

Motion Synchronization Control For a Large Civil Aircraft's Hybrid Mechatronics Actuation System Using Observer-Based Backstepping Control

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Abstract

The electro-mechanical and servo-hydraulic actuators that make up the hybrid mechatronics actuation system must be synchronized in motion for all mechatronics applications, but particularly for big civil aircraft. Force-Fighting which is the difference of force between two actuators when both actuators are pushing together the control surface. Force-Fighting problem takes birth when both actuators are not synchronized in a hybrid mechatronics actuation system. The present research addresses the issue of Force-Fighting and aims to enhance motion synchronization. An observer-based backstepping control strategy is proposed to achieve synchronized motion in a hybrid mechatronics actuation system. Furthermore, Trajectory generates acceleration, velocity, and position signals at a frequency that both servo hydraulic and electro mechanical actuator can easily follow. Extended state observer is designed to cope the problems such as uncertainties, coupling terms, disturbances as well as unavailability of state signals which are very important for motion synchronization. In order to confirm whether the suggested approach is effective, simulation experiments are performed in Matlab/Simulink. A comparison was made between the results of this study and previously published works. Comparison shows that proposed strategy is more effective in reducing force Force-Fighting, improving load rejection performance and synchronizing motion in hybrid mechatronics actuation system.

Keywords: Backstepping Control; Motion Synchronization; Hybrid mechatronics actuation system, Electro mechanical Actuator; Servo Hydraulic actuators; Extended state observer, etc

I. INTRODUCTION

Actuator failure is one of the primary concerns in today's aviation vehicle control research. [1-4]. Recently, extensive research was done to outline every potential problem that can occur in aerospace vehicle systems, and Also, some of the authors have focused on the impact of safety to address these problems through artificial intelligence—[5, 6]. In order to improve reliability, safety and dependability, hybrid mechatronics actuation systems have been included into the main flight control systems. The Airbus A320 is one such example, which powers the elevator, rudder, and aileron with a hybrid mechatronics actuation system [7]. Actuators are a crucial part of the flight control system since they manage the motion and movement of the control surface of the aircraft [8]. For a long time, The aircraft's control surface was only powered by hydraulic power through actuators. Afterwards, the key topic became the safety and reliability for the flight control system. Similar redundant actuation configurations are implemented to meet safety and reliability requirements as the aircraft industry progresses. Afterwards, It is discovered that when common-mode and common-cause failures happen in comparable redundant actuation systems, safety risk still poses an issue. It has imposed limitations on future advancements aimed at improving the reliability and safety of similar

redundant-actuation-system [9, 10]. It is decided to add an electromechanical actuator to the redundant-actuation system in addition to a hydraulic actuator as a result of further advancements in the field of redundant actuation system research so that the aviation sector can address the failure of common-mode and a common-cause, and increase the redundant actuation system's reliability and safety [11, 12].

Recent research advancements have led to the development of a heterogeneous (hybrid) drive actuation system—known as the Hybrid Mechatronic Actuation System (HAS)— comprising Electromechanical Actuators (EMA) and Electro-Hydraulic Servo Actuators (SHA). This integration significantly enhances the reliability and safety of the aircraft's actuation system [13]. The study of more electric aircraft has made it possible to enhance reliability by adding generating drives, actuators, power electronics, electrical distribution systems, and electric motors [14, 15]. SHA and EMA worked together to create the hybrid mechatronics actuation system that satisfies the need for exceptional reliability and safety. Additionally, it lowers the common-mode and common-cause errors, finally strengthening the actuation system of the aircraft and increasing its robustness and efficiency. [16].

The previous study assisted us in creating the mechatronics hybrid actuation system (HAS); however, there are still certain issues that need to be resolved. The mechanics of the SHA and EMA are dissimilar. Despite receiving identical pilot command input signals, SHA and EMA generate varying displacement and force outputs because they are based on distinct actuation mechanisms [17]. When both actuators are rigidly coupled to the aircraft's control surface, an intercoupling effect arises between the EMA and SHA. Force-Fighting occurs as a result of both actuators simultaneously exerting force on the control surface. This term refers to the difference in output forces between two distinct, redundant actuators operating at the same time. Force-Fighting has an impact on the aircraft control surface's tracking effectiveness and may even cause damage to it [10]. So, The aviation sector must create a controller that can effortlessly synchronize the movements of two actuators and resolve the issue of Force-Fighting. Salman made some attempts to use various control strategies to tackle the Force-Fighting problem. [18-22]. It is discovered that synchronization plays a crucial role in movement control to lessen Force-Fighting [23-25]. Eventually, the design of synchronization controllers became the industry's primary concern [26-28]. Force-Fighting is very important to eliminate to achieve the synchronous output force from hybrid actuation system. Force-Fighting was eliminated by establishing a position demand offset, which was accomplished by importing the real actuator force and the average actuator force difference into the integrator [29]. Studies have also shown how to create controllers for a hybrid mechatronics actuation system (HAS) made up of an EMA and SHA that deal with static force [17, 30].

