Switching-Based Fault-Tolerant Control for an F-16 Aircraft with Thrust Vectoring

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Abstract—Thrust vectoring technique enables aircraft to perform various maneuvers not available to conventional-engined planes. This paper presents an application of switching control concepts to fault-tolerant control design for an F-16 aircraft model augmented with thrust vectoring. Two controllers are synthesized using a switching logic, and they are switched on a fault parameter. During normal flight conditions, the F-16 aircraft relies on no vectored thrust and the elevator. The thrust vectoring nozzle is only turned on in the presence of elevator failures. Two elevator failure scenarios, lock and loss of effectiveness, are considered. Nonlinear simulation results show that the switching control can guarantee the stability and performance of the faulted system.

I. INTRODUCTION

Thrust vectoring provides the capability to turn the jet exhaust, and this allows the aircraft to create lifting forces with its motors similar to the forces created by aerodynamic surfaces. Thrust vectoring technology has been successfully demonstrated on military aircraft [1]. For example, the F-15 STOL (short takeoff and landing) and the YF-22 both used pitch-only vectoring for enhanced pitch maneuvering. The F-18 HARV (high angle of attack research vehicle) and the X-31 both used pitch and yaw thrust vectoring paddles to explore maneuvering at high angles of attack and performed tactical utility evaluations. Those programs showed that the thrust vectoring can provide additional control power and prevent the aircraft from loss of control.

Actuator failure is one of the major factors causing aircraft loss of control. In the last three decades, the need for increased flight safety and aircraft reliability has drawn significant research in the area of fault-tolerant control (see [2], [3] and references therein). A fault-tolerant control system can compensate for failure or damage of flight control effectors or lifting surfaces, using the remaining effectors to generate compensating forces and moments. There are two approaches classified, the passive approach and the active approach. In the passive approach, a robust control law is designed against a set of pre-defined fault models and the control gain is not recalculated in real-time in the presence of actuator failures. The active approach reacts to the fault events actively by reconfiguring control actions so that the stability and performance of the entire system can be maintained.

One key ingredient in any fault-tolerant systems is redundancy, which is implemented by either hardware or software [2]. In this paper, a pitch-only thrust vectoring nozzle is used as a redundant control effector for an F-16 aircraft. An active fault-tolerant control system is designed, which reacts to the elevator failures actively by adjusting the thrust vectoring nozzle so that the stability and performance of the fault system can be maintained.

The linear parameter-varying (LPV) control technique [4], [5], [6] is an approach to scheduling control gains with stability and performance guarantees. A fault-tolerant LPV controller is synthesized with pre-defined fault models using linear matrix inequality (LMI) optimization [7], [8]. The LPV controller explicitly takes into account the relationship between real-time fault variations and performance. The LPV control technique has been successfully applied to fault-tolerant control of military or civil aircraft, such as a HiMAT (highly maneuverable aircraft technology) vehicle [7] and a Boeing 747-100/200 transport aircraft [8], [9].

This paper presents an application of the switching concept proposed in [10] to the fault-tolerant control design for the F-16 with thrust vectoring. Different from the previous LPV-based fault-tolerant control, the control system consists of two controllers (denoted as \(K_1\) and \(K_2\)) corresponding to the healthy or fault condition rather than one controller designed for both healthy and fault conditions. \(K_1\) and \(K_2\) are both LPV controllers, or \(K_1\) is a robust linear time-invariant (LTI) controller and \(K_2\) is an LPV controller. When no actuator failures happen or actuators have minor failures, the controller \(K_1\) is active, and the closed-loop system achieves satisfactory performance. If actuator failures are severe, then the control system switches from \(K_1\) to \(K_2\), whose gain varies with the detected fault to achieve acceptable performance with stability guarantee. In addition, instead of using all actuators including redundant ones all the time, the control system in this paper turns on the redundant thrust vectoring nozzle only when the elevator is in failure. Thus, the proposed control method is less conservative and more practical.

