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Robust Aircraft Performance using Hypersurface Gain Scheduling LQI Controller for Supermaneuverable Aircraft

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Abstract- **A new approach to cater to abrupt gain switching at the boundaries of steady-state trim points occurs during Conventional Gain Scheduling (CGS) applied to aircraft flight control applications. The primary purpose of this research is to improve the stability properties of a supermaneuverable aircraft during different mission tasks. A flight control system based on Linear Quadratic Integral (LQI) controller is adopted to guarantee stability and performance of the aircraft by keeping the states and control constraints under consideration. Assisted manual mode based on angular rates feedback is designed to provide stability during the pilot maneuver. A series of pilot-controlled maneuvers are performed to demonstrate the effectiveness of the proposed Gain Scheduling over the CGS technique. The results show smooth aircraft performance during different phases of maneuver.**

Index Terms-- **Conventional Gain Scheduling (CGS), Linear Quadratic Integral (LQI), Gain Switching, Flight Envelope, Trim Point**

I. INTRODUCTION

Modern Fighter aircraft are designed to exhibit relaxed stability to improve performance and maneuverability [1]. Fighter aircraft have a wide operating range, resulting in a large flight envelope, which includes the aircraft's maximum altitude, maximum and minimum speed, maximum withstand g-force and other flight characteristics. Non-linearity increases due to the instability of aircraft especially in the case of highly maneuverable aircraft [2], [3]. To provide closed-loop stability, robustness, and performance, of high order system such as aircraft, an effective controller is necessary throughout the flight envelope [4].

Gain scheduling is one of the most essential strategies for integrating nonlinearities into linear time-varying parameters that deliberately rely on the system's states, inputs, and outputs [5]. The Gain Scheduling (GS) control technique consists of a series of linear controllers that are widely used for the system with parameter-dependent or varying non-linear dynamics [6], [7]. The behavior of aircraft is highly dependent on aerodynamic forces that are a function of Mach, altitude, α, β, and control surfaces [8]. These parameters help determine the series of trim points that represent plant dynamics. The effort is made in terms of optimization to obtain trim points that represent the ideal plant dynamic. However, variation in dynamics is observed, when we switch from one trim point to another which ultimately affects the controller performance and risks the stability of the system. Conventional Gain scheduling cannot deal with transition constraints [9].

Trim points spacing causes a highly discontinuous behavior during a transition of controller gain which causes large variation and shift in controller output [10]. To improve and maintain the aircraft's stability, robustness, and performance during switching from one trim point to another, an interpolation of controller dynamics is required [11].

Multiple control strategies are applied for flight control applications. Among known modern control strategies are Linear Quadratic (LQ) Methods, Model Predictive Control (MPC), and Nonlinear Dynamic Inversion (NDI). MPC and NDI are effective for nonlinear control applications and their performance is highly dependent on model accuracy [12]. Linear Quadratic Integral (LQI) control is a multi-state feedback controller that satisfies your desired need with minimum control effort. The controller gains can be optimized using a gradient or metaheuristic approach to cater to input and output constraints for localized trim points of the flight envelope. The development of control law helps in improving the handling characteristics of highly unstable aircraft [1], [13], [14].

The simulations were performed using a series of pilot maneuvers. The proposed technique shows improved transient response as compared to conventional gain scheduling control. The method interpolates the controller gain value between trim points and effectively eliminates the abrupt and discontinuous transition of gains.

II. PROBLEM STATEMENT

The gain switching at the boundaries of neighboring trim points substantially reduces the dynamic stability of aircraft which is one of the key concerns with traditional GS. The transition is significantly discontinuous in each scenario, which might produce huge swings in the controller output.

Our approach is to build a hypersurface using continuous linear interpolation of the controller gains that were optimized for localized trim points.

III. AIRCRAFT MODEL

Advanced tactical aircraft is used for this study. The aircraft resembles a naval version of American YF-23 fighter aircraft. The prototype is a single-seat, twin-engine stealth fighter aircraft equipped with unconventional control surfaces i.e, canard and Ruddervator. [15].

