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MRAC Adaptive Control Design for an F15 Aircraft Pitch Angular Motion Using Dynamics Inversion and Fractional-Order Filtering

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ABSTRACT

This study proposes a fractional adaptive control scheme design for a longitudinal pitch angular motion control of a military F15 aircraft. The aircraft behavior will be forced to follow a chosen model reference in an MRAC (Model Reference Adaptive Control) configuration combined with dynamics inversion technique such that the transient response becomes invariant even in the presence of uncertainties or variations for a reference input by introducing a fractional-order transfer function pre-filter. Based on Lyapunov theory, the updating control law minimizes the error between the plant output and the model reference one. This controller is set in a cascade with a linear dynamic compensator. Simulation results on a military aircraft model with comparison to preceding results illustrate the effectiveness and the superiority of the proposed control strategy.

1. Introduction

Controlling a military aircraft is a very challenging task for automation engineers because of the complexity of the plant model: huge nonlinearities, multiple coupled outputs, very disturbing environment, and extreme maneuvering conditions. In this study, the main motivation is to design a simple fractional adaptive controller that is able to guarantee stability and a high level of performance for this kind of system. Many control strategies have been proposed to deal with aircraft and flight supervision like Fuzzy Logic Controllers [1], PD control [2], robust H∞ control [3], Fault-tolerant control [4], and adaptive control [5].

Model reference adaptive control (MRAC) schemes are proving to be efficient with nonlinear control problems, as they allow us to deal with uncertainties in the model and unknown or slowly varying parameters. An adaptive learning algorithm makes it possible to track the modifications in the plant dynamics [6][7]. This is a major advantage of such adaptive controllers, as the majority of practical plants' models are nonlinear, with unknown parameters and unconsidered nonlinear dynamics [8]. Besides, there are multiple possible actuator failures and an infinite variety of possible surface damages for the military aircraft, and any discrepancy between the model and reality can lead to false detection [9]. Many different approaches have been successfully flown on manned aircraft [10], like the retrospective cost adaptive control (RCAC) to a linearized aircraft dynamic with an unknown transition to non-minimum-phase dynamics [11], adaptive control of aircraft lateral movement in landing mode [12], etc.

Based on a chosen reference model that produces reference signals, an active identification algorithm, and an adaptive control law, MRAC controllers are more efficient within linear feedback control loops and lose their performance or even stability with nonlinear systems. Usually, one has to suppose that the plant model is linearizable [13]. MRAC adaptive control is particularly efficient for accommodating unknown changes in the aircraft structure and parameters, as demonstrated by many works in the literature [14], even in the presence of asymmetric damages.

Recently, a great focus of the scientific research community was directed to fractional-order systems and their applications [15-17]. These models containing fractional-order operators have proven to be more able to model a wide range of physical systems comparatively to ordinary integer-order ones [18]. This is particularly due to their interesting characteristics like long memory [19] and filtering effect [20], which made them extensively applied in feedback control loops in order to improve their performance and robustness [21][22].

In this work, the proposed control strategy is to implement a nonlinear Dynamic Inversion control loop in addition to the MRAC control outer loop for an F15 aircraft pitch angular motion (see Fig. 1). This inner loop controller has been used by several authors in literature [24-26]. The aim of this control action is to decouple the system axes in order to deal with uncertainties and actuator failures and help the pilot. With this control configuration, the choice of the reference model is able to impose desired flying performances.

Fig. 1. F15 Eagle aircraft [23]

Our control system is designed for the adaptive control of the angular pitch rate and the pitch angle, respectively, in the case of an F-15 aircraft whose flight may be affected or not by wind shears. This study concerns the longitudinal motion of an aircraft flying at 6000 m altitude, having velocity V0 = 100 m/s.

This paper is organized as follows: Section 2 gives some basic definitions for fractional-order systems. Section 3 presents the linear modelization of the F15 aircraft using the dynamical inversion method. And Section 4 introduces the proposed model reference adaptive control design and the fractional-order shaping filters. Simulation results are presented in Section 5, whereas Section 6 gives concluding remarks to this work.

2. Fractional Order Systems

Fractional operators are classical tools in engineering; they have been used in mechanics since at least the 1930s and in electrochemistry since the 1960s. In the control field, an increasing interest began mainly after the first contributions of Oustaloup and Podlubny [27][28].

