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Fractional order modeling and control of dissimilar redundant actuating system used in large passenger aircraft

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Abstract In this paper, a methodology has been developed to address the issue of force fighting and to achieve precise position tracking of control surface driven by two dissimilar actuators. The nonlinear dynamics of both actuators are first approximated as fractional order models. Based on the identified models, three fractional order controllers are proposed for the whole system. Two Fractional Order PID (FOPID) controllers are dedicated to improving transient response and are designed in a position feedback configuration. In order to synchronize the actuator dynamics, a third fractional order PI controller is designed, which feeds the force compensation signal in position feedback loop of both actuators. Nelder-Mead (N-M) optimization technique is employed in order to optimally tune controller parameters based on the proposed performance criteria. To test the proposed controllers according to real flight condition, an external disturbance of higher amplitude that acts as airload is applied directly on the control surface. In addition, a disturbance signal function of system states is applied to check the robustness of proposed controller. Simulation results on nonlinear system model validated the performance of the proposed scheme as compared to optimal PID and high gain PID controllers.
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1. Introduction

Reliability of aircraft actuating system is of major concern when a new aircraft is designed. Traditional redundant actuating system, i.e. two similar actuators driving a single control surface, cannot meet the reliability requirement of large aircraft. The main reason is that if the fault occurs due to common reason, it may lead to the failure of whole actuating system. Therefore the use of Dissimilar Redundant Actuating System (DRAS) has become a good solution in modern

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aircraft in order to make the system more reliable.[1] DRAS used in this research consists of one Hydraulic Actuator (HA) and one Electro Hydraulic Actuator (EHA), and both drive one control surface in order to deliver large torque. Since the driving mechanisms of both actuators are different, failure of whole system due to common cause can be reduced effectively, and eventually the reliability of system increases.

Traditionally, there are two operating modes of DRAS: one is Active/Active (A/A) mode and the other is Active/Passive (A/P) mode.[2] In A/P mode, the passive channel is isolated from bypass valve. In A/A mode, both actuators drive one control surface simultaneously. Because of their different static and dynamic behavior, they cannot share load equally and often fight against one another to position the load. So a serious force fighting occurs on aileron plane that degrades the system performance and may damage the control surface.

Several control strategies have been proposed in literature to deal with force fighting issue and to achieve precise tracking of control surface, for example, in Refs.[3,4], integral action controller is proposed based on the information of position and force feedback and it was deduced that position feedback can reduce the force fighting more effectively as compared to force feedback. The authors[5,6] proposed states difference feedback controller to deal with force fighting which has been effectively reduced from 500% to 7% of stall load. PID controller,[7] due to its simple structure, is used to deal with dynamical force equalization. Also fuzzy PI controller is designed in a recent survey[8] for position and force synchronization of dissimilar redundant actuators, which also reduced force fighting effectively. Adaptive technique is employed[9] to decouple the HA and EHA, and feed-forward compensator is proposed to match the dynamics of both actuators. All such techniques need more accurate model of system in order to enhance the controller performance.

In recent years, fractional order calculus, which is a generalized version of integral order calculus, has gained more attention due to its accuracy in modeling the dynamics of systems and its simplicity in model structure to represent higher order processes. Identification of fractional order model has gained wide demand in scientific community despite of its difficult task because it requires not only the estimation of model parameters but also the determination of fractional power. Most of identification methods found in the literature are the extension of regular integer order systems, require a priori knowledge of the fractional differentiation orders, and estimate only the model's parameters.[10,11] However, very few papers are based on identification of both model parameters and differential power.[12] On the other hand, fractional order controllers show better transient performance when they are applied to fractional order systems. FOPID controller has been adopted in many applications such as speed control of DC motor,[13] torsional system's backlash vibration suppression control,[14] position tracking control of Electro Hydraulic Servo System (EHSS),[15] pitch and yaw angle control of Twin Rotor Aerodynamic System (TRAS),[16,17] motion control of gun control system[18] and so on. FOPID controller provides robustness, abundant dynamics, fine tracking and low sensitivity to external disturbances as compared to integral order controller.[19] In practical applications of FOPID controller, tuning of controller parameters is one of the most challenging problem. Closed-loop stability and tracking performance of system are highly influenced by setting controller gain to optimal value. To deal with such problem, various optimization techniques have been employed based on time domain[19,20] and frequency domain constraints.[21–23]

In this paper, three FOPID controllers are designed for nonlinear DRAS in order to reduce the force fighting and to precisely track the aircraft control surface. EHA/HA system used in A/A mode is under study. Prior to the controller design, fractional order models of both actuators are identified based on the input-output data from nonlinear system in which coefficients are estimated using Recursive Least Square (RLS) algorithm and fractional powers are adjusted using steepest descent algorithm so that square of error is minimized. Based on identified model, two FOPID controllers are designed for each actuator in position feedback configuration. The force fighting phenomenon is dealt with using third fractional order PI controller that feeds the force compensation signal in the position feedback loop of both actuators. Nelder-Mead (N-M) optimization technique is adopted to tune the controllers' parameters according to the design objectives based on both time and frequency domains. The performance of the proposed scheme is compared with a group of PID controllers that are designed for this system. In order to test the robustness of the proposed scheme, the control surface of aircraft is subjected to the influence of large air load.

The rest of the paper is organized as follows: the nonlinear model of DRAS is presented in Section 2. Section 3 consists of problem formulation and control strategy. Fractional order model identification and fractional power identification algorithms are discussed in Section 4. The overview of FOPID controller design is presented in Section 5 and it also covers the benefits in term of design freedom and stability region as compared to conventional PID controller. N-M optimization algorithm and performance criteria are explained in Section 6. Simulation results on a nonlinear model are presented in Section 7. Finally concluding remarks are given in Section 8 to show effectiveness of the proposed scheme.

1.1. Mathematical definitions

Definition 1. Grunwald Letnikov approximation[24] of fractional order system is defined as

$$D^{\alpha}x(t) = \lim_{h\to 0}\frac{1}{h^{\alpha}}\sum_{k=0}^{[t/h]}(-1)^{k}\binom{\alpha}{k}x(t-kh) \tag{1}$$

where h is sampling time and the operator, t/h is the number of approximation addends, D^{α} defines fractional differentiation or integration depends on the sign of λ. Newton binomial $\binom{\alpha}{k}$ is generalized to non-integer order using Eular function as

$$\binom{\alpha}{k} = \frac{\Gamma(\alpha+1)}{\Gamma(k+1)\Gamma(\alpha-k+1)} \tag{2}$$

where $\Gamma(\cdot)$ is the Gamma function.

Stability theorem 1.[25] *A fractional order transfer function $G(s) = N(s^{\zeta})/D(s^{\zeta})$, where $N(s^{\zeta})$ and $D(s^{\zeta})$ are coprime polynomials, is BIBO stable if and only if*

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