Furthermore, improving tracking control precision and accuracy requires the controller design to consider uncertainties, external disturbances, nonlinear dynamics, and the coupling effects between the EMA and EHSA. One of the most effective solution to the issue of forces fighting of hybrid mechatronics actuation system is to synchronize movement of different actuators which are working in parallel mechanism [10]. Rehman has concentrated on applying various control approaches to synchronize motion for hybrid mechatronics actuation systems that combine electrohydrostatic and

servo hydraulic systems [31-35]. Wang attempted to suggest sensorless control for synchronizing the hybrid mechatronics actuation system's motion [36-38]. Developments in hybrid mechatronics actuation system research enabled Cochoy et al. to use displacement, velocity, and force state signals to create a force equalization controller [11]. The ideal hypothesis suggests that in order to design a controller, all contributed signals must be taken into consideration. Allow the hybrid mechatronics actuation system to anticipate system movement by obtaining these state variables. Acquiring all of the state signals from an airplane's physical actuation system is difficult. A hybrid mechatronics actuation system (HAS) test bench was created to address this issue by adding many sensors and achieving all-state signals [13]. These approaches would, however, greatly increase the actuators' weight and cost, which would restrict how widely they might be used. In the current research, a mathematical model of hybrid mechatronics actuation system is presented then extended observer based backstepping control method is proposed. Proposed control technique is simulated in Matlab/Simulink.

II. DESCRIPTION OF THE PROBLEM

The main elements of a hybrid mechatronics actuation system are the control surface, EMA, and SHA as shown in Fig. 1. A servo hydraulic actuation system is an electrically powered actuation system that regulates the flow/motion of hydraulic fluid towards an actuator. Servo valves often require very little electrical signal to operate powerful hydraulic cylinders. Accurate control of force, position, pressure and velocity can be achieved using servo valves. They also have fast movement and good damping properties. An electromechanical actuator (EMA) is a device that converts electrical power into mechanical force using an electric motor. An electric current is used by electric motors to rotate a spindle. This spinning motion is converted to linear motion by the use of gears. u_{sv} and u_m serve as the input control signals for the servo hydraulic actuator (SHA) and electromechanical actuator (EMA), respectively. The airplane control surface is rigidly linked to the EMA and SHA. Whereas EMA uses an electric motor as its actuation element, SHA uses a servo valve. An airplane experiences Force-Fighting when two actuators press together the control surface. Force-Fighting arises from unequal output forces between the two actuators; however, it can be avoided when both actuators apply equal force to the control surface. Force-Fighting occurs because compared to the EMA, the SHA offers quicker actuation. EMA responds more slowly than a servo valve due to the motor's longer response time. Force-Fighting can be eliminated by coordinating the movements of two actuators so that each one contributes equally to driving the aircraft's control surface. Mathematically it is given by;

$$\text{Force Fighting} = F_{fight} = F_s - F_m \quad (1)$$

$$F_{fight} = F_s - F_m = k_s(x_s - x_c) - k_m(x_m - x_c) \quad (2)$$

$$F_{fight} = F_s - F_m = k(x_s - x_m) \quad \therefore k_m = k_s = k \quad (3)$$

Where x_c shows linear movement of control surface of aircraft, x_m shoes the movement of electro mechanical actuator, x_s shows the

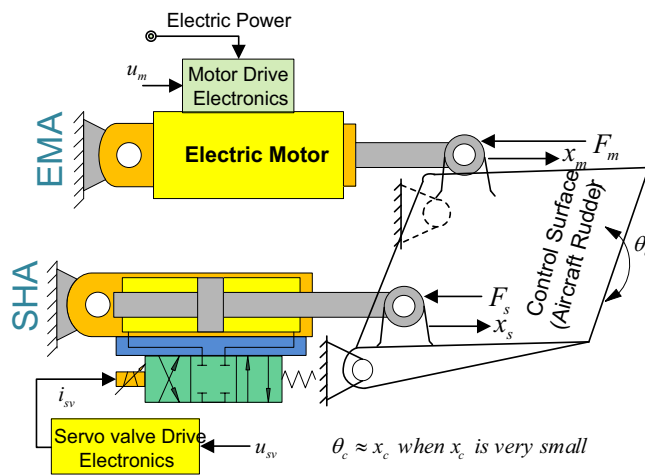


Fig. 1 Hybrid Mechatronics Actuation System Design

movement of servo hydraulic actuator, F_m shows the force provided by servo mechanical actuator and F_s shows the force provided by servo hydraulic actuator. The interpretation of equation (3) indicates that When the displacement of both actuators in a hybrid mechatronics actuation system is the same, Force-Fighting won't occur, as long as both actuators exhibit identical transmission stiffness, everything will work fine.

III. MATHEMATICAL REPRESENTATION OF THE HYBRID MECHATRONIC ACTUATION SYSTEM:

Each component of the hybrid mechatronic actuation system—including the control surface, electromechanical actuator, and servo-hydraulic actuator that all will be modeled separately.