The paper is organized as follows. Section II provides a quick review of parameter-dependent switching control. Section III presents the nonlinear longitudinal model of the F-16 with vectored thrust. The fault-tolerant control problem is formulated in Section IV.A, following which the control synthesis conditions are given in Section IV.B. Section V shows the simulation results using switching-based fault-tolerant control applied to the nonlinear F-16 model. Finally, the paper concludes in Section VI.
II. BACKGROUND OF PARAMETER-DEPENDENT SWITCHING CONTROL

A switched system is a class of hybrid dynamical systems consisting of a family of continuous-time subsystems and a rule that orchestrates the switching between them [11]. Stability analysis of switched systems is a significant and challenging problem (see [12], [13] and references therein). Similar to classical control theory, Lyapunov functions play an important role in the stability problem of switched systems. For a set of stable LTI systems, if there exists a common Lyapunov function, the resulting switched system is stable under arbitrary switching sequences. The existence of a common Lyapunov function is not only a sufficient, but also a necessary condition for asymptotic stability under arbitrary switching [11].

However, if the switching signal is restricted, the asymptotic stability of the switched system can also be proved even in the absence of a common Lyapunov function. Due to the intrinsic discontinuous nature of switched systems, multiple Lyapunov functions have been shown to be useful tools for providing stability in such cases. Using multiple Lyapunov functions to form a discontinuous Lyapunov function offers more freedom and greater possibilities for demonstrating stability, for constructing a nontraditional Lyapunov function, and for achieving the stabilization of the switched systems.

In the absence of a common Lyapunov function, the switching signal can be restricted by a switching logic, which is a rule that determines the switching between a family of systems. Various switching rules have been proposed, and they are generally classified into two categories: state-dependent and time-dependent. For fault-tolerant control of aircraft, the dynamic behavior of the system is significantly affected by actuator failures, which are usually described using a fault parameter. Thus, it is more practical to apply the parameter-dependent switching logic proposed in [10].

Consider a generalized open-loop LPV system as follows of the scheduling parameter $\rho$. Assume that the time-varying parameter $\rho$ is measurable in real-time, and its value is bounded in a compact set $\mathcal{P}$. Suppose that the parameter set $\mathcal{P}$ is partitioned into a finite number of closed subsets $\{\mathcal{P}_i\}_{i \in \mathcal{Z}_N}$ by means of a family of switching surfaces $S_{ij}$ $(i, j \in \mathcal{Z}_N)$, where the index set $\mathcal{Z}_N = \{1, 2, \ldots, N\}$. In each parameter subset, the dynamic behavior of the system is governed by the equation

$$\
\left[\begin{array}{c}
\dot{x}(t) \\
\dot{e}(t) \\
\dot{y}(t)
\end{array}\right] = \left[\begin{array}{ccc}
A_i(\rho) & B_{1,i}(\rho) & B_{2,i}(\rho) \\
C_{1,i}(\rho) & D_{11,i}(\rho) & D_{12,i}(\rho) \\
C_{2,i}(\rho) & D_{21,i}(\rho) & D_{22,i}(\rho)
\end{array}\right] \left[\begin{array}{c}
x(t) \\
d(t) \\
u(t)
\end{array}\right], \forall \rho \in \mathcal{P}_i,
$$

where the plant state $x \in \mathbb{R}^{n_x}$, $e \in \mathbb{R}^{n_e}$ is the controlled output, and $d \in \mathbb{R}^{n_d}$ is the disturbance input. $y \in \mathbb{R}^{n_y}$ is the measurement for control, and $u \in \mathbb{R}^{n_u}$ is the control input. All of the state-space data are continuous functions of the parameter $\rho$. It is assumed that

(A1) $A_i(\rho)$’s have the same size for all subsets $\{\mathcal{P}_i\}_{i \in \mathcal{Z}_N}$.

(A2) $(A_i(\rho), B_{2,i}(\rho), C_{2,i}(\rho))$ triple is parameter-dependent stabilizable and detectable for all $\rho \in \mathcal{P}_i$.

