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Fractional Order Fault Tolerant Control - A Survey

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ABSTRACT

In this paper, a comprehensive review of recent advances and trends regarding Fractional Order Fault Tolerant Control (FOFTC) design is presented. This novel robust control approach has been emerging in the last decade and is still gathering great research efforts mainly because of its promising results and outcomes. The purpose of this study is to provide a useful overview for researchers interested in developing this interesting solution for plants that are subject to faults and disturbances with an obligation for a maintained performance level. Throughout the paper, the various works related to FOFTC in literature are categorized first by considering their research objective between fault detection with diagnosis and fault tolerance with accommodation, and second by considering the nature of the studied plants depending on whether they are modelized by integer order or fractional order models. One of the main drawbacks of these approaches lies in the increase in complexity associated with introducing the fractional operators, their approximation and especially during the stability analysis. A discussion on the main disadvantages and challenges that face this novel fractional order robust control research field is given in conjunction with motivations for its future development. This study provides a simulation example for the application of a FOFTC against actuator faults in a Boeing 747 civil transport aircraft is provided to illustrate the efficiency of such robust control strategies.

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Nomenclature

FTC	Fault Tolerant Control
FOFTC	Fractional Order Fault Tolerant Control
FOS	Fractional Order System
FOC	Fractional Order Control
FOSMO	Fractional Order Sliding Mode Observer
FOFD	Fractional Order Fault Detection
UIO	Unknown input observers

1. Introduction

The continuous development of technological and industrial processes, driven by competition and the increasingly complex and refined needs of consumers, has made these systems very vulnerable to the slightest defect. While most controller design approaches assume perfect condition of the physical components such as actuators and sensor, it is rarely the case in real world application, as these components can suffer malfunctions which degrade overall performance and stability, and with the emphasis on controller reliability and safety, the field of fault tolerant control systems emerged as one of the most pertinent topic in control theory, it has garnered a lot of interest from control engineers. With numerous books and papers published and various fault tolerant control techniques investigated fault tolerant control systems became an essential element in every safety critical system [1, 2].

From a historical point of view, the research in FTC was predominantly conducted by the aircraft controls system community [3], motivated by the necessity to design reliable control strategies that are able to maintain acceptable levels of performance in the event of unexpected components failure during flight. The issue of tolerance against faults is extremely important on the grounds that uncompensated faults and failures in components such as sensors and actuators can be the cause of terrible performance degradation, and in aircraft where safety is critical these unaccounted for failures can lead to disastrous human and material losses. One infamous example of such disasters is the crash of Alaska Airlines Flight 261, where a jammed horizontal stabilizer caused the MD-83 aircraft to dive nose down into the Pacific Ocean killing all 88 passengers and crew members onboard [4].

Several survey papers have been published [5, 6], and numerous books dedicated to the rigorous study, design, and analysis of the Fault Tolerant Control Systems, notably the book by Blanke et al. [7] which presents the main ideas and approaches of FTC, while the book by Tao et al. [8] treated the topic of fault tolerant control against actuator failures by presenting different techniques for a wide range of system classes and with applications to aircraft and flight control. Recently, the introduction of fractional calculus in the field of engineering and in particular in systems control, has completely changed the state of the art of research by monopolizing a large number of academic theses and R&D projects in industry [9, 10].

Fractional calculus is based on the generalization of the integration and differentiation to any arbitrary order; it has been successfully utilized for the design of new control techniques. One of the earliest fractional order controllers were the CRONE controller and the $PI^{\lambda}D^{\mu}$ controllers [11], it has been demonstrated that fractional order controllers can improve system performances and stability, as well as provide robustness against disturbances and modeling uncertainties [12, 13]. Since then, fractional calculus has been introduced in several control schemes and methods such as sliding mode control [14], predictive control [15, 16], and particularly adaptive control [17, 18, 19]. Recently, many research works have proposed Fault Tolerant Controllers using fractional order models in order to improve the efficiency and performance of the controlled plants [20, 21].

The main contribution of the present paper is the focus on FTC control systems using fractional order operators. As such, all fractional order FTC algorithms, are included in the review. This paper provides the reader with a brief summary of the control strategies as well as relevant literature [22]. FOFTC control algorithms enable us to deal with a wider class of systems, including non-integer order model processes, and give us an effective means of improving the robustness and performance of these controls against system failures. The major drawback is the increased complexity both in specifying the problem and modeling the system, and in diagnosing and designing the control.

The purpose of this paper is to provide a state of the art that can be easily used as a basis to familiarize the reader with fractional order robust control of processes with actuators redundancies. The most recent advances, and research directions are pointed out and a numerical example is provided in order to illustrate the efficiency od such robust controllers. The remaining part of this manuscript is organized as follows: Section 2 will discuss the state of the art of fractional order FTC, distinguishing diagnostic-oriented works from those dealing with fault-tolerant control.

2. Fractional Order Fault Tolerant Control Approaches

One of the earliest papers discussing fractional order diagnosis and fault tolerant control (FTC) are [23] where the authors proposed a second order sliding mode technique for fault detection in fractional order systems, and in [24] where the parity space method for fault detection was extended for fractional order systems. It was shown that the fractional order residuals are more sensitive to additive sensor faults. Besides, three methods for fractional residuals generation have been discussed in [25].

Following these works, this topic received a great deal of attention among researchers from the fields of fractional order control and fault tolerant control alike, and consequently they have been able to develop sensible controller structures that can rigorously handle possible faults that might occur during system operation.

The development of fault diagnosis approaches and fault tolerant control systems have been studied as two distinct entities [5, 26], therefore it is natural to classify the recent contribution between these two topics, although there is a great overlap in research and application between FD and FTC as sometimes there's an inherent need for fault detection / identification in the design of efficient fault tolerant control strategies [27, 28].

2.1. Fractional Order Fault Detection and Diagnosis

One can classify the recent works on the fractional order fault detection (FOFD) in regard to the utilized approaches; and one of the most popular technique used is the fractional order sliding mode observers (FOSMO) [29, 30, 31, 32] due to the fact that a fractional sliding surface can provides more flexibility in the design of enhanced observers in terms of performances, as in [23], where the authors showed that the proposed FOSMO was able to successfully detect the fault in a short amount of time after its occurrence.

Another popular approach among researchers is design of fractional order unknown input observers (UIO) for fault detection and estimation [33, 34, 35, 36] these types of observers ensure robust fault diagnosis capability in the presence of uncertainties that arise from disturbances, modeling errors, and non linearities [37].

The dynamic parity space approach has widely been used in the integer order case, for the fractional order case, a few papers have been interested in this approach in the recent years [25, 38, 39], these works have demonstrated that fractional residuals generated from such approach have high sensitivity to faults especially sensor faults, thus ensuring strong detectability of these faults [24].

Other approaches to fractional order fault detection have also been considered and studied, a notable example are the learning based approaches such as neural network Disturbance observers [40], single layer and double layer radial basis function neural networks (RBFNN) [41], and recurrent wavelet fuzzy neural networks (RWFNN) [42]. Other approaches comprise state observers for actuator faults [43] and sensor faults [44, 45, 46, 47], Fractional observers [48], high gain observers [49] and Generalized fractional order observers [50] for robust fault isolation, adaptive non linear observers [51], Non-fragile H_∞ filter for fault detection [52, 53], fractional disturbance observers [54].

