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Modified adaptive second order sliding mode control: Perturbed system response robustness☆

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ABSTRACT

Sensitivity to parameters, which is negative for any system; for an aircraft is destructive. In this respect, an Adaptive Second-order Sliding Mode Control (AS-SMC) is proposed to manage the unknown time-varying aircraft parameter uncertainty and un-modeled coupling perturbations. The employed adaptivity relaxes the required knowledge of the perturbation bound, the suggested sliding surface improves the system stability and bypassing the SMC reaching phase enhances the performance robustness. The effectiveness of the scheme in providing low tolerance responses with respect to the basic controller is illustrated through extensive simulations. The response is more appreciated when the system operates in a high angle of attack/sideslip conditions.

1. Introduction

Aircraft controllers are expected to provide accurate command tracking. A robust, well-tuned controller will suppress external disturbances and make the system insensitive to parameter uncertainty. Due to nonlinear and time-varying nature of an aircraft system, its controller design is a tough task. Traditionally, Gain Scheduling Proportional-Integral-Derivative (GS-PID) controllers are utilized for handling different types of the system manoeuvres.

Apart from GS-PID other robust control techniques have also been developed that could be applied. An approximate constraint-following based adaptive robust control scheme for control of uncertain mechanical systems has been proposed in [1]. The robust Fractional Order PID design which is widely used for control of uncertain systems has presented in [2]. Aircraft roll angle control using H_∞ has been studied in [3,4]. In [5], a robust backstepping-based aircraft roll dynamics control has been discussed. Modern aircrafts often exhibit a limit cycle oscillation in the roll angle known as the "wing rock phenomenon" at a high angle of attack operations; a simple adaptive control has been worked out to suppress this oscillation in [6]. A two-loop PI/linear active disturbance rejection control and H_∞ control scheme has been suggested in [7]; where the outer loop enforces trajectory tracking and the H_∞ inner loop keeps attitude under control.

Another type of robust control methods with numerous applications is the sliding mode control. The attitude fault-tolerant control of a satellite with reaction-wheel failures, uncertainties, and unknown external disturbances using a third-order SMC has been proposed in [8]. SMC for control of nonlinear-uncertain magnetic levitation process has been reported in [9]. Using an adaptive second order sliding mode for fault detection has been reported in [10]. A direct power control strategy based on SMC is implemented to enhance the robustness of the doubly-fed induction generator in [11]. Design of an

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intelligent controller for reduction of chattering phenomenon resulting from SMC in control of robotic arm has been found in [12]. Fuzzy SMC for a nonlinear system control has been worked out in [13]. A novel second-order sliding mode control to handle sliding mode dynamics with mismatched term has been introduced in [14]. Efficient vehicle braking on a non-uniform road using an adaptive SMC strategy has been successfully implemented in [15]. Investigation on the application of a novel robust adaptive second-order sliding mode tracking control technique for uncertain dynamical systems with matched and unmatched disturbances has been reported in [16].

Regarding the application of SMC to aircraft control, an adaptive fuzzy sliding mode roll control of an aircraft under high perturbations is discussed in [17]. In [18], a second-order sliding mode control for the altitude tracking of an aircraft has been reported. Second-order sliding mode control has also been used to extend the flight envelope and reduce the sensitivity to the parametric uncertainty and/or signal perturbations in [19]. The procedure for a frequency-domain-based synthesis technique using pseudo-sliding mode for robust aircraft flight control has been presented in [20]. A comprehensive strategy that combines improved fast non-singular terminal sliding mode control and an extended state observer to solve the problems of uncertainty in the aeronautical field has been analyzed in [21]. In [22], a discontinuous SMC and a super-twisting continuous control law are designed to control the aircraft system parameter uncertainties. Robust trajectory tracking for unmanned aircraft systems using a non-singular terminal modified super-twisting SMC is another study in control and guidance of aircrafts to contain the system uncertainty [23].

In the aforementioned studies, the level of uncertainty and disturbances are moderate; whereas higher levels of uncertainty (30%) and perturbations (high angle of attack) may also become a concern, as it is analyzed here. The response robustness of the uncertain system is substantially improved by the proposed AS-SMC which the reaching phase is eliminated by forcing the sliding surface to include the initial condition [24]. The adaptive gain automatically adjusts the controller gain to track the "unknown" time-varying upper bound of the uncertainty. Introducing a sliding surface variable by a linear combination of the sideslip angle and the roll rate strengthens the algorithm to withstand strong perturbations. The results indicate that the suggested scheme provides more coherent responses despite 30% variations in the aircraft aerodynamic parameters than using the aircraft basic controller. This is supported by the theoretic proof and certified by numerous simulations.

