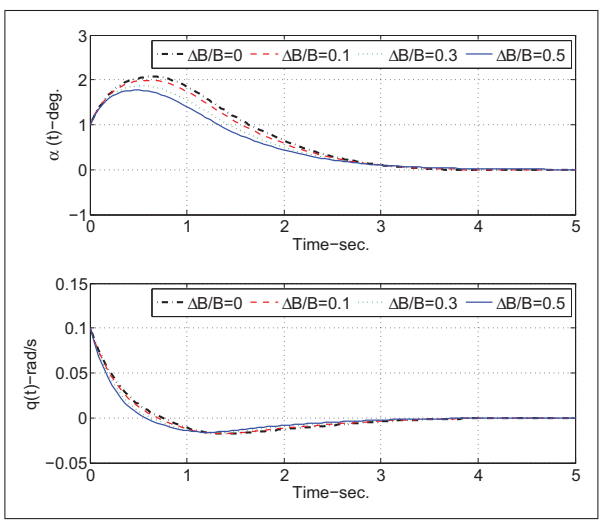

Fig. 9. The closed-loop response of the angle of attack and pitch rate at $M = 0.7$ in the presence of input uncertainty.

Figure 11 shows the time response of the angle of attack and pitch rate of the closed-loop system due to uncertainty in the A_{rr} part of the A matrix, which corresponds to the rigid-body aircraft dynamics; see Eq.(1). The time responses of the bending and torsional motion of the wing-tip are shown in Fig. 12. As expected, in this case only the performance of rigid-body dynamics degrades as uncertainty increases. We also notice that the performance of the fuzzy controller is poor in the presence of any uncertainty in the A_{re}, A_{er}, which represent the coupling between the rigid-body dynamics and flexible wing, and A_{ee} which represents the flexible wing model.

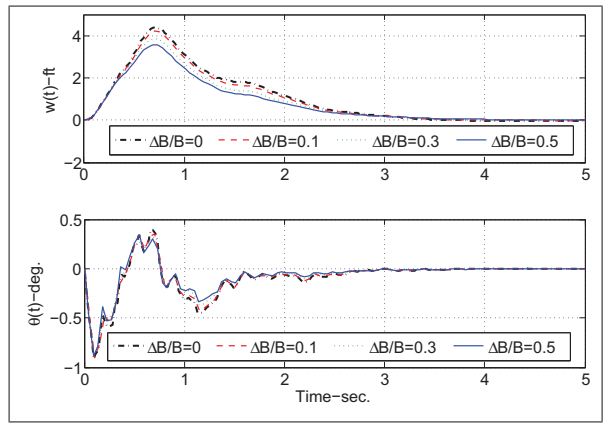

Fig. 10. The closed-loop response of bending and torsional deflections of the wing-tip at $M = 0.7$ in the presence of input uncertainty.

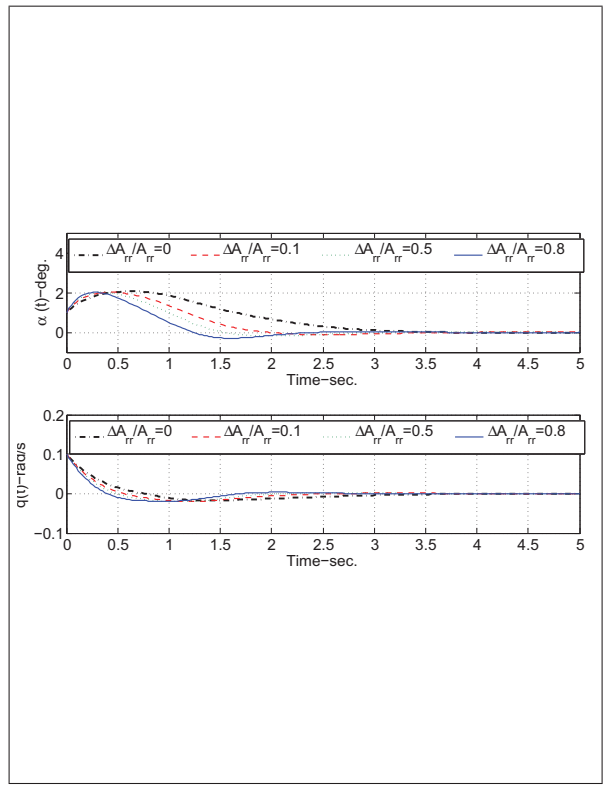

Fig. 11. The closed-loop response of the angle of attack and pitch rate at $M = 0.7$ in the presence of system uncertainty.

V. CONCLUSIONS AND FUTURE WORK

In this paper, we have presented a preliminary model-based fuzzy controller which can effectively stabilize an aircraft with flexible wings. We assume all the states are available for feedback and consider the input control constraint. To achieve the control objective subject to input constraint, we have utilized the convex optimization techniques based on the LMIs. Simulation results indicate that the accuracy of the T-S fuzzy model and performance of the T-S fuzzy controller are satisfactory even when the aircraft is unstable. Though the proposed stabilizing controller is nonlinear, but its structure is simple and easy to implement. Future topics

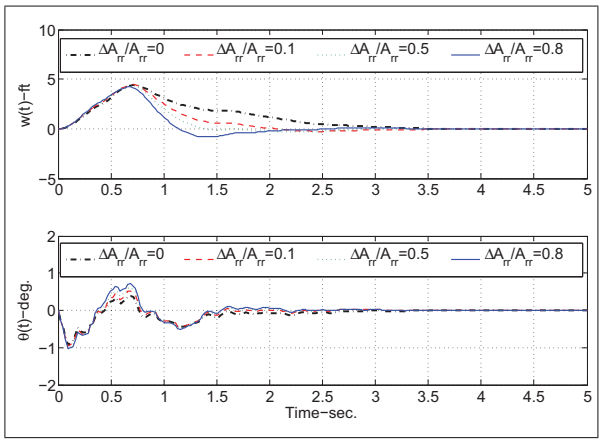

Fig. 12. The closed-loop response of bending and torsional deflections of the wing-tip at $M = 0.7$ in the presence of system uncertainty.

for research and improvement in this direction could be considering the output-feedback with fuzzy observer, external disturbances such as wind-gust, structured uncertainty in the T-S fuzzy model, actuator rate limit, and time-delay in the control system.

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