Chapter

Performance Improvement for Fighter Aircraft Using Fuzzy Switching LQI Controller

Emre Kemer, Hasan Başak and Hayri Baytan Özmen

Abstract

In this work, a switching linear quadratic integral (LQI) controller based on fuzzy logic is designed for the load-factor tracking problem of high-performance aircraft referred to as the Aero-Data Model in Research Environment (ADMIRE). ADMIRE is a new generation aircraft and has a wide flight operation envelope in terms of altitude and speed. Hence, it is difficult to design a flight controller to achieve a high tracking performance. First, the LQI controller is selected due to good tracking performance and robustness in the model dynamics. Combining switching LQI controller and fuzzy logic improves the transient performance of the closed-loop switched system. The results obtained with the fuzzy switching controller have been compared with the conventional LQI and the switching LQI in terms of robust demand tracking. The simulation results have demonstrated that the fuzzy switching controller is superior to the conventional LQI and switching LQI controllers due to better transient performance and robust stability.

Keywords: fuzzy logic, switching control, LQI, load-factor tracking, fighter aircraft

1. Introduction

Conventional aircrafts have aileron, elevator, and rudder control effectors. Flight control systems are generally developed using one control effector for each rotational degree of freedom. The aileron is utilized to obtain a roll motion, a pitch motion is obtained by using the elevator, and the rudder effector controls the yaw motion of the aircraft. The control problem is the determination of the deflections of control effectors that produce the desired motion specified by a flight controller that transfers the pilot's command given by a control stick. Three control effectors can generate desired motions. However, modern aircrafts have more control effectors than conventional aircrafts [1]. The design of reliable flight control systems is difficult for modern aircrafts because these aircrafts are becoming more complicated. Also, the performance of flight control systems must be very high and the stability of the aircraft has demanded the development of different control systems [2]. In recent years, linear control systems have been developed assuming that flight dynamics are linear time-invariant about the operation points and the longitudinal dynamics are decoupled from lateral ones. Zhang et al. [3] proposed a mixed H_2/H_∞ flight controller using enhanced linear matrix inequality, which stabilizes the aircraft system in case of actuator loss. A gain scheduled linear quadratic regulator method is designed in [4] for vehicle dynamics where the flight period is divided into different intervals because flight condition varies during the flight. A proportional-integral-derivative (PID) flight control system is investigated in ref. [5] whose performance is not satisfactory due to uncertainties and nonlinearities of vehicle dynamics. A flight controller law is designed based on optimal control theory in ref. [6] ensuring the reliability of aircraft for pilot's commands in case of all operating conditions. A resilient linear controller is proposed by Bouvier et al. [7] for the dynamic of aircraft in the presence of a loss of control authority. Offline reference regulators and robust control allocation flight controllers were developed in ref. [8] for aerodynamic nonlinearities and parametric uncertainties. Besides, nonlinear controller methods have been proposed by researchers. For example, a nonlinear dynamic inversion control law is proposed by Da Costa et al. [9] where the nonlinear dynamics are transformed into linear dynamics using state or output feedback assuming timescale separation between attitude and altitude rates. Nonlinear dynamic inversion controllers require precise knowledge of all nonlinearities that is not possible for modern fighter aircraft [10]. Sliding mode differentiator [11], disturbance observer-based sliding mode control [12], and disturbance observer-based dynamic surface controller [13] are developed considering nonlinearities and external disturbances.

A backstepping control based on fuzzy logic system is designed in ref. [14] for vehicle dynamics with state constraints and actuator fault. A fuzzy tracking controller [15] was proposed to satisfy the properties of disturbance rejection in aircraft vehicles. Takagi-Sugeno fuzzy robust controller was developed by Luan et al. [16] for the problem of part transportation. An adaptive fuzzy controller [17] was designed for a vehicle dynamic with input saturation.

In this chapter, we develop a control approach based on a switching control with a fuzzy logic rule, which is evaluated in a nonlinear ADMIRE aircraft model. Combined switching control with fuzzy logic has better tracking performance and strong robustness for the nonlinear model of ADMIRE aircraft.

2. The ADMIRE aircraft model

The Aeronautical Research Institute of Sweden developed the ADMIRE model using the generic aero-data model with dynamic models of an engine, actuators, atmosphere, and sensors. The ADMIRE model has 12 states but generally, these states were reduced to simply nonlinear dynamics of the system. The short-period longitudinal flight dynamics governing the ADMIRE benchmark model are given as follows [18–20]:

$$\left|\begin{matrix}\dot{\alpha}\\ \dot{q}\end{matrix}\right| = \begin{bmatrix} Z_\alpha & Z_q \\ M_\alpha & M_q \end{bmatrix}\begin{bmatrix}\alpha \\ q\end{bmatrix} + \begin{bmatrix} Z_{\delta_e} & Z_{t_{ss}} \\ M_{\delta_e} & M_{t_{ss}} \end{bmatrix}\begin{bmatrix}\delta_e \\ t_{ss}\end{bmatrix}$$

$$\mathrm{n_z} = \begin{bmatrix}\mathrm{n_{z\alpha}} & \mathrm{n_{zq}}\end{bmatrix}\begin{bmatrix}\alpha \\ \mathrm{q}\end{bmatrix} + \begin{bmatrix}\mathrm{n_{z\alpha}} & \mathrm{n_{zq}}\end{bmatrix}\begin{bmatrix}\delta_\mathrm{e} \\ \mathrm{t_{ss}}\end{bmatrix} \qquad (1)$$

where state variables $\boldsymbol{\alpha}$ and $\boldsymbol{q}$ are the angles of attack and the Euler pitch rate, respectively. The control inputs are the elevator angle, $\boldsymbol{\delta_e}$ and throttle setting, $\boldsymbol{t_{ss}}$, respectively, and the output variable is load-factor, $\boldsymbol{n_z}$ (**Figure 1**).

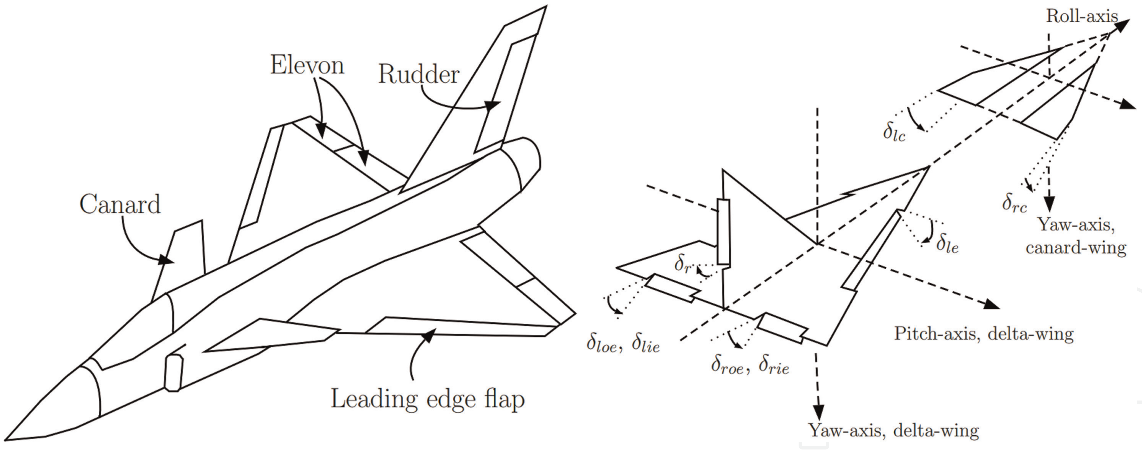

Figure 1.
ADMIRE aircraft model and control surfaces.

