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Robust Pitch Attitude Hold with MRAC for a Nonlinear Light Combat Aircraft Model

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Abstract—**In this paper, we implement a robust model reference adaptive control (MRAC) as part of an ongoing effort to demonstrate practical application of a nonlinear control system to the pitch -attitude hold of an aircraft model. We show that MRAC can improve transient performance and compensate changes in the performance characteristics of the aircraft mid-flight by evaluating an example where a change in center of gravity of the aircraft is coupled with decreased control effectiveness.**

I. Introduction

Model reference adaptive control, originally proposed in [1], [2], serves as a means of improving existing feedback architectures such that, in the face of system uncertainties or physical phenomena that cannot be adequately captured, performance requirements can be still be met [3]–[5].

For example, a change in center of gravity (CG) of the aircraft (provoked by burning fuel or dropping cargo payload) or reduced control effectiveness (provoked by damage to the aircraft) is equally difficult to measure and model adequately, and can therefore lead to undesirable transient performance in the feedback control for longitudinal dynamics of the aircraft [6].

This research is part of an ongoing GAČR project launched in 2016 (by Henrion et al.) for verification and validation of control laws. Specifically, we consider a case where model reference adaptive control (MRAC) interacts with a nonlinear flight mechanics model. The verification and validation of these novel flight control laws remains a difficult yet important benchmark in the field of control engineering [7]–[11].

In this paper, we implement a MRAC to demonstrate practical application of nonlinear control systems. We then show that MRAC can improve transient performance and compensate changes in the mid-flight performance characteristics of the aircraft by evaluating an example where a change in center of gravity of the aircraft is coupled with reduced control effectiveness.

The organization of this paper is as follows: Section II presents the necessary mathematical preliminaries, Section III discusses the design of the standard MRAC architecture for a nonlinear model, Section IV discusses the flight model and integrator augmentation, Section V shows the efficacy of our results by considering (CG change with reduced control effectiveness), and Section VI contains both our conclusions and suggestions for further research.

II. Mathematical Preliminaries

We begin by briefly stating the notation used throughout this paper. Specifically, $\mathbb{R}$ denotes the set of real numbers, $\mathbb{R}^n$ denotes the set of $n \times 1$ real column vectors, $\mathbb{R}^{n\times m}$ denotes the set of $n \times m$ real matrices, $\mathbb{R}_+$ (resp., $\overline{\mathbb{R}}_+$) denotes the set of positive (resp., non-negative-definite) real numbers, $\mathbb{R}_+^{n\times n}$ (resp., $\overline{\mathbb{R}}_+^{n\times n}$) denotes the set of $n \times n$ positive-definite (resp., non-negative-definite) real matrices, $\mathbb{S}^{n\times n}$ denotes the set of $n \times n$ symmetric real matrices, $\mathbb{D}^{n\times n}$ denotes the set of $n \times n$ real matrices with diagonal scalar entries, $(\cdot)^T$ denotes the transpose operator, $(\cdot)^{-1}$ denotes the inverse operator, $\mathrm{tr}(\cdot)$ denotes the trace operator, $\|\cdot\|_2$ denotes the Euclidian norm, $\|\cdot\|_{\mathrm{F}}$ denotes the Frobenius matrix norm, $[A]_{ij}$ denotes the ij-th entry of the real matrix $A \in \mathbb{R}^{n\times m}$, and "$\triangleq$" denotes the equality by definition. Next, we introduce some fundamental results that are needed to develop the main results of this paper. We begin with the following definition.

Definition 1. For a convex hypercube in $\mathbb{R}^n$ defined by $\Omega = \{\theta \in \mathbb{R}^n : (\theta_i^{\min} \le \theta_i \le \theta_i^{\max})_{i=1,2,\ldots,n}\}$ where $(\theta_i^{\min}, \theta_i^{\max})$ represent the minimum and maximum bounds for the i^{th} component of the n-dimensional parameter vector θ. Additionally, for a sufficiently small positive constant ϵ, a second hypercube is defined by $\Omega_\epsilon = \{\theta \in \mathbb{R}^n : (\theta_i^{\min} + \epsilon \le \theta_i \le \theta_i^{\max} - \epsilon)_{i=1,2,\ldots,n}\}$ where $\Omega_\epsilon \subset \Omega$. Then the projection operator $\mathrm{Proj} : \mathbb{R}^n \times \mathbb{R}^n \to \mathbb{R}^n$ is defined component-wise by

