Indirect Adaptive Interval Type-2 Fuzzy Sliding Mode Controller Design for Flexible Air-breathing Hypersonic Vehicles

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Abstract: An indirect adaptive interval type-2 fuzzy sliding mode controller (AIT2-FSMC) for flexible air-breathing hypersonic vehicle (FAHV) longitudinal model is presented in this paper. The proposed controller is designed by combining an adaptive Mamdani linguistic based interval type-2 fuzzy logic system (IT2-FLS) with sliding mode control technique. For the sake of the FAHV longitudinal model stably controlled under parametric and structural uncertainties which mainly come from varying aerodynamic interferences, flexible modes in airframe mutual couplings and fuel consumptions in practical conditions, we decouple the model through feedback linearization and design the main controller by sliding mode control technique to achieve the system convergence. Moreover, three adaptive interval type-2 fuzzy logic systems, which uses difference combinations of velocity and altitude tracking errors, pitch angle and slip slide angle as the inputs of antecedent sets, are designed to estimate nonlinear time varying functions and inverse matrix with bounded uncertainties. The adaptive law of the IT2-FSMC is derived through Lyapunov synthesis approach to guarantee the system asymptotic stability. Several comparisons under different levels of complex parametric and structural uncertainties have been done. The simulation results validate the performance of the proposed controller with robustness and effectiveness.

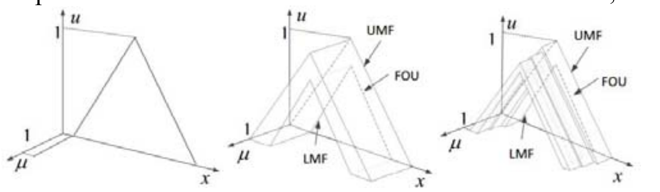
Keywords: adaptive control, type-2 fuzzy logic system, air-breathing hypersonic vehicle; uncertainty.

1. INTRODUCTION

Hypersonic flight technology was started with the concept of hypersonic combustion in 1950s and has been worldwide studied since 1960s (Curran, 2001). Hypersonic refers in particular to speed faster than 5 Mach. Moreover, hypersonic vehicles are also defined with reusability and high payload capacities (Bertin & Cummings, 2003). To date, lots of fundamental works have been done in generic hypersonic flight vehicles (GHFV) such as aerodynamics analysis and design, basic control systems, propulsion systems and so forth (Shaughnessy, Pinckney, & McMinn, 1990). In order to further improve the flight duration and effective payload, research focus is gradually focus on air-breathing hypersonic vehicles (AHV). The mainstream of the AHV aerodynamic shape is wave-rider shape and two models which already been tested based on this type of airframe are X-43A and X-51A from NASA (Hank, Murphy, & Mutzman, 2008). However, there still are lots of researches to be done before making practical use of AHV. Currently most disclosed control related studies for GHFV and AHV are for rigid longitudinal model, whereas the couplings between scramjet engine and airframe will generate resonance frequencies which make flexible effects of AHV cannot be neglected. Besides, internal disturbances in flexible air-breathing hypersonic vehicles (FAHV) can also come from structural uncertainties, which are caused by the changing resonance frequencies under different fuel loads. On the other hand, external disturbances are mainly coming from aerodynamic parametric uncertainties which occur in conditions of severe atmospheric interferences. All the internal and external disturbances together will make great challenges to robustness and effectiveness of FAHV control systems.

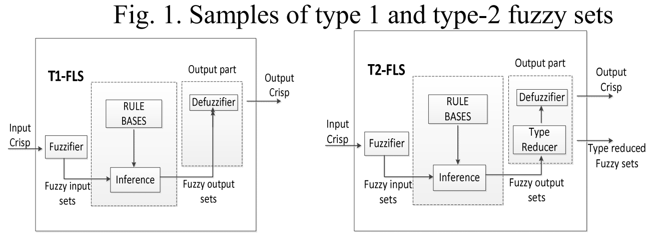
Sliding Mode Control (SMC), which belongs to special nonlinear control methods, is one of the typical control methods among robust control theory. Being proposed in 1950s, sliding mode control has been widely applied into theoretical research and practical applications (Liu & Sun, 2007). The principle of SMC is to design a system switch hyperplane based on the expected system dynamic characteristics, so that the controller can drive system states within a bounded region to achieve system convergence and stability. Nevertheless, the discrete switch characteristics of SMC (e.g. time delay switch, spatial lag switch or large inertia and so forth) will generate chattering effect which is not good to desired system responses. So far, researchers have used different methods to solve the chattering effect such as using filter (Su, Darkunov, & Ozguner, 1993), reducing switch gain (Hwang, 1996), replacing sign functions with saturation functions (Xu, Mirmirani, & Ioannou, 2004), using quasi-sliding mode control (Slotine & Sastry, 1983), using high-order sliding mode control (Levant, 2003), optimization with a variety of methods, adaptive sliding mode control (Wheeler, Su, & Stepanenko, 1998), hybrid algorithms like neural networks, fuzzy systems and so on (Lin, Chen, & Roopaed, 2011).

Type-1 fuzzy sets (T1-FSs) (originally called, known as fuzzy sets) were introduced by Zadeh in 1965 and was adopted into control in 1974 (Hagras, 2007). The concept of type-2 fuzzy sets (T2-FSs) was brought out by Zadeh as the expansion of type-1 fuzzy sets in the year after 1974. The differences between type-1 and type-2 fuzzy sets are mainly represented in the membership functions (MFs). A sample between type-1, interval type-2 and type-2 fuzzy sets can be seen in Fig.1 a)-c). The x axis is called universe of discourse, the u axis presents primary membership value whereas the μ axis stands for second membership. Type-1 fuzzy membership functions are fixed, which means type-1 fuzzy sets have no uncertainties associated with them. Type-2 fuzzy membership functions are themselves fuzzy. In Fig. 1 b) - c) higher curves of interval type-2 and type-2 FSs are called upper MF (UMF) and the curve beneath UMF is called lower MF (LMF). The banded region between UMF and LMF is named as footprint of uncertainty (FOU). FOU adds another degree of freedom in MF, making IT2-FSs & T2-FSs more capable to deal with uncertainties than T1-FSs. The structures of type-1 fuzzy logic system and type-2 fuzzy logic system are shown in Fig. 2 a) - b) separately. In Fig. 2 b), which is different from Fig. 2 a), the "Type reducer" transforms the inference engine output from T2-FS into T1-FS before the final defuzzification. As the simplified general type-2 fuzzy logic systems, interval type-2 fuzzy logic systems (IT2-FLSs), whose secondary membership value is 1, have some advantages in computational costs than T2-FLS. Therefore IT2-FLSs are widely studied and used into applications. The results reveal the IT2-FLSs can reduce design rules and the output of IT2-FLSs can be smoother than that of T1-FLS, etc.