3. Fuzzy switching control development

In this section, a fuzzy switching control will be developed for the ADMIRE fighter aircraft. **Figure 2** illustrates a schematic of the control structure. Here, linear quadratic integral (LQI) control computes an optimal state feedback gain for the regulating closed-loop system. The control law consists of the solution of the Riccati equation in the linear-quadratic regulatory framework with the integral of the output variable. The linearized dynamics of the aircraft at a trim condition with state-space realization are given as:

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) \\ y(t) &= Cx(t) + Du(t) \end{aligned} \tag{2}$$

The objective of the LQI control is to find the state feedback control law, such as

$$u(t) = -K[x(t) e_I(t)]^T \tag{3}$$

where $\boldsymbol{K}$ is the feedback gain matrix, and $\boldsymbol{e_I(t)}$ is the integral state for the output variable. The optimal feedback law minimizes the quadratic performance index.

$$J = \int_0^\infty \left(x^T Q x + x^T R\, u\right) dt \tag{4}$$

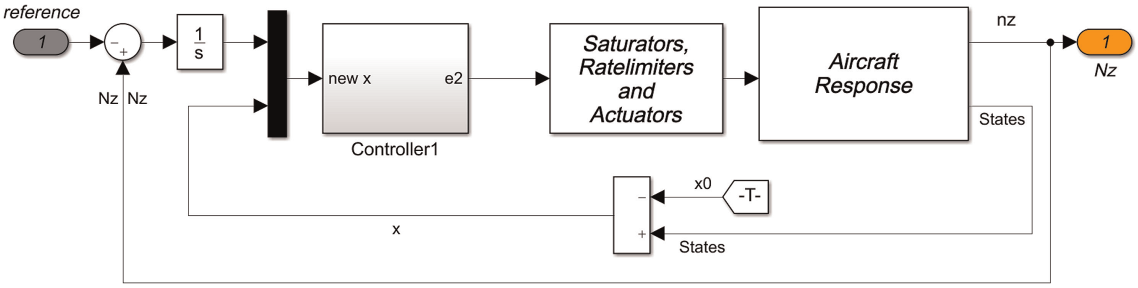

Figure 2.
Schematic of the control structure.

In which $\boldsymbol{Q}$ is a positive semi-definite weight matrix, and $\boldsymbol{R}$ is a positive-definite weight matrix.

Then, this control law guarantees that the output $\boldsymbol{y}(\boldsymbol{t})$ tracks the demand signal $\boldsymbol{r}(\boldsymbol{t})$. In fact, $\boldsymbol{e_I}(\boldsymbol{t})$ is

$$e_I(t) = \int_0^t (r(\tau) - y(\tau))d\tau \tag{5}$$

The state-space presentation of augmented dynamic is written as:

$$\begin{vmatrix} \dot{x}(t) \\ \dot{e}_I(t) \end{vmatrix} = \begin{vmatrix} A(t) & 0 \\ -C(t) & 0 \end{vmatrix} \begin{vmatrix} x(t) \\ e_I(t) \end{vmatrix} + \begin{vmatrix} B(t) \\ -D(t) \end{vmatrix} u(t) \tag{6}$$

To cover the flight envelope, the flight envelope is divided into some cells. Augmented switched state-space model is given as:

$$\begin{vmatrix} \dot{x}_{\sigma(t)}(t) \\ \dot{e}_{I\sigma(t)}(t) \end{vmatrix} = \begin{vmatrix} A_{\sigma(t)}(t) & 0 \\ -C_{\sigma(t)}(t) & 0 \end{vmatrix} \begin{vmatrix} x_{\sigma(t)}(t) \\ e_{I\sigma(t)}(t) \end{vmatrix} + \begin{vmatrix} B_{\sigma(t)}(t) \\ -D_{\sigma(t)}(t) \end{vmatrix} u(t) \tag{7}$$

The system matrices of Eq. (7) are rewritten as:

$$\begin{vmatrix} A_{\sigma(t)} & B_{\sigma(t)} \\ C_{\sigma(t)} & D_{\sigma(t)} \end{vmatrix} = \begin{vmatrix} A_i & B_i \\ C_i & D_i \end{vmatrix}, \mathrm{i} = 1, \dots, M \tag{8}$$

where $\boldsymbol{\sigma}(\boldsymbol{t})$ is a switching rule that takes values $\{\mathbf{1}, \dots, \boldsymbol{M}\}$, $\boldsymbol{M}$ is the number of subsystems. The switched control scheme is

$$u(t) = -K_{\sigma(t)}[x(t)e_I(t)]^T \tag{9}$$

To design a fuzzy switching controller, ADMIRE flight envelope has been divided into four overlapping cells as shown in **Figure 3** with the dotted lines showing the boundaries between cells. Here, the fuzzy switching control law is

$$u(t) = -K_{fuzzy\sigma(t)}[x(t)e_I(t)]^T \tag{10}$$

The controller gains are designed using the data from each related cell center, and the fuzzy switching controller is computed as follows, based on the fuzzy logic rule:

$$K_{fuzzy\sigma(t)} = \begin{cases} K_1 & Alt \le 1550 \; and \; Mach \le 0.6, \\ K_2 & Alt \le 1550 \; and \; Mach \ge 1.1, \\ K_3 & Alt \ge 4500 \; and \; Mach \ge 1.1, \\ K_4 & Alt \ge 4500 \; and \; Mach \le 0.6, \\ \rho_1 K_1 + \rho_2 K_2 & Alt \le 1550 \; and \; Mach \in (0.6,1.1), \\ \rho_2 K_2 + \rho_3 K_3 & Alt \in (1550,\ 4500) \; and \; Mach \ge 1.1, \\ \rho_3 K_3 + \rho_4 K_4 & Alt \ge 4500 \; and \; Mach \in (0.6,1.1), \\ \rho_1 K_1 + \rho_4 K_4 & Alt \in (1550,\ 4500) \; and \; Mach \le 0.6, \\ \rho_1 K_1 + \rho_2 K_2 + \rho_3 K_3 + \rho_4 K_4 & Alt \in (1550,\ 4500) and \; Mach \in (0.6,1.1), \end{cases}$$

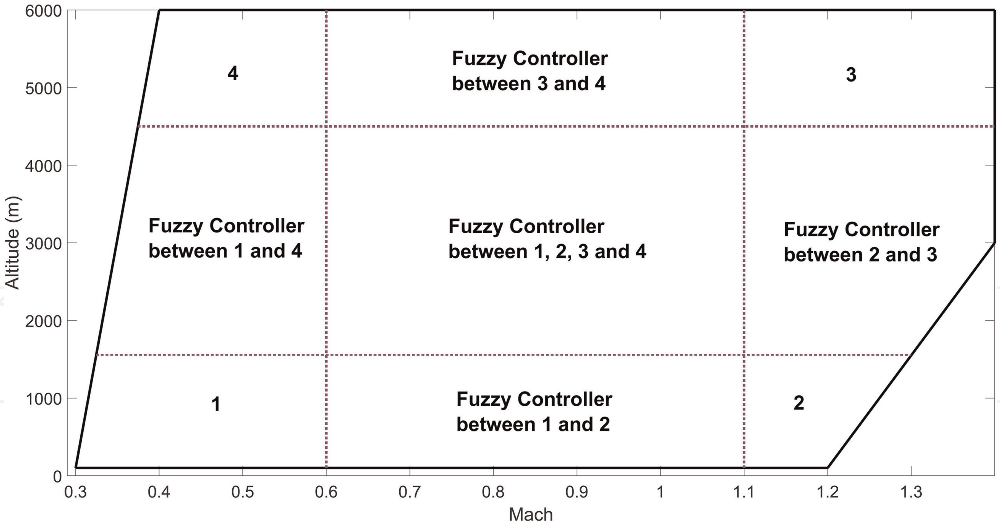

Figure 3.
Flight envelope with the four overlapping cells.