One very interesting approach is the synchronization of a fractional order chaotic system in order to achieve fault diagnosis as illustrated in [55] with the application in ball bearing systems. Kalman Filter design was also studied, in [35, 56]. Fractional KF were developed to detect faults in FOS whereas in [57] a bank of Unscented Kalman Filters was implemented to detect actuator faults in a wind turbine.

2.2. Fractional Order FTC Designs

2.2.1 Sliding Mode-Based FTC

Similarly to fault detection approaches, the sliding mode technique has been the most popular approach among researchers in conceiving reliable fractional fault tolerant control strategies, since this approach possess attractive features in terms of reducing the chattering during the sliding phase and smoother control efforts [58]. These works include [59, 60, 61, 62, 63, 64, 65, 66, 67, 68], additionally other fractional sliding mode structures have also been studied such as Terminal sliding mode control [69, 51] and nonsingular terminal sliding mode [32, 70].

Furthermore, in some papers, the sliding mode approach is used in combination with other control approaches, most notably Fuzzy SMC [71, 72], where in [71] the authors developed a fuzzy fault tolerant sliding mode controller for fractional systems based on fast adaptive fault estimation, other considered approaches include robust H_∞ adaptive output feedback SMC [73], neural adaptive SMC [74] and adaptive sliding mode synchronisation of chaotic systems [60, 61].

2.2.2 Adaptive Control-Based FTC

Another technique commonly used in FOFTC is the adaptive control, the authors in [75] constructed a robust fractional fault tolerant adaptive control scheme for a class of non linear systems, meanwhile in [76] an adaptive neural network backstepping controller for fractional order nonlinear systems with actuator failures was investigated, on the other hand the papers [77, 78, 79, 80] propose a fuzzy adaptive control strategy against actuator faults.

2.2.3 PID-Based FTC

Moreover some works have been concerned with the implementation of fractional order PID (FO-PID) controllers in efficient fault tolerant control structures [81, 82, 83], for example in [84, 85] the authors were able to showcase the superior performances of such controllers compared to their integer order counterparts in dealing with unexpected faults, and in [86] the design of a FOPID controller combined with a fractional active disturbance rejection controller was able to provide satisfactory control and robustness for reentry flight control of hyper-sonic aircraft under actuator faults. In the mean time, in [87] a so-called Tilt Integral Derivative (TID) which is a type of FOPID controller where the Proportional action is replaced by Fractional integrator of order $1/n$ was proposed and successfully implemented for the level control of a two tanks system in the presence of actuator and components faults; whereas in [88] a FOPID controller along with a Tilt PID T-PID controller were design for the voltage control of a self-excited induction generator subjected to voltage sensor faults.

2.2.4 Feedback Control-Based FTC

On top of that, fractional order feedback controllers for fault compensation were also studied; in [43] and [89] the authors developed fractional adaptive state feedback controllers able to ensure closed loop stability in presence of actuator faults, and in [45] a fractional output feedback control law was constructed for the control of fractional order interval systems with sensor faults, whereas in [90, 91] the authoes designed a fractional dynamic output feedback controller structure for robust system stabilization under actuator faults.

2.2.5 Backstepping Control-Based FTC

Additionally, researchers investigated other approaches such as eigen structure assignement control technique [92], fractional backstepping control [93, 94, 95] such in [95] a backstepping fault tolerant control strategy was adopted for uncertain fractional order nonlinear systems with unknown control direction.

3. Classification of FOFTC Based on Systems Type

Similar to the integer order case, the fractional fault tolerant control has been investigated and implemented for various classes of systems, at the outset we can divide said classes into two main categories; namely the integer order systems and fractional order system.

Integer-order systems: Given the attractive features the fractional order controllers offer in terms of improved system behavior, flexibility in the design and an ever increasing ease of use and implementation, researchers were drawn to the idea of incorporating the fractional order operators in the fault accommodation or fault detection structure for conventional models of integer systems that represent real world physical systems [96]. This is illustrated in [70] where the authors considered a FONTSM control law to achieve actuator fault compensation for an integer order model of legged robot systems, or in [97] whereupon a fractional order modeling scheme was utilized for the external short circuit fault diagnosis in lithium ion batteries.

Other applications include unmanned aerial vehicles (UAV) [98, 99, 100, 101, 102], rigid spacecraft [67, 32], autonomous underwater vehicles (AUV) [92], hydraulic turbines [103] and wind turbines [65, 57, 104], high speed trains [105, 106, 107, 108], robotic manipulators [109, 51], and industrial processes [110]. However, despite these advantages there are few drawbacks worth mentioning for this field: one of which is the increase in complexity.

Fractional order systems: The main results regarding fractional order fault diagnosis and fault tolerant control stem from the study of the fractional order systems, we can further categorize these contributions by system classes: Fractional commensurate systems [111, 112], linear systems [44, 56, 113], linearized systems [92], singular systems [43, 114], fractional order nonlinear systems [115, 116, 117, 118, 119], non strict nonlinear feedback systems [120], Lipschitz descriptor [121, 47], switched systems [122], time delayed fractional systems [53, 123, 124], Fuzzy fractional order systems [68, 73, 71, 125], fractional chaotic systems [60, 61, 126, 127], complex networked systems [128], multi-agent systems [129, 130, 131], multi-input single-output systems (MISO) [78], cyber-physical systems [132], and Markovian systems [133].

One of the main drawbacks for these approaches lies in the increase in complexity associated with introducing the fractional operators, especially during the stability analysis, although when dealing with fractional order systems or plants described by fractional differential equations, the stability analysis phase is rather systematic like in integer order control, due to the fact that many stability analysis results have been extended to the case of fractional order systems like Lyapunov theorem [134, 135].

4. Fractional Adaptive Actuator Failure Compensation for a Class of Linear Systems

In this section we will design a new controller structure for accommodating actuator failure by using a fractional sliding surface with an adaptive parameter update law as represented in Fig. 1.

4.1. Basic Elements of Fractional Order Sliding Surfaces

Sliding mode control is a particular type of variable structure control (VSC) designed to constrain system states to remain withing a neighborhood of the sliding surface by a switching function, this enables the behavior of the controlled system to be adjusted based on the selection of the switching function. This control technique has the advantage of being robust to a particular class of uncertainties. Sliding mode control can be extended to fractional order systems, either by using fractional order sliding surfaces or by using he equivalent controller structure with fractional order elements [136].