a) T1 FS   b) interval T2 FS   c) (general) T2 FS

Fig. 1. Samples of type 1 and type-2 fuzzy sets



a) T1 FLS   b) T2 FLS

Fig. 2. Structures of fuzzy logic systems

Fuzzy sliding mode control (FSMC) or sliding mode fuzzy logic control (SMFC) (Niknam, Khooban, Kavousifard, & Soltanpour, 2014), which uses fuzzy logic systems to improve the performances of sliding mode control, has already been studied for decades. As the improved version of fuzzy sliding mode control, interval type-2 fuzzy sliding mode control has shown the combinations of both advantages of the two control techniques, which is not only more capable of handling uncertainties or disturbances but also can dramatically reduce the number of rules (Gao, Yuan, Yi, & Li, 2015). Several interval type-2 fuzzy sliding mode controllers have been proposed by theoretical studies and applied in systems with characteristics of nonlinearity and time-varying (Lin & Chen, 2010; Lin, et al., 2011; Lin, Chen, & Roopaei, 2010; Roopaei & Zolghadri, 2011).

In general, this paper proposes an indirect adaptive interval type-2 fuzzy sliding mode controller (AIT2-FSMC) for FAHV longitudinal model. We design a sliding mode controller as the general controller based on differential geometric control theory to make the system convergence. Adaptive interval type-2 fuzzy logic systems are designed to estimate the uncertainty bounded nonlinear time-varying functions and inverse matrix values online to compensate the sliding mode controller. The adaptive laws, which are used for optimizing the consequent parts values in the IT2-FLS, is derived through Lyapunov synthesis approach. Step commands in velocity and altitude channels are used to verify the effectiveness and robustness under different levels of uncertainties of the proposed AIT2-FSMC. The comparisons of simulations validate high robustness of the controller.

The rest of this paper is organized as follows: Section 2 describes brief introduction of the flexible air-breathing hypersonic vehicle longitudinal model; Section 3 provides detail design processes of the proposed AIT2-FSMC including the adaptive interval type-2 fuzzy logic systems design and the controller design with adaptive law and analysis of the system stability; Section 4 compares several simulations under different levels of aerodynamic parameter and structural uncertainties; Section 5 draws conclusions.

2. MODEL DESCRIPTION

2.1 *Flexible Air-breathing Hypersonic Model Description*

Hypersonic vehicles are with very complex dynamics and aerodynamic characteristics. It is quite difficult to build its complete and accurate model with 6 degrees of freedom. Due to above reasons and concerning confidential issues, there are three FAHV simplified models (Sun, Huang, Qian, & Wang, 2012; Yang, Yi, Tan, & Yuan, 2014) unveiled to the public. We choose the one which demonstrates the flexible modes being reflected through moment and forces and is derived based on the assumption of flexible effects as free-free beam (Jason T, Bolender, & Doman, 2007). Moreover, the canard deflection (shown in Fig. 3) as an additional control variable was introduced in order to avoid constrains from unstable zero dynamics (Fiorentini, Serrani, Bolender, & Doman, 2009).

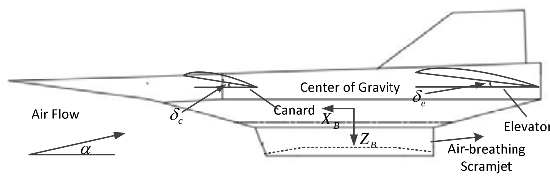


Fig. 3. Air-breathing Hypersonic Vehicle

The nonlinear longitudinal FAHV dynamic model equations are given below (Gao, et al., 2015):

$$\dot{V} = \left(T\cos\alpha - D\right)/m - g\sin\gamma \tag{1}$$

$$\dot{\gamma} = \left(L + T\sin\alpha\right)/(mV) - g\cos\gamma/V \tag{2}$$

$$\dot{h} = V\sin\gamma \tag{3}$$

$$\dot{\alpha} = q - \dot{\gamma} \tag{4}$$

$$\dot{q} = M_{yy}/I_{yy} \tag{5}$$

$$\ddot{\eta}_i = -2\xi_i\omega_i\dot{\eta}_i - \omega_i^2\eta_i + N_i, \qquad i = 1,2,3 \tag{6}$$

There are eleven flight states composed in the model, where $\left[V, \gamma, h, \alpha, q\right]$ and $\boldsymbol{\eta} = \left[\eta_1, \dot{\eta}_1, \eta_2, \dot{\eta}_2, \eta_3, \dot{\eta}_3\right]$ represent rigid-body states and the first three flexible modes, respectively. V, γ, h, α, q stand for the vehicle speed, flight path angle, altitude, angle of attack and pitch rate separately. The mode frequencies which relate to fuel level was given in (David O et al., 2008) and can be seen in table 1. In particular, the three flexible-mode-frequencies $\omega_{1,m}$, $\omega_{2,m}$, $\omega_{3,m}$ with the damping ratio constant ξ_i=0.02 will cause severe resonances which should be constrained or reduced in order to keep FAHV stably controlled. The nominal FAHV model is based on the condition of 50% fuel level. The canard deflection δ_c and elevator deflection δ_e are designed to be ganged together. Their relationship is presented through the negative canard deflection gain k_{ec} as: $\delta_c = k_{ec}\delta_e$, $k_{ec} = -C_L^{\delta_e}/C_L^{\delta_c}$.

Table 1. Vehicle mass and model frequencies under different fuel levels

Fuel level	0%	30%	50%	70%	100%
Mass, slag/feet	93.57	126.1	147.9	169.6	202.2
$\omega_{1,m}$ rad/s	22.78	21.71	21.17	20.73	20.17
$\omega_{2,m}$ rad/s	68.94	57.77	53.92	51.24	48.4
$\omega_{3,m}$ rad/s	140	117.8	109.1	102.7	95.6