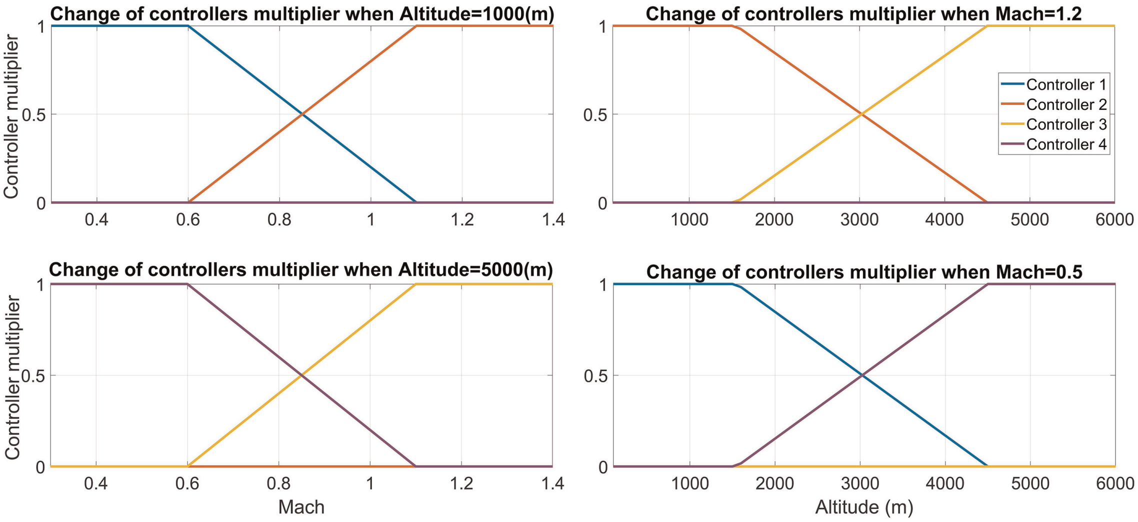

Figure 4.
Fuzzy controller rules between two cells.

where ρ_i, i $[1\ 4]$ are multipliers for the related controllers as given in **Figures 4** and 5. **Figure 4** illustrates fuzzy controller rules between two cells. One can see that multiplier of the controller change linearly between active two cells, also multipliers of passive cells remain zero. In addition, the change of the controller multipliers for overlapping four cells is given in **Figure 5**.

4. Simulation results and discussion

This section represents simulation results and evaluates the performance of the developed control law using MATLAB/Simulink. Three controller strategies are compared in this section, which are the single LQI controller, the switched LQI controller given in Eq. (9), and the fuzzy switching LQI controller given in Eq. (10). The single LQI controller is designed for the data, which is taken at the center of the ADMIRE flight envelope, whereas the switched controller is designed using the flight envelope,

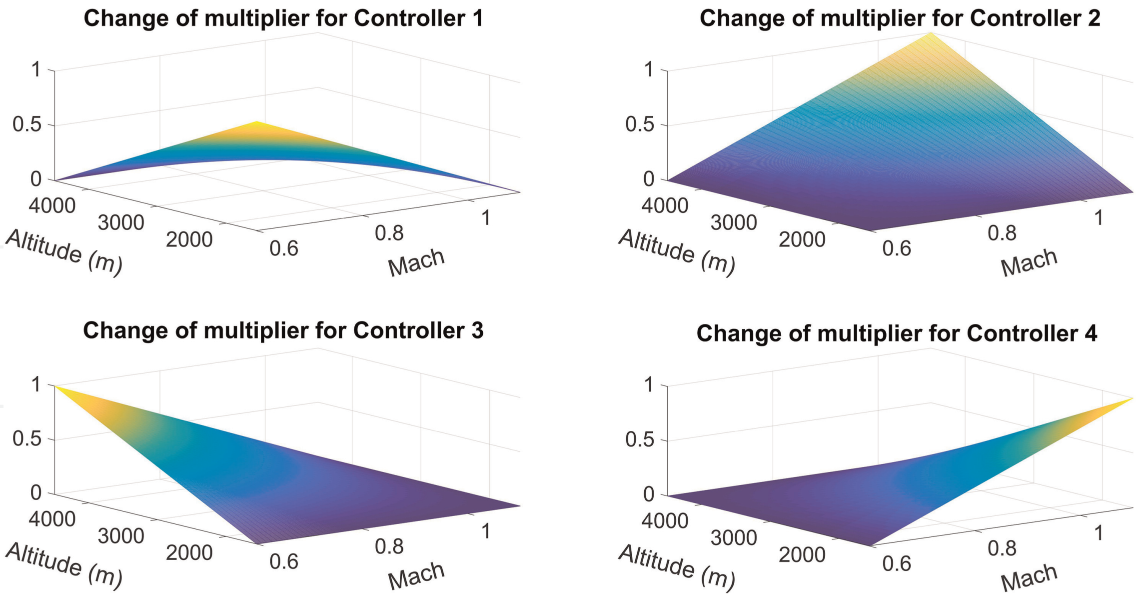

Figure 5.
Fuzzy controller rules for overlapping four cells.

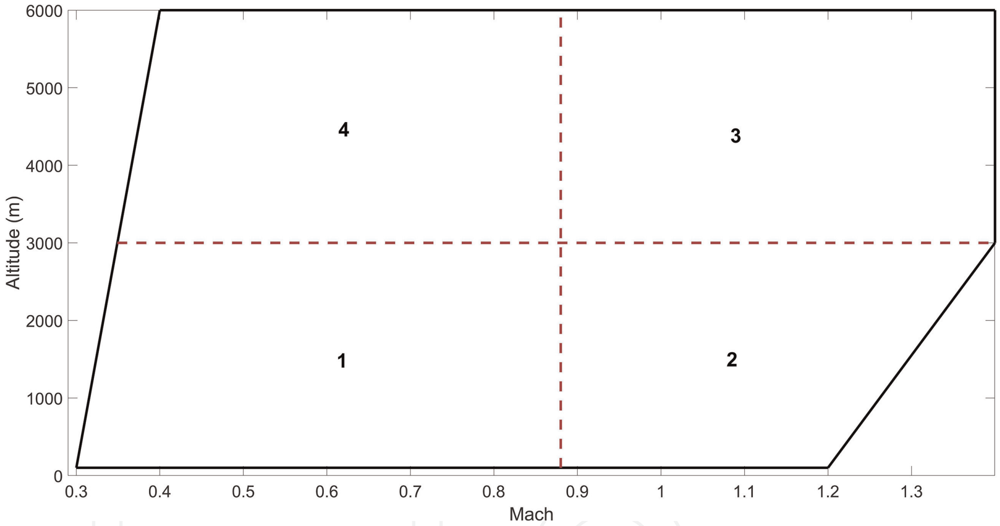

Figure 6.
Flight envelope with the four cells.

which has been divided into four cells as shown in **Figure 6** with the dashed lines showing the boundaries between cells. The feedback gains of the switched controller are computed based on the data of each cell center.

The simulation scenarios were performed to analyze the robust stability and performance of the closed-loop system at flight conditions (Mach = {0.75, 0.9, 0.75} and altitude = {5000, 1500, 4500} m). The pilot command is constricted such that the load-factor N_z stays within the design limits -3 g < N_z <9 g over the flight envelope. Load-factor demand and responses of the closed-loop system with the controllers at flight condition of Mach = 0.75 and Alt = 5000 is illustrated in **Figure 7**. The load-factor response with the single LQI is slower than the switched and fuzzy switching controllers. The switched controller has an oscillatory response during the switching, which is an undesired effect during flight operation. **Figure 8** gives the angle of attack and the Euler pitch rate responses of the closed-loop system with the single LQI, switched, and