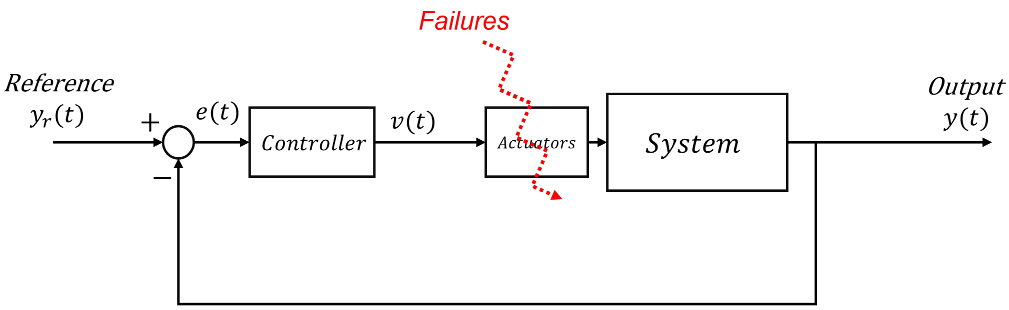


Fig. 1. Control loop under actuator failures

For the integer order cases consider the following double integrator system

$$\ddot{y}(t) = u(t) \tag{1}$$

Initially consider the following feedback control law

$$u(t) = -ky(t), \quad k \in \mathbb{R}^+ \tag{2}$$

by substituting the input into (1), multiplying both sides by $\dot{y}$, and integrating we get the following relationship

$$\dot{y}^2 + ky^2 = c \tag{3}$$

where $c > 0$, this corresponds to an ellipse; the control law does not make the position and velocity move towards the origin, hence it is not appropriate [137].

Consider now the control law

$$u(t) = \begin{cases} -k_1 y(t), & y\dot{y} < 0 \\ -k_2 y(t), & otherwise \end{cases} \tag{4}$$

where $0 < k_1 < 1k_2$, an asymptotically stable motion is obtained, where the variables go towards zero.

By defining the switching function

$$\mathbf{S}(y, \dot{y}) = my + \dot{y}, \quad m \in \mathbb{R}^+ \tag{5}$$

and using the variable structure control law given by

$$u(t) = \begin{cases} -1, & \mathbf{S}(y, \dot{y}) > 0 \\ 1, & \mathbf{S}(y, \dot{y}) < 0 \end{cases} \tag{6}$$

or, alternatively

$$u(t) = -\operatorname{sign}(\mathbf{S}(t)) \tag{7}$$

High-frequency switching between the two different control structures will take place as the system trajectories repeatedly cross the line defined by

$$\mathcal{L}_s = \{(y, \dot{y}) : \mathbf{S}(y, \dot{y}) = 0\} \tag{8}$$

which will confine the trajectories and make them 'slide' along the line $\mathcal{L}_s$, this behavior is described as *ideal sliding motion* [137].

The switching function satisfies $\mathbf{S} = 0$ for all $t \geq t_s$, which also satisfies

$$\dot{\mathbf{S}}(t) = m\dot{y}(t) + \ddot{y}(t) = m\dot{y}(t) + u(t) = 0 \tag{9}$$

The equivalent control law maintaining the motion on the line $\mathcal{L}_s$ is selected as

$$u(t) = -m\dot{y}(t), \quad (t \geq t_s) \tag{10}$$

For the fractional order case, (5) can be generalized as follows

$$\mathbf{S}(y, \mathcal{D}^\alpha y) = my + \mathcal{D}^\alpha y, \ 0 < \alpha < 1 \tag{11}$$

When the sliding motion occurs, $\mathbf{S}(y, \mathcal{D}^\alpha y) = 0$ the following differential equation is satisfied

$$\mathcal{D}^\alpha y = -my \tag{12}$$

This corresponds to a fractional order integrator in closed loop. The equivalent control law (10) can be obtained as follows

$$\begin{aligned} \mathbf{S} = my + y^{(1+\alpha)} \Longrightarrow & \dot{\mathbf{S}} = m\dot{y} + \mathcal{D}^{(2+\alpha)}y = m\dot{y} + u^{(\alpha)} = 0 \\ & \Longrightarrow u = -my^{(1-\alpha)} \end{aligned} \tag{13}$$

In order to minimize t_s and to reduce the amplitudes of the high-frequency switching, the following control law is proposed [136]

$$u(t) = -m\mathcal{D}^{(1-\alpha)}y - \rho\mathcal{I}^\beta \operatorname{sign}(\mathbf{S}(t)), \quad 0 < \alpha, \beta < 1 \tag{14}$$

By taking into account (11) and (14), we have

$$\begin{aligned} \dot{\mathbf{S}} &= m\dot{y} + \mathcal{D}^{(2+\alpha)}y = m\dot{y} - m\dot{y} - \rho\mathcal{I}^{\beta-\alpha} \operatorname{sign}(\mathbf{S}(t)) \\ &= -\rho\mathcal{I}^{\beta-\alpha} \operatorname{sign}(\mathbf{S}(t)) \end{aligned} \tag{15}$$

Taking into account that

$$\mathcal{I}^\mu \operatorname{sign}(x) = \begin{cases} \mathcal{I}^\mu\{1\}, & x \geq 0 \\ \mathcal{I}^\mu\{-1\}, & x < 0 \end{cases} \tag{16}$$

and using the Riemann-Liouville definition for the fractional-order derivative, it can be concluded that

$$\operatorname{sign}\left[\mathcal{I}^\mu \operatorname{sign}(x)\right] = \operatorname{sign}(x), \quad -1 < \mu < 1 \tag{17}$$

So, for $\rho > 0$, and $-1 < \beta - \alpha < 1, \mathbf{S} > 0$ implies $\dot{\mathbf{S}} < 0$, and $S < 0$ implies $\dot{\mathbf{S}} > 0$, and the reachability condition $\mathbf{S}\dot{S} < 0$ is always satisfied [136].

4.2. Actuator Faults Modeling

We consider the following actuator fault pattern

$$u_j^f(t) = \overline{u}_j(t), \quad t \geq t_j, \quad j = 1, 2, 3 \tag{18}$$

The constant value $\overline{u}_j(t)$ and the time of occurrence t_j are unknown. Equation (18) describes a lock in place fault, which is very common to encounter in flight control systems such as rudder and ailerons [99].

In order to take account of time varying faults the pattern (18) is remodeled as,

$$u_j^f(t) = \overline{u}_j + \overline{d}_j(t), \quad t \geq t_j, \quad j = 1, 2, 3 \tag{19}$$

With

$$\overline{d}_j(t) = \sum_{l=1}^{n_d} \overline{d}_{jl} f_{jl}(t) \tag{20}$$

for unknown constant values $\overline{d}_{jl}$ and known signals $f_{jl}(t), j = 1, \ldots, m, l = 1, \ldots, n_d, \quad n_d \geq 1$.

The actuator failure model given in (19) can be used to approximate a great number of failure cases, by a judicious choice of the basic functions $f_{jl}(t)$ [8].

In the presence of actuator faults, $u(t)$ can be expressed as [138],

$$u(t) = \rho v(t) + \sigma \left(u^f(t) - \rho v(t) \right) = \rho(I - \sigma)v(t) + \sigma u^f(t) \tag{21}$$

where u is the system input, v is the controller output, $\overline{u}$ is the additive fault signal. $\sigma = diag\{\sigma_1, \sigma_2, \sigma_3\}$, with $\sigma_j = 1$ if the j^{th} actuator has a failure and $\sigma_j = 0$ otherwise.
$\rho = diag\{\rho_1, \rho_2, \rho_3\}$. For lock-in-place, $\rho = 0$; for loss of effectiveness, $0 < \rho_i < 1$, $i = 1 : 3$ and $\overline{u} = 0$.