Coefficients L, T, D, M, N_i which determine the lift, thrust, drag, pitching moment and generalized forces are given as:

$$\begin{cases} L \approx 0.5\rho V^2 s C_L(\alpha, \boldsymbol{\delta}, \boldsymbol{\eta}) \quad D \approx 0.5\rho V^2 s C_D(\alpha, \boldsymbol{\delta}, \boldsymbol{\eta}) \\ T \approx 0.5\rho V^2 s\left[C_{T,\phi}(\alpha)\phi + C_T(\alpha) + C_T^{\eta}\boldsymbol{\eta}\right] \\ M_{yy} \approx z_T T + 0.5\rho V^2 s\bar{c} C_M(\alpha, \boldsymbol{\delta}, \boldsymbol{\eta}) \\ N_i \approx 0.5\rho V^2 s\left[N_i^{\alpha^2}\alpha^2 + N_i^{\alpha}\alpha + N_i^{\delta_e}\delta_e + N_i^{\delta_c}\delta_c + N_i^0 + N_i^{\eta}\boldsymbol{\eta}\right] \end{cases} \tag{7}$$

$$\begin{cases} C_{T,\phi}(\alpha) = C_T^{\phi\alpha^3}\alpha^3 + C_T^{\phi\alpha^2}\alpha^2 + C_T^{\phi\alpha}\alpha + C_T^{\phi} \\ C_T(\alpha) = C_T^3\alpha^3 + C_T^2\alpha^2 + C_T^1\alpha + C_T^0 \\ C_L(\alpha, \boldsymbol{\delta}, \boldsymbol{\eta}) = C_L^{\alpha}\alpha + C_L^{\delta_e}\delta_e + C_L^{\delta_c}\delta_c + C_L^0 + \boldsymbol{C}_L^{\eta}\boldsymbol{\eta} \\ C_D(\alpha, \boldsymbol{\delta}, \boldsymbol{\eta}) = C_D^{\alpha^2}\alpha^2 + C_D^{\alpha}\alpha + C_D^{\delta_e^2}\delta_e^2 + C_D^{\delta_e}\delta_e + C_D^{\delta_c^2}\delta_c^2 \\ \qquad + C_D^{\delta_c}\delta_c + C_D^0 + \boldsymbol{C}_D^{\eta}\boldsymbol{\eta} \\ C_M(\alpha, \boldsymbol{\delta}, \boldsymbol{\eta}) = C_M^{\alpha^2}\alpha^2 + C_M^{\alpha}\alpha + C_M^{\delta_e}\delta_e + C_M^{\delta_c}\delta_c + C_M^0 + \boldsymbol{C}_M^{\eta}\boldsymbol{\eta} \\ \boldsymbol{C}_j^{\eta} = \left[C_j^{\eta_1} \ \ 0 \ \ C_j^{\eta_2} \ \ 0 \ \ C_j^{\eta_3} \ \ 0\right], \quad j = T, L, D, M \\ \boldsymbol{N}_i^{\eta} = \left[N_i^{\eta_1} \ \ 0 \ \ N_i^{\eta_2} \ \ 0 \ \ N_i^{\eta_3} \ \ 0\right], \quad i = 1,2,3 \end{cases} \tag{8}$$

where the air density ρ is defined as $\rho = \rho_0\exp(-h/h_0)$ with $\rho_0 = 6.7429\times10^{-5}\,Slug/ft^3$ and $h_0 = 24000\,ft$, the deflection vector is defined as $\boldsymbol{\delta} = [\delta_e, \delta_c]^T$. A second-order engine model is introduced as：

$$\ddot{\phi} = -2\xi_n\omega_n\dot{\phi} - \omega_n^2\phi + \omega_n^2\phi_c \tag{9}$$

where ζ_n is the engine damping ratio, ω_n is the nominal engine frequency. The bounded actuators are set as:

$$\delta_e, \delta_c \in \left[-20^{\circ}, 20^{\circ}\right], \phi \in \left[0.05, 1.5\right] \tag{10}$$

The output vector is $\boldsymbol{y} = \left[V, h\right]^T$.

3. CONTROL DESIGN

In order to minimize the impacts of the flexible air-breathing hypersonic vehicle (FAHV) interferences which occurs by parametric uncertainties and variability in operating conditions and flexible effects, we design an indirect adaptive interval type-2 fuzzy sliding mode controller (AIT2-FSMC). This section draws the design details including FAHV input-output feedback linearization, controller design process, adaptive law and system stability analysis processes respectively. The overall control scheme is shown in Fig. 4.

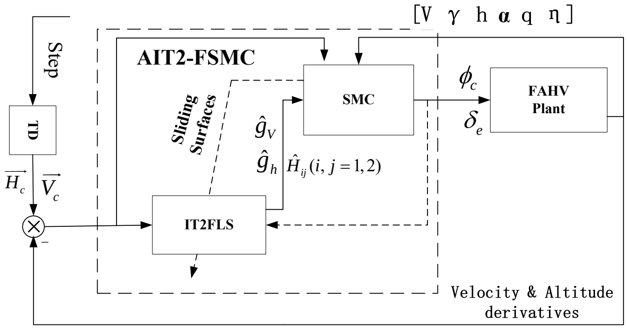


Fig. 4. Overall Control Scheme

3.1 Sliding Surfaces Design

We use the throttle setting value ϕ_c and elevator deflection δ_e as the control vector $\boldsymbol{u}$ to make the whole flight control system track a given reference-commands vector $\left[v_c, h_c\right]^T$ in velocity and altitude channels respectively, which means the system should make the tracking error $\left[e_v, e_h\right]^T$ converge to zero, where $e_v = v - v_c$, $e_h = h - h_c$. v, v_c, h, h_c are real-time signals and command signals in velocity and altitude, respectively. However, the FAHV longitudinal model in section 2 should be decoupled before the control design process. Therefore, we use velocity and altitude tracking errors to define the sliding surfaces as:

$$S_v = \left(d/dt + \lambda_1\right)^3\int_0^t e_v dt \tag{11}$$

$$S_h = \left(d/dt + \lambda_2\right)^4\int_0^t e_h dt \tag{12}$$

3.2 Feedback Linearization of FAHV

In order to obtain the full state feedback linearization form of FAHV longitudinal model, we calculate the first derivative of equation (11) and (12) respectively based on differential geometric control theory (Xu, et al., 2004). We get the following equations which include high order commands of $\ddot{v}, \ddot{v}_c, h^{(4)}, h_c^{(4)}$:

$$\begin{cases}\dot{S}_v = -\dddot{V}_c + g_v + 3\lambda_v \ddot{e}_v + 3\lambda_v^2 \dot{e}_v + \lambda_v^3 e_v + H_{11}\delta_e + H_{12}\phi_c \\ \dot{S}_h = -h_c^{(4)} + g_h + 4\lambda_h \dddot{e}_h + 6\lambda_h^2 \ddot{e}_h + 6\lambda_h^3 \dot{e}_h + \lambda_h^4 e_h + H_{21}\delta_e + H_{22}\phi_c\end{cases} \tag{13}$$

where

$$g_v = (\omega_1 \cdot \ddot{\boldsymbol{x}}_0 + \dot{\boldsymbol{x}}^{\mathrm{T}} \cdot \boldsymbol{\Omega}_2 \cdot \dot{\boldsymbol{x}}) / m \tag{14}$$