$$\mathrm{Proj}(\theta, y) \triangleq \begin{cases} \left(\frac{\theta_i^{\max} - \theta_i}{\epsilon}\right) y_i, & \text{if } \theta_i > \theta_i^{\max} - \epsilon \text{ and } y_i > 0 \\ \left(\frac{\theta_i - \theta_i^{\min}}{\epsilon}\right) y_i, & \text{if } \theta_i < \theta_i^{\min} + \epsilon \text{ and } y_i < 0 \\ y_i, & \text{otherwise} \end{cases} \quad (1)$$

where $y \in \mathbb{R}^n$ [12]. It follows from Definition 1 that

$$(\theta - \theta^*)^T(\mathrm{Proj}(\theta, y) - y) \le 0, \quad \theta^* \in \mathbb{R}^n, \quad (2)$$

holds [12], [13].

Remark 1. Throughout the paper, we use the generalization of this definition to matrices as $\mathrm{Proj_m}(\Theta, Y) = \big(\mathrm{Proj}(\mathrm{col}_1(\Theta), \mathrm{col}_1(Y)), \ \ldots \ , \ \mathrm{Proj}(\mathrm{col}_m(\Theta), \mathrm{col}_m(Y))\big)$, where $\Theta \in \mathbb{R}^{n\times m}$, $Y \in \mathbb{R}^{n\times m}$, and $\mathrm{col}_i(\cdot)$ denotes the i-th column operator. In this case, for a given $\Theta^* \in \mathbb{R}^{n\times m}$, it follows from (2) that $\mathrm{tr}\left[(\Theta-\Theta^*)^T(\mathrm{Proj_m}(\Theta,Y)-Y)\right]= \sum_{i=1}^{m}\left[\mathrm{col}_i(\Theta-\Theta^*)^T(\mathrm{Proj}(\mathrm{col}_i(\Theta),\mathrm{col}_i(Y))-\mathrm{col}_i(Y))\right]\leq 0$, holds.

III. Standard MRAC Preliminaries

We are now ready to introduce results of the standard model reference control preliminaries and design from [14]. Specifically, consider the uncertain dynamical system given by

$$\dot{x}(t) = Ax(t) + Bu(t) + D\delta(x(t)), \quad x(0) = x_0, \tag{3}$$

where $x(t) \in \mathbb{R}^n$ is the state vector available for feedback, $u(t) \in \mathbb{R}^m$ is the control input restricted to the class of admissible controls consisting of measurable functions, $\delta : \mathbb{R}^n \mapsto \mathbb{R}^m$ is the uncertainty, $A \in \mathbb{R}^{n\times n}$ is an unknown system matrix, $B \in \mathbb{R}^{n\times m}$ is an unknown control input matrix, $D \in \mathbb{R}^{n\times m}$ is a known uncertainty input matrix, and the pair (A, B) is controllable. The following assumption is standard in the model reference adaptive control literature.

Assumption 1. The uncertainty matrix in (3) can be parametrized as

$$\delta(x) = W^T\sigma(x), \quad x \in \mathbb{R}^n, \tag{4}$$

where $W \in \mathbb{R}^{s\times m}$ is an unknown weight matrix and $\sigma : \mathbb{R}^n \mapsto \mathbb{R}^s$ is a known basis function of the form $\sigma(x) = \left[\sigma_1(x), \sigma_2(x), \ldots, \sigma_s(x)\right]^T$. In addition, the unknown control input is parametrized as

$$B = D\Lambda, \tag{5}$$

where $\det(D^TD) \neq 0$ and $\Lambda \in \mathbb{R}+^{m\times m} \cap \mathbb{D}^{m\times m}$ is an unknown control effectiveness matrix.