A) Control Surface's Mathematical Model

The motion dynamics of the aircraft's control surface are governed by Newton's laws and are expressed as follows:

$$(F_s + F_m)r_c = j_c \ddot{\theta}_c + F_{dr}r_c \quad (4)$$

$$F_s = k_s (x_s - x_c) \quad (5)$$

$$F_m = k_m (x_m - x_c) \quad (6)$$

Where k_s is transmission stiffness coefficient for servo hydraulic actuator, k_m is transmission stiffness coefficient for electro mechanical actuator r_c is radial distance and, j_c is inertial moment during angular motion θ_c of control surface. It is discovered that the angular displacement is quite small. Under such circumstances, θ_c and x_c may be interpreted as linear [39], and provided by the relationship;

$$x_c = \theta_c r_c \quad (7)$$

B) Servo Hydraulic Actuation System's Mathematical Model

A servo valve actuator is made up of a hydraulic cylinder, a servo valve, and a few more accessories. A servo valve is a very useful tool for controlling the flow of fluid and is frequently used in applications where the goal is to control motion using fluid power [40, 41]. Past research indicates that the dynamics of a hydraulic cylinder and servo valve are provided by [17];

$$x_{sv} = k_{sv} u_{sv} \quad (8)$$

$$Q_{sv} = k_{sq} x_{sv} \quad k_{sc} p_f \quad (9)$$

Where x_{sv} is the servo valve's spool displacement, u_{sv} is a signal fed into the servo valve's coil and k_{sq} is flow over opening gain, k_{sc} is flow over pressure gain.

The servo hydraulic actuator's force and flow dynamics are provided by [17,42];

$$Q_{sv} = A_j \dot{x}_s + \frac{v_j}{4E_j} \dot{p}_f + k_{ac} p_f \quad (10)$$

$$F_j = m_j \ddot{x}_s + B_j \dot{x}_s + F_s$$

Where E_j is the oil bulk modulus, v_j is Effective volume of a piston, A_j is piston area of operation, p_f is load pressure, k_{ac} leakage coefficient, $F_j = A_j p_f$ is the force that the jack provided, B_j is damping coefficient, m_j is the piston mass.

Let suppose the state vector of servo hydraulic actuation system is $x_1 = [x_{11}, x_{12}, x_{13}]^T = [x_s, \dot{x}_s, \ddot{x}_s]^T$ and $u_1 = u_{sv}$. The servo hydraulic actuation system's state space form is provided by;

$$\Omega_{SHA} = \begin{cases} \dot{x}_{11} = x_{12} \\ \dot{x}_{12} = x_{13} \\ \dot{x}_{13} = f_1(x_1) + g_1 + \sigma_1 u_1 \end{cases} \quad (11)$$

Where;

$$f_1(x_1) = -\frac{4E_j k_{hs} (k_s + k_{ac})}{m_j v_j} x_{11} - \frac{4E_j A_j^2 + 4E_j B_j (k_s + k_{ac}) + v_j}{m_j v_j} x_{12}$$

$$- \frac{4E_j m_j (k_s + k_{ac}) + B_j v_j}{m_j v_j} x_{13}$$

$$g_1 = \frac{4E_j k_{hs} (k_{sq} + k_{ac})}{m_j v_j} x_c - \frac{k_{hs}}{m_j} \dot{x}_c$$

$$\sigma_1 = \frac{4A_j E_j k_{sq} k_v}{m_j v_j}$$

C) Electro Mechanical Actuation System's Mathematical Model

In an electro-mechanical actuator, the electric motor's electrical dynamics are provided by [13, 43];

$$u_m = k_m \omega_m + L_m \frac{di_m}{dt} + R_m i_m \quad (12)$$

$$T_m = k_{bm} i_m \quad (13)$$

i_m , L_m and R_m are current, inductance and resistance of armature respectively. ω_m is the angular velocity, k_{bm} is back emf constant, T_m is electromagnetic torque. The torque generated by the motor overcomes the damping dynamics and is transformed into inertial dynamics and load torque.

$$T_m - T_L = j_m \frac{d\omega_m}{dt} + B_m \omega_m \quad (14)$$

Where T_L is load torque, B_m is damping constant, j_m is total inertia. The transmission relationship between translational and rotational parts is as follow;

$$\begin{cases} \dot{x}_m = \frac{1}{\eta_m k_{gm}} \omega_m \\ T_L = \frac{1}{\eta_m k_{gm}} F_m \end{cases} \quad (15)$$

Where k_{gm} is transmission coefficient, η_m is transmission efficiency.

Assume that the electro mechanical actuator's state vectors are $x_2 = [x_{21}, x_{22}, x_{23}]^T = [x_m, \dot{x}_m, \ddot{x}_m]^T$ and control input for electro mechanical actuator is $\mu_2 = \mu_m$. The electro mechanical actuator's state space is provided by;

$$\Omega_{EMA} = \begin{cases} \dot{x}_{21} = x_{22} \\ \dot{x}_{22} = x_{23} \\ \dot{x}_{23} = f_2(x_2) + g_2 + \sigma_2 u_2 \end{cases} \quad (16)$$