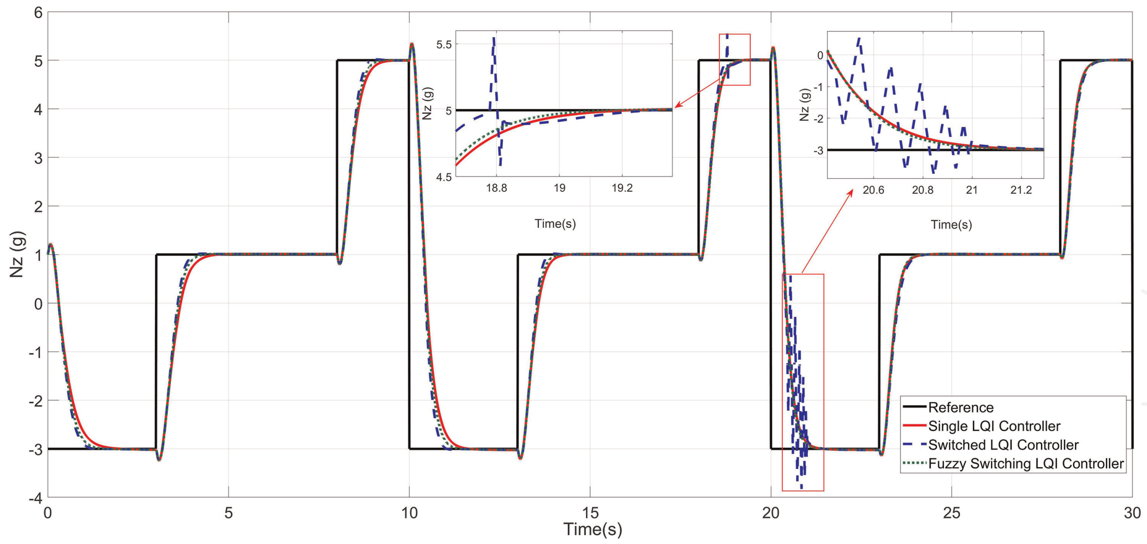

Figure 7.
Load-factor responses of the closed-loop systems at flight condition Mach = 0.75 and alt = 5000.

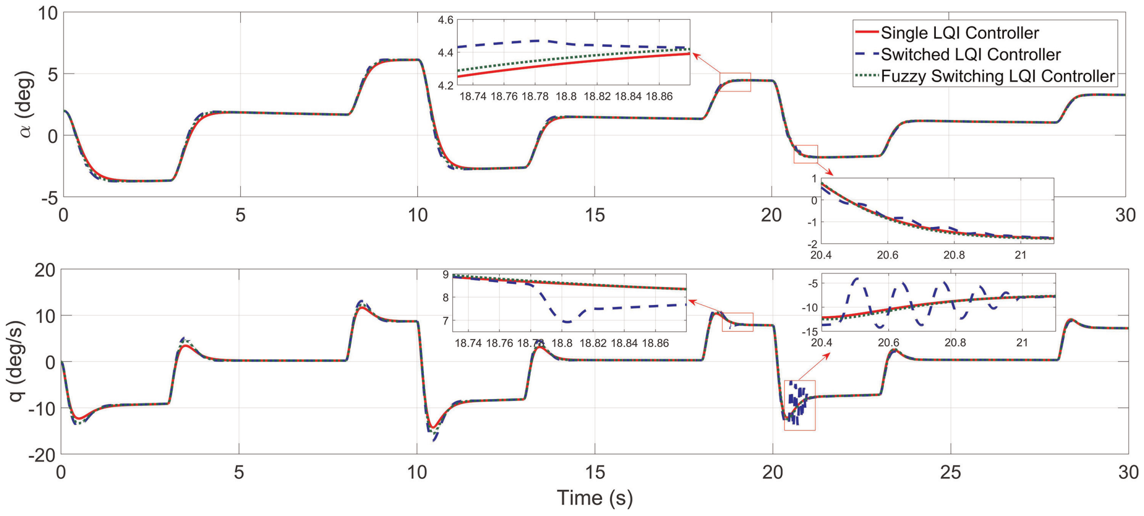

Figure 8.
State variables, the angle of attack, and the Euler pitch rate responses at flight condition Mach = 0.75 and alt = 5000.

the proposed fuzzy switching LQI controllers. One can see from the bottom plot of **Figure 8** that the Euler pitch rate response has an oscillation during switching with the switched controller. However, the proposed fuzzy switching controller has the best transient performance. The corresponding control inputs to the related controllers are given in **Figure 9**. Elevon deflection generates values between -4 deg. and 2 deg. Oscillations are also seen in this elevon deflection and throttle setting, t_{ss} when the switched controller is used. **Figures 10** and **11** give the indexes of the switched controller and the change in the coefficients of the fuzzy switching controller, respectively. Feedback gains K_1, K_2 and K_4 are employed for the switched controller, but all computed controller gains are used with the fuzzy switching controller. **Figure 12** illustrates the trajectory movement in the flight envelope for the different controllers.

In the second scenario, simulation is started at flight condition Mach = 0.9 and Altitude = 1500 m. Load-factor demand and responses of the closed-loop systems are

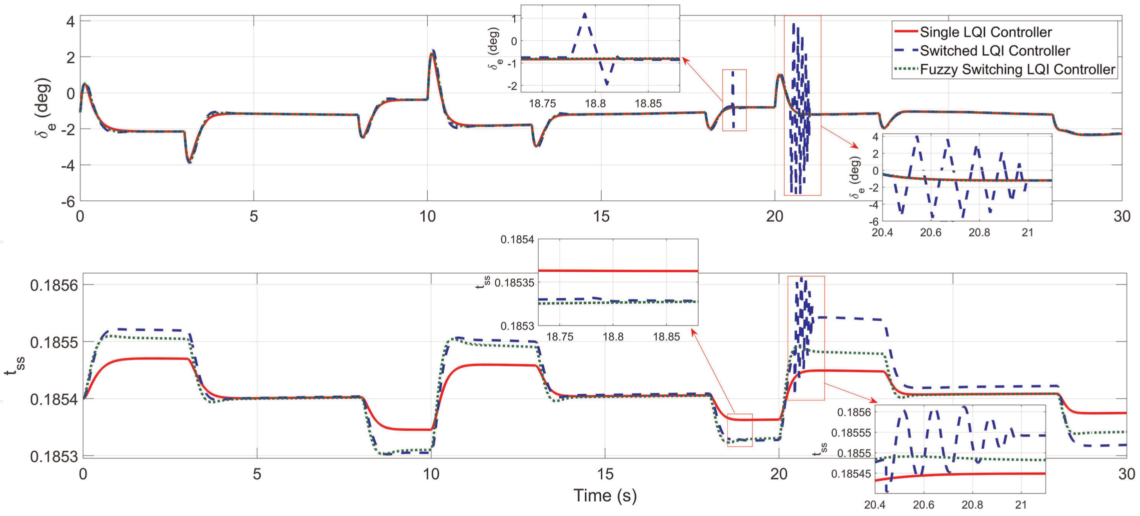

Figure 9.
Control inputs of the single, switched, and fuzzy switching controllers at flight condition Mach = 0.75 and alt = 5000.

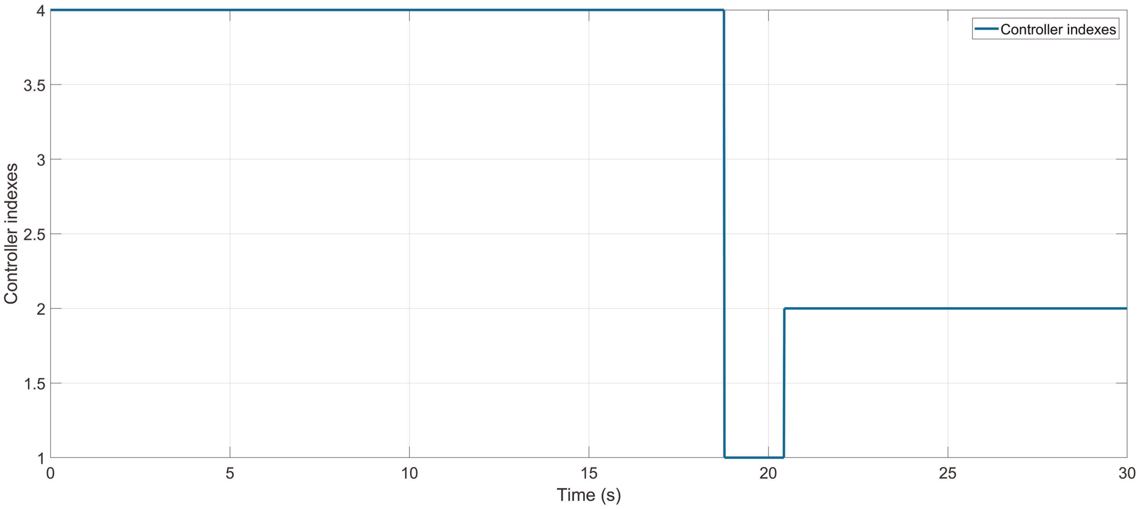

Figure 10.
Index of the switched controller gains at flight condition Mach = 0.75 and alt = 5000.