2.1. Definition of Fractional Order Integration

Let $\alpha \epsilon c$, $\Re > 0$, $c \epsilon R$ and f a locally integrable function defined on $[c, +\infty]$. The α order integral of f, of lower bound c is defined as [7]:

$$I_c^{\mu}f(t)\overset{\Delta}{=}\int_c^t \frac{(t-\tau)^{\mu-1}}{\Gamma(\mu)} f(\tau)d\tau \tag{1}$$

With $t \geq c$, and Γ is the Euler function. The formula (1) is called Riemann-Liouville Integral. Usually, the control loop is discreet, and we use a sampled approximation of (1) given by:

$$I_c^{\mu} f(k\Delta) = \frac{\Delta}{\Gamma(\mu)}\sum_{\tau=0}^{k-1}(k\Delta-\tau\Delta)^{\mu-1} f(\tau\Delta) \tag{2}$$

With Δ is Sampling Period.

2.2. Approximation of Fractional Order Transfer Function

For the purpose of our design, we need to use an integer order model approximation of the fractional-order filtering transfer function. For this aim, we have used the so-called singularity function method [29], and precisely for the case interesting our approach that is a fractional second order system of the form (3) with μ a positive real number such that 0< μ <0.5.

$$G(s)=\frac{1}{\left(\frac{s^2}{\omega_n^2}+2\xi\frac{s}{\omega_n}+1\right)^{\mu}} \tag{3}$$

The parameters μ and ξ in equation (3) are chosen by the designer by a try and error procedure in order to set the best performance for the fractional-order filter, whereas the frequency ω_n should fit the plant operating frequency bandwidth.

We can approximate (3) by the function:

$$H(s)=\frac{\left(\frac{s}{\omega}+1\right)\left(\frac{s}{\omega+1}\right)^{\beta}}{\left(\frac{s^2}{\omega^2}+2\alpha\frac{s}{\omega}+1\right)} \tag{4}$$

With $\alpha=\xi^m$ And $\beta=1-2\mu$, which also can be represented by the function,

$$H(s)=\frac{\left(\frac{s}{\omega}+1\right)}{\left(\frac{s^2}{\omega^2}+2\alpha\frac{s}{\omega}+1\right)}\frac{\prod_{i=1}^{N-1}(1+\frac{s}{z_i})}{\prod_{i=1}^{N}(1+\frac{s}{p_i})} \tag{5}$$

The singularities are given by:

$$p_j=(ab)^{j-1}a.z_1 \qquad j=1,2,3,\dots N$$

$$z_i=(ab)^{i-1}z_1 \qquad i=2,3,\dots N-1$$

with, $z_1=w\sqrt{b}$, $a=10^{\frac{\varepsilon_p}{10(1-\beta)}}$, $b=10^{\frac{\varepsilon_p}{10\beta}}$, $\beta=\frac{\log(a)}{\log(ab)}$ and ε_p is Tolerated error in dB.

The order of approximation N is computed by fixing the frequency band of work, specified by $\omega_{\max}$, so that:

$p_{N-1} < \omega_{\max} < p_N$ Which leads to:

$$N = \text{integer part of}\left[\frac{\log\left(\frac{\omega_{\max}}{p_1}\right)}{\log(ab)}+1\right]+1 \tag{6}$$

H(s) can be then be written under a parametric shape function of order N+2:

$$H(s) = \frac{b_{m0}s^N + b_{m1}s^{N-1} + \ldots. + b_{mN}}{s^{N+2} + a_{m1}s^{N+1} + \ldots\ldots + a_{mN+2}} \tag{7}$$

a_{mi} and b_{mi} are calculated from the singularities p_i, z_i and α, ω.

3. F15 Dynamics Model

In fact, most control laws are developed by decoupling the longitudinal model and the lateral model. In order to derive the dynamical equations of the aircraft, some hypotheses are necessary. The standard model of six degrees of freedom can be obtained by considering the hypothesis of a flat earth and the aircraft to be asymmetrical rigid body [15].

Besides, three geometric marks are associated with the aircraft: the aircraft, the wind, and the stability one. A benchmark is chosen following the application domain. The aircraft dynamic can be represented by 12 state equations.

The angular velocity is represented by the states p, q, and r.

The translation movement is described by the states V, α, and β.

The orientation of the aircraft is given by the Euler equations thanks to the angles ψ, θ, and φ.

The aircraft position is given by x, y and h.

However, the decoupled model contains fewer equations with the help of other hypotheses. In our study, only the longitudinal model is considered for simplicity.

3.1. Dynamical Inversion

In general, the aircraft control design is achieved by linearizing the nonlinear model around many flight points (which combines the Mach number and the altitude). This operation allows the diminution of the operating envelope around a lonely point until we obtain an asymptotical variation. This means that the operating envelope is decomposed into different linear regions.

The dynamical inversion aims to create only one regulator for the entire flight envelope by linearizing the state feedback for it in order to get an equivalent linear system.