(A3) The matrix functions $[B_{2,i}(\rho) D_{12,i}(\rho)]$ and $[C_{2,i}(\rho) D_{22,i}(\rho)]$ have full row ranks for all $\rho \in \mathcal{P}_i$.

(A4) $D_{11,i}(\rho) = 0$ and $D_{22,i}(\rho) = 0$.

Given the open-loop LPV system (1), the switching LPV control technique permits using the most suitable controller for different parameter subsets, and switching among them according to the evolution of the parameter. The switched LPV controllers are in the form of

$$\
\left[\begin{array}{cc}
A_{k,i}(\rho) & B_{k,i}(\rho) \\
C_{k,i}(\rho) & D_{k,i}(\rho)
\end{array}\right] \left[\begin{array}{c}
x_k(t) \\
y(t)
\end{array}\right], \forall \rho \in \mathcal{P}_i,
$$

where the dimension of the controller state is $x_k \in \mathbb{R}^{n_k}$, and $n_k = n_x$. Each controller is activated in a specific parameter subset $\mathcal{P}_i$. The switching between the different controllers is governed by a switching signal $\sigma$, which is determined by the evolution of the parameter $\rho$ and represents the active parameter subset.

Fig. 1(a) shows two parameter regions, $\mathcal{P}_i$ and $\mathcal{P}_j$, separated by a switching surface $S_{ij}$. The evolution of the switching signal $\sigma$ is shown in Fig. 1(b), where the switching signal changes its value right after the parameter hits the switching surface. This usually requires the continuity of Lyapunov function across the switching surface. To relax the continuity requirement, the switching logic with average dwell time will be used in this paper.

Denote $N_\sigma(T, t)$ as the number of switchings among the subsets $\mathcal{P}_i$’s on an interval $(t, T)$. The switching signal $\sigma$ has average dwell time $\tau_a$ if there exist two positive numbers $N_0$ and $\tau_a$ such that

$$\
N_\sigma(T, t) \leq N_0 + \frac{T - t}{\tau_a}, \quad 0 \leq t \leq T,
$$

where $N_0$ is called the chatter bound. This idea relaxes the concept of dwell time, allowing the possibility of switching fast when necessary and then compensating for it by switching sufficiently slow later on.

Assume that there exist a family of positive definite matrix functions $\{X_i(\rho)\}_{i \in \mathcal{Z}_N}$, and each of them is smooth over the
corresponding parameter subset $\mathcal{P}_i$. The multiple parameter-dependent Lyapunov functions can then be defined as
\[ V_\sigma(x, \rho) = x^T X_\sigma(\rho)x. \] (4)

Generally speaking, for a switched LPV system to be stable, the value of the discontinuous Lyapunov function $V_\sigma$ is not necessarily decreasing over the entire parameter trajectory. In fact, it is enough to require that the value of $V_\sigma$ decreases only in the active parameter region $\mathcal{P}_i$ provided a proper switching logic is adopted. Fig. 2 shows a discontinuous Lyapunov function for switching with average dwell time. For simplicity, two parameter subsets are considered. The solid lines represent the Lyapunov function sequence $V_1$ in the parameter subset $\mathcal{P}_1$, and the dashed lines represent $V_2$ in the parameter subset $\mathcal{P}_2$. For either $V_1$ or $V_2$, the thick lines denote the activated Lyapunov functions and the thin ones denote the inactivated ones. Note that the activated Lyapunov function sequence decreases when the parameter trajectory is within each parameter subset, but it may increase when the parameter trajectory crosses the boundary of the parameter subsets.

![Discontinuous Lyapunov functions for switching with dwell time](image)

Fig. 2. Discontinuous Lyapunov functions for switching with dwell time ($Z_N = \{1, 2\}$).