$$\begin{aligned} g_h = {} & 3\ddot{V} \cdot \dot{\gamma} \cdot \cos\gamma - 3\dot{V} \cdot \dot{\gamma}^2 \cdot \sin\gamma + 3\dot{V} \cdot \ddot{\gamma} \cdot \cos\gamma - 3V \cdot \dot{\gamma} \cdot \ddot{\gamma} \cdot \sin\gamma \\ & - V \cdot \dot{\gamma}^3 \cdot \cos\gamma + (\omega_1 \cdot \ddot{\boldsymbol{x}}_0 + \dot{\boldsymbol{x}}^{\mathrm{T}} \cdot \boldsymbol{\Omega}_2 \cdot \dot{\boldsymbol{x}}) \cdot \sin\gamma / m \\ & + V \cdot (\boldsymbol{\pi}_1 \cdot \ddot{\boldsymbol{x}}_0 + \dot{\boldsymbol{x}}^{\mathrm{T}} \cdot \boldsymbol{\Pi}_2 \cdot \dot{\boldsymbol{x}}) \cdot \cos\gamma \end{aligned} \tag{15}$$

$$\begin{aligned} H_{11} = {} & \left(c_e \rho V^2 Sc / 2m \cdot I_{yy}\right)\left(C_M^{\delta_e} - C_L^{\delta_e} C_M^{\delta_c} / C_L^{\delta_c}\right) \\ & \bullet\left(\left(\partial T / \partial\alpha\right)\cos\alpha - T \cdot \sin\alpha - \partial D / \partial\alpha\right) \end{aligned} \tag{16}$$

$$H_{12} = \left(\partial T / \partial\phi\right)\omega^2 \cos\alpha / m \tag{17}$$

$$\begin{aligned} H_{21} = {} & \left(\rho V^2 Sc / 2mI_{yy}\right)\left(C_M^{\delta_e} - C_L^{\delta_e} C_M^{\delta_c} / C_L^{\delta_c}\right) \\ & \left[\cos\gamma\left(\left(\partial T / \partial\alpha\right)\sin\alpha + T\cos\alpha + \partial L / \partial\alpha\right)\right. \\ & \left. + c_e \sin\gamma\left(\left(\partial T / \partial\alpha\right)\cos\alpha - T\sin\alpha - \partial D / \partial\alpha\right)\right] \end{aligned} \tag{18}$$

$$H_{22} = \left(\partial T / \partial\phi\right)\omega^2 \sin(\alpha + \gamma) / m \tag{19}$$

where $\boldsymbol{x} = \left[V \; \gamma \; \alpha \; \phi \; h\right]^{\mathrm{T}}$ and $\ddot{\boldsymbol{x}}_0 = \left[\ddot{V} \; \ddot{\gamma} \; \ddot{\alpha}_0 \; \ddot{\phi}_0 \; \ddot{h}\right]^{\mathrm{T}}$. Then (13) can be written as:

$$\begin{bmatrix} \dot{S}_v \\ \dot{S}_h \end{bmatrix} = \begin{bmatrix} g_v + \sum_{i=0}^{2} C_3^{2-i} \lambda_v^{i+1} e_v^{(2-i)} - \dddot{V}_c \\ g_h + \sum_{j=0}^{3} C_4^{3-j} \lambda_h^{j+1} e_h^{(3-j)} - h_c^{(4)} \end{bmatrix} + \boldsymbol{H} \cdot \boldsymbol{u} \tag{20}$$

where

$\boldsymbol{u} = \begin{bmatrix} \delta_e & \phi_c \end{bmatrix}^T$, $\boldsymbol{H} = \begin{bmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{bmatrix}$, λ_v, λ_h are all real and $\begin{bmatrix} 3\lambda_v & 3\lambda_v^2 & \lambda_v^3 \end{bmatrix}$ $\begin{bmatrix} 4\lambda_h & 6\lambda_h^2 & 6\lambda_h^3 & \lambda_h^4 \end{bmatrix}$ in (13) are Hurwitz polynomials.

3.3 Adaptive Interval Type-2 Fuzzy Sliding Mode Controller Design

The sliding mode process can be divided into two phases which are reaching phase with $S_v, S_h \neq 0$ and sliding phase with $S_v, = 0, S_h = 0$. With the form of equation (20), the sliding controller is then designed to drive the derivatives of the sliding surfaces to satisfy the following forms:

$$\begin{bmatrix} \dot{S}_v \\ \dot{S}_h \end{bmatrix} = \begin{bmatrix} -m_1 sat(S_1 / \Omega_1) - m_2 S_1 \\ -m_3 sat(S_2 / \Omega_2) - m_4 S_2 \end{bmatrix} \tag{21}$$

where m_i $(i = 1, \ldots, 4)$ and Ω_1, Ω_2 are strictly positive constants. Substituting (21) into (20), we can get:

$$\boldsymbol{u} = \begin{bmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{bmatrix}^{-1} \begin{bmatrix} \dddot{V}_c - \sum_{i=0}^{2} C_3^{2-i} \lambda_v^{i+1} e_v^{(2-i)} - f_v - u_v \\ h_c^{(4)} - \sum_{j=0}^{3} C_4^{3-j} \lambda_h^{j+1} e_h^{(3-j)} - f_h - u_h \end{bmatrix} \tag{22}$$

where $u_v = m_1 sat(S_1 / \Omega_1) + m_2 S_1, u_h = m_3 sat(S_2 / \Omega_2) + m_4 S_2$.

In real-time dynamics, there are a lot of uncertainties including the flexible effect uncertainties, structural variability, unknown disturbances and high order derivate of variables in FAHV decoupled model which cannot be easily obtained from sensors. However, those uncertainties means the calculation values of g_v and g_h and $H_{ij|i,j=1,2}$ in (14) - (19) may not reflect the values they should stand for. Moreover, this phenomenon is not expected because it will make negative contributions to robustness of the control system and cause serious consequences simultaneously. Because both T1-FLS and T2-FLS (including IT2-FLS) are universal approximator (Li, Yi, & Zhang, 2014; Mendel, Hagras, Tan, Melek, & Ying, 2014), we replace g_v , g_h and H_{ij} with uncertainty-bounded approximation values $\hat{g}_v$, $\hat{g}_h$ and $\hat{H}_{ij}$ which are generated from Mamdani based IT2-FLSs for the potential to perform better than T1-FLSs and less computational intensive than T2-FLS. Then (22) can be expressed as:

$$\begin{bmatrix} \delta_e \\ \phi_c \end{bmatrix} = \hat{\boldsymbol{H}}^{-1} \begin{bmatrix} \dddot{V}_c - \sum_{i=0}^{2} C_3^{2-i} \lambda_v^{i+1} e_v^{(2-i)} - \hat{g}_v - u_v \\ h_c^{(4)} - \sum_{j=0}^{3} C_4^{3-j} \lambda_h^{j+1} e_h^{(3-j)} - \hat{g}_h - u_h \end{bmatrix} \tag{23}$$