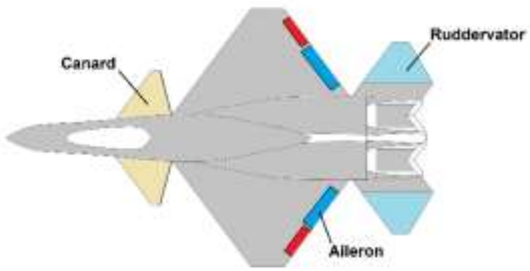


FIGURE 1. YF-23 with canard aircraft [16]

IV. FLIGHT DYNAMIC MODEL

The 6-DoF nonlinear model is used to represent a mathematical model of aircraft. The Flight Dynamic Model (FDM) model is represented by two reference frames. The aircraft is represented in the body axis frame. The inertial frame is taken as a reference frame to the aircraft axis [17]. The rotation of the earth is ignored. Furthermore, the mass and moment of Inertia of aircraft are kept constant.

The control surface and throttle settling limits are defined in Table I.

TABLE I
CONTROL INPUTS LIMITS

Control Inputs	Inputs Limits
Ruddervator (Elevator)	± 30 (deg)
Ruddervator (Rudder)	± 30 (deg)
Aileron	± 30 (deg)
Throttle	0 - 1

V. TRIMMING AND LINEARIZATION

Trimming is the process of finding the steady-state equilibrium condition where the aircraft is usually in a steady level flight due to balanced forces. It is a measure of the control deflection, where aircraft states are in equilibrium. Furthermore, linear and angular accelerations are zero.

A. TRIM POINTS

The change in aircraft speed and altitude significantly affect the behavior of aircraft which can be explained by Bernoulli's principle. Multiple trim points are obtained by variation of velocity and altitude of the flight envelope.

TABLE II
FLIGHT ENVELOPE TRIM POINTS FOR GAIN SCHEDULING

Altitude (ft.)	Mach Number					
0	0.3	0.4	0.5	0.6	0.7	0.8
5000	0.3	0.4	0.5	0.6	0.7	0.8
10000	0.3	0.4	0.5	0.6	0.7	0.8
15000	0.3	0.4	0.5	0.6	0.7	0.8
20000	0.3	0.4	0.5	0.6	0.7	0.8
25000	0.3	0.4	0.5	0.6	0.7	0.8
30000	0.3	0.4	0.5	0.6	0.7	0.8
35000	X	0.4	0.5	0.6	0.7	0.8
40000	X	0.4	0.5	0.6	0.7	0.8
45000	X	X	X	0.6	0.7	0.8
50000	X	X	X	0.6	0.7	0.8

B. Linear Parameter Varying (LPV) Model

For Linear control design and analysis 6-Degree of Freedom (DoF) nonlinear model is linearized around trim points. A sequence of linearized trim points along a curve corresponds to the combination of scheduling variables Mach and altitude which form varying models represented in state space. This set of linear state space models whose dynamics vary as a function of scheduling parameters is termed as Linear Parameter Varying (LPV) model [18]. In this way, nonlinear aircraft models can be modeled as parametrized linear systems.

The linear state-space representation of a system is given below:

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) \\ y(t) = Cx(t) + Du(t) \end{cases} \tag{1}$$