Basicallly, all we need is the fact that there exists a positive constant $\mu$ such that $V_j(\rho) \leq \mu V_i(\rho)$ when switching from $\mathcal{P}_i$ to $\mathcal{P}_j$ [13]. Due to the interchangeability of $i$ and $j$, the Lyapunov function on the switching surface must satisfy
\[ \frac{1}{\mu} V_j(\rho) \leq V_i(\rho) \leq \mu V_j(\rho), \quad \forall \rho \in \mathcal{S}_{ij}, \] (5)

where $\mu > 1$. It allows the change of Lyapunov function by $\mu$ times of its value before switching. As a consequence, the average switching frequency over a finite time interval is limited to $\frac{1}{\tau_2 \mu}$ to compensate for possible increase of Lyapunov function.

III. F-16 AIRCRAFT MODEL AUGMENTED WITH THRUST VECTORING

The system to be controlled is the longitudinal F-16 aircraft model based on NASA Langley Research Center wind tunnel tests [14]. The model is a collection of modules specifying the aircraft mass and geometric properties, the aircraft actuator models, the equations of motion, the atmospheric model, the aerodynamics, and the propulsion system. For more details on nonlinear simulation of the F-16 model, readers can refer to the references [16], [17].

The F-16 is powered by an after-burning turbofan jet engine, which produces a thrust force in the $x$-axis, as shown in Fig. 3(a). In order to design a fault-tolerant control system, the F-16 aircraft is augmented with a simple thrust vectoring model as shown in Fig. 3(b).

![Aircraft model without and with thrust vectoring](image)

Fig. 3. Aircraft model without and with thrust vectoring.

The states used to describe the motion of the aircraft in longitudinal axis are as follows. $V$ (ft/s) is the total aircraft velocity, $\alpha$ (rad) is the angle of attack, $q$ (rad/s) is the pitch rate, and $\theta$ (rad) is the pitch angle. The resulting nonlinear equations of longitudinal motion are given as follows:
\[
\begin{align*}
\dot{V} &= \frac{1}{m} \left( F_x \cos \alpha + F_z \sin \alpha \right), \quad (6) \\
\dot{\alpha} &= \frac{1}{mV} \left( -F_x \sin \alpha + F_z \cos \alpha \right) + q, \quad (7) \\
\dot{q} &= I_y, \quad (8) \\
\dot{\theta} &= q, \quad (9)
\end{align*}
\]

where $m$ is the aircraft mass, $F_x$ and $F_z$ are the force components along $x$ and $z$ body axes respectively, $I_y$ is the moment of inertia about the $y$ body axis, and $M_y$ is the pitching moment. The $x$ and $z$ axes forces and the pitching moment in (6)-(9) contain aerodynamic, gravitational and thrust components.

\[
\begin{align*}
F_x &= \overline{\alpha} S C_{x,t} - mg \sin \theta + T_x, \quad (10) \\
F_z &= \overline{\alpha} S C_{z,t} + mg \cos \theta + T_z, \quad (11) \\
M_y &= \overline{\alpha} S C_{m,t} + M, \quad (12)
\end{align*}
\]

where $\overline{\alpha}$ is the dynamic pressure, $S$ is the wing surface area, and $\overline{\alpha}$ is the wing mean aerodynamic chord. A complete description of the total coefficients $C_{x,t}$, $C_{z,t}$, and $C_{m,t}$ can be found in [14], which also provides the aerodynamic data in tabular form.

Denote the thrust vector angle by $\delta_{\text{ptv}}$, as shown in Figure 3(b). With the right-handed (forward, starboard, and down) coordinate system, the thrust components are then given by
\[
\begin{align*}
T_x &= T \cos \delta_{\text{ptv}}, \quad (13) \\
T_z &= -T \sin \delta_{\text{ptv}}, \quad (14) \\
M_T &= -l_T T \sin \delta_{\text{ptv}}, \quad (15)
\end{align*}
\]

where $l_T$ is the moment arm from the center of gravity to the thrust application point.