Based on (14) - (15), the first two dominant contribution variables in g_v, g_h are velocity and altitude. Simultaneously, substituting (7) - (8) into (16) - (19), the two variables which have cumulative maximum orders in H_{11}, H_{21} and H_{12}, H_{22} are velocity & pitch angle and velocity & side slip angle, respectively. Therefore, we define e_v, e_h , e_v, γ and e_v, Θ where $\Theta = \alpha + \gamma$ as the antecedent input variables of IT2-FLSs in approximating $\hat{g}_v, \hat{g}_h$, $\hat{H}_{11}, \hat{H}_{21}$ and $\hat{H}_{12}, \hat{H}_{22}$ separately. Additionally, we can achieve smaller total fuzzy rules in these three systems to lower computational resource cost. The Mamdani rule based IT2-FLSs consist of a collection of IF-THEN rules in the following forms:

1) IT2-FLS for $\hat{g}_v, \hat{g}_h$:

$Rule^k$: If x_v is $\widetilde{S_v^k}$ and x_h is $\widetilde{S_h^k}$, then Ψg_v is $\widetilde{T_v^k}$ and Ψg_h is $\widetilde{T_h^k}$

2) IT2-FLS for $\hat{H}_{ij|i,j=1,2}$:

$Rule^k$: If x_v is $\widetilde{S_v^k}$ and x_γ is $\widetilde{S_\gamma^k}$, then ΨH_{11} is $\widetilde{T_{H_{11}}^k}$, ΨH_{21} is $\widetilde{T_{H_{21}}^k}$

$Rule^k$: If x_v is $\widetilde{S_v^k}$ and x_Θ is $\widetilde{S_\Theta^k}$, then ΨH_{12} is $\widetilde{T_{H_{12}}^k}$, ΨH_{22} is $\widetilde{T_{H_{12}}^k}$

where k=1,2,…,m. m is the number of rules, $x_v = e_v$, $x_h = e_h$, $x_\gamma = \gamma$, $x_\Theta = \Theta$. The antecedent sets $\widetilde{S_v^k}, \widetilde{S_h^k}, \widetilde{S_\gamma^k}, \widetilde{S_\Theta^k}$ which have 5 rules separately are IT2-FSs, and consequent sets $\widetilde{T_v^k}, \widetilde{T_h^k}, \widetilde{T_{H_{ij}}^l}$ (i, j=1, 2) are T1-FSs.

The firing set $\mathcal{F}^k(x)$ and degree of firing f^k associated with the k^{th} rule (k=1,2,…,m) are

$$\mathcal{F}_{v/h}^{k}(x)=\mu_{\widetilde{S}_v^k}(x_v)\mu_{\widetilde{S}_h^k}(x_h)=[\underline{f}_{v/h}^{k},\overline{f}_{v/h}^{k}] \tag{24}$$

$$\mathcal{F}_{H_{ij}}^{k}|_{i=1,2;\,j=1}(x)=\mu_{\widetilde{S}_v^k}(x_v)\mu_{\widetilde{S}_\gamma^k}(x_\gamma)=[\underline{f}_{\gamma}^{k},\overline{f}_{\gamma}^{k}] \tag{25}$$

$$\mathcal{F}_{H_{ij}}^{k}|_{i=1,2;\,j=2}(x)=\mu_{\widetilde{S}_v^k}(x_v)\mu_{\widetilde{S}_\Theta^k}(x_\Theta)=[\underline{f}_{\Theta}^{k},\overline{f}_{\Theta}^{k}] \tag{26}$$

where $\underline{f}_{v/h}^{k}=\underline{\mu}_{\widetilde{S}_v^k}(x_v)\underline{\mu}_{\widetilde{S}_h^k}(x_h)$, $\overline{f}_{v/h}^{k}=\overline{\mu}_{\widetilde{S}_v^k}(x_v)\overline{\mu}_{\widetilde{S}_h^k}(x_h)$, $\underline{f}_{l}^{k}=\underline{\mu}_{\widetilde{S}_v^k}(x_v)\underline{\mu}_{\widetilde{S}_l^k}(x_l)$, $\overline{f}_{l}^{k}=\overline{\mu}_{\widetilde{S}_v^k}(x_v)\overline{\mu}_{\widetilde{S}_l^k}(x_l)$ ($l=\gamma,\Theta$). The $\underline{\mu}_{\widetilde{S}_{k_1}^k}(x_{k_1})$ and $\overline{\mu}_{\widetilde{S}_{k_1}^k}(x_{k_1})$ are LMF and UMF grades of $\mu_{\widetilde{S}_{k1}^k}(x_{k1})$ respectively ($k_1=v,h$), the $\underline{\mu}_{\widetilde{S}_l^k}(x_l)$ and $\overline{\mu}_{\widetilde{S}_l^k}(x_l)$ are LMF and UMF grades of $\mu_{\widetilde{S}_l^k}(x_l)$ respectively. Assume $\mathcal{C}_v^k$, $\mathcal{C}_h^k$ and $\mathcal{C}_{H_{ij}}^k$ are the centroid of the k^{th} consequent set $\widetilde{T_v^k}$ and $\widetilde{T_h^k}$ and $\widetilde{T_{H_{ij}}^k}\,|\,i,j=1,2$ respectively. By using the singleton fuzzification, product inference, centre-average defuzzification, and the centre-of-sets type reducer, the IT2-FLSs type-reducer are given by (Mendel, et al., 2014)

$$\Psi g_{v\mathrm{c}}=\int_{\mathcal{C}_v^1}\cdots\int_{\mathcal{C}_v^m}\int_{f^1}\cdots\int_{f^m}1\Bigg/\frac{\sum_{k=1}^{m}f_{v/h}^{k}\mathcal{C}_v^k}{\sum_{k=1}^{m}f_{v/h}^{k}}=[\Psi g_{vl},\Psi g_{vr}] \tag{27}$$

$$\Psi g_{h\mathrm{c}}=\int_{\mathcal{C}_h^1}\cdots\int_{\mathcal{C}_h^m}\int_{f^1}\cdots\int_{f^m}1\Bigg/\frac{\sum_{k=1}^{m}f_{v/h}^{k}\mathcal{C}_h^k}{\sum_{k=1}^{m}f_{v/h}^{k}}=[\Psi g_{hl},\Psi g_{hr}] \tag{28}$$