Now state space in terms of longitudinal and lateral-directional dynamics are represented in equations 5 and 7 respectively:

$$\begin{bmatrix} \Delta\dot{u} \\ \Delta\dot{w} \\ \Delta\dot{q} \end{bmatrix} = \begin{bmatrix} X_u & X_w & 0 \\ Z_u & Z_w & u_0 \\ M_u + M_{\dot{w}}Z_u & M_w + M_{\dot{w}}Z_w & M_q + M_{\dot{w}}u_0 \end{bmatrix} \begin{bmatrix} \Delta u \\ \Delta w \\ \Delta q \end{bmatrix} + \begin{bmatrix} X_{\delta_e} & X_{\delta_c} \\ Z_{\delta_e} & X_{\delta_c} \\ M_{\delta_e} + M_{\dot{w}}Z_{\delta_e} & M_{\delta_c} + M_{\dot{w}}Z_{\delta_c} \end{bmatrix} \begin{bmatrix} \Delta\delta_e \\ \Delta\delta_c \end{bmatrix} \tag{2}$$

In this study, the Angle Of Attack (α) limit has been defined in the problem. Therefore the vertical velocity w has been transformed to the α in the model [19]. The relation can be expressed in the following way:

$$\Delta\alpha \approx \frac{\Delta w}{u_0} \tag{3}$$

Now the longitudinal states are $\boldsymbol{x} = [\Delta\boldsymbol{u}\,\Delta\boldsymbol{\alpha}\,\Delta\boldsymbol{q}]$ and the longitudinal control inputs are $\boldsymbol{u} = [\Delta\boldsymbol{\delta_e}\,\Delta\boldsymbol{\delta_c}]$.

Similarly, state-space in terms of lateral-direction dynamics is represented here:

$$\begin{bmatrix} \Delta\dot{\beta} \\ \Delta\dot{p} \\ \Delta\dot{r} \end{bmatrix} = \begin{bmatrix} \frac{Y_\beta}{u_0} & \frac{Y_p}{u_0} & -(1-\frac{Y_r}{u_0}) \\ L_\beta & L_p & L_r \\ N_\beta & N_p & N_r \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta\beta \\ \Delta p \\ \Delta r \end{bmatrix} + \begin{bmatrix} 0 & \frac{Y_{\delta_r}}{u_0} \\ L_{\delta_a} & L_{\delta_r} \\ N_{\delta_a} & N_{\delta r} \end{bmatrix} \begin{bmatrix} \Delta\delta_a \\ \Delta\delta_r \end{bmatrix} \quad (4)$$

Where the lateral states are $\boldsymbol{x} = [\Delta\boldsymbol{\beta}\ \Delta\boldsymbol{p}\ \Delta\boldsymbol{r}\ \Delta\boldsymbol{\phi}\ \Delta\boldsymbol{y}]$ and the control vector $\boldsymbol{u} = [\Delta\boldsymbol{\delta_a}\ \Delta\boldsymbol{\delta_r}]$

The state-space consists of aerodynamic derivatives that are computed using flight dynamic tools based on the panel method called Athena Vortex-Lattice-Method (VLM). Athena VLM computes aerodynamic stability and control derivatives at multiple trim points by variation of Mach and altitude. Furthermore, Athena VLM provides a state-space model by linearizing the aircraft at steady-state conditions.

VI. CONTROLLER DESIGN

A. LQI Control Architecture

Linear quadratic methods are output feedback design methods for state variable models based on quadratic cost performance criteria to obtain optimal gain for the desired response.

LQI guarantees that reference inputs that change slowly are tracked. This is accomplished by adding new states to the system. These states represent the error between the reference inputs and the actual system outputs. The LQI state feedback control rule is given for the system represented by the following eq. 5.

$$u = -K\,[x; x_i] = -Kz \quad (5)$$

where x_i is an additional integral state and The enhanced system's states are denoted by z. The following Fig. 2 is a generic block diagram of a system including an LQI controller:

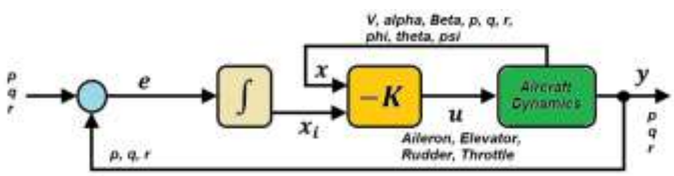


FIGURE 2. LQI based Angular Rate Control Architecture

After incorporating the integral states, the extended state space representation becomes:

$$\begin{bmatrix} \dot{x} \\ \dot{x}_i \end{bmatrix} = \begin{bmatrix} A & 0 \\ -C & 0 \end{bmatrix} \begin{bmatrix} x \\ x_i \end{bmatrix} + \begin{bmatrix} B \\ -D \end{bmatrix} u \quad (6)$$

which implies that

$$\begin{cases} \dot{z} = A_{aug} z + B_{aug} u \\ y = Cx + Du \end{cases} \quad (7)$$

The Linear Quadratic Regulator (LQR) controller's cost function is shown in Fig. 8:

$$J(u) = \int_0^\infty (x'Qx + u'Ru) \quad (8)$$

The LQR controller is utilized for Multiple Input Multiple Output (MIMO) applications. In the MIMO system, LQR is used to regulate all the states. LQR is also used for reference tracking.

B. Controller Tuning

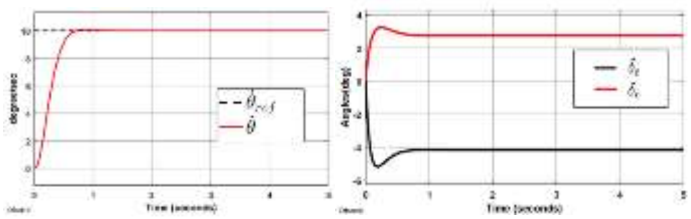
The process of identifying the controller parameters that provide the desired output is known as controller tuning [20]. Tuning a controller is often taken as an optimization problem for finding suitable gains for the desired response. Deterministic as well meta-heuristic approaches were adopted for gain optimization [21]. A gradient-based optimization approach is suitable for solving a convex problem. For a non-convex problem, such as aircraft which is highly nonlinear it is difficult to find global minima for optimal gains [22], [23].

LQI controller cost function consists of two design matrices Q and R. The Q and R are square matrices and their dimension depends on the number of states and inputs respectively. In the case of longitudinal control where we have three states, $\boldsymbol{x} = [\Delta\boldsymbol{u}\ \Delta\boldsymbol{\alpha}\ \Delta\boldsymbol{q}]$ and we need to control the aircraft speed and pitch rate of the aircraft so there are two additional error states in the system that we need to minimize as shown in (7). The dimension of the Q matrix will be 5x5. In addition, the longitudinal inputs are elevator, canard, and Throttle. In this case, the dimension of design matrix R is 3x3 as shown in (11).

$$Q = \begin{bmatrix} q_{11} & q_{12} & q_{13} & q_{14} & q_{15} \\ q_{21} & q_{22} & q_{23} & q_{24} & q_{25} \\ q_{31} & q_{32} & q_{33} & q_{34} & q_{35} \\ q_{41} & q_{42} & q_{43} & q_{44} & q_{45} \\ q_{51} & q_{52} & q_{53} & q_{54} & q_{55} \end{bmatrix} R = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} \quad (9)$$

Generally, diagonal parameters are utilized to weigh the individual states and coupling weights are taken as zero. In this way, individual state contribution is observed and the gain tuning problem is simplified. A desired 10deg/s Pitch rate tracking is performed to analyze the elevator and canard effectiveness during loop maneuver. Thrust is utilized to maintain aircraft speed.

An LQI controller forms a set of Linear Parameter Varying (LPV) controllers that would allow a fighter plane to fly at various altitudes and speeds. This necessitates a new operating controller with a focus on preserving stability and appropriate flying characteristics. It is incredibly difficult to build a single LPV controller that can operate over this spectrum of the flight envelope. [4].



(a) Pitch Rate Response (b) Elevator and Canard Response

FIGURE 3. Pitch rate response to elevator and canard actuator input

VII. GAIN SCHEDULING

Gain scheduling (GS) in a multi-variable framework, particularly for a multi-input system, must be possible. States are separated into scheduling states and non-scheduling states [24].