Where;

$$f_2(x_2) = -\frac{R_m k_{ms}}{L_m j_m k_{gm}^2 \eta_m^2} x_{21} - \frac{k_{bm} k_m k_{gm}^2 \eta_m^2 + L_m k_{ms} + R_m B_m k_{gm}^2 \eta_m^2}{L_m j_m k_{gm}^2 \eta_m^2} x_{22}$$

$$- \frac{B_m L_m + j_m R_m}{j_m L_m} x_{23}$$

$$g_2 = \frac{R_m k_{ms}}{L_m j_m k_{gm}^2 \eta_m^2} x_c + \frac{k_{ms}}{j_m k_{gm}^2 \eta_m^2} \dot{x}_c \quad \sigma_2 = \frac{k_{bm}}{L_m j_m k_{gm} \eta_m}$$

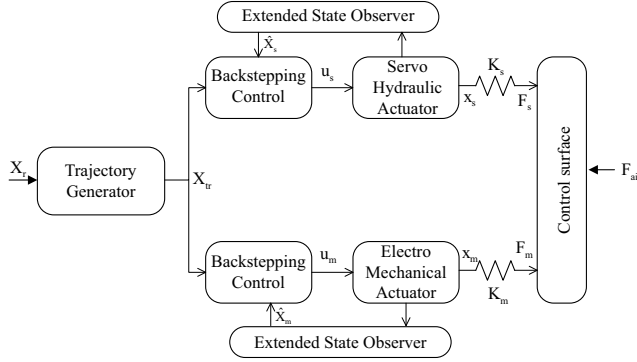


Fig. 2 Schematic diagram of hybrid actuation along with controller

IV. EXTENDED STATE OBSERVER BASED BACKSTEPPING CONTROL

The whole schematic of the proposed backstepping motion synchronization controller based on an extended state observer is shown in Fig. 2. The proposed strategy composed of trajectory generator, extended state observer, backstepping controller, servo hydraulic actuator, electro-mechanical actuator and a control surface. In diagram, X_r is reference pilot command signal, X_{tr} is reference signal generated by trajectory, u_m, u_s are control signals for actuators, K_m, K_s are stiffness of actuator's rod that connect actuator with control surface, F_m, F_s are forces provided by actuators, F_{air} is external force on control surface, x_m, x_s are forces provided by actuators.

A) Trajectory Generator:

The desired motion tracking application is effectively served by the trajectory-based systems. For this reason, a trajectory is created. A trajectory generator, that produces signals for position (x_{tr}), velocity ($\dot{x}_{tr}$), and acceleration ($\ddot{x}_{tr}$) creates the desired motion. This work makes use of the motion trajectory formulated by [31, 44, 45]. The trajectory derived from a second-order transfer function is expressed as:

$$x_{tr} = \frac{\omega_{tr}^2}{s^2 + 2\zeta_{tr}\omega_{tr}s + \omega_{tr}^2} x_r \quad (17)$$

Where $\omega_{tr}, \zeta_{tr}, x_r$ are reference natural frequency, damping factor, and input signal respectively.

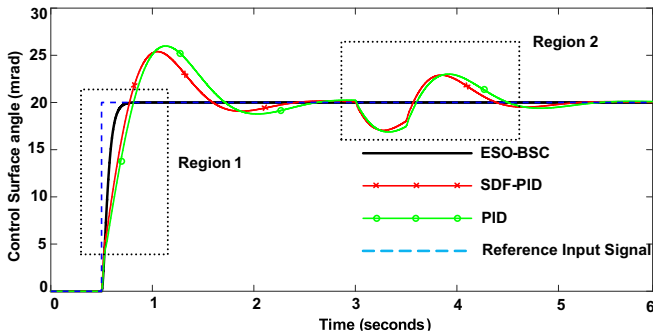


Fig. 3 Tracking response against step input command

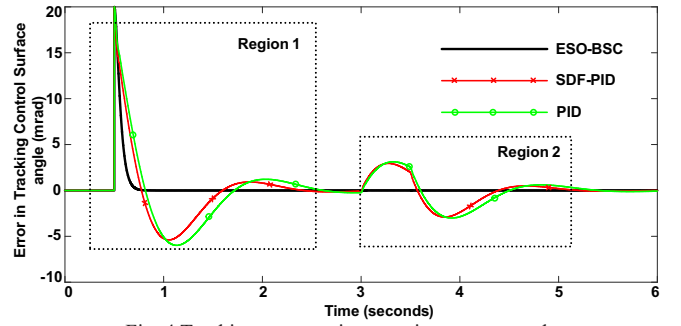


Fig. 4 Tracking error against step input command

B) Backstepping Control:

In this section, Backstepping integrator controller is designed for hybrid actuation system. New state variables for representing States of mechatronics hbrid actuation system are given by:

$$\begin{cases} z_{i1} = x_{i1} - x_d \\ z_{i2} = x_{i2} - \alpha_{i1}(z_{i1}) \\ z_{i3} = x_{i3} - \alpha_{i2}(z_{i1}, z_{i2}) \end{cases} \quad \begin{aligned} &\therefore i = 1 \Rightarrow SHA \\ &\therefore i = 2 \Rightarrow EMA \end{aligned} \quad (18)$$

Where $\dot{x}_{i3} = \int_{t_0}^t g_i u_i$ and x_d is desired input and while $\alpha_{i1}(z_{i1}), \alpha_{i3}(z_{i3})$ are virtual control inputs. Systems can achieve stability and convergence with the aid of virtual control inputs. The Lyapunov function can be used to find these virtual control inputs. In backstepping control, the Lyapunov approach is used to minimize error to guarantee that the position tracking error remains within acceptable limits, ultimately leading to boundedness and final convergence.