The primary actuators for pitch control consist of the elevator and the thrust vectoring nozzle. The deflection and rate limits for the elevator and the thrust vectoring nozzle are
\[|\delta_e| \leq 25^\circ, |\dot{\delta}_e| \leq 60^\circ/\text{s}, |\delta_{ptv}| \leq 17^\circ, \text{ and } |\dot{\delta}_{ptv}| \leq 60^\circ/\text{s}.\]

The throttle \(\delta_{th}\) is also an input to the aircraft, but it primarily controls the aircraft trajectory other than attitude [15]. Since the throttle setting indirectly affects the states through the power output from the engine, the actual power level is also considered as a state variable in longitudinal dynamics. Two linearized models of the F-16 at a trim condition are obtained, one without vectored thrust and the other with thrust vectoring.

\[
\begin{bmatrix} x_p \\ y \end{bmatrix} = \begin{bmatrix} A_i & B_i \\ C & 0 \end{bmatrix} \begin{bmatrix} x_p \\ u_i \end{bmatrix}, \quad i = 1, 2, \quad (16)
\]

where \(u_1 = [\delta_{th} \delta_e]^T\) and \(u_2 = [\delta_{th} \delta_{ptv} \delta_e]^T\). The matrices \(A_1, B_1, A_2,\) and \(B_2\) are obtained using linearization at the trim condition with

\[
x_p^{eq} = [V^{eq} \alpha^{eq} q^{eq} \theta^{eq} \omega^{eq}]
\]

\[
= [180 \text{ ft/s} \quad 35^\circ \quad 0 \text{ deg/s} \quad 0^\circ \quad 62],
\]

\[
u^{eq} = [\delta_{th}^{eq} \delta_{ptv}^{eq} \delta_e^{eq}]
\]

\[
= [0.8238 \quad 0^\circ \quad -11.3006^\circ].
\]

The outputs of the linearized plant are the velocity \(V\), the pitch rate \(q\), and the flight path angle \(\gamma\).

IV. SWITCHING-BASED FAULT-TOLERANT CONTROL SYNTHESIS

A. Control Objectives

The control objective is to track the command of the pitch rate. It is formulated as a model-following problem, where the ideal model to be followed is chosen to be a second-order filter based on desired flying qualities. A block diagram of the system interconnection for synthesizing a switching-based fault-tolerant control system is shown in Fig. 4, where the F-16 aircraft is represented by two linearized models with different inputs \(u_1\) and \(u_2\). The inputs of the interconnected open-loop system include the sensor noise signal \(n\), the pitch rate command \(\dot{q}_{cmd}\), and the control inputs. The outputs of the interconnected open-loop system are weighted error signals \(e_p\) and \(e_u\), and the measurement \(y\).

![Fig. 4. Weighted open-loop interconnection for the F-16 aircraft.](image)

Two controllers, \(K_1\) and \(K_2\) are designed for the healthy and fault conditions, respectively. Generally, the controller \(K_1\) is used. The controller \(K_2\) is turned on only when an elevator failure happens. The fault-tolerant control system automatically activates and adjusts the thrust vectoring nozzle, and it can automatically turn off the thrust vectoring nozzle when the failure is repaired. The dynamics of the actuators are modeled as either first- or second-order filters.

\[
\begin{align*}
\begin{cases}
\delta_{th} = \frac{1}{\tau_{th}s + 1} \left(1 - \frac{1}{0.2s + 1}\right), \\
\delta_{ptv} = \frac{1}{\tau_{ptv}s + 1} \left(1 - \frac{1}{0.07s + 1}\right), \\
\delta_e = \frac{3944}{s^2 + 2\zeta\omega_n s + \omega_n^2} + \frac{8497}{88.8s + 3944}.
\end{cases}
\end{align*}
\]