By taking: $\bar{b} = b(I - \sigma)\rho$ we can write

$$u(t) = \bar{b}v(t) + \sigma u^f(t) \tag{22}$$

In order to address the lock-in place fault, the following redundant condition assumption is considered [8]:

Assumption 1 *It is assumed that all the actuator of the studied system are redundant, meaning they perform the same task for the control of the system.*

Remark 1 *It is important to clarify that the problem of actuator redundancy is inherent to the system structure, meaning that redundant actuators of the same nature with similar structure must be present (available) before the design of the controller. Additionally we will consider a class of systems where all the redundant actuators are governed by the same control signal (to be designed), such control scheme is referred to as equal actuation scheme [57].*

$$v_1(t) = v_2(t) = \ldots = v_m(t)$$

With respect to Assumption 1, with an equal actuation scheme, a MISO control system with redundant and similar actuators can be simplified to a SISO system, and only having to design one control signal $v_0(t)$ that will govern all the redundant actuators [139].

For the remainder of this chapter, we will utilize (22) to describe the control system subjected to actuator faults.

4.3. Fractional Adaptive Controller Design for a Class of Linear Systems

In this work, we consider the class of linear second order systems defined by the controllable canonical state representation with m redundant actuators of the form

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx \end{aligned} \tag{23}$$

with $A = \begin{bmatrix} 0 & 1 \\ -a_1 & -a_2 \end{bmatrix}$, $B = \begin{bmatrix} 0 & 0 & \dots & 0 \\ b_1 & b_2 & \dots & b_m \end{bmatrix} \in \Re^{2\times m}$, $C = [1 \;\; 0]$.

In the presence of actuator failures described by (22), equation (23) can be rewritten as

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = -\sum_{j=1}^{2} a_j x_j + \sum_{j=1}^{m} b_j u_j \\ y = x_1 \end{cases} \tag{24}$$

or

$$\ddot{y} = -\sum_{j=1}^{2} a_j x_j + \sum_{j=1}^{m} b_j u_j \tag{25}$$

where u_j, $j = 1, ..., m$ are the input actuators which may fail during system operation. Actuator failures may be typically modelled as:

$$u_j(t) = \bar{u}_j(t), \quad for\; t \geq t_j$$

where t_j is the time instant at which the j-th actuator fails.

Regarding the redundant structure of the system, in the presence of possible actuator failures and using an equal or proportional actuation scheme, each system input $u_j(t)$ can be expressed as follows:

$$u_j(t) = (1 - \sigma_j(t))\, \gamma_j v(t) + \sigma_j(t)\bar{u}_j(t) \tag{26}$$

with $\sigma_j = 1$ if the j-th actuator fails and $\sigma_j = 0$ otherwise, v is a scalar control input signal to be designed, and γ_j a coefficient describing the contribution the j-th actuator.

Using (26), (25) can be rewritten as

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = -\sum_{j=1}^{2} a_j x_j + \sum_{j=1}^{m} b_j\left((1 - \sigma_j(t))\gamma_j(t)v(t) + \sigma_j(t)\bar{u}_j(t)\right) \end{cases} \tag{27}$$

Which can be written into the following compact form

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = -\sum_{j=1}^{2} a_j x_j + \bar{b}v + \sum_{j=1}^{m} b_j \sigma_j \bar{u}_j \end{cases} \tag{28}$$

where

$$\bar{b} = \sum_{j=1}^{m} b_j(1 - \sigma_j(t))\gamma_j(t)$$

and

$$\bar{u} = [\bar{u}_1 ... \bar{u}_m]^T$$

Let us take the output $y = x_1$, we define the tracking error as

$$e(t) = y_r(t) - y(t) \tag{29}$$

Let us define the following fractional order sliding surface

$$s(t) = \mathcal{D}^{\alpha} e(t) + \lambda e(t) \tag{30}$$

Using the properties of the fractional order derivative [140] (p. 46, p. 74), considering a zero initial condition $e(0) = 0$, we have,

$$e(t) = \int_0^t \dot{e}(\tau)d\tau = D^{-1}\dot{e}(t) \tag{31}$$

Equation (30) can be rewritten as

$$s(t) = \mathcal{D}^{\alpha-1}\dot{e}(t) + \lambda e(t) \tag{32}$$

Taking the time derivative of $s(t)$ we get

$$\dot{s} = \mathcal{D}^{\alpha-1}\ddot{e} + \lambda\dot{e} = \mathcal{D}^{\alpha-1}\left(\ddot{y_r} - (-\sum_{j=1}^{2} a_j x_j + \bar{b}v + \sum_{j=1}^{m} b_j\sigma_j\bar{u}_j)\right) + \lambda\dot{e} \tag{33}$$

Denoting $h = \mathcal{D}^{\alpha-1}\ddot{y_r} + \lambda\dot{e}$, we have

$$\dot{s} = -\mathcal{D}^{\alpha-1}(-\sum_{j=1}^{2} a_j x_j + \bar{b}v + \sum_{j=1}^{m} b_j\sigma_j\bar{u}_j) + h \tag{34}$$

The equivalent control law is given by

$$v_{eq} = \frac{1}{\bar{b}}\left(\sum_{j=1}^{2} a_j x_j - \sum_{j=1}^{m} b_j\sigma_j\bar{u}_j + \mathcal{D}^{1-\alpha}h + k_1\mathcal{D}^{1-\alpha}s + k_0 sign(s)\right) \tag{35}$$

In order to avoid the chattering phenomenon caused by high frequency switching of the sliding mode control, sign function is replaced the hyperbolic tangent function $\tanh(.)$, thus (35) becomes,

$$v_{eq} = \frac{1}{\bar{b}}\left(\sum_{j=1}^{2} a_j x_j - \sum_{j=1}^{m} b_j\sigma_j\bar{u}_j + \mathcal{D}^{1-\alpha}h + k_1\mathcal{D}^{1-\alpha}s + k_0 \tanh(s/\epsilon)\right) \tag{36}$$

Replacing (36) in (34) we obtain

$$\dot{s} = -k_1 s - k_0\mathcal{D}^{\alpha-1}\tanh(s/\epsilon) \tag{37}$$

The problem is that the parameters a_j, $\bar{u}_j$, σ_j are unknown, so the equivalent control law (35) cannot be implemented.

Instead we propose the following adaptive control law [141]:

$$v = \theta^T E - \sum_{j=1}^{m} \beta_j^T \omega_j \tag{38}$$

where

$$\begin{cases} \beta_j^T = b_j\sigma_j[\bar{u}_j \; d_{j1} \; d_{j2} \; ... \; d_{jn_j}] \\ \omega_j^T = [1 \; f_{j1} \; f_{j2} \; ... \; f_{jn_j}] \\ E = \left[\mathcal{D}^{-\alpha}e, \mathcal{D}^{1-\alpha}e, \dot{e}\right] \\ \theta = [\theta_1, \theta_2, \theta_3]^T \end{cases} \tag{39}$$

where ω_j and E are regression vectors, and β_j and θ are parameters' vectors.

Let us denote v^* the optimal value of v, we have

$$v^* = \theta^{*T} E - \sum_{j=1}^{m} \beta_j^{*T}\omega_j + \varepsilon(E) \tag{40}$$

where $\varepsilon(E)$ is the optimal approximation error for v.