Theorem: The hybrid actuation system controlled by servo hydraulic actuator and electro-mechanical actuator will be stable if the conditions listed below are met;

$$\begin{aligned} \alpha_{i1}(z) &= -k_{i1}x_1 + \dot{x}_d \\ \alpha_{i2}(z_{i1}, z_{i2}) &= -k_{i2}z_{i2} - z_{i1} + \dot{\alpha}_{i1}(z_{i1}) \\ u_i &= \frac{1}{\sigma_i} (-z_{i2} - f_i(x_i) - g_i + \dot{\alpha}_{i2}(z_{i1}, z_{i2}) - k_{i3}z_{i3}) \end{aligned} \quad \begin{aligned} &\therefore i = 1 \Rightarrow SHA \\ &\therefore i = 2 \Rightarrow EMA \end{aligned} \quad (19)$$

Where k_{i1}, k_{i2}, k_{i3} are controller gains that are used to tune backstepping controller

Proof. Step 1: By considering its time derivative can be expressed as

$$\dot{z}_{i1} = \dot{x}_{i1} - \dot{x}_d \quad (20)$$

Using Equation (16), Equation (18) can be expressed as

$$\dot{z}_{i1} = z_{i2} + \alpha_{i1}(z_{i1}) - \dot{x}_d \quad (21)$$

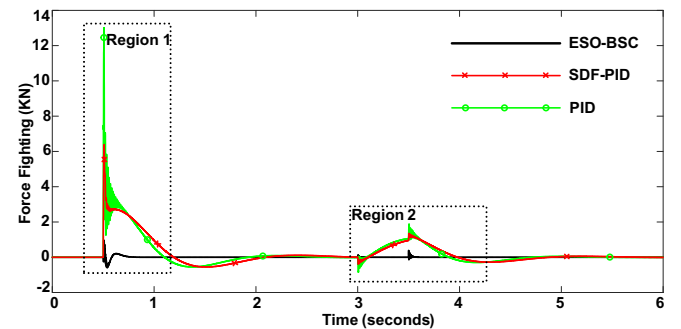


Fig. 5 Force-Fighting against step input and jerk load

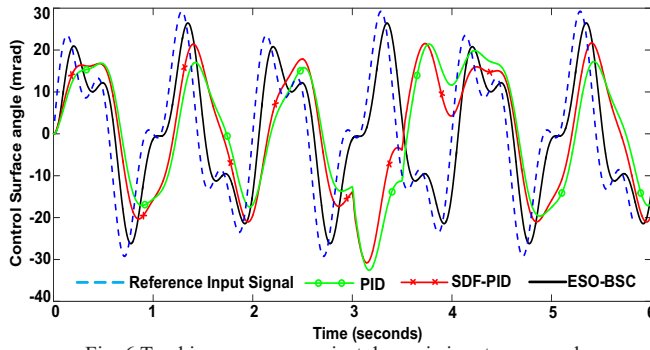


Fig. 6 Tracking response against dynamic input command

Create the Lyapunov function that follows

$$V_{i1} = \frac{1}{2} z_{i1}^2 \quad (22)$$

The control system's stability is ensured by the provided Lyapunov function if the virtual control law is

$$\alpha_{i1}(z_{i1}) = -k_{i1} z_{i1} + \dot{x}_d \quad (23)$$

From this, it follows that

$$\dot{V}_{i1} = z_{i1} z_{i2} - k_{i1} z_{i1}^2 \quad (24)$$

Whereby successive blacktrackig iterations will eliminate cross-term products.

Step 2: By considering z_{i2} , its time derivative can be expressed as

$$\dot{z}_{i2} = \dot{x}_{i2} - \dot{\alpha}_{i1}(z_{i1}) \quad (25)$$

One can write (23) by (16), as

$$\dot{z}_{i2} = z_{i3} + \alpha_{i2}(z_{i1}, z_{i2}) - \dot{\alpha}_{i1}(z_{i1}) \quad (26)$$

Create the Lyapunov function that follows

$$V_{i2} = V_{i1} + \frac{1}{2} z_{i2}^2 \quad (27)$$

The control system's stability is ensured by the provided Lyapunov function If the law of virtual control is

$$\alpha_{i2}(z_{i1}, z_{i2}) = -k_{i2} z_{i2} - z_{i1} + \dot{\alpha}_{i1}(z_{i1}) \quad (28)$$