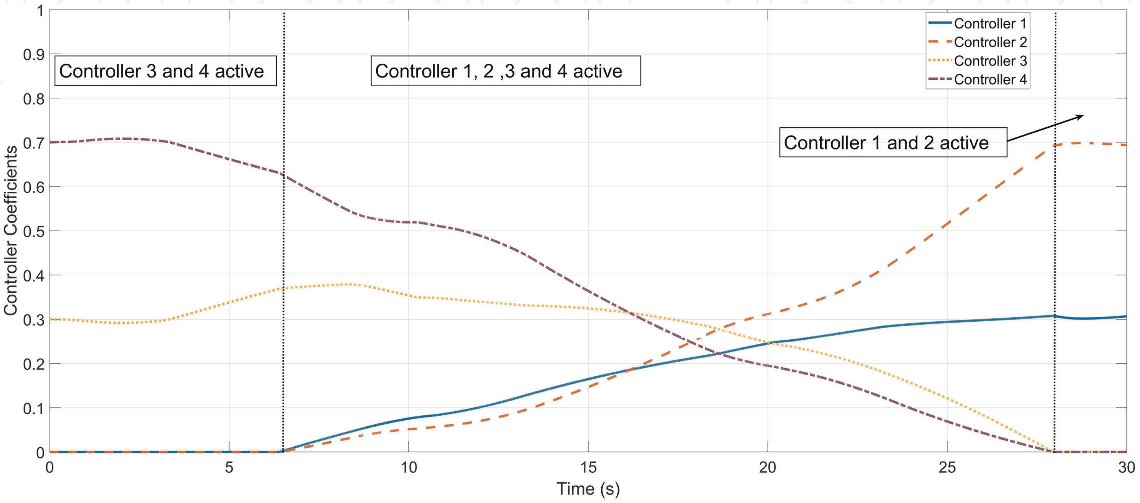

Figure 11.
Varying coefficients of the fuzzy switching controller at flight condition Mach = 0.75 and alt = 5000.

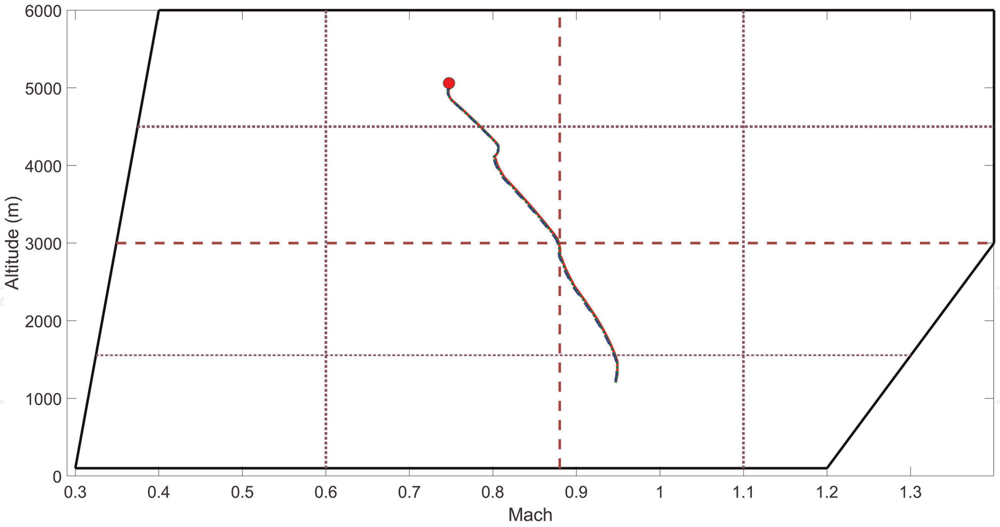

Figure 12.
Altitude responses with the different controllers at flight condition Mach = 0.75 and alt = 5000.

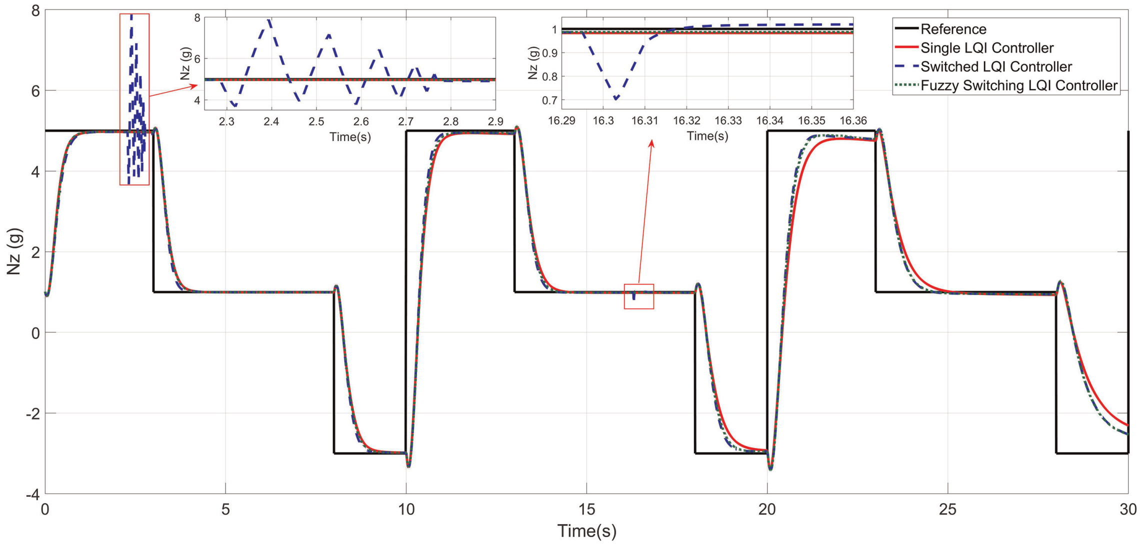

Figure 13.
Load-factor responses of the closed-loop systems at flight condition Mach = 0.9 and altitude = 1500 m.

given in **Figure 13**. Closed-loop response with the single LQI controller is the slowest amongst the controllers. Load-factor tracking response settles a larger steady-state error than the responses of other controllers. The switched controller has an undesired oscillatory response during the switching instances. **Figure 14** gives the angle of attack and the Euler pitch rate responses of the closed-loop system with the single LQI, switched, and the proposed fuzzy switching LQI controllers. The angle of attack increases at t = 20 sec for a larger demand of load-factor. Input responses of the related controllers are given in **Figure 15**. Throttle setting control input is the largest with the switched controller. The single LQI controller requires 0.288 of the throttle setting in the second scenario. **Figures 16** and **17** display the index of the switched controller and the varying coefficients of the fuzzy switching controller, respectively. All computed feedback gains are employed with the fuzzy switching controller, whereas feedback gains K_1, K_2, and K_4 are used for the switched controller. **Figure 18** illustrates the trajectory movement in the flight envelope for the different controllers.