3.2. Aircraft Linearized Model

The linearized model is represented as [30]:

$$\dot{x} = Ax + B\delta + B_v v \tag{8}$$

$$y = Cx \tag{9}$$

Where, as represented in Fig. 2, $x = [Vx\,\alpha\ q\ \theta\ H\,]^T$ is the parameters' vector, V_x is the longitudinal speed, α is angle of attack, q is Pitch angular velocity, θ is Pitch angle, H is Flight altitude, $\delta = [\delta P\ \delta T\,]^T$ is the control vector, δ_P is the turning of the rudder, δ_T is Motor control, $v = [v_x v_z]^T$ is the disturbance vector (wind).

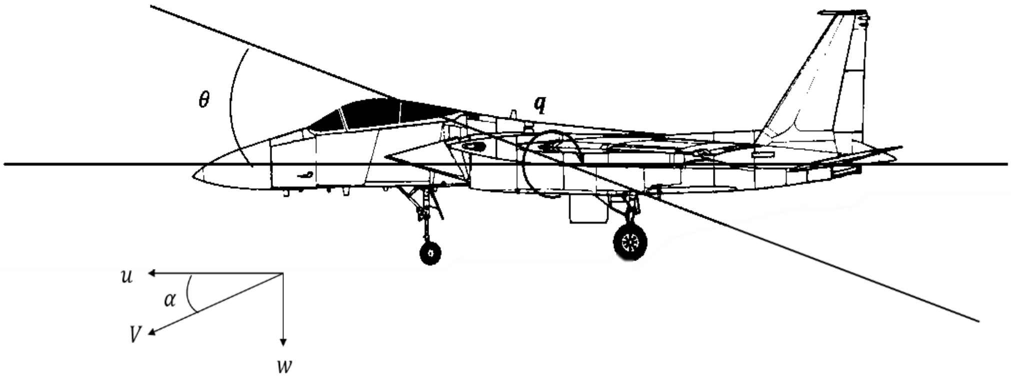

Fig. 2. Aircraft longitudinal dynamics

Using equation (8) and (9) we obtain,

$$\delta = B^{+}(\dot{x} - Ax - B_v \nu) \tag{10}$$

$$x = C^{+}y = C^{+}y_c \tag{11}$$

where $(.)^{+}$ represents the pseudo-inverse matrix.

Substituting (10) in (11) we get,

$$\begin{aligned} \delta &= B^{+}(C^{+}\dot{y}_c - C^{+}C\,Ax - B_v \nu) \\ &= (CB)^{+}(\dot{y}_c - CAx) - B^{+}B_v \nu \end{aligned} \tag{12}$$

The term $B^{+}B_v \nu$ represents the wind disturbances, which appear in (12) if these are measured and disappear when they are unknown (sensor problem). The system is transformed into a SISO problem by introducing the vector T,

$$\delta = T\delta_P \ ,T = [0\ 1]^T \tag{13}$$

The control law becomes,

$$\delta_P = T^{+}\delta = (CBT)^{+}(\dot{y}_c - CAx) \tag{14}$$

Which can be rewritten as

$$\delta_P = T^{+}\delta = (CBT)^{+}(\dot{y}_c - CAx) - B^{+}B_v \nu \tag{15}$$

If disturbances are known.

4. Model Reference Adaptive Control

4.1. Adaptive Control Design

Using a Lyapunov-based approach [8], [31], we will construct an adaptive adjustment algorithm for the system's parameters (Fig. 3). First, we write the error differential equation $e = y - y_m$, then we try to find out a Lyapunov function and an adaptation law such that we get $e = y - y_m \ \rightarrow 0$.

We consider the system with a first-order state-space model as,

$$\dot{x} = Ax + Bu \tag{16}$$

where $A \in \mathbb{R}^2 \times \mathbb{R}^2$ and $B \in \ \mathbb{R}^2$.

An adaptive controller is designed to allow the pitch angel to follow a reference pattern specified as:

$$\ddot{\theta}_m + 2\zeta_m\omega_m\dot{\theta}_m + \omega_m^2\theta_m = \omega_m^2 r \tag{17}$$

This allows us to introduce the following reference model:

$$\dot{x}_m = A_m x_m + B_m r \tag{18}$$

where $r(t)$ is a bounded reference signal. $A_m \in \mathbb{R}^2 \times \mathbb{R}^2$ is a matrix known and Hurwitz, $B_m \in \mathbb{R}^2$ is also known.

The control law is then described by:

$$u = K_x x + k_r r \tag{19}$$

where $K_x \in \mathbb{R}^2$ and $k_r \in \mathbb{R}$ are constant but with known ideal gains.