Remark 2. For the case when the nonlinear uncertain dynamical system given by (3) includes bounded exogenous disturbances, measurement noise, and/or the uncertainty in (3) cannot be perfectly parameterized, then Assumption 1 can be relaxed by considering

$$\delta(t,x) = W(t)^T\sigma(x) + \varepsilon(t,x), \quad x \in \mathcal{D}_x, \tag{6}$$

where $W(t) \in \mathbb{R}^{s\times m}$ is an unknown time varying weight matrix satisfying $\left|\left|W(t)\right|\right|_{\mathrm{F}} \leq w$, $w \in \mathbb{R}_+$, and $\left|\left|\dot{W}(t)\right|\right|_{\mathrm{F}} \leq \dot{w}$, $\dot{w} \in \mathbb{R}_+$; $\sigma : \mathcal{D}_x \mapsto \mathbb{R}^s$ is a known basis function of the form $\sigma(x) = \left[\sigma_1(x), \sigma_2(x), \ldots, \sigma_s(x)\right]^T$; $\varepsilon : \overline{\mathbb{R}} \times \mathcal{D}_x \mapsto \mathbb{R}^m$ is the system modeling error satisfying $\left|\left|\varepsilon(t,x)\right|\right|_2 \leq \epsilon$, $\epsilon \in \mathbb{R}_+$; and $\mathcal{D}_x$ is a compact subset of $\mathbb{R}^n$.

Next, consider the reference system capturing a desired, ideal closed-loop dynamical system performance given by

$$\dot{x}_{\mathrm{r}}(t) = A_{\mathrm{r}}x_{\mathrm{r}}(t) + B_{\mathrm{r}}c(t), \quad x_{\mathrm{r}}(0) = x_{\mathrm{r}0}, \tag{7}$$

where $x_{\mathrm{r}}(t) \in \mathbb{R}^n$ is the reference state vector, $c(t) \in \mathbb{R}^m$ is a given piecewise continuous bounded command, $A_{\mathrm{r}} \in \mathbb{R}^{n\times n}$ reference system matrix (we shall assume that it is Hurwitz), and $B_{\mathrm{r}} \in \mathbb{R}^{n\times m}$ is the command input matrix. The objective of the model reference adaptive control problem is to construct an adaptive feedback control law $u(t)$ such that the state vector $x(t)$ asymptotically follows the reference state vector $x_{\mathrm{r}}(t)$. For the purpose of stating the preliminaries associated with the model reference adaptive control, consider the feedback control law given by

$$u(t) = u_n(t) + u_a(t), \tag{8}$$

where $u_n(t)\mathbb{R}^m$ is control signal generated by the nominal feedback control law and $u_a(t) \in \mathbb{R}^m$ is related to the adaptive feedback control law. Additionally, let the nominal feedback control law be given by

$$u_n(t) = -K_1x(t), \tag{9}$$

where $K_1 \in \mathbb{R}^{m\times n}$ is the nominal feedback gain such that $A_r = A - DK_1$. Now, using (8) and (9) in (3) along with Assumption 1 yields

$$\begin{aligned}\dot{x}(t) &= A_rx(t) + B_rc(t) \\ &\quad + D\Lambda\left[u_a(t) + W_\sigma^T\sigma(x(t)) + W_{u_n}^Tu_n(t)\right], \end{aligned}\tag{10}$$

where $W_\sigma \triangleq W\Lambda^{-1} \in \mathbb{R}^{s\times m}$ and $W_{u_n} \triangleq I - \Lambda^{-1} \in \mathbb{D}^{m\times m}$. Next, let the adaptive feedback control law subject to Remark 2 be given by

$$u_a(t) = -\hat{W}_\sigma^T(t)\sigma(x(t)) - \hat{W}_{u_n}^T(t)u_n(t), \tag{11}$$

where $\hat{W}_\sigma(t) \in \mathbb{R}^{s\times m}$ and $\hat{W}_{u_n}(t) \in \mathbb{R}^{m\times m}$ are the estimates of W_σ and W_{u_n}, respectively, satisfying the weight update laws

$$\dot{\hat{W}}_\sigma(t) = \mathrm{Proj}\left[\hat{W}_\sigma(t), \gamma_\sigma\sigma(x(t))e^T(t)PD\right], \tag{12}$$

$$\hat{W}_\sigma(0) = \hat{W}_{\sigma0},$$

$$\dot{\hat{W}}_{u_n}(t) = \mathrm{Proj}\left[\hat{W}_{u_n}(t), \gamma_{u_n}u_n(t)e^T(t)PD\right], \tag{13}$$