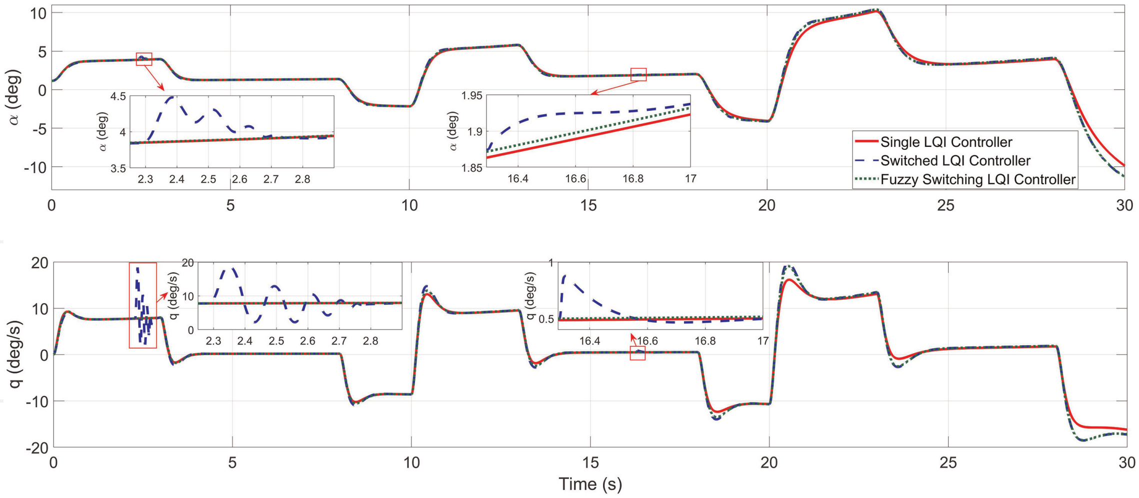

Figure 14.
State variables, the angle of attack, and the Euler pitch rate responses at flight condition Mach = 0.9 and altitude = 1500 m.

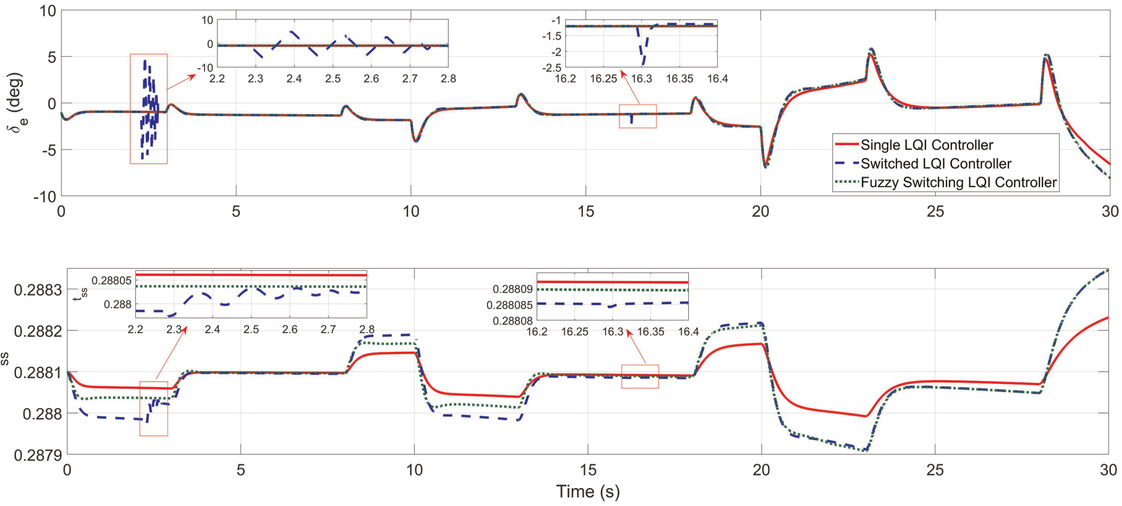

Figure 15.
Control inputs of the single LQI, switched and fuzzy switching controllers at flight condition Mach = 0.9 and altitude = 1500 m.

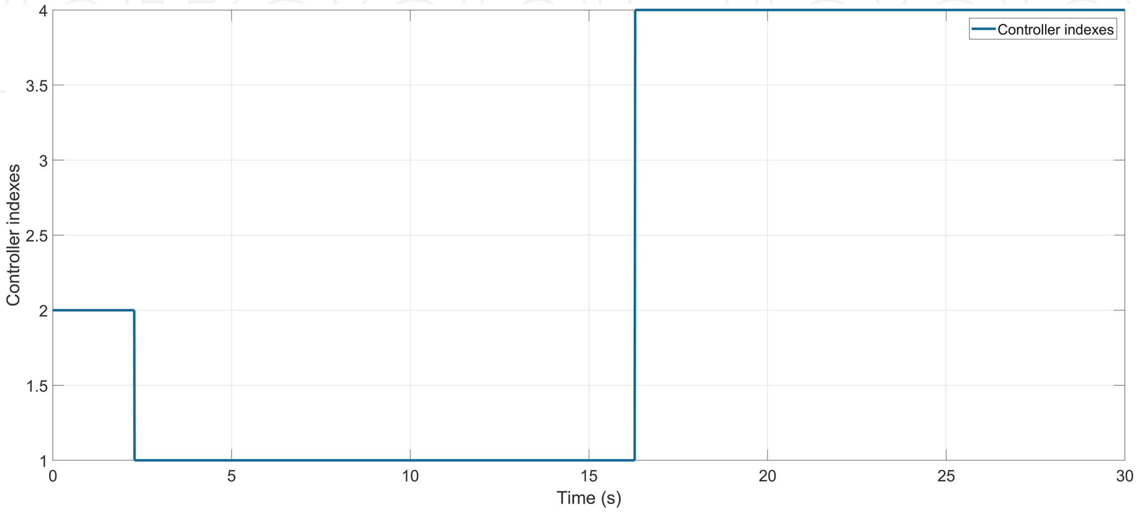

Figure 16.
Index of the switched controller gains at flight condition Mach = 0.9 and altitude = 1500 m.

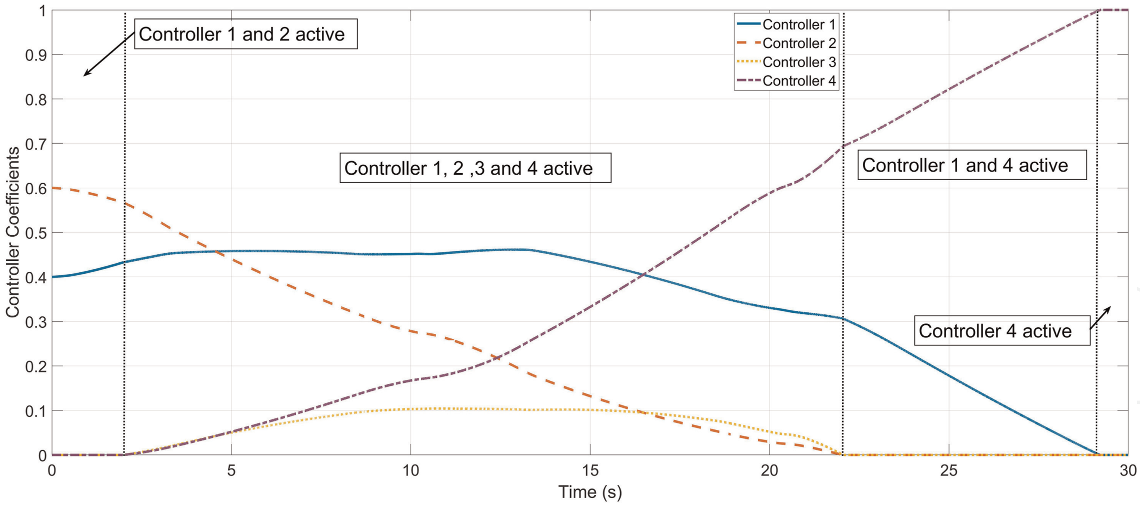

Figure 17.
Varying coefficients of the fuzzy switching controller at flight condition Mach = 0.9 and altitude = 1500 m.