The goal is to find K_x^* and k_r^* so that the closed-loop model and the reference model have the same dynamics. In other words, the pattern match condition is verified and written in the form:

$$\begin{gathered} A + BK_x^* = A_m \\ Bk_r^* = B_m \end{gathered} \tag{20}$$

We introduce the estimation error defined by: $\tilde{K}_x(t) = K_x(t) - K_x^*$ et $\tilde{k}_r(t) = k_r(t) - k_r^*$

The closed-loop response is, therefore:

$$\dot{x} = \left(\underbrace{A + BK_x^*}_{A_m} + B\tilde{K}_x\right)x + (\underbrace{Bk_r^*}_{B_m} + B\tilde{k}_r)r \tag{21}$$

The error dynamic $e(t) = x_m(t) - x(t)$ in closed-loop is written as:

$$\dot{e} = \dot{x_m} - \dot{x} = A_m e - B\tilde{K}_x x - B\tilde{k}_r r \tag{22}$$

4.2. Stability Analysis

We chose a Lyapunov function based on the varying parameters of the controller K_x and K_r.Thus, we put

$$V(e, \tilde{K}_x, \tilde{k}_r) = e^T P e + |b|(\tilde{K}_x \Gamma_x^{-1} \tilde{K}_x^T + \frac{\tilde{k}_r^{\,2}}{\gamma_r}) \tag{23}$$

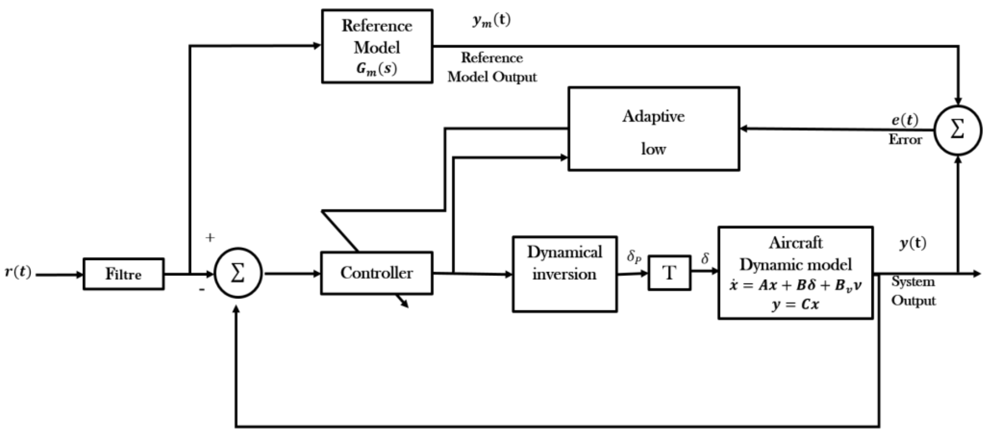

Fig. 3. Adaptive MRAC control of F15 aircraft pitch angular motion using dynamic inversion and dynamical compensation

Where $\Gamma_x = \Gamma_x^T > 0 \in \mathbb{R}^2 \times \mathbb{R}^2$ is a symmetric learning matrix positive definite for $K_x(t)$, γ_r is a learning parameter for k_r and $P = P^T > 0 \in \mathbb{R}^2 \times \mathbb{R}^2$ is the solution for the following Lyapunov equation:

$$PA_m + A_m{}^T P = -Q \tag{24}$$

where $Q = Q^T > 0 \in \mathbb{R}^2 \times \mathbb{R}^2$

The Lyapunov function derivative is given by:

$$\dot{V}(e, \widetilde{K}_x, \tilde{k}_r) = \dot{e}^T Pe + e^T P\dot{e} + |b|(2\widetilde{K}_x \Gamma_x^{-1} \dot{\widetilde{K}}_x{}^T + \frac{2\dot{\tilde{k}}_r \tilde{k}_r}{\gamma_r}) \tag{25}$$

Substituting (20) in (23), we have:

$$\begin{gathered} \dot{V}(e, \widetilde{K}_x, \tilde{k}_r) = \\ e^T(PA_m + A_m{}^T P)e + 2e^T PB[-\widetilde{K}_x x - \tilde{k}_r r] \\ +|b|(2\widetilde{K}_x \Gamma_x^{-1} \dot{\widetilde{K}}_x{}^T + \frac{2\dot{\tilde{k}}_r \tilde{k}_r}{\gamma_r}) \end{gathered} \tag{26}$$

where $2e^T PB = 2e^T \bar{P} b$ and $\bar{P} = [p_{12} \;\; p_{22}]^T$.