A GS approach based on LQI control is adopted with Mach and Altitude acting as a scheduling parameter. For the trim analysis, only subsonic flight conditions are analyzed with a variation of altitude as shown in Table II. GS architecture consists of three major components Flight Dynamic Model (FDM), LQI controller, and switch that act as a gain scheduler as shown in 4. The switch incorporates loop-Up tables that are made up of a series of controller gains at multiple operating points. Pilot Stick generates desired inputs in terms of angular rates to perform different aerobatic and fighter maneuvers.

A. Continuous Multi-Surface Gain (CMSG) Scheduling

The controller gains obtain from the LQI controller are matrices and their dimension depends on feedback states and control inputs. A Continuous Multi-Surface Gain (CMSG) scheduling approach is presented that uses multi-state LQI gains that are interpolated linearly between each trim condition to form a hypersurface of gains. The selection of trim point spacing is the most crucial and challenging task. A CMSG Scheduling based LQI Control Architecture has been shown in Fig. 4.

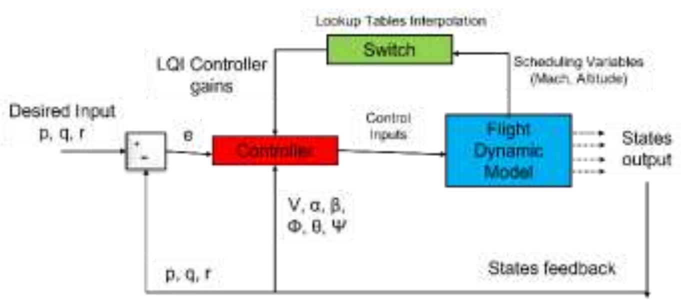


FIGURE 4. CMSG Scheduling based LQI Control Architecture

VIII. SIMULATION AND RESULTS

A. Maneuver Modelling

For Gain Scheduling analysis 45◦ Up-Line and Split-S maneuvers are performed.

a) 45◦ Up-Line: The maneuver consists of three phases as shown in 5. To translate the maneuver into pilot commands we model the desired rate input.

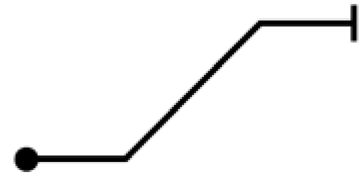


FIGURE 5. 45º Up-Line Maneuver

In the cruise phase, the angular rate is zero to maintain level flight. For the 45˚ pitch up maneuver, the pitch rate should be increased until the pitch angle reaches the desired angle, and then for the pitch down pitch rate should be decreased until an aircraft is in level flight. The desired pitch rate command is shown in Fig. 6. During the maneuver, both the yaw rate and roll rate command remain zero.

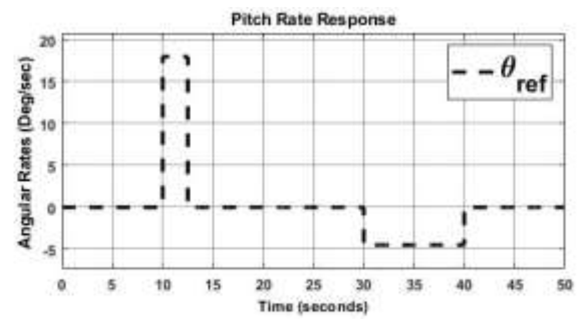


FIGURE 6. Pitch Rate command for 45º Up-Line Maneuver

b) Split-S: The Split-S maneuver consists of three phases as shown in 7. To translate the maneuver into pilot commands pitch rate and roll rate command is required where the yaw rate is kept at zero as the maneuver does not require any yaw movement.