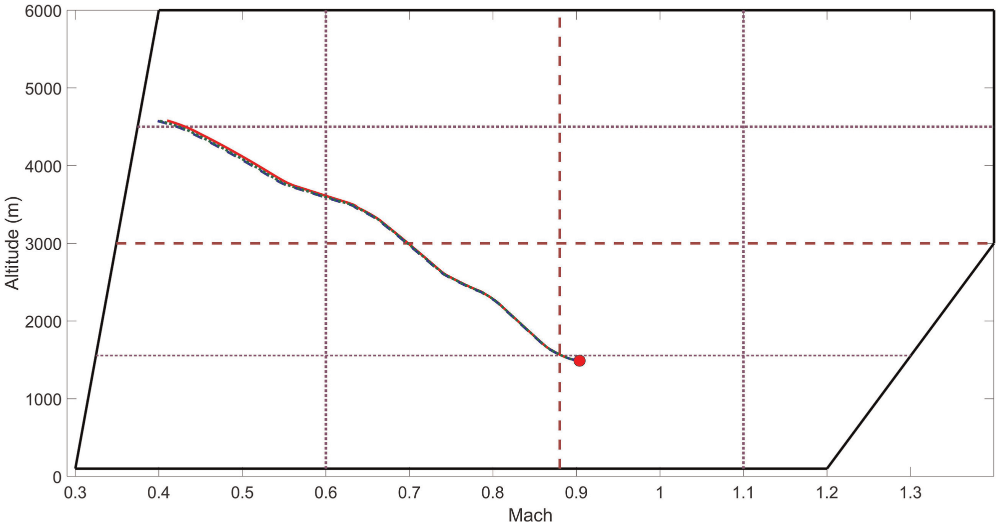

Figure 18.
Altitude responses with the different controllers at flight condition Mach = 0.9 and altitude = 1500 m.

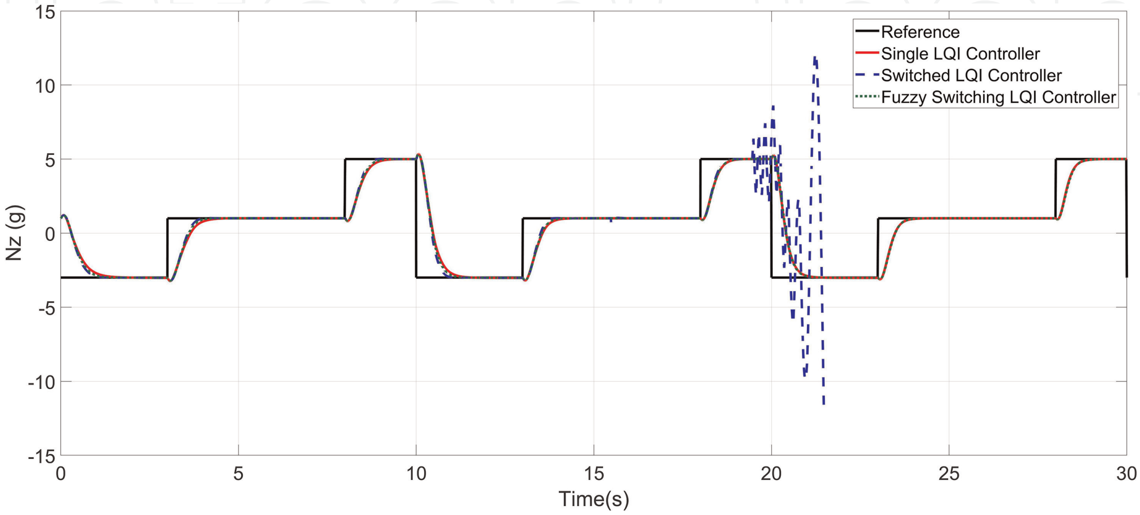

Figure 19.
Load-factor responses of the closed-loop systems at flight condition Mach = 0.75 and altitude = 4500 m.

These simulation results also demonstrate the efficacy of the proposed fuzzy switching controller.

In the third scenario, simulation is started at flight condition Mach = 0.75 and Altitude = 4500 m. Load-factor demand and responses of the closed-loop systems are given in **Figure 19**. It is clearly seen that the switched controller is unable to stabilize the aircraft when the controller switches. Load-factor tracking performance is successful with the fuzzy switching controller. The switched controller drives the closed-loop system from stability to instability shown in **Figures 20** and **21**. The index of the switched controller and the varying coefficients of the fuzzy switching controller are given in **Figures 22** and **23**, respectively. **Figure 24** illustrates the trajectory movement in the flight envelope for the different controllers. The fuzzy switching controller improves the load-factor tracking performance and enhances the stability of the aircraft.

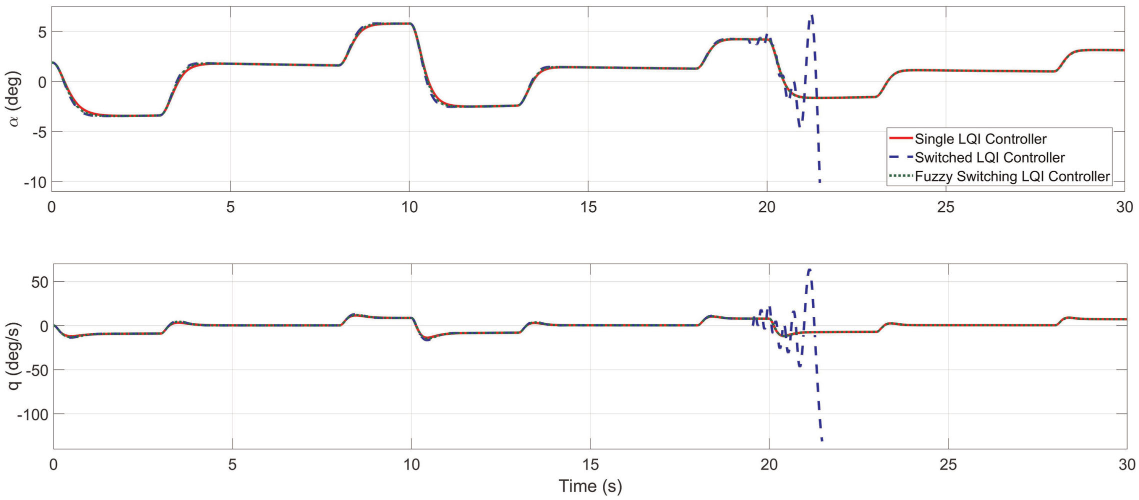

Figure 20.
State variables, the angle of attack, and the Euler pitch rate responses at flight condition Mach = 0.75 and altitude = 4500 m.

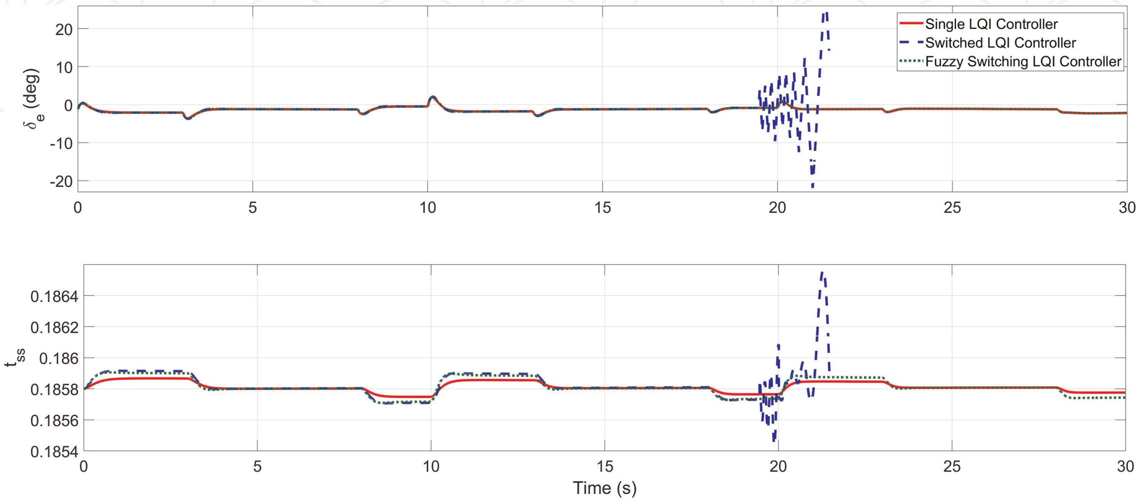

Figure 21.
Input responses of the single, switched, and fuzzy switching controllers at flight condition Mach = 0.75 and altitude = 4500 m.