Finally,

$$\dot{V}(e, \widetilde{K}_x, \tilde{k}_r) = -e^T Qe + 2|b|\widetilde{K}_x \left(-xe^T \bar{P} sgnb + \Gamma_x^{-1} \dot{\widetilde{K}}_x{}^T\right) + 2|b|\tilde{k}_r(-re^T \bar{P} sgnb + \frac{\dot{\tilde{k}}_r}{\gamma_r}) \tag{27}$$

Thus, the parameters' updating laws are

$$\dot{K}_x^T = \Gamma_x x e^T \bar{P} sgnb \tag{28}$$

$$\dot{k}_r = \gamma_r r e^T \bar{P} sgnb \tag{29}$$

Replacing (28) and (29) in (27), we get:

$$\dot{V}(e, \widetilde{K}_x, \tilde{k}_r) = -e^T Qe \leq -\lambda_{min}(Q)\|e\|_2^2 \leq 0 \tag{30}$$

And because $\dot{V}(e, \widetilde{K}_x, \tilde{k}_r) < 0$ this implies that $e(t)$, $K_x(t)$ and $k_r(t)$ are bounded.

4.3. Dynamical Compensator

The linear dynamical compensator allows us to introduce terms in the characteristic polynomial such that the system poles are moved to the left half-plane, see Fig. 2. In this work, the dynamical compensator is a proportional-derivative action [8],

$$G_c(s) = K_P + K_D s \tag{31}$$

4.4. Reference Shaping Filter

A reference model is used in order to specify the desired response. Thus, we need a shaping filter allowing us to design a realizable and adequate control action. As long as the controller is adaptive, the adjustment is operated on the error between the output and the reference model. In general, the reference model is described by an LTI model. It contains all the performance specifications like the rise time, the time response, and also robustness specifications, and stability margins.

In this work, we propose a fractional order filter in the form of a second order-like transfer function given by equation (3), where μ is a positive real number with 0< μ<1.

One can notice that the fractional-order filter has a stabilizing effect on the overall control system. Indeed, the fractional-order transfer function (3) is stable and is set to give improved output behavior [32].

5. Simulation Results

The numerical simulations have been performed in Matlab/Simulink environment. We consider the linear longitudinal model provided by NASA Dryen for the military F-15 Aircraft. This linear model was obtained for small variations around operating conditions which are the altitude H=6000m and the speed V0=100 m/s.

5.1. Experiment Setting

The system represented by equations (4) and (5) is characterized by the following matrices:

$$A=\begin{bmatrix}-0.0112 & -0.0365 & 0 & -0.5601 & 0.0001\\ -0.0065 & -1.1182 & 1 & 0.0001 & 0.0001\\ 0.0015 & 8.3089 & -0.9412 & 0 & -0.0001\\ 0 & 0 & 1 & 0 & 0\\ -0.0017 & -13.5803 & 0 & 13.5803 & 0\end{bmatrix};$$
$$B=\begin{bmatrix}-0.0811 & -0.08110\\ -0.0688 & -0.0688\\ -5.9799 & -5.9799\\ 0 & 0\\ 0 & 0\end{bmatrix};B_v=-\begin{bmatrix}a_{11} & a_{12}/V_0\\ a_{21} & a_{22}/V_0\\ a_{31} & a_{32}/V_0\\ a_{41} & a_{32}/V_0\\ a_{51} & a_{52}/V_0\end{bmatrix} \quad (32)$$

$$C=[0 \quad 0 \quad 1 \quad 0 \quad 0] \quad (33)$$

The disturbances are described by,

$$v_x=-v_{x0}\sin\frac{2\pi}{T_0}t\,,v_z=-v_{z0}(1-\cos\frac{2\pi}{T_0}t) \quad (34)$$

With T_0 =60s, the period when the aircraft undergoes the wind disturbances v_{x0}=15m/s, v_{z0}=7 m/s.

Simulation is realized with the following settings. Sampling time $dt=0.0001s$. Dynamical compensator $K_P=1$, $K_D=1$. Reference model $\xi=0.75$, $\omega_n=1.5$. Adaptation parameter, $fractional$, $\gamma_r=5$, $\Gamma_x=[5\ 0;0\ 5]$, integer $\gamma_r=1$, $\Gamma_x=[1\ 0;0\ 1]$. Reference $r(t)=25\ deg/s$. Initial condition: $x0\ =[100\quad 7\quad 0\quad 20\quad 6000]$. Filter $\xi c=0.75$, $\omega n=1.5$.

The simulation framework is depicted in Fig. 4. The fractional shaping filter is designed for μ = 0.7 and approximated using the singularity function method with a tolerated error of 2 dB and a maximal bandwidth of $\omega_{max}=10^4$ Hz, whereas the integer one has the form of equation (3) with μ = 1.