$$\hat{W}_{u_n}(0) = \hat{W}_{u_n0},$$

where $\gamma_\sigma \in \mathbb{R}_+^{s\times s} \cap \mathbb{S}^{s\times s}$ and $\gamma_\sigma \in \mathbb{R}_+^{m\times m} \cap \mathbb{S}^{m\times m}$ are the learning rate matrices, $e(t) \triangleq x(t) - x_r(t)$ is the system error state vector, and $P \in \mathbb{R}_+^{n\times n} \cap \mathbb{S}^{n\times n}$ is the solution of the Lyapunov equation

$$0 = A_r^TP + PA_r + R, \tag{14}$$

where $R \in \mathbb{R}_+^{n\times n} \cap \mathbb{S}^{n\times n}$ can ve viewed as an additional learning rate. Note that because A_r is Hurwitz, it follows from the converse Lyapunov theory [15] that there exists a unique P satisfaying (14) for a given R. In addition, the projection bounds are defined such that

$$\left|[\hat{W}_\sigma(t)]_{ij}\right| \leq \hat{W}_{\sigma,\max,i+(j-1)n}, \tag{15}$$

$$\text{for } i = 1, \ldots, n \text{ and } j = 1, \ldots, m,$$

$$\left|[\hat{W}_{u_n}(t)]_{ij}\right| \leq \hat{W}_{u_n,\max,i+(j-1)m}, \tag{16}$$

$$\text{for } i = 1, \ldots, m \text{ and } j = 1, \ldots, m,$$

where $\hat{W}_{\sigma,\max,i+(j-1)n} \in \mathbb{R}_+$ and $\hat{W}_{u_n,\max,i+(j-1)m} \in \mathbb{R}_+$ denote (symmetric) element-wise projection bounds. Note that the these results can be readily applied to the case when asymmetric projection bounds are considered. Now, using (11) in (10) yields

$$\begin{aligned}\dot{x}(t) &= A_r x(t) \\ &\quad + B_r c(t) - D\Lambda\left[\tilde{W}_\sigma^T \sigma(x(T)) + \tilde{W}_{u_n}^T u_n(t)\right], \end{aligned} \quad (17)$$

and the system error dynamics is given using (3) and (7) as

$$\begin{aligned}\dot{e}(t) &= A_r e(t) \\ &\quad - D\Lambda\left[\tilde{W}_\sigma^T \sigma(x(T)) + \tilde{W}_{u_n}^T u_n(t)\right], \quad e(0) = e_0, \end{aligned} \quad (18)$$

where $\tilde{W}_\sigma \triangleq \hat{W}_\sigma - W_\sigma \in \mathbb{R}^{s\times m}$ and $\tilde{W}_{u_n} \triangleq \hat{W}_{u_n} - W_{u_n} \in \mathbb{R}^{m\times m}$. Note that the weight update laws given by (12) and (13) can be derived using Lyapunov analysis by considering the Lyapunov function candidate (see, for example, [14])

$$\begin{aligned}&\mathcal{V}(e, \tilde{W}_\sigma, \tilde{W}_{u_n}) = \\ &\qquad e^T P e + \gamma_\sigma^{-1} \mathrm{tr}\ \tilde{W}_\sigma^T \tilde{W}_\sigma + \gamma_{u_n}^{-1} \mathrm{tr}\ \tilde{W}_{u_n}^T \tilde{W}_{u_n}, \end{aligned} \quad (19)$$

to show the system error state vector $e(t)$ and the weight errors $\tilde{W}_\sigma$ and $\tilde{W}_{u_n}$ are Lyapunov stable, and are therefore bounded and $e(t) \to 0$ as $t \to \infty$.

IV. Flight Mechanics and Integrator Augmentation

The following utilizes MATLAB and Simulink nonlinear light combat aircraft model [16] with the appropriate routines for trimming. For the linearized flight configuration of an aircraft operating at an altitude 3950 meters and a mach number of 0.739 ($\delta(x(t)) = 0$, $\Lambda = I$), the decoupled longitudinal dynamics are of the form

$$\dot{x}_p(t) = A_p x(t) + B_p u(t), \quad x_p(0) = x_{p0}, \quad (20)$$

where $x_p(t) = \begin{bmatrix} v & \alpha & q & \theta \end{bmatrix}^T \in \mathbb{R}^{n_p}$ is the state vector available for feedback, $u(t) \in \mathbb{R}^m$ is the known input restricted to the class of admissible controls consisting of measurable functions of the form (8),