Thus, the following can be directly derived

$$\dot{V}_{i2} = -k_{i1} z_{i1}^2 - k_{i2} z_{i2}^2 + z_{i2} z_{i3} \quad (29)$$

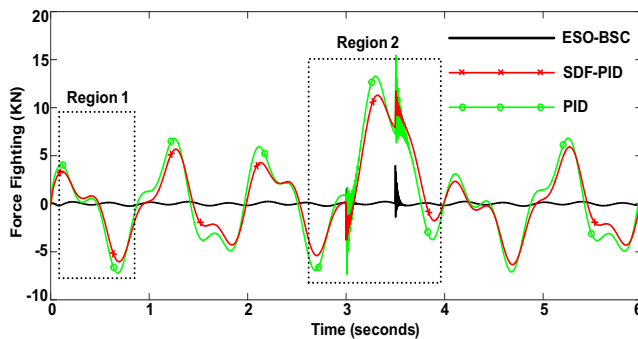


Fig. 7 Force-Fighting against Dynamic input and jerk load

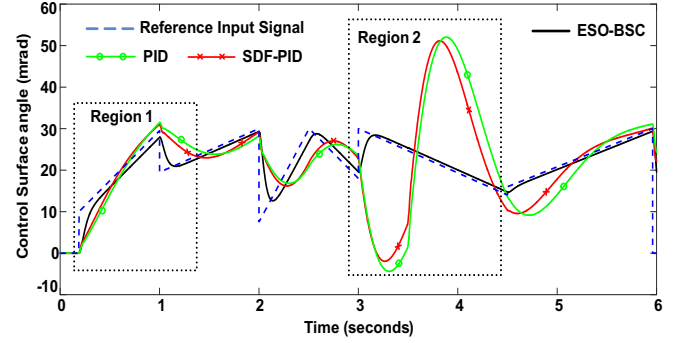


Fig. 8 Tracking response against realtime signal as input command

Thus, the following can be directly derived

$$\dot{V}_{i2} = -k_{i1} z_{i1}^2 - k_{i2} z_{i2}^2 + z_{i2} z_{i3} \quad (30)$$

Step n: By considering z_{i3} , its time derivative can be expressed as

$$\dot{z}_{i3} = \dot{x}_{i3} - \dot{\alpha}_{i2}(z_{i1}, z_{i2}) \quad (31)$$

One can write (28) by (16) as

$$\dot{z}_{i3} = f_i(x_i) + g_i + \sigma_i u_i - \dot{\alpha}_{i2}(z_{i1}, z_{i2}) \quad (32)$$

Let us construct the Lyapunov function in the following form

$$V_{i3} = V_{i2} + \frac{1}{2} z_{i3}^2 \quad (33)$$

Stability of the control system is ensured by the given Lyapunov function, provided that the control law takes the following form

$$u_i = \frac{1}{\sigma_i} (-z_{i2} - f_i(x_i) - g_i + \dot{\alpha}_{i2}(z_{i1}, z_{i2}) - k_{i3} z_{i3}) \quad (34)$$

Then, one can easily obtain

$$\dot{V}_{i3} = -k_{i1} z_{i1}^2 - k_{i2} z_{i2}^2 - k_{i3} z_{i3}^2 \quad (35)$$

However, the control law of equation (31), all of the SHA and EMA state variables, such as displacements, velocities, and accelerations, are necessary for the control rules to work. However, in actual aircraft actuation systems, only displacement sensors are available to monitor either the linear displacement of the actuator cylinder or the angular displacement of the control surface. Consequently, in order to supply the desired immeasurable state variables, a state observer is needed.

C) Extended State Observer

To estimate the uncertainties and the motion states of the actuation

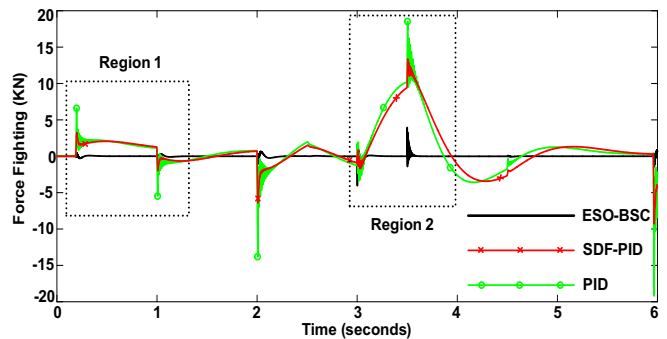


Fig. 9 Force-Fighting with realtime input signal and jerk load

systems, an extended state observer will be built in this part for the electromechanical actuator and the servo hydraulic actuator, respectively. All plant-affecting elements, including nonlinearities, uncertainties, and disturbances, are viewed by the extended state observer as a total uncertainty, or extended state, that requires observation [46-48]. Better performance, ease of implementation, and relative independence from the plant's mathematical model are the benefits of including the extended state.

Let suppose the extended state is $x_{i4} = f_i(x_i) + g_i$, then state equation of actuator is given by;

$$\Omega_i : \begin{cases} \dot{x}_{i1} = x_{i2} \\ \dot{x}_{i2} = x_{i3} \\ \dot{x}_{i3} = x_{i4} + \sigma_i u_i \\ \dot{x}_{i4} = h_i \\ y_i = x_{i1} \end{cases} \quad \begin{matrix} \therefore i = 1 \Rightarrow SHA \\ \therefore i = 2 \Rightarrow EMA \end{matrix} \quad (36)$$

Where h_i is variation rate of the uncertainty, and it is considered to be bounded.