5.2. Comparative Results

The comparative simulation results for the MRAC control of the pitch angle when using an ordinary integer order shaping filter against the proposed fractional-order one are given in Fig. 5 and Fig. 6. Table 1 presents the comparative evaluation of the system performance.

Table 1. Comparative Performance evaluation

	Integer case	Fractional case
Rise time	1.7373 s	1.7403 s
Response time	5.6910 s	5.3654 s
Static error	0.0025	$3.09\ 10^{-4}$

From these simulation results we can notice the suppression of oscillation in case of fractional order filter as observed in Fig. 5 and Fig. 6. The rise time is better in integer cases, but the response time is improved with fractional-order filtering. The time performance is close because the same adaptation laws are used. However, it is obvious that the steady-state error is drastically reduced with this proposed control scheme, improving the control precision better in terms of precision (the error is almost divided by 10).

It is worthy to notice that in the considered control problem, adaptive control is more efficient than other fixed controllers such as PID controller because the aircraft model and dynamics are partially unknown or varying in time.

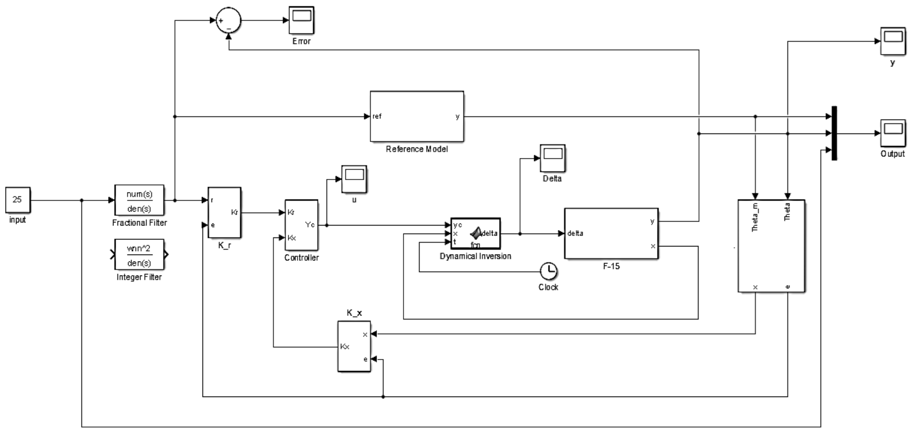

Fig. 4. Simulink block-scheme

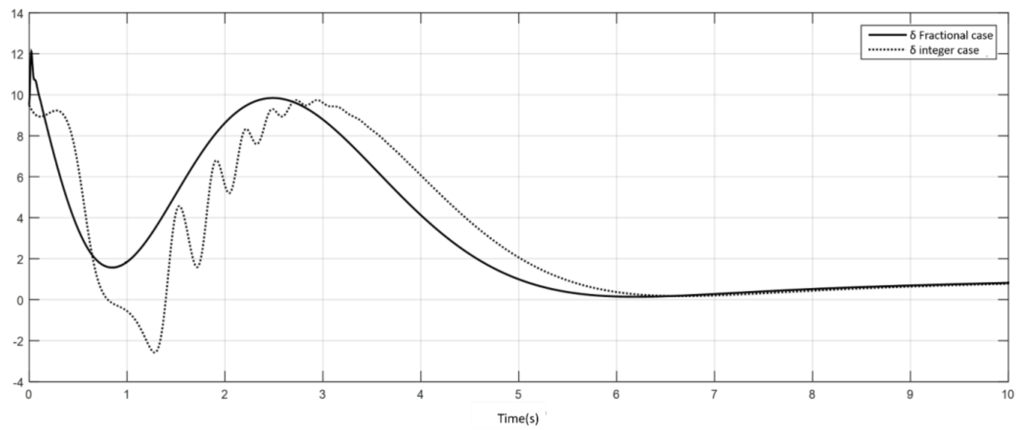

Fig. 5. Comparative Pitch angle output

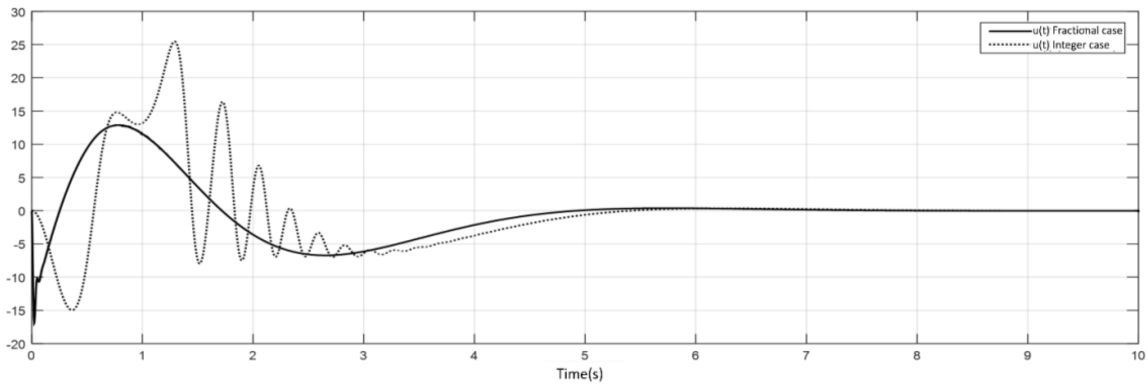

Fig. 6. Control signals

5.3. Simulation of Maneuver Case

In this section, we will simulate an 80° manoeuver of the pitch angle. The equilibrium position is obtained with a negative angle. The aircraft is initially in descent position. The result is shown in Fig. 7 to Fig. 10.