$$A_p = \begin{bmatrix} -0.0457 & -4.7762 & -0.5514 & -9.8100 \\ -0.0003 & -1.4398 & 0.9874 & -0.0001 \\ 0.0001 & -10.6785 & -1.8974 & 0.0000 \\ 0 & 0 & 1.0000 & 0 \end{bmatrix} \in \mathbb{R}^{n_p \times n_p}, \quad (21)$$

$$B_p = \begin{bmatrix} -1.5774 & -0.0871 & -24.7695 & 0 \end{bmatrix}^T \in \mathbb{R}^{n_p \times m}. \quad (22)$$

To include integral action such that perfect asymptotic set point tracking and rejection of constant disturbances are assured, we introduce the augmented form [17]. Let $c(t) \in \mathbb{R}^{n_c}$ be a piecewise continuous command function and $x_c(t) \in \mathbb{R}^{n_c}$ be the state integrator satisfying

$$\dot{x}_c(t) = E_p x_p(t) - c(t), \quad x_c(0) = x_{c0}, \quad (23)$$

where $E_p = \begin{bmatrix} 0 & 0 & 0 & 1 \end{bmatrix} \in \mathbb{R}^{n_c \times n_p}$ allows the chosen subset of $x_p(t)$ to follow $c(t)$. For the nonlinear dynamics, it naturally follows that (3) and (4), subject to Assumption 1, become

$$\dot{x}(t) = Ax(t) + Bu(t) + DW^T\sigma(x) + B_r c(t), \quad (24)$$

where $x(t) = \begin{bmatrix} x_p^T & x_c^T \end{bmatrix}^T \in \mathbb{R}^n$, $n = n_p + n_c$, is the augmented state vector, $x(t) = \begin{bmatrix} x_{p0}^T & x_{c0}^T \end{bmatrix}^T \in \mathbb{R}^n$,

$$A = \begin{bmatrix} A_p & 0_{n_p \times n_c} \\ E_p & 0_{n_c \times n_c} \end{bmatrix} \in \mathbb{R}^{n \times n}, \quad (25)$$

$$D = \begin{bmatrix} B_p^T & 0_{n_p \times m} \end{bmatrix}^T \in \mathbb{R}^{n \times m}, \quad (26)$$

$$B_r = \begin{bmatrix} 0_{n_p \times n_c}^T & -I_{n_c \times n_c} \end{bmatrix}^T \in \mathbb{R}^{n \times n_c}. \quad (27)$$

Note that (24), with (25)-(27), assumes the form of (10). Hence, (19) is still satisfied, $\tilde{W}_\sigma$ and $\tilde{W}_{u_n}$ are Lyapunov stable, and are therefore bounded, and $e(t) \to 0$ as $t \to \infty$. The pitch attitude hold nominal control law was designed using the linear-quadratic (LQ) approach. We can now design the LQ nominal feedback controller and obtain the gains for (9) such that desired transient performance is achievable.

V. Application to a Nonlinear Aircraft Model

In order to illustrative the efficacy of our results, we review an example where the CG of the aircraft and the control effectiveness are altered for a nonlinear model of an aircraft. The nominal control is obtained using (21) and (22) where the appropriate weights and penalties were used to obtain the following gain matrix

$$K_1 = \begin{bmatrix} 0.0008 & 0.5170 & -1.0974 & -7.8921 & -3.6515 \end{bmatrix}. \quad (28)$$

The solution to (14) where $A_r = A - DK_1$ is computed as

$$P = \begin{bmatrix} 1214.9 & -0.79444 & 3.1972 & -5.4245 & 10.951 \\ -0.79444 & 0.74793 & 0.56456 & 0.038297 & -0.20682 \\ 3.1972 & 0.56456 & 4.443 & -0.5 & -0.32831 \\ -5.4245 & 0.038297 & -0.5 & 0.32831 & -0.5 \\ 10.951 & -0.20682 & -0.32831 & -0.5 & 1.1782 \end{bmatrix}, \quad (29)$$

where $R = I_{5\times 5}$. For the proposed design, we use (11), (12), and (13) with $\hat{W}_{\sigma,\max} = 0.5$ and $\hat{W}_{u_n,\max} = 1$. To help visualize the longitudinal controller, a block diagram is provided in Figure 1, where $\delta_{el} \in \mathbb{R}$ is the elevator input.