$$\begin{aligned}\Psi H_{ij\mathrm{c}}|_{i=1,2;\,j=1}&=\int_{\mathcal{C}_{Hij}^1}\cdots\int_{\mathcal{C}_{Hij}^m}\int_{f^1}\cdots\int_{f^m}1\Bigg/\frac{\sum_{k=1}^{m}f_{\gamma}^{k}\mathcal{C}_{H_{ij}|_{i=1,2;j=1}}^k}{\sum_{k=1}^{m}f_{\gamma}^{k}}\\&=[\Psi H_{ijl},\Psi H_{ijr}]_{i=1,2;\,j=1}\end{aligned} \tag{29}$$

$$\begin{aligned}\Psi H_{ij\mathrm{c}}|_{i=1,2;\,j=2}&=\int_{\mathcal{C}_{Hij}^1}\cdots\int_{\mathcal{C}_{Hij}^m}\int_{f^1}\cdots\int_{f^m}1\Bigg/\frac{\sum_{k=1}^{m}f_{\Theta}^{k}\mathcal{C}_{H_{ij}|_{i=1,2;j=2}}^k}{\sum_{k=1}^{m}f_{\Theta}^{k}}\\&=[\Psi H_{ijl},\Psi H_{ijr}]_{i=1,2;\,j=2}\end{aligned} \tag{30}$$

where $f^k,\mathcal{C}_v^k,\mathcal{C}_h^k$ $\mathcal{C}_{H_{ij}}^k$ (i, j=1, 2) are T1-FSs in IT2-FLSs.

We use new symbols θ and ξ to denote

$$\begin{aligned}\theta_{v,h}&=(\theta_{v,h}{}^{1},\theta_{v,h}{}^{2},\ldots,\theta_{v,h}{}^{m})^{T}\\&=\left(\mathcal{C}_{v,h}{}^{1},\mathcal{C}_{v,h}{}^{2},\ldots,\mathcal{C}_{v,h}{}^{m}\right)^{T}=\mathcal{C}_{v,h}\end{aligned} \tag{31}$$

$$\begin{aligned}\theta_{H_{ij}}&=(\theta_{H_{ij}}{}^{1},\theta_{H_{ij}}{}^{2},\ldots,\theta_{H_{ij}}{}^{m})^{T}\\&=\left(\mathcal{C}_{H_{ij}}{}^{1},\mathcal{C}_{H_{ij}}{}^{2},\ldots,\mathcal{C}_{H_{ij}}{}^{m}\right)^{T}=\mathcal{C}_{H_{ij}}\end{aligned} \tag{32}$$

$$\xi_{v,h\varsigma}^{k}=f_{v/h\varsigma}^{k}\Big/\sum_{k=1}^{m}f_{v/h\varsigma}^{k} \tag{33}$$

$$\xi_{H_{ij}\varsigma}^{k}|_{i=1,2;\,j=1}=f_{\gamma\varsigma}^{k}\Big/\sum_{k=1}^{m}f_{\gamma\varsigma}^{k}\ ,\ \xi_{H_{ij}\varsigma}^{k}|_{i=1,2;\,j=2}=f_{\Theta\varsigma}^{k}\Big/\sum_{k=1}^{m}f_{\Theta\varsigma}^{k} \tag{34}$$

where ς represents lower and upper respectively. $\theta_{v,h}$ denotes θ_v or θ_h and $\xi_{v,h}^k$ denotes ξ_v^k or ξ_h^k respectively. $f_{v/h\varsigma}{}^{k}$ and $f_{H_{ij}\varsigma}{}^{k}$ stand for the firing values which are used to compute the boundaries $\Psi g_{v,h\varsigma}$ and $\Psi H_{ij\varsigma}$ in (27) - (30) and can be obtained by using the Karnik-Mendel iterative method(Mendel, et al., 2014) Based on IT2-FLS theory, the uncertainty terms $\hat{g}_v$, $\hat{g}_h$ and $\hat{\boldsymbol{H}}$ in (23) can be achieved by

$$\begin{cases}\hat{g}_v=(\Psi g_{vl}+\Psi g_{vr})/2=\theta_v^{T}\left(\xi_{vl}+\xi_{vr}\right)/2\\ \hat{g}_h=(\Psi g_{hl}+\Psi g_{hr})/2=\theta_h^{T}\left(\xi_{hl}+\xi_{hr}\right)/2\\ \hat{H}_{ij|\,i,\,j=1,2}=(\Psi H_{ijl}+\Psi H_{ijr})/2=\theta_{Hij}{}^{T}\left(\xi_{Hijl}+\xi_{Hijr}\right)/2\end{cases} \tag{35}$$

3.4 Adaptive Law

In order to adjust the consequence part parameters in the IT2-FLSs, the optimal parameter estimation $\theta_{g_v}^{*}$, $\theta_{g_h}^{*}$ and $\theta_{H_{ij}|i,j=1,2}^{*}$ are defined as:

$$\theta_{g_v}^{*}=\arg\min_{\theta_{g_v}\in\Gamma\theta_{g_v}}\left\{\sup_{V\in U_v}\left|g_v-\hat{g}_v\right|\right\} \tag{36}$$

$$\theta_{g_h}^{*}=\arg\min_{\theta_{g_h}\in\Gamma\theta_{g_h}}\left\{\sup_{H\in U_h}\left|g_h-\hat{g}_h\right|\right\} \tag{37}$$

$$\theta_{H_{ij}}^{*}=\arg\min_{\theta_{H_{ij}}\in\Gamma\theta_{H_{ij}}}\left\{\sup_{H\in U_H}\left|H_{ij}-\hat{H}_{ij}\right|\right\} \tag{38}$$

where $\Gamma_{\theta_{g_v}}$, $\Gamma_{\theta_{g_h}}$ and $\Gamma_{\theta_{H_{ij}}}$ are compact sets of $\theta_{g_v}^{*}$, $\theta_{g_h}^{*}$ and $\theta_{H_{ij}}^{*}$, respectively. They are defined as:

$$\Gamma_{\theta_{g_v}}=\left\{\theta_{g_v}\in R^{25}\mid 0<\left|\theta_{g_v}\right|\le M_{g_v}\right\} \tag{39}$$

$$\Gamma_{\theta_{g_h}}=\left\{\theta_{g_h}\in R^{25}\mid 0<\left|\theta_{g_h}\right|\le M_{g_h}\right\} \tag{40}$$

$$\Gamma_{\theta_{H_{ij}}}=\left\{\theta_{H_{ij}}\in R^{25}\mid 0<\left|\theta_{H_{ij}}\right|\le M_{H_{ij}}\right\} \tag{41}$$

where M_{g_v} , M_{g_h} and $M_{H_{ij}}$ are positive constants. Then the minimum of approximation errors can be defined as :

$$\omega=\begin{bmatrix}g_v-\hat{g}_v^{*}\\ g_h-\hat{g}_h^{*}\end{bmatrix}+\left[\boldsymbol{H}-\hat{\boldsymbol{H}}^{*}\right]\begin{bmatrix}\delta_e\\ \phi_c\end{bmatrix} \tag{42}$$