At a healthy condition, the control inputs are \(\delta_{th}\) and \(\delta_e\). The deflections and rates of \(\delta_{th}\) and \(\delta_e\) are fed into \(W_{u1}\) to penalize the control efforts. The acceleration of the elevator is also penalized. The weighting function \(W_{u1}\) is given by

\[
W_{u1} = \text{diag} \left\{ \frac{1}{2}, \frac{1}{10}, \frac{1}{100}, \frac{1}{1000}, \frac{1}{5000} \right\}.
\]

At a fault condition, the thrust is vectored. To satisfy the first assumption in Section II, the dynamics of the throttle is ignored, which has the slowest response time among the three actuators. Thus, the weighted open-loop interconnections for the healthy and fault conditions have the same number of states. The deflection and rate of the thrust vectoring control surface are penalized through \(W_{u2}\), which is given by

\[
W_{u2} = \text{diag} \left\{ \frac{1}{2}, \frac{1}{17}, \frac{1}{34}, \frac{1}{100}, \frac{1}{1000}, \frac{1}{5000} \right\}.
\]

The weighting functions \(W_{act1}\) and \(W_{act2}\) can be derived from the dynamic equations of the actuators given in (17)–(19).

The other weighting functions are chosen as

\[
W_{\text{ideal}} = \frac{51.84}{s^2 + 11.52s + 51.84},
\]

\[
W_p = \frac{0.818s + 70.71}{s + 0.71},
\]

\[
W_n = \text{diag} \left\{ 0.8, 0.6, 0.1 \right\}.
\]

where the ideal model is a second-order system with a natural frequency of 7.2 rad/s and a damping ratio of 0.8.

The elevator fault is modeled using a fault parameter \(\rho\), which varies from 0 (failure case) to 1 (healthy case). It is obvious that the dynamic behavior of the interconnected open-loop system depends on the fault parameter \(\rho\). Thus, the weighted open-loop system can be formulated as a switched LPV system given by (1), which consists of two subsystems. The value of the fault parameter \(\rho\) varies around 1 in the subsystem without thrust vectored and it varies between 1 and 0 in the subsystem with thrust vectoring.
B. Synthesis Conditions
The fault-tolerant controllers \( K_1 \) and \( K_2 \) are designed using the synthesis conditions for switching control with average dwell time \([10]\). Partition the fault parameter set into two subsets, \( \mathcal{P}_1 = \{ \rho : 1 \geq \rho \geq \rho_c \} \) and \( \mathcal{P}_2 = \{ \rho : \rho_c \geq \rho \geq 0 \} \), where the boundary value \( \rho_c \) is very close to 1. Given \( \lambda_0 > 0, \mu > 1 \), if there exist positive definite matrix functions \( R_i, S_i \) such that for any \( \rho \in \mathcal{P}_i (i = \{1, 2\}) \)

\[
N_{R,i}^T \begin{bmatrix}
R_i A_T^i + A_i R_i + \lambda_0 R_i & (\star) \\
C_{1,i} R_i & -\gamma_i I \\
B_{1,i}^T & 0 \\
\end{bmatrix} < 0,
\]

(25)

\[
N_{S,i}^T \begin{bmatrix}
A^T_i S_i + S_i A_i + \lambda_0 S_i & (\star) \\
B_{1,i}^T S_i & -\gamma_i I \\
C_{1,i} & 0 \\
\end{bmatrix} < 0,
\]

(26)

where \( N_{R,i} \) and \( N_{S,i} \) are matrices whose columns form bases of the null spaces of \( [B_{2,i}^T, D_{12,i}^T, 0] \) and \( [C_{2,i}, D_{21,i}, 0] \), and for \( \rho = \rho_c \),

\[
\frac{1}{\mu} R_i \leq R_i \leq \mu R_i,
\]

(28)

then the closed-loop switched system is exponentially stabilized by switching between the controllers \( K_1 \) and \( K_2 \) with average dwell time

\[
\tau_a > \frac{\ln \mu}{\lambda_0}.
\]

(29)