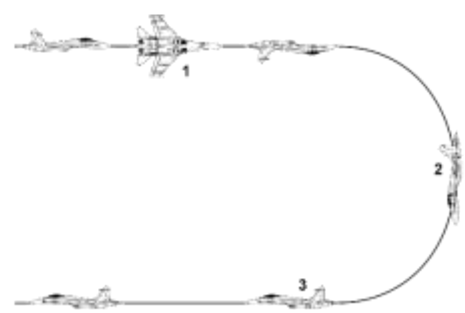
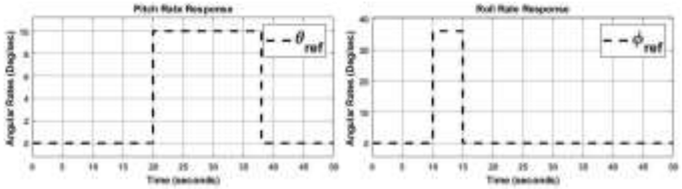


FIGURE 7. Split-S Maneuver

In the cruise phase, the angular rate is zero to maintain level flight. For inverted flight 180◦ roll maneuver is required and then pitch maneuver to perform half-loop until the aircraft comes to level flight. The required pitch and roll rates are shown in Fig. 8. The duration of the desired rate depends on the required angle to achieve a particular aircraft orientation.

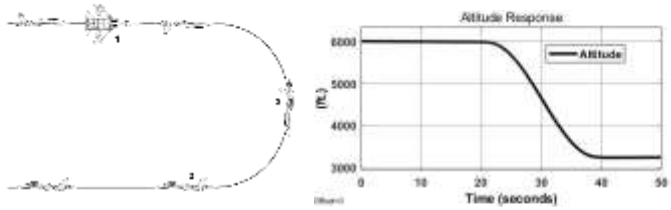


(a) Pitch Rate Command (b) Roll Rate Command

FIGURE 8. Desired Reference Input

B. CGS and CMSG Scheduling Comparison

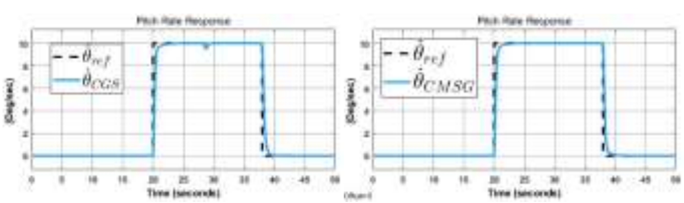
Split-S Maneuver is performed. The aircraft model was set to Mach 0.5 at a height of 6000 ft. feet for simulation testing. These dynamics were chosen since they are offset from any ideal trim points (i.e. 5000 ft.), allowing evaluation of gain set distant from its designed trim point. The Altitude loses as the maneuver is performed. In the case of Conventional Gain Scheduling (CGS) when altitude reduces to the next trim point boundary (i.e. 5000 ft.), we observed gain shifting that produce a swing in the response.



(a) Split-S Maneuver (b) Altitude Response

FIGURE 9. Altitude Variation during Split-S Maneuver

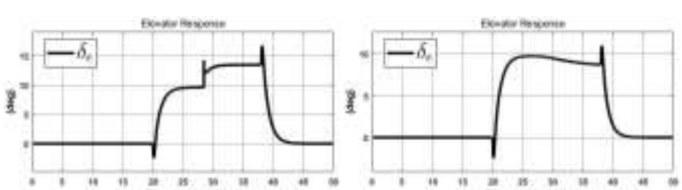
Where in the case of Continuous Multi-Surface Gain (CMSG) Scheduling the gain transition is linear between the trim point spacing. The overall response is smooth throughout the maneuver. Fig. 10a represents discontinuous response whereas, Fig. 10b shows level response due to continuous gain variation.