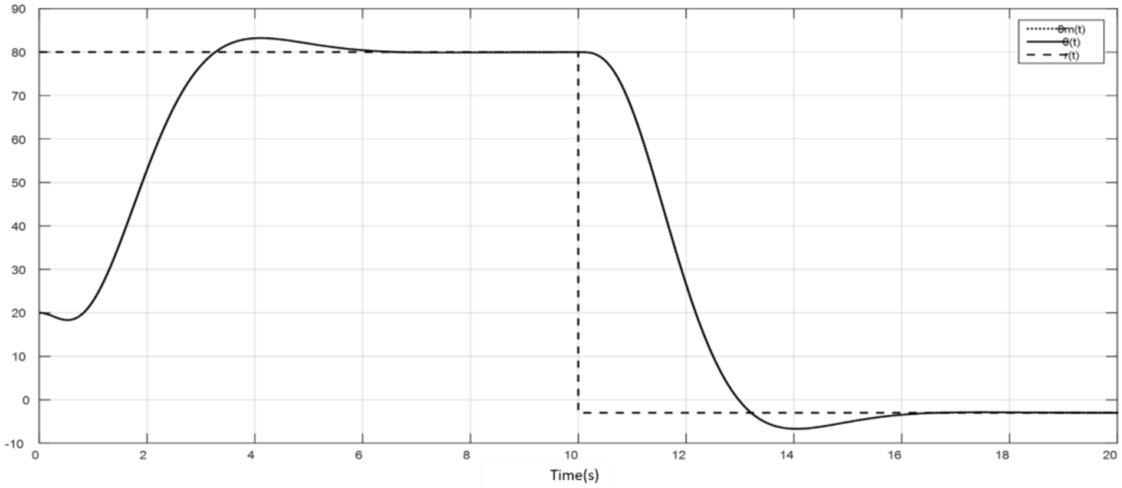

Fig. 7. Pitch angle response (Maneuver) in the fractional-order case

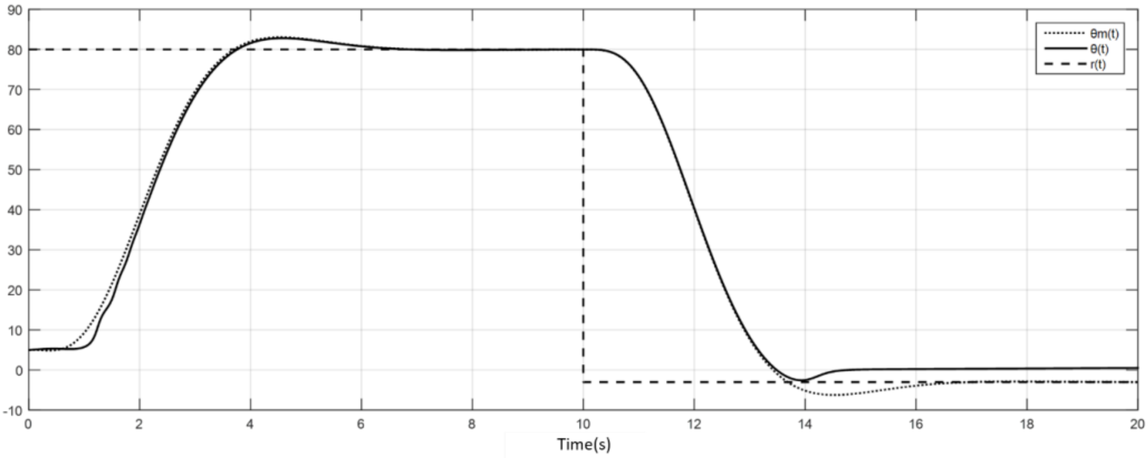

Fig. 8. Pitch angle response (Maneuver) in the integer-order case

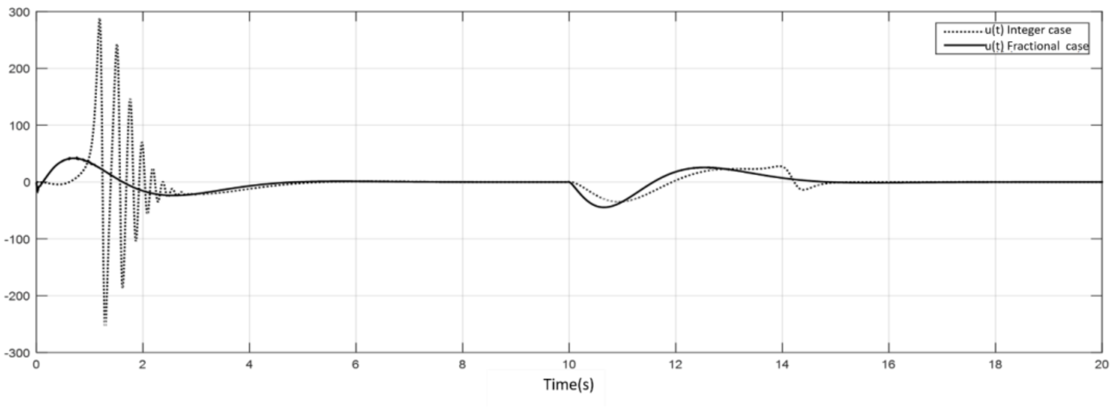

Fig. 9. Comparative control signals

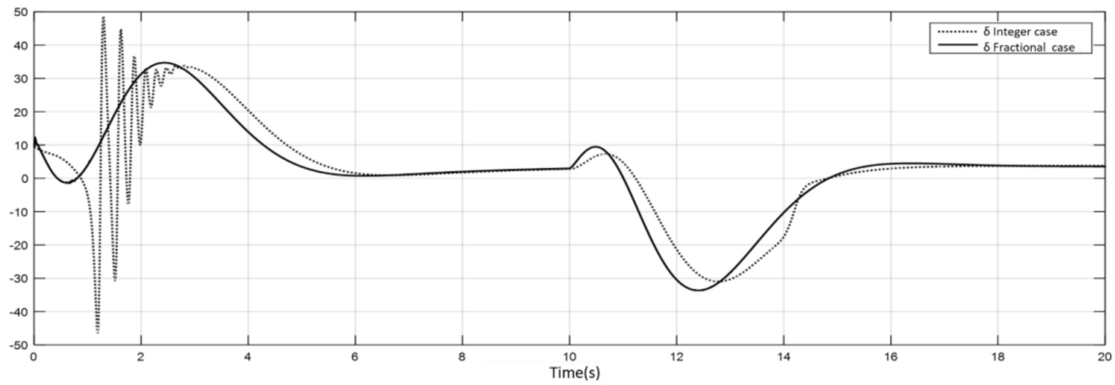

Fig. 10. Comparative reflexing angle δ response (Maneuver).

Remarks:

- The maximal speed reached for this maneuver is 325 m/s (1170 km/h), which is physically possible because the F15 ceiling is 2655 km/h.

- The reached altitude is 16104 m (the maximum altitude for an F15 is 19812 m.

It is obvious from Fig. 7 to Fig. 10 that the adaptive MRAC control scheme is able to suppress the chattering phenomena in the case of fractional order filtering, which improves the smoothness and the performance of the reference signal [33], [34], but also implies a different setting for the adaptation control law (adaptation gains).

6. Conclusions

In this paper, a novel adaptive MRAC control design has been proposed for the pitch angle control of an F15 aircraft using the dynamical inversion and a shaping filter of fractional order. Using an adaptive MRAC (Model Reference Adaptive Control) design has made the transient aircraft response invariant even in the presence of uncertainties or variations for a reference input that is pre-filtered by a fractional-order transfer function. The originality of this work is the introduction of a fractional-order pre-filter in order to improve the maneuvering performance. The stability analysis of this adaptive controller has been performed based on Lyapunov theory.

Simulation results have clearly shown the ability of the proposed control scheme to improve the aircraft dynamics and suppress the chattering phenomena despite the strong nonlinearity and complexity of this plant. Future research work will concern the extension of the study to the case of system uncertainties and robust control and the implementation of the proposed adaptive controllers on real plants.

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