The \( H_{\infty} \) performance of the closed-loop switched system is maintained as \( \gamma = \max \{ \gamma_1, \gamma_2 \} \). Note that the state-space matrices in the LMI's (25)–(26) are functions of the fault parameter \( \rho \). The Lyapunov functions \( R_i 's \) and \( S_i 's \) can be defined as affine functions of the fault parameter \( \rho \),

\[
R_i (\rho) = R_i^0 + \rho R_i^1, \quad S_i (\rho) = S_i^0 + \rho S_i^1.
\]

(30)

(31)

Theoretically, the synthesis conditions (25)–(28) must hold for any value of the fault parameter \( \rho \in \mathcal{P} \), where \( \mathcal{P} = \{ \rho : 0 \leq \rho \leq 1 \} \). In this paper, the parameter-dependency is dealt with using “gridding” approach, and the grid points are set as \( \mathcal{P}_1 = \{ 1.0, 0.9 \} \) and \( \mathcal{P}_2 = \{ 0.9, 0.1 : 0 \} \). The gains of the controllers \( K_1 \) and \( K_2 \) are constructed using the solved matrices \( R_i 's \) and \( S_i 's \) \([10]\).

If there is a common quadratic Lyapunov function existing for the entire parameter set \( \mathcal{P}_1 \cup \mathcal{P}_2 \), the switched LPV control can be reduced to a general LPV control problem, and the boundary condition (28) can be removed. It is easier to implement the resulting LPV controller than the switching-based control scheme. Also, the fault parameter is allowed to vary arbitrarily fast. However, using switched LPV control with multiple parameter-dependent Lyapunov functions can reduce the conservatism, because the performance at the healthy condition is not sacrificed by guaranteeing the system stability in the entire fault parameter set.

V. NONLINEAR SIMULATION
The switching-based fault-tolerant control scheme is tested via nonlinear simulations. The tracking command input \( q_{cmd} \) is a doublet with a magnitude of \( \pm 5^\circ \). Two different fault scenarios under consideration are: (1) the elevator is stuck at 1.25 sec; (2) the elevator loses 30% of its effectiveness at 1.25 sec. For both cases, the elevator fault is assumed to be fixed at 3.25 sec. Fig. 5 shows the nonlinear time responses using the elevator and the throttle. The solid lines are the actual responses, and the dashed ones are the command inputs. It is seen in Fig. 5(a) that the pitch rate response nicely tracks the command when the elevator is working in its healthy condition. However, as shown in Fig. 5(b), the stability of the system cannot be maintained when the elevator is stuck.

![Fig. 5. Time responses using the elevator and the throttle.](image)

For comparison, a switching-based fault-tolerant control system consisting of two LPV controllers \( K_1 \) and \( K_2 \) are designed with \( \lambda_0 = 0.1 \) and \( \mu = 1.1 \). The achieved performance levels in the two parameter subsets are 102.7330 and 102.7346, which are very close to each other. It implies that the thrust vectoring can provide additional control power in the presence of elevator failures to stabilize the system and recover the performance.

The simulation results for the two fault scenarios are shown in Figs. 6–9. For both cases, it is observed that the throttle vectoring nozzle is on around 1.25 sec when the elevator is stuck or loses its effectiveness, and off around 3.25 sec when the elevator failures are repaired. The switched control scheme guarantees the stability of the fault system. Although there are transients during controller switching, the overall performance is acceptable.

VI. CONCLUSION AND FUTURE WORK
This paper presents a switching-based fault-tolerant control design for the longitudinal F-16 aircraft model augmented with thrust vectoring. During normal flight conditions, the aircraft relies on no vectored thrust and the elevator. A switching-based fault-tolerant control system is designed, which reacts to the elevator failures by turning on the thrust vectoring nozzle and recalculating the control gains. The thrust vectoring provides additional control power so that the stability and performance of the fault system are guaranteed. The switching logic of average dwell time is used to avoid the possible transient instability caused by switching between controllers. The nonlinear simulation shows that the
fault system achieves acceptable tracking performance. In the future work, fault detection and fault-tolerant control will be considered together.

REFERENCES