Rewriting equation (33) in matrix form:

$$\begin{aligned} \dot{X}_i &= A_i X_i + B_i u_i + E_i h_i \quad \therefore i = 1 \Rightarrow SHA \\ y_i &= C_i X_i \quad \therefore i = 2 \Rightarrow EMA \end{aligned} \quad (37)$$

$$A_i = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix}, B_i = \begin{bmatrix} 0 \\ 0 \\ \sigma_i \\ 0 \end{bmatrix}, C_i = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}, E_i = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

Now, extended state observer for the system in (34), is given by;

$$\dot{\hat{X}}_i = A_i \hat{X}_i + B_i u_i + L_i C_i (X_i - \hat{X}_i) \quad \therefore i = 1 \Rightarrow SHA \quad \therefore i = 2 \Rightarrow EMA \quad (38)$$

Where $\hat{X}_i = [\hat{x}_{i1}, \hat{x}_{i2}, \hat{x}_{i3}, \hat{x}_{i4}]^T$, $L_i = [\alpha_{i1}, \alpha_{i2}, \alpha_{i3}, \alpha_{i4}]^T$ is state and designed vector for extended state observer. Observer gain can be found through pole placement, one typical example is

$$L_i = [4\omega_i, 6\omega_i^2, 4\omega_i^3, \omega_i^4]^T \quad (39)$$

Where ω_i is the extended state observer's tuning parameter and it is observer's bandwidth.

V. SIMULATION RESULTS AND DISCUSSION

The effectiveness of the proposed extended state observer based controller is verified by implementing it on a simulation model of a large civil aircraft's hybrid mechatronics actuation system. MATLAB/Simulink is used to build up the simulation, and Table 1 contains a list of the model's parameters.

Furthermore, to provide a more objective illustration of extended observer based backstepping controller, the performance of the three control algorithms listed below will be analyzed under three different simulation scenarios:

Extended State Observer Based Backstepping Control (ESO-

BSC): The parameters for Backstepping control are $K_{i1}=60$, $K_{i2}=12000$, $K_{i3}=200$, $K_{i4}=0.1$, $K_{i5}=2500$, $K_{i6}=950$, The value for tuning parameter for observer is $\omega_1 = \omega_2 = 10000$.

Extended State Observer Based Backstepping Control (ESO-BSC): The parameters for Backstepping control are $K_{i1}=60$, $K_{i2}=12000$, $K_{i3}=200$, $K_{i4}=0.1$, $K_{i5}=2500$, $K_{i6}=950$, The value for tuning parameter for observer is $\omega_1 = \omega_2 = 10000$.

PID Control: The Conventional PID control with following parameters is used: SHA: $K_{Ph}=3.8$, $K_{Ih}=20$, $K_{Dh}=0.1$, and EMA: $K_{Pm}=16$, $K_{Im}=2$, $K_{Dm}=0.5$

State difference feedback PID Control (SDF-PID): The state-difference feedback strategy which is given by Cochoy et al. [11]. This proposed control method use same PID control which has been designed in previous section alongwith state difference feedback of displacement, velocity and Force-Fighting with following coefficients $K_{SDF-X}=150$, $K_{SDF-V}=10$, $K_{SDF-F}=2 \times 10^{-6}$

TABLE I PARAMETERS OF ACTUATION SYSTEMS

Actuation Parts	Parameters	Values
Servo Hydraulic Actuator (SHA)	Gain Coefficient k_{sv}	3.04×10^{-4} m/A
	Flow /opening gain k_{sq}	2.7 m ² /s
	Flow / pressure gain k_{sc}	1.75×10^{-11} (m ³ /s)Pa
Servo Hydraulic Actuator (SHA)	Gain Coefficient k_{sv}	3.04×10^{-4} m/A
	Flow /opening gain k_{sq}	2.7 m ² /s
	Flow / pressure gain k_{sc}	1.75×10^{-11} (m ³ /s)Pa
	Area of Piston A_j	1.1×10^{-3} m ²
	Cylinder chamber volume v_j	1.1×10^{-4} m ³
	Piston mass, including chamber m_j	25 Kg
	Damping constant B_j	1×10^4 N.s/m
	Bulk modulus constant E_j	8×10^8 Pa
	Coefficient of Leakage k_{ac}	1×10^{-11} (m ³ /s)Pa
Electro-mechanical Actuator (EMA)	Bake emf constant k_m	0.161 V/(rad/s)
	Armature Inductance L_m	4.13×10^{-3} H
	Armature resistance R_m	0.54 Ω
	Electromagnetic coefficient k_{bm}	0.64 Nm/A
	Total inertia of rotating parts j_m	1.136×10^{-3}
	Damping coefficient B_m	4×10^{-3} Kg.m ²
	Transmission coefficient k_{gm}	1.256×10^3
	Transmission efficiency η_m	0.9 rad/m
Control Surface	Connection stiffness, k_s , k_m	1×10^8 N/m
	Control surface's radial distance r_{cs}	0.1 m
	Control surface's moment of inertia j_{cs}	6.0 Kg.m ²

A) Simulation Results Using A Step Input Command

The ESO-BSC clearly performs better than PID control and SDF-PID control in terms of disturbance rejection and motion tracking response as shown in Fig. 3. Region 1 shows initial tracking performance when there is no external load, it is clear that ESO-BSC is faster in achieving reference input signal as compared to PID control and SDF-PID control. ESO-BSC has no overshoot while PID and SDF-PID has overshoot. Overshoot (Oscillations) takes longtime to settle down. When time is at 3 seconds then jerk load called pulse load acts on control surface of aircraft. Pulse load is pulse of 8KN with a period of 3 sec. Region 2 shows the performance under jerk load. Region 2 clearly shows that ESO-BSC has better disturbance and load rejection performance compared to SDF-PID and PID. SDF-PID has better disturbance rejection performance as compared to PID.