We impose the following assumption on the approximation error:

Assumption 2 *For all actuator failures, $\varepsilon(E)$ is bounded as follows*

$$\varepsilon^2(E) \leq \varepsilon_0 s^2 + \varepsilon_1 \tag{41}$$

Where ε_0 and ε_1 are positive constants.

We have

$$e_v = v^* - v = \tilde{\theta}^T E - \sum_{j=1}^{m} \tilde{\beta}_j^{*T} \omega_j + \varepsilon(E) \tag{42}$$

Where $\tilde{\theta} = \theta^* - \theta$ and $\tilde{\beta}_j = \beta_j^* - \beta_j$.

By adding and subtracting $\mathcal{D}^{\alpha-1}(\bar{b}v^*)$ to (34) we obtain

$$\dot{s} = \mathcal{D}^{\alpha-1}\bar{b}(v^* - v) - \mathcal{D}^{\alpha-1}(-\sum_{j=1}^{2} a_j x_j + \bar{b}v^* + \sum_{j=1}^{m} b_j \sigma_j \bar{u}_j) + h \tag{43}$$

Using (36) we get

$$\dot{s} = \mathcal{D}^{\alpha-1}\bar{b}e_v - k_1 s - k_0 \mathcal{D}^{\alpha-1} \tanh(s/\epsilon) \tag{44}$$

Consider the following quadratic cost function of the error

$$\begin{aligned} J(\theta, \beta) &= \frac{1}{2}\bar{b}\left(e_{v_e} + \sum_{j=1}^{m} e_{v_{fj}}\right)^2 \\ &= \frac{1}{2}\bar{b}(v^* - \theta^T E - \sum_{j=1}^{m} \beta_j^{*T}\omega_j)^2 \end{aligned} \tag{45}$$

where e_{v_e} and $e_{v_{fj}}$ are the gap between the controls v_e , v_{fj} and the unknown optimal values v_e^*, v_{fj}^*, $j = 1, ..., m$.

Using the gradient descent method, the update laws for parameters vectors that minimizes (45) are given by

$$\begin{aligned} \dot{\theta} &= -\eta_1 \nabla_\theta J(\theta, \beta) \\ \dot{\beta}_j &= -\eta_2 \nabla_{\beta_j} J(\theta, \beta) \qquad j = 1, ..., m \end{aligned} \tag{46}$$

We have $\nabla_\theta J(\theta, \beta) = -E\bar{b}e_v$ and $\nabla_{\beta_j} J(\theta, \beta) = \omega_j \bar{b}e_v$, hence

$$\begin{aligned} \dot{\theta} &= \eta_1 E\bar{b}e_v \\ \dot{\beta}_j &= -\eta_2 \omega_j \bar{b}e_v \qquad j = 1, ..., m \end{aligned} \tag{47}$$

The term $\bar{b}e_v$ is unavailable, however it can be extracted from (44) as follows

$$\mathcal{D}^{\alpha-1}\bar{b}e_v = \dot{s} + k_1 s + k_0 \mathcal{D}^{\alpha-1} \tanh(s/\epsilon) \tag{48}$$

We get

$$\begin{aligned} \bar{b}e_v &= \mathcal{D}^{1-\alpha}(\dot{s} + k_1 s + k_0 \mathcal{D}^{\alpha-1} \tanh(s/\epsilon)) \\ &= \mathcal{D}^{1-\alpha}(\dot{s} + k_1 s) + k_0 \tanh(s/\epsilon) \end{aligned} \tag{49}$$

Replacing (49) in the adaptive law and adding a σ-modification term to improve the robustness of the adaptive law we obtain

$$\begin{cases} \dot{\theta} = \eta_1 E(\mathcal{D}^{1-\alpha}(\dot{s} + k_1 s) + k_0 \tanh(s/\epsilon)) - \eta\hat{\sigma}\theta \\ \dot{\beta}_j = -\eta_2 \omega_j (\mathcal{D}^{1-\alpha}(\dot{s} + k_1 s) + k_0 \tanh(s/\epsilon)) - \eta\hat{\sigma}\beta_j \qquad j = 1, ..., m \end{cases} \tag{50}$$

Where $\hat{\sigma}$ is a small positive constant.

4.4. Stability Analysis

The main purpose of this section is to perform the stability properties of the proposed fractional order adaptive robust controller in presence of actuator faults in a second order linear system with redundant actuators. These properties are stated in the following theorem.

Theorem 1 *Consider a second order linear system with redundant actuators (23) with actuator faults verifying Assumption 2. Given the designed fractional order sliding surface (30), by employing the adaptive control law (38) that is updated by (50), the desired tracking performance can be guaranteed and the closed loop system is asymptotically stable.*

Proof: Let us choose the following Lyapounov candidate function

$$V = \frac{1}{2}s^2 + \frac{1}{2\eta_1}\tilde{\theta}^T\tilde{\theta} + \frac{1}{2\eta_2}\sum_{j=1}^{m}\tilde{\beta}_j^T\tilde{\beta}_j \tag{51}$$

Its time derivative is given as follows

$$\dot{V} = s\dot{s} - \frac{1}{\eta_1}\tilde{\theta}^T\dot{\theta} + \frac{1}{\eta_1}\tilde{\theta}^T\dot{\theta}^* - \frac{1}{\eta_2}\sum_{j=1}^{m}\tilde{\beta}_j^T\dot{\beta}_j + \frac{1}{\eta_2}\sum_{j=1}^{m}\tilde{\beta}_j^T\dot{\beta}_j^* \tag{52}$$

Using (44) and (50), (52) gives,

$$\begin{aligned}\dot{V} =& s(\mathcal{D}^{\alpha-1}\bar{b}e_v - k_1 s - k_0\mathcal{D}^{\alpha-1}\tanh(s/\epsilon)) - \frac{1}{\eta_1}\tilde{\theta}^T(\eta_1 E\bar{b}e_v - \eta_1\sigma\theta) \\ &+ \frac{1}{\eta_1}\tilde{\theta}^T\dot{\theta}^* + \frac{1}{\eta_2}\sum_{j=1}^{m}\tilde{\beta}_j^T\left(\eta_2\omega_j\bar{b}e_v + \eta_2\hat{\sigma}\beta_j\right) + \frac{1}{\eta_2}\sum_{j=1}^{m}\tilde{\beta}_j^T\dot{\beta}_j^*\end{aligned} \tag{53}$$

$$\begin{aligned}\dot{V} =& -k_1 s^2 - k_0 s\mathcal{D}^{\alpha-1}\tanh(s/\epsilon) + s\mathcal{D}^{\alpha-1}\bar{b}e_v - (e_v - \varepsilon(E))\bar{b}e_v + \sigma\tilde{\theta}^T\theta + \frac{1}{\eta_1}\tilde{\theta}^T\dot{\theta}^* \\ &+ \sum_{j=1}^{m}\hat{\sigma}\tilde{\beta}_j^T\beta_j + \frac{1}{\eta_2}\sum_{j=1}^{m}\tilde{\beta}_j^T\dot{\beta}_j^* \\ =& -k_1 s^2 - k_0 s\mathcal{D}^{\alpha-1}\tanh(s/\epsilon) + s\mathcal{D}^{\alpha-1}\bar{b}e_v - \bar{b}e_v^2 + \varepsilon(E)\bar{b}e_v + \sigma\tilde{\theta}^T\theta + \frac{1}{\eta_1}\tilde{\theta}^T\dot{\theta}^* \\ &+ \sum_{j=1}^{m}\hat{\sigma}\tilde{\beta}_j^T\beta_j + \frac{1}{\eta_2}\sum_{j=1}^{m}\tilde{\beta}_j^T\dot{\beta}_j^*\end{aligned} \tag{54}$$