Substituting (33) , (23)into (20) , we can get:

$$\begin{aligned}\begin{bmatrix}\dot{S}_v\\ \dot{S}_h\end{bmatrix}&=\begin{bmatrix}\sum_{i=0}^{2}c_ie_v^{(i)}+g_v-\ddot{V}_c\\ \sum_{j=0}^{3}c_je_h^{(j)}+g_h-h_c^{(4)}\end{bmatrix}+\boldsymbol{H}\begin{bmatrix}\delta_e\\ \phi_c\end{bmatrix}-\hat{\boldsymbol{H}}\begin{bmatrix}\delta_e\\ \phi_c\end{bmatrix}+\hat{\boldsymbol{H}}\begin{bmatrix}\delta_e\\ \phi_c\end{bmatrix}\\&=\begin{bmatrix}\theta_{gv}^{*}\xi_v^{T}-\theta_{gv}\xi_v^{T}-u_v\\ \theta_{gh}^{*}\xi_h^{T}-\theta_{gh}\xi_h^{T}-u_h\end{bmatrix}+\left(\theta_H^{*}\xi_H^{T}-\theta_H\xi_H^{T}\right)\begin{bmatrix}\delta_e\\ \phi_c\end{bmatrix}+\omega\\&=\begin{bmatrix}\phi_{gv}^{T}\left(\xi_{gvl}+\xi_{gvr}\right)/2-u_v\\ \phi_{gh}^{T}\left(\xi_{ghl}+\xi_{ghr}\right)/2-u_h\end{bmatrix}\\&\quad+\frac{1}{2}\begin{bmatrix}\phi_{H11}^{T}\left(\xi_{H11l}+\xi_{H11r}\right)&\phi_{H12}^{T}\left(\xi_{H12l}+\xi_{H12r}\right)\\ \phi_{H21}^{T}\left(\xi_{H21l}+\xi_{H21r}\right)&\phi_{H22}^{T}\left(\xi_{H22l}+\xi_{H22r}\right)\end{bmatrix}\begin{bmatrix}\delta_e\\ \phi_c\end{bmatrix}+\omega\end{aligned} \tag{43}$$

where $\phi_{gv}=\theta_{gv}^{*}-\theta_{gv}$, $\phi_{gh}=\theta_{gh}^{*}-\theta_{gh}$, $\phi_{H_{ij}|i,j=1,2}=\theta_{H_{ij}}^{*}-\theta_{H_{ij}}$

The Lyapunov candidates are chosen as following for analysing the close-loop system stability.

$$V=\frac{S^{T}S}{2}+\frac{\phi_{gv}^{T}\phi_{gv}}{2\gamma_1}+\frac{\phi_{gh}^{T}\phi_{gh}}{2\gamma_2}+\frac{\phi_{\mathrm{H}ij}^{T}\phi_{\mathrm{H}ij}}{2\gamma_{ij}} \tag{44}$$

The time derivative of (44) is:

$$\dot{V}=S^{T}\dot{S}+\frac{\phi_{gv}^{T}\dot{\phi}_{gv}}{\gamma_1}+\frac{\phi_{gh}^{T}\dot{\phi}_{gh}}{\gamma_2}+\frac{\phi_{Hij}^{T}\dot{\phi}_{Hij}}{\gamma_{ij}} \tag{45}$$

Substituting (43) into (45), we can calculate the following adaptive laws of $\theta_v,\theta_h,\theta_{H_{ij}|i,\,j=1,2}$ as:

$$
\begin{cases}
\dot{\theta}_v = \gamma_1 S_v\left(\xi_{vl} + \xi_{vr}\right)/2; \qquad \dot{\theta}_h = \gamma_2 S_h\left(\xi_{hl} + \xi_{hr}\right)/2 \\
\dot{\theta}_{H_{11}} = \gamma_3 S_v \delta_e \left(\xi_{H_{11}l} + \xi_{H_{11}r}\right)/2; \;\; \dot{\theta}_{H_{12}} = \gamma_4 S_v \phi_c \left(\xi_{H_{12}l} + \xi_{H_{12}r}\right)/2 \\
\dot{\theta}_{H_{21}} = \gamma_5 S_h \delta_e \left(\xi_{H_{21}l} + \xi_{H_{21}r}\right)/2; \;\; \dot{\theta}_{H_{22}} = \gamma_6 S_h \phi_c \left(\xi_{H_{22}l} + \xi_{H_{22}r}\right)/2
\end{cases} \quad (46)
$$

Substituting the adaptive law (46) into (45), we can get:

$$
\begin{aligned}
\dot{V} &= S^T\left(\omega - \begin{bmatrix} u_v \\ u_h \end{bmatrix}\right) \\
&= S^T\omega - m_{11}S_v sat(S_v) - m_{12}S_v^2 - m_{21}S_h sat(S_h) - m_{22}S_h^2 \quad (47) \\
&\le S^T\omega - m_{11}\left|S_v\right| - m_{12}S_v^2 - m_{21}\left|S_h\right| - m_{22}S_h^2
\end{aligned}
$$

when $\boldsymbol{\omega}$ is small enough and $m_{ij}(i, j = 1, 2)$ are strictly positive constants, we can guarantee the values of (47) no larger than 0 and make tracking errors converge to zero.

4. SIMULATIONS

4.1 Robust verification under structural uncertainties

In this part, four different levels of fuel capacities in Table 1 including 30% and 50% (nominal value), 70% and 100% are studied respectively to verify robustness of the proposed adaptive interval type-2 fuzzy sliding mode controller (AIT2-FSMC) in Fig. 5 and the compared type-1ones (AT1-FSMC) in Fig.6. However, the condition with 0% fuel capacity is not included because it is not realistic to increase altitude and velocity at the same time. In Fig. 5 and Fig. 6, the FAHV velocity and altitude tracking errors increase successively with the increasing of fuel capacities. Simultaneously, the deflections of elevator (Dec), throttle settings and flexible mode vibrations in Fig. 7-8 are also presented the situations of successively increasing. However, the actuator's responses are far from saturation settings in AIT2-FSMC or AT1-FSMC under 100% fuel capacity, whereas the flexible modes are also well constrained.