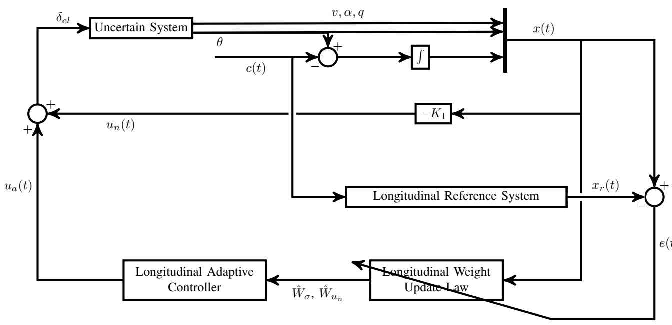

Figure 1. Longitudinal MRAC Block Diagram

In the event that the aircraft CG is shifted to the rearward-most position, the new uncertain longitudinal dynamics in the form of (24) with the integrator become

$$A = \begin{bmatrix} -0.0457 & -4.7510 & 0 & -9.8100 & 0 \\ -0.0003 & -1.4396 & 0.9874 & 0 & 0 \\ -0.0192 & -92.3347 & -2.6109 & 0 & 0 \\ 0 & 0 & 1.0000 & 0 & 0 \\ 0 & 0 & 0 & 1.0000 & 0 \end{bmatrix}, \quad (30)$$

$$D = \begin{bmatrix} -1.5774 & -0.0871 & -29.7114 & 0 & 0 \end{bmatrix}^T. \quad (31)$$

Figures 2 and 3 shows the effects caused by the CG change to the short period and phugoid modes for the angle of attack and pitchrate, respectively.

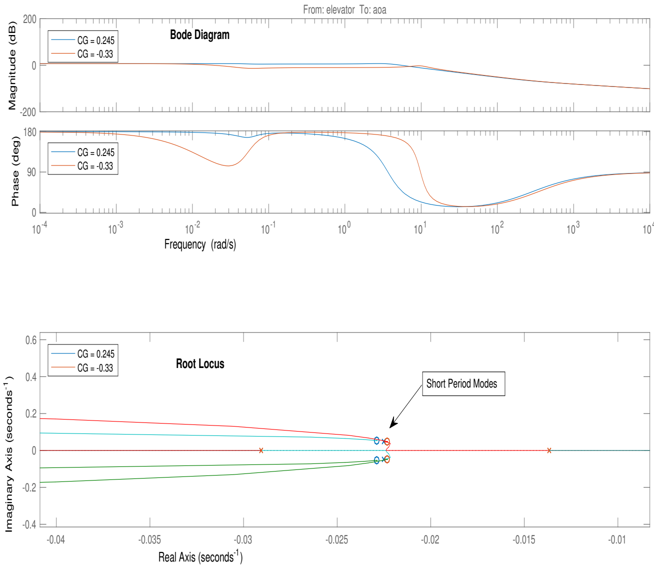

Figure 2. Bode and Root Locus Plots for Angle of Attack

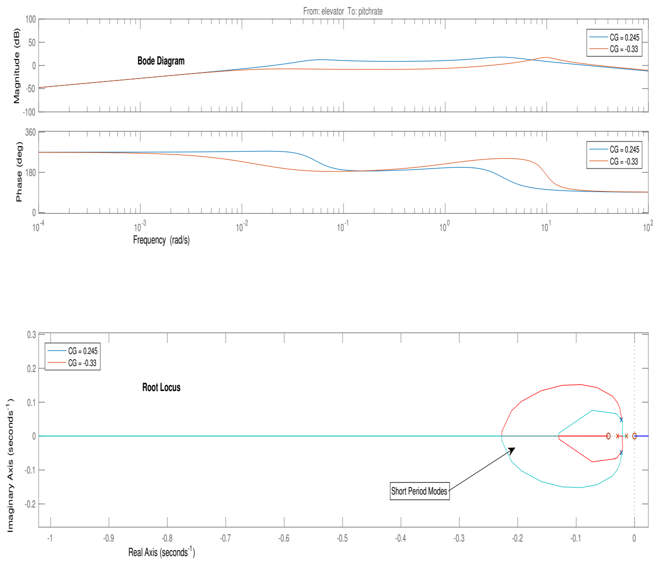

Figure 3. Bode and Root Locus Plots for Pitchrate

The following results were achieved using MATLAB Simulink. Figures 4 to 7 show the results of the nominal controller pitch-attitude hold with and without the MRAC augmentation when the change in CG (30) and (31) (at $t = 35$ seconds) is coupled with reduced control effectiveness ($\Lambda = 0.5$).