From Assumption 2 and by the help of the following inequalities.

$$\sigma\tilde{\theta}^T\theta \leq -\frac{\sigma}{2}\|\tilde{\theta}\|^2 + \frac{\sigma}{2}\|\theta^*\|^2 \tag{55}$$

$$\sigma\tilde{\beta}_j^T\beta_j \leq -\frac{\sigma}{2}\|\tilde{\beta}_j\|^2 + \frac{\sigma}{2}\left\|\tilde{\beta}_j^*\right\|^2 \tag{56}$$

$$\frac{1}{\eta_1}\tilde{\theta}^T\dot{\theta}^* \leq \frac{\sigma}{4}\|\tilde{\theta}\|^2 + \frac{1}{\sigma\eta_1^2}\left\|\dot{\theta}^*\right\|^2 \tag{57}$$

$$\frac{1}{\eta_2}\tilde{\beta}_j^T\dot{\beta}_j^* \leq \frac{\sigma}{4}\|\tilde{\beta}_j\|^2 + \frac{1}{\sigma\eta_2^2}\left\|\dot{\beta}_j^*\right\|^2 \tag{58}$$

$$\begin{aligned}\varepsilon(E)\bar{b}e_{v_0} &\leq \frac{1}{4}\bar{b}e_{v0}^2 + \bar{b}\varepsilon^2(E) \\ &\leq \frac{1}{4}\bar{b}e_{v0}^2 + \bar{b}\left(\varepsilon_0 s^2 + \varepsilon_1\right)\end{aligned} \tag{59}$$

$$s\mathcal{D}^{\alpha-1}\bar{b}e_v \leq \frac{1}{4}b(x)e_{v0}^2 + \bar{b}s^2 \tag{60}$$

Equation (54) can be bounded as follows

$$\begin{aligned}\dot{V} \leq &- k_1 s^2 - k_0 s\mathcal{D}^{\alpha-1}\tanh(s/\epsilon) + \frac{1}{4}\bar{b}e_{v0}^2 + \bar{b}s^2 - \bar{b}e_v^2 \\ &+ \frac{1}{4}\bar{b}e_{v0}^2 + \bar{b}\left(\varepsilon_0 s^2 + \varepsilon_1\right) - \frac{\sigma}{2}\|\tilde{\theta}\|^2 + \frac{\sigma}{2}\|\theta^*\|^2 \\ &+ \frac{\sigma}{4}\|\tilde{\theta}\|^2 + \frac{1}{\sigma\eta^2}\left\|\dot{\theta}^*\right\|^2 - \frac{\sigma}{2}\sum_{j=1}^{m}\|\tilde{\beta}_j\|^2 + \frac{\sigma}{2}\sum_{j=1}^{m}\left\|\tilde{\beta}_j^*\right\|^2 \\ &+ \frac{\sigma}{4}\sum_{j=1}^{m}\|\tilde{\beta}_j\|^2 + \frac{1}{\sigma\eta_2^2}\sum_{j=1}^{m}\left\|\dot{\beta}_j^*\right\|^2\end{aligned} \tag{61}$$

Thus

$$\begin{aligned}\dot{V} \leq &- (k_1 - \bar{b}(1+\varepsilon_0))s^2 - k_0 s\mathcal{D}^{\alpha-1}\tanh(s/\epsilon) - \frac{\sigma}{4}\|\tilde{\theta}\|^2 \\ &- \frac{1}{2}\bar{b}e_{v0}^2 + \frac{\sigma}{2}\|\theta^*\|^2 + \frac{1}{\sigma\eta^2}\left\|\dot{\theta}^*\right\|^2 - \frac{\sigma}{4}\sum_{j=1}^{m}\|\tilde{\beta}_j\|^2 \\ &+ \frac{\sigma}{2}\sum_{j=1}^{m}\left\|\tilde{\beta}_j^*\right\|^2 + \frac{1}{\sigma\eta_2^2}\sum_{j=1}^{m}\left\|\dot{\beta}_j^*\right\|^2 + \bar{b}\varepsilon_1\end{aligned} \tag{62}$$

We define a positive bound ψ_i for each failure pattern i

$$\psi_i = \sup_{t\in[t_i,t_{i+1})}\left(\frac{\sigma}{2}\|\theta^*\|^2 + \frac{1}{\sigma\eta^2}\left\|\dot{\theta}^*\right\|^2 + \frac{\sigma}{2}\sum_{j=1}^{m}\left\|\tilde{\beta}_j^*\right\|^2 + \frac{1}{\sigma\eta_2^2}\sum_{j=1}^{m}\left\|\dot{\beta}_j^*\right\|^2 + \bar{b}\varepsilon_1\right) \tag{63}$$

Equation (62) becomes

$$\begin{aligned}\dot{V} \leq &- \frac{1}{2}\bar{b}e_{v0}^2 - (k_1 - \bar{b}(1+\varepsilon_0))s^2 - k_0 s\mathcal{D}^{\alpha-1}\tanh(s/\epsilon) \\ &- \frac{\sigma}{4}\|\tilde{\theta}\|^2 - \frac{\sigma}{4}\sum_{j=1}^{m}\|\tilde{\beta}_j\|^2 + \psi_i\end{aligned} \tag{64}$$

Assuming that $|\bar{b}| < B$, the parameter k_1 is chosen such that: $k_1 > (1+\varepsilon_0)B$

Define: $\bar{\beta} = min\left(2(k_1 - B(1+\varepsilon_0)), \frac{1}{2}\sigma\eta_1, \frac{1}{2}\sigma\eta_2\right)$, we can write [139]

$$\dot{V} \leq -\frac{1}{2}\bar{b}e_{v0}^2 - k_0 s\mathcal{D}^{\alpha-1}\tanh(s/\epsilon) - \frac{\bar{\beta}}{2}s^2 - \frac{\bar{\beta}}{2\eta_1}\|\tilde{\theta}\|^2 - \frac{\bar{\beta}}{2\eta_2}\sum_{j=1}^{m}\|\tilde{\beta}_j\|^2 \tag{65}$$

Thus

$$\dot{V} \leq -\bar{\beta}V + \psi_i \tag{66}$$

Given that $V \geq \frac{\psi_i}{\bar{\beta}}$ we have $\dot{V} \leq 0$.