(a) CGS (b) CMSG

FIGURE 10. Pitch Rate Response Comparison

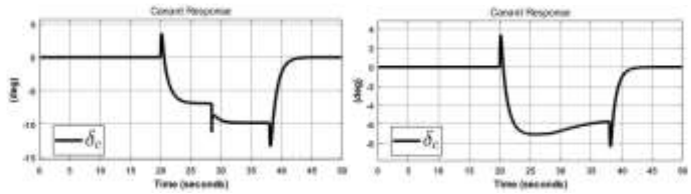
The discontinuity in pitch rate response is also reflected in the control input response. Whereas CMSG helps in avoiding the instant switching of gain. The Elevator response to pitch rate command in the case of CGS and CMSG is shown in Fig. 11a and 11b.



(b) CGS (b) CMSG

FIGURE 11. Elevator Response Comparison

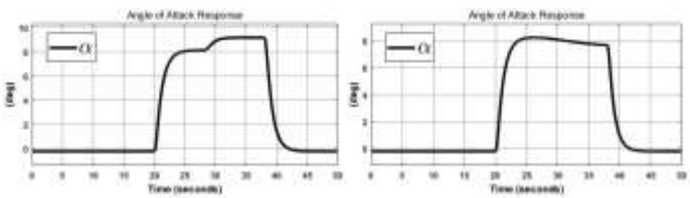
The canard deflection is opposite to Elevator as the canard is placed forward to the center of gravity position. However, the irregular transition of CGS is also reflected in the canard response as shown in Fig. 12a.



(c) CGS (b) CMSG

FIGURE 12. Canard Response Comparison

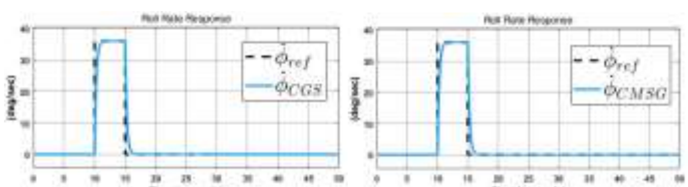
During the maneuver, the angle of attack may vary and increase to a limit where flow began to separate and cause stall conditions. So jagged angle of attack (AOA) response is not desirable as observed in Fig. 13a. CMSG scheduling eliminates the jagged AOA effect as shown in Fig. 13b that causes system instability.



(d) CGS (b) CMSG

FIGURE 13. Angle of Attack Response Comparison

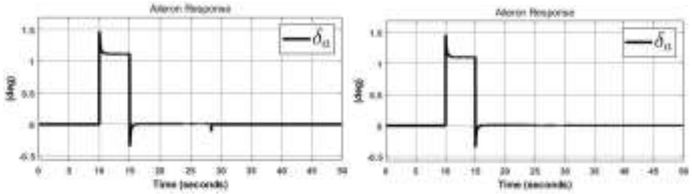
Fig. 14a shows that the effect of gain switching is not observed in the case of roll rate. But the switching effect can be observed in aileron deflection as the control effort of the aileron tries to counter it, as shown in Fig. 15a.



(e) CGS (b) CMSG

FIGURE 14. Roll Rate Response Comparison

The aircraft with unstable characteristics are often non-minimum phase systems as model zero appear in the right-half plane causing the system to behave initially reverse to the desired value and then follow the desired trajectory The inverse response in aileron control effort is due to the non-minimum phase behavior of a system.



(f) CGS (b) CMSG

FIGURE 15. Aileron Response Comparison

IX. CONCLUSION

Continuous Multi-Surface Gain (CMSG) Scheduling based LQI controller, improves aircraft's dynamic response for LPV System The LPV model is composed of several Gain Scheduled (GS) multi-input and multi-state LQI controllers gain that govern the angular velocities of the aircraft in roll, pitch, and yaw. The controller gains were optimized for localized trim points. A continuous linear interpolation of controller gain to generate a multi-gain surface between trim points. Using a 45◦ Up-Line and Split-S maneuver, the CMSG Scheduling strategy was compared to conventional gain scheduling strategies. The results demonstrate improved transient response, settling time, faster rise times, reduced steady-state errors, and less inconsistent controller behavior during gain transitions.

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