The nominal controller is unable to compensate for change in dynamics, and the elevator deflection is undesireable. For the MRAC, the pitch and angle of attack transient performance improves significantly, error is minimized, and the elevator deflection remains practical. However, the initial transient performance of the MRAC during the adaptation phase of the controller can remain undesirable even if Lyapunov stability is assured. This behavior can be improved through an direct uncertainty minimization scheme [17] and implementation of an artificial basis function [18].

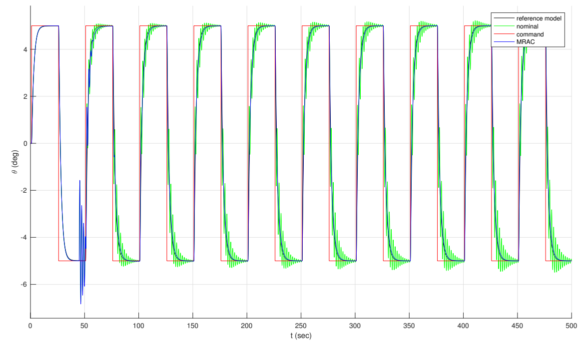

Figure 4. Pitch of Aircraft with CG Change ($\gamma_\sigma = 0.1$, $\gamma_{u_n} = 1$, CG $= -0.33$, $\Lambda = 0.5$)

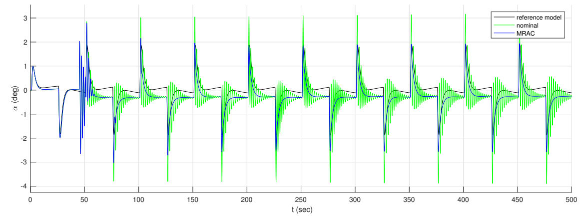

Figure 5. Angle of Attack of Aircraft with CG change ($\gamma_\sigma = 0.1$, $\gamma_{u_n} = 1$, CG $= -0.33$, $\Lambda = 0.5$)

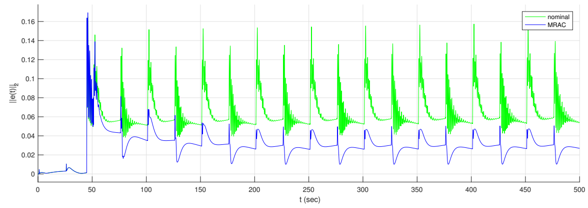

Figure 6. Error of Aircraft with CG Change ($\gamma_\sigma = 0.1$, $\gamma_{u_n} = 1$, CG $= -0.33$, $\Lambda = 0.5$)

VI. Conclusion

In this paper, we considered an MRAC design as a means of improving transient performance for the pitch-attitude hold of a nonlinear model, we added a state integrator augmentation and designed a nominal controller, and we demonstrated the

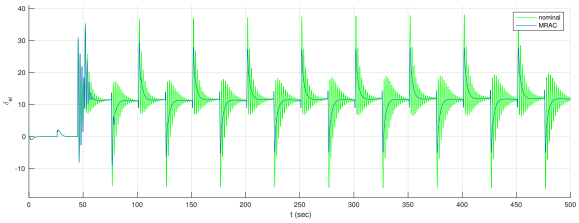

Figure 7. Elevator Deflection of Aircraft with Cg Change ($\gamma_\sigma = 0.1$, $\gamma_{u_n} = 1$, CG $= -0.33$, $\Lambda = 0.5$)

efficacy of our results for an where a change in center of gravity is coupled with reduced control effectiveness. For future work, we will consider other nonlinear aircraft models with this control framework. Additionally, we will consider moment and sum of squares framework (for example, [19]) for adaptive control law verification and validation such that unmodeled dynamics are considered.

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