5. Simulation Example: Actuator FOFTC for Lateral Dynamics of a Boeing 747

The Boeing 747 is an intercontinental large body transport aircraft [16], the full dynamic equations describing the flight of the Boeing 747 are of eighth order, however for control purposes they are usually decoupled into two fourth order subsystems [17], one represents the longitudinal motion with the altitude and pitching movements, and the other represents the lateral motion defined by rolling and yawing movements, the linearized lateral motion dynamics of the Boeing 747 in horizontal flight at $40,000ft$ and forward speed of $U_0 = 774ft/sec(0.8\text{Mach})$ are

$$\dot{x}(t) = Ax(t) + Bu(t) \tag{67}$$

with

$$A = \begin{bmatrix} -0.0558 & -0.9968 & 0.0802 & 0.0415 \\ 0.598 & -0.115 & -0.0318 & 0 \\ -3.05 & 0.388 & -0.456 & 0 \\ 0 & 0.0805 & 1 & 0 \end{bmatrix} \tag{68}$$

$$B = \begin{bmatrix} 0.00729 \\ -0.475 \\ 0.1532 \\ 0 \end{bmatrix}$$

The state vector is defined $x(t) = [\beta, y_r, p, \phi]^T$ where β is the side-slip angle, y_r represents the yaw rate, p is the roll rate, and ϕ is the roll angle. The control is provided by the rudder $u(t) = \delta_r(t)$, and we chose the yaw rate y_r as the output $y(t) = x_2(t)\, y_r(t)$.

In order to ensure actuator redundancy needed for failure compensation, we add two more rudder segments δ_{r2} and δ_{r3}, thus the input matrix of augmented system becomes [3].

$$B = [b_1, b_2, b_3] = \begin{bmatrix} 0.00729 & 0.01 & 0.005 \\ -0.475 & -0.5 & -0.3 \\ 0.1532 & 0.2 & 0.1 \\ 0 & 0 & 0 \end{bmatrix} \tag{69}$$

5.1. Simulation Results

In the following we will study the effectiveness of the proposed fractional order fault tolerant controller by performing numerical simulations for the control of the lateral motion dynamics of the Boeing 747 subjected to actuator failures, for that matter we will use the model given in (68) with redundant actuators according to the augmented actuation scheme (69) see Fig. 2. The simulations are performed in MATLAB/Simulink using the FOMCON toolbox [22]. The parameters and initial conditions of all the subsequent simulations are given in Table 1.

In addition, for the Fourier series basis functions we will take the time period $T = 200\ sec$ and $N = 10$ (21 components). In order to demonstrate the controller's ability to handle failures in various flight conditions, two failure scenarios are considered for two different reference signals: $y_r(t) = 0\ rad/s$ for the stabilization of the yaw rate, and $y_r(t) = 0.01\ \sin(0.1\pi t)$ for the tracking of a sinusoidal trajectory, the failure scenarios are presented as follows:

Scenario 1: The third actuator fails at $t = 10s$ and becomes stuck $(u_3^f(t) = 0.02\ rad)$, and at $t = 50s$ the second actuator fails and oscillates according to the following pattern $u_2^f(t) = 0.03\sin(0.1t)$. The response of the system is shown in Fig. 3 and Fig. 4, we can clearly see that despite the occurrence of actuator failures and the sudden jumps observed at $t = 10s$ and $t = 50s$ caused by the abrupt loss of control of the third and second actuators respectively, the controller managed to efficiently keep the output very close to the reference. We can also notice from the control input values that the healthy actuators will accommodate for the deviations of the faulty actuators. Control signals in Fig. 3 and Fig. 4 show that the signal V_f was able to efficiently approximate all the failure values.

Fig. 2. Boeing 747 airplane

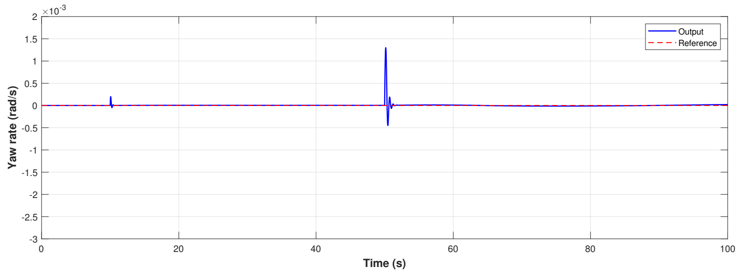
Table 1. Controller parameters values

Parameter	Value
k_1	2
k_0	2
γ_1	5
γ_2	0.01
σ	0.01
ϵ	0.01
λ	15
α	0.8

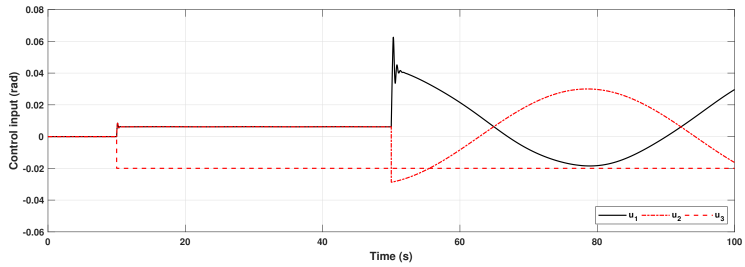
Scenario 2: The third actuator fails at $t = 10\ s$ and locks in-place at $u_3^f(t) = -0.02\ rad$, then at $t = 50\ s$ the second actuators also locks in place at $u_2^f(t) = 0.05\ rad$. System response and control inputs are displayed in Fig. 5 and Fig. 6, the controller ensures good tracking in the presence of the failures, healthy actuators are able to smoothly compensate for the abrupt jumps arising from the instant when an actuator fails, and the control performances are guaranteed with only one actuator that is still operational.

We can observe from control signals behavior in Fig. 5 and Fig. 6 that, when it is not equal to 0, the reference signal can influence the approximation of the failure signal in V_f, a proposed solution to eliminate this effect is to add the reference signal (and possibly its fractional order derivatives) in the regression vector E.

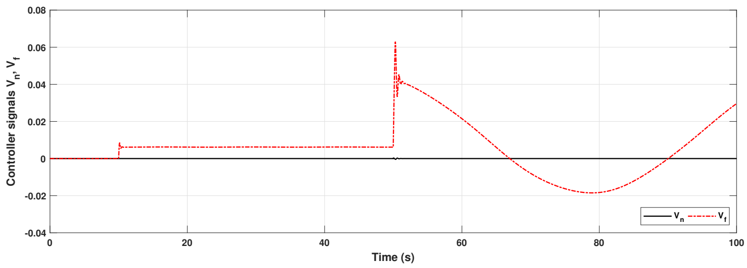
This example gives a clear idea of the feasibility and usefulness of this type of fault-tolerant fractional-order control. Several developments can be undertaken in future work among which the use of variants of the Kalman filter for a better identification of the loss of control effectiveness and the magnitude of the low degree of stuck faults in a closed-loop nonlinear B747 aircraft.