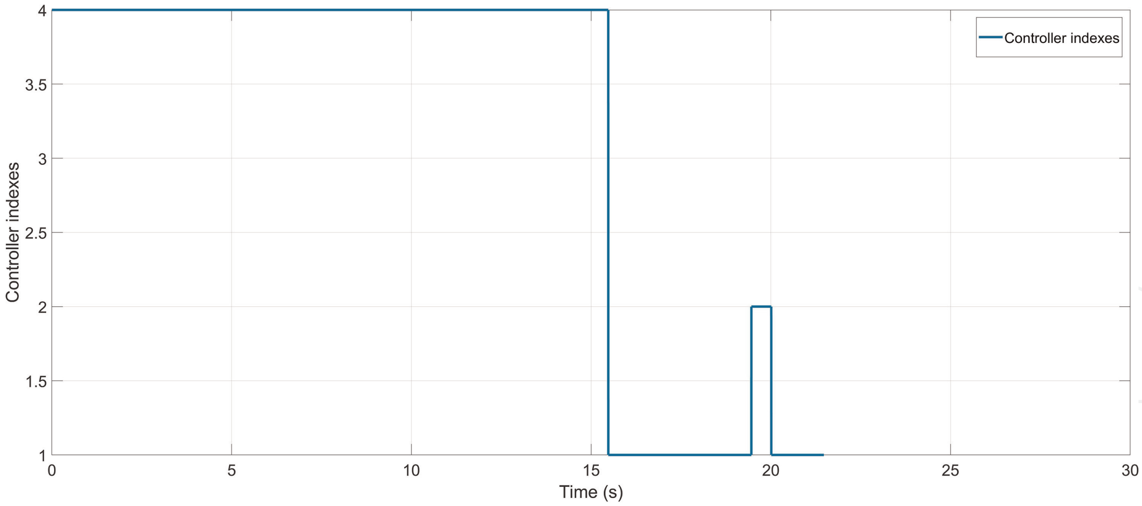

Figure 22.
Index of the switched controller gains at flight condition Mach = 0.75 and altitude = 4500 m.

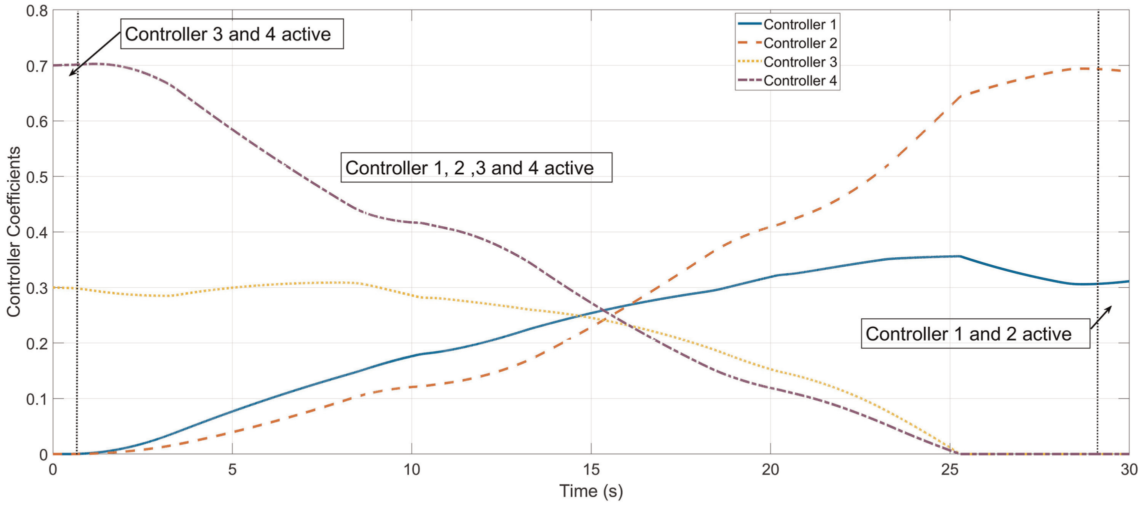

Figure 23.
Varying coefficients of the fuzzy switching controller at flight condition Mach = 0.75 and altitude = 4500 m.

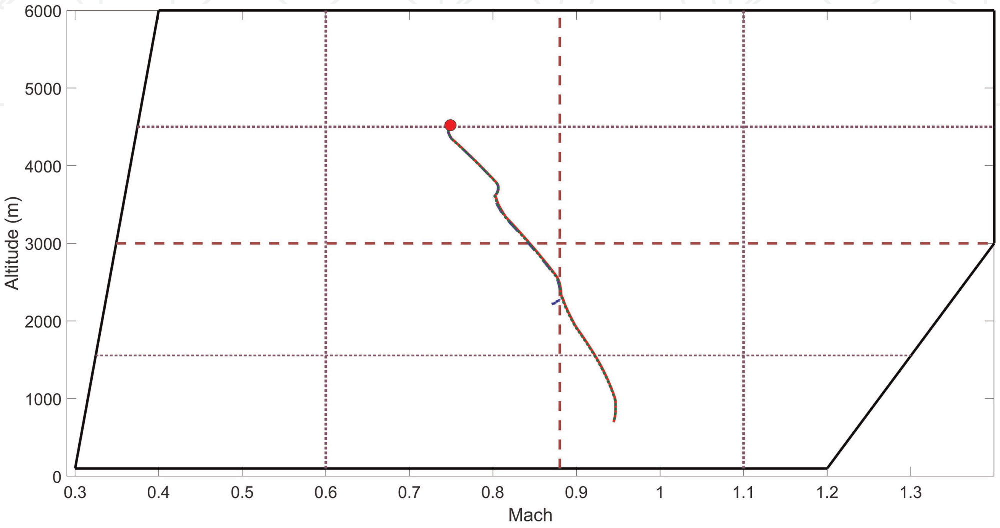

Figure 24.
Altitude responses with the different controllers at flight condition Mach = 0.75 and altitude = 4500 m.

5. Conclusions

In this chapter, a fuzzy switching controller for the ADMIRE aircraft model has been developed and verification of the control scheme was conducted using MATLAB/Simulink. Here, a switching controller is designed for the stabilization of high-performance aircraft. To improve the switching controller performance, the fuzzy logic rule has been defined and used to obtain a robust stabilization control structure instead of a single conventional LQI and the switched LQI controller.

The proposed controller scheme was compared with the standard switched and the single conventional LQI controller for load-factor tracking and robust stability under the load-factor variations. The main conclusions of the simulation results are given as follows:

- The proposed fuzzy switching controller provides better transient performance rather than the single conventional LQI and the switched controllers.

- The standard switch controller drives the ADMIRE aircraft nonlinear model from stability to instability due to switching between controllers.

- The proposed fuzzy switching controller has significant potential to improve tracking performance.

- The proposed fuzzy switching controller is effective in increasing the stability of the nonlinear system.

- Therefore, the proposed fuzzy switching controller can be preferred to control complicated and nonlinear aircraft systems. Future work will involve the stability analysis of closed-loop systems under the fuzzy switching rule.

Conflict of interest

The authors declare no conflict of interest.

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