Furthermore, results were also compared with respect to tracking error as shown in Fig. 4. Region 1 which shows initial response when step input is applied, it shows that proposed ESO-BSC has faster response and less tracking error as compared to SDF-PID and PID control. Even the error is very small for ESO-BSC in region 2 where external load acts on control surface of aircraft. Force-Fighting occurs when there is a mismatch between two actuators's output forces. These actuators are EMA and SHA. It results from SHA and EMA having distinct dynamic characteristics. In Fig. 5, Region 1 shows initial Force-Fighting. Force-Fighting at start for PID is 13KN. Force-Fighting is 6.4KN for SDF-PID. Force-Fighting for ESO-BSC is 1KN. Minimum Force-Fighting has been observed for ESO-BSC. Similarly, behavior is observed for Force-Fighting when external pulse load acts on control surface as shown in region 2 of Fig. 5.

B) Simulation Results Using A Dynamic Input Command

Simulations are also performed with dynamic signal as input command. The ESO-BSC clearly performs better than PID control and SDF-PID control in terms of disturbance rejection and motion tracking response is shown in Fig. 6. Region 1 shows initial tracking performance when there is no external load, it is clear that ESO-BSC is faster in achieving reference input signal as compared to PID control and SDF-PID control. ESO-BSC has less oscillation and faster response in achieving desired tracking response as compared to PID and SDF-PID. When time is at 3 seconds then external load acts on control surface of aircraft. External load is of pulse type which is of 8KN with a period of 3 sec. Region 2 shows the performance under external load. Region 2 clearly shows that ESO-BSC has better disturbance and load rejection performance compared to SDF-PID and PID. SDF-PID has better disturbance rejection performance as compared to PID.

Furthermore, results were also compared with respect to Force-Fighting. It is important to reduce Force-Fighting. Motion synchronization can not be achieved in the presence of Force-Fighting. In Fig. 7 Region 1 shows initial Force-Fighting (Force-Fighting at start). Force-Fighting at start for PID is 4KN. Force-Fighting is 3KN for SDF-PID. Force-Fighting for ESO-BSC is 0.5KN. Minimum Force-Fighting has been observed for ESO-BSC. Similar behavior is observed for Force-Fighting when external pulse load acts on control surface as shown in region 2.

C) Simulation Results Using A Real-time Input Signal

Simulations are also performed with realtime signal as input command. The ESO-BSC clearly performs better than PID control and SDF-PID control in terms of disturbance rejection and motion tracking response as shown in Fig. 8. Region 1 shows initial tracking performance when there is no external load, it is clearly shows that ESO-BSC is faster in achieving and tracking reference input signal as compared to PID control and SDF-PID control. ESO-BSC has faster response in achieving desired tracking response as compared to PID and SDF-PID. When time is at 3 seconds then external load acts on control surface of aircraft. External load is of pulse type which is of 8KN with a period of 3 sec. Region 2 shows the performance under external load. Region 2 clearly shows that ESO-BSC has better disturbance and load rejection performance compared to SDF-PID and PID. SDF-PID has better disturbance rejection performance as compared to PID.

Furthermore, results were also compared with respect to Force-Fighting. It is important to reduce Force-Fighting. Motion synchronization can not be achieved in the presence of Force-Fighting. In Fig. 9, Region 1 shows initial Force-Fighting. The Force-Fighting at start for PID is 6.2 KN. Force-Fighting is 3KN for SDF-PID. Force-Fighting for ESO-BSC is 0.5KN. Minimum Force-Fighting has been observed for ESO-BSC. Force-Fighting exhibits similar behavior when an external pulse load acts on the control surface as shown in region 2.

VI. CONCLUSIONS

This paper presents state observer based backstepping controller for hybrid mechatronics actuation system. The purpose of the extended state observer is to address issues with coupling terms, uncertainties, disturbances, and the unavailability of state signals, and all of which are critical for synchronizing motion. Trajectory generates position, and velocity signals which also help in motion synchronization. The objective is to reduce Force-Fighting which can only be achieved by motion synchronization in hybrid mechatronics actuation system. The simulations have been carried out in MATLAB/Simulink, considering different conditions of external air load (as disturbances) and command input signals. Proposed strategy is checked under step input pilot command, dynamic input pilot command, and realtime input pilot command and load is applied in the form of jerk (pulse load). It is found that proposed strategy has less initial Force-Fighting in comparison with control techniques used in published literature. Furthermore, Proposed strategy also has less Force-Fighting when external air load act on control surface. Result shows that proposed strategy perform better than published literature techniques.

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