Yaw rate



Control inputs



Controller signals V_n, V_f

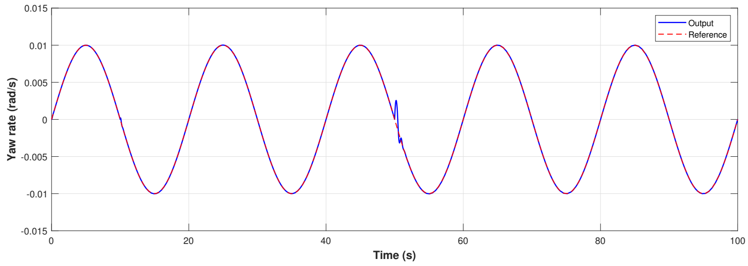
Fig. 3. Simulation results for scenario 1 (stabilization)

6. Conclusion

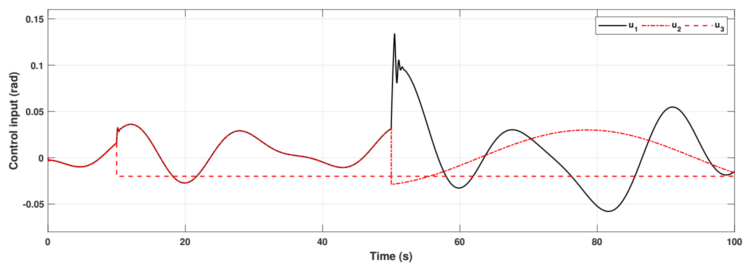
This paper presented an exhaustive state of the art review of the current works an advances in Fractional Fault tolerant control systems. It can be seen that this topic is attracting more and more researchers from both the fields of fault tolerant control and fractional order control due to its novelty and the tremendous potential that the fractional order control possesses in terms of flexibility in the design and improvement of performances. We have also discussed certain obstacles that we encounter in studying these approaches; however by virtue of its advantages and the gathered interest from the researchers, it is safe to assume this field of study will keep expanding and evolving, with new design techniques and deeper mathematical tools.

FOFTC control schemes are designed to deal with a wide class of systems, including non-integer order model processes, and provide an effective means of improving the robustness and performance of these controls against system failures. The major drawback is the increased complexity both in specifying the problem and modeling the system, and in diagnosing and designing the control. In order to illustrate the efficiency of such robust control strategies, a simulation example of an FOFTC against actuator faults applied to a Boeing 747 aircraft was provided with different actuator faults scenarios.

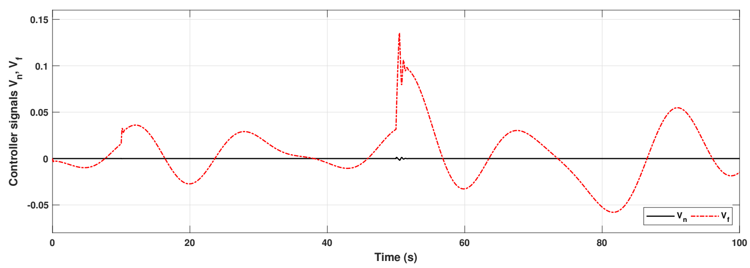
Author Contribution: All authors contributed equally to the main contributor to this paper. All authors read and approved the final paper.



Yaw rate



Control inputs



Controller signals V_n, V_f

Fig. 4. Simulation results for scenario 1 (tracking)

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Conflicts of Interest: The authors declare no conflict of interest.

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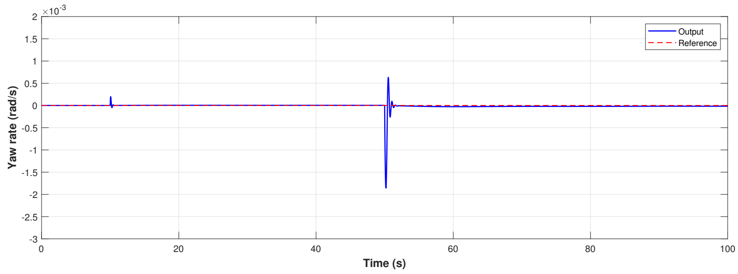
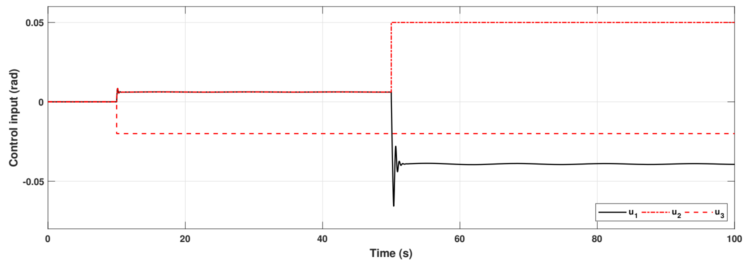
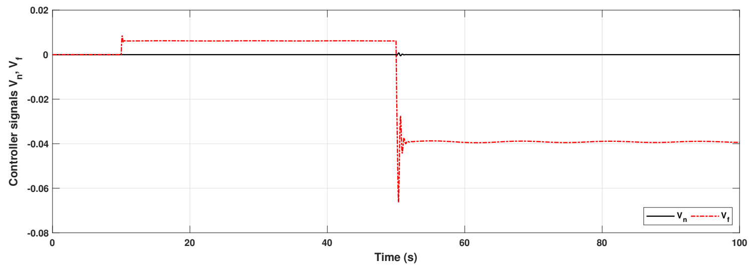


Yaw rate



Control inputs



Controller signals V_n, V_f

Fig. 5. Simulation results for scenario 2 (stabilization)

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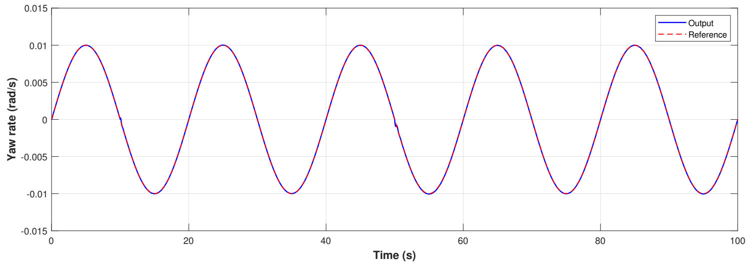
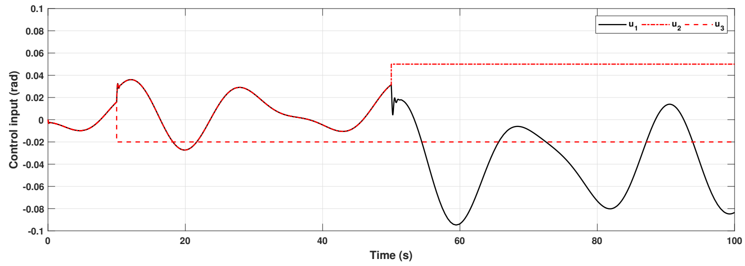
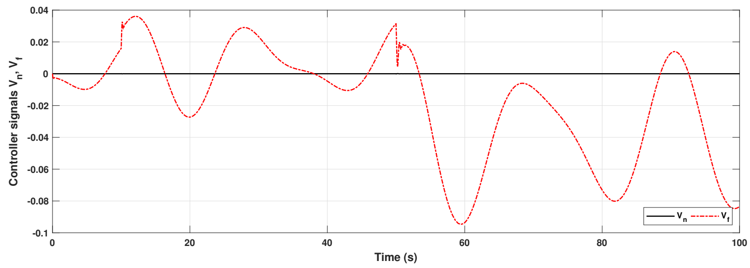


Yaw rate



Control inputs



Controller signals V_n, V_f

Fig. 6. Simulation results for scenario 2 (tracking)

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