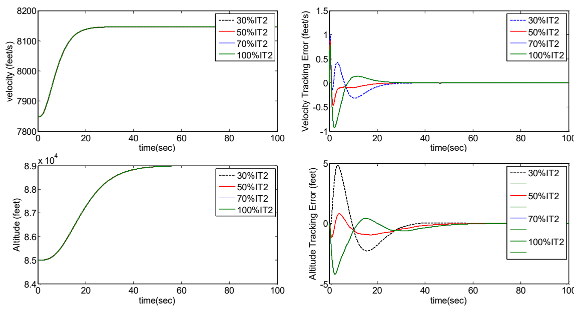


Fig. 5. Velocity and Altitude Responses with Fuel Capacity from 30% to 100% of the AIT2-FSMC

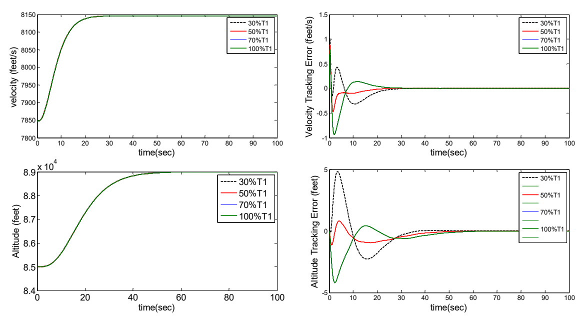


Fig. 6. Velocity and Altitude Responses with Fuel Capacity from 30% to 100% of the AIT2-FSMC

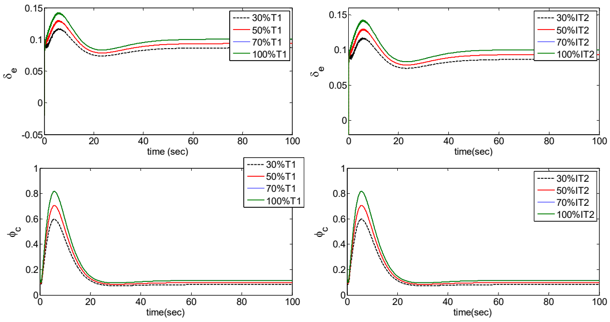


Fig. 7. Actuators Responses in Different Levels of Fuel Capacities

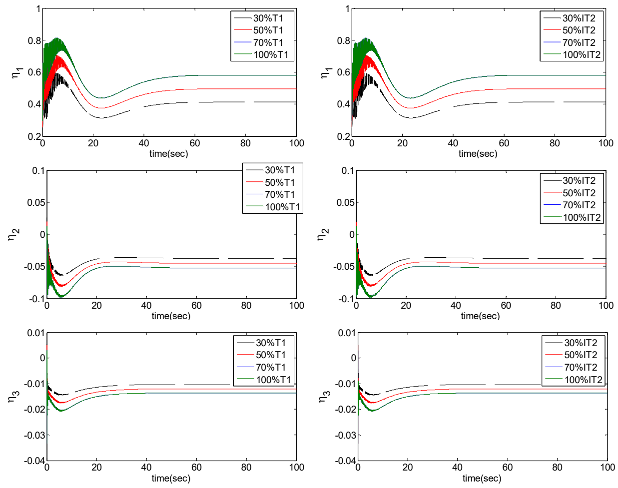


Fig. 8. Flexible Mode Responses in Different Levels of Fuel Capacities

4.2 Robust verification under parametric uncertainties

The AIT2-FSMC and AT1-FSMC show strong robustness with the constant aerodynamic parametric uncertainties which vary from 10% to 30% with nominal fuel capacity level. The aerodynamic coefficients of the lift and thrust are decreasing whereas the drag and pitch moment are increasing with the same level, simultaneously. The two controllers deteriorate with the increase of parametric uncertainty as shown in Fig. 9 and Fig. 10. However, AIT2-FSMC shows better performances both in tracking errors and actuators' responses. Different from what we proposed in (Gao, Yuan, Yi, & Li, 2015) which only adopted adaptive laws to estimate $\hat{g}_v$, $\hat{g}_h$, the AIT2-FSMC and AT1-FSMC comparison results show minor different behaviour between each other, however, the AIT2-FSMC behaves still better than the AT1-FSMC. The result should be occurred in $\hat{H}_{ij|i,j=1,2}$ estimation which make the system with better capabilities in dealing with parametric and structural uncertainties, and promoted the type-1 fuzzy logic systems' performance to a certain degree.

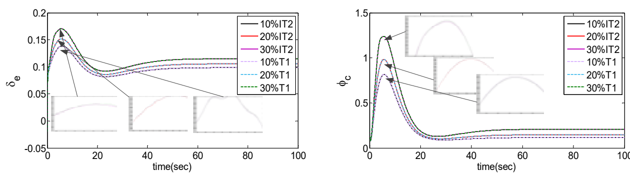


Fig. 9. Responses of Actuators under 10%, 20% and 30% Parametric Uncertainties

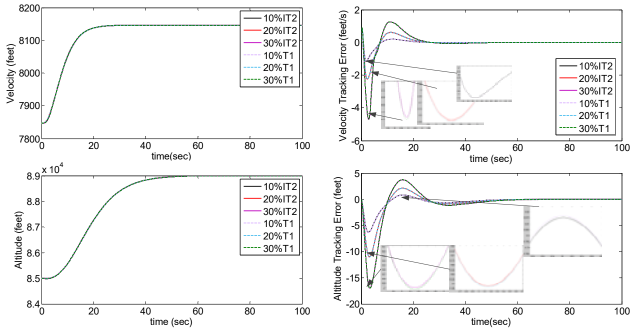


Fig. 10. Responses of Tracking Errors under 10%, 20% and 30% Parametric Uncertainties

5. CONCLUSIONS

The complex and volatile external environment and the internal conditions with flexible vibrations and varying structural uncertainties of FAHV make great challenges in designing a controller with high robustness and effectiveness. An indirect interval type-2 fuzzy sliding mode controller (AIT2-FSMC), which uses sliding mode controller as the core controller and uses adaptive IT2-FLSs to estimate time-varying nonlinear functions and inverse matrix values based on the feedback linearization of FAHV, is presented. The consequent fuzzy sets are tuned online through adaptive laws which are derived through Lyapunov synthesis approach. Different levels of external and internal uncertainties are used to verify the robustness of the AIT2-FSMC. The simulations comparisons show that AIT2-FSMC has certain improvements than the AT1-FSMC especially facing with high levels of uncertainties whereas there are minor differences between the AIT2-FSMC and AT1-FSMC with non-external disturbances. In general, the simulation results validate the robustness and effectiveness of the proposed controller.

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