In the followings, AS-SMC is detailed in Section 2. In Section 3, the system dynamics and the basic controller are briefly described. The application of the algorithm to the aircraft roll control is elaborated in Section 4. In Section 5, the simulation results are presented and lastly, the conclusion comes in Section 6.

2. Modified adaptive second-order sliding mode control

Consider the following SISO uncertain nonlinear system,

$$\begin{aligned} &\dot{\eta} = b(\eta, x) && \left|\delta_f(x)\right| < d_f \\ &\dot{x}_i = x_{i+1} \quad i = 1\dots n-1 && |\delta_g(x)| < d_g \\ &\dot{x}_n = f_0(x) + \delta_f(x) + g_0(x)(1 + \delta_g(x))u\,, && g_0(x)(1 - d_g) > 0 \end{aligned} \tag{1}$$

where $u \in R^1$ is the system input, $y \in R^1$ is the system output, $x \in R^n$ is the system states, f_0 and g_0 are known functions and δ_f and δ_g are the unknown uncertain smooth bounded functions. The zero dynamics, η is presumed asymptotically stable and without loss of generality, the origin is the desired steady state.

The first stage of the design includes introducing a stable sliding surface such as the following linear Hurwitz polynomial one,

$$s = x_n + \sum_{i=1}^{n-1} c_i x_i \tag{2}$$

where the choice of c determines the x decaying rate. The design objective is to present a control input u, to force s and $\dot{s}$ to zero in a finite time despite uncertainty. In this respect, the control is partitioned into u_0 which cancels the known dynamics and a switching control u_s to provide response robustness [25]. Where the exact upper bound of the uncertainty is not available and or it is time-varying, adaptive gain yields better results. Moreover, the annoying chattering phenomena is subdued if a filtered switching is applied. Those for a relative degree one system are interpreted as using AS-SMC. Therefore, the issues are addressed together by a single super twisting switching control action as below,

$$\begin{aligned} &u = u_0 + u_s && u_s = -g_0^{-1} L[u_1 + u_2] \\ &u_1 = k_s |s|^{0.5} sign(s) && \dot{u}_2 = -T u_2 + sign(s) \end{aligned} \tag{3}$$

where T is the filter time constant and L is a time-varying adjustable gain derived using the following adaptation law,

$$\dot{L} = \begin{cases} \frac{1}{\alpha}|s| & s\dot{s} > 0, \quad |s| > c_1 \\ -\gamma & s\dot{s} < -c_2 \qquad\qquad L_{\min} < L \le \bar{L} \\ 0 \ or \ -\frac{\gamma}{10} & else \end{cases} \tag{4}$$

In (4), α, γ, c_1 and c_2 are the positive constants of appropriate value. $\bar{L}$ and L_{min} are the upper and lower bounds of L which is system dependent.

To establish the stability condition, the following Lyapunov function is utilized and its derivative is calculated,

$$\begin{aligned} &V = \tfrac{1}{2}s^2 + \tfrac{1}{2}\alpha(L-\bar{L})^2 \Rightarrow \\ &\dot{V} = s\dot{s} + \alpha(L-\bar{L})\dot{L} \end{aligned} \tag{5}$$

$\dot{s}$ in (5) is obtained by taking the derivative of (2) and substituting the variables from (1) as given below,

$$\dot{s} = \dot{x}_n + \sum_{i=1}^{n-1} c_i\dot{x}_i = f_0(x) + \sum_{i=1}^{n-1} c_i x_{i+1} + \delta_f(x) + g_0(x)(1+\delta_g(x))u \tag{6}$$

The u_0 component of u is assigned in a way to cancel out the known system dynamics ($\delta_f = \delta_g = 0$) as defined by,

$$u_0 = -{g_0}^{-1}\left(f_0 + \sum_{i=1}^{n-1} c_i x_{i+1}\right) \tag{7}$$

Now, by inserting u_0 (7) and u_s (3) in (6), $\dot{V}$ (5) is obtained as follows,

$$\dot{V} = s\big(g_0\delta_g u_0 + \delta_f - (1+\delta_g)L(u_1+u_2)\big) + \alpha(L-\bar{L})\dot{L} \tag{8}$$

In (8), δ_f is replaced by its upper bound, d_f and $1+\delta_g$ in the denominator by its lower bound, $1-d_g$ to reach the following inequality,

$$\begin{aligned} &\dot{V} \le (1+\delta_g)s\left(\left|\frac{g_0 d_g u_0 + d_f}{1-d_g}\right| - L(u_1+u_2)\right) + \frac{\alpha(L-\bar{L})\dot{L}}{1-d_g}, \qquad \left|\frac{d_g u_0 + d_f}{1-d_g}\right| = d \le d_m \\ &\dot{V} \le s\left[d - L\big(k_s|s|^{0.5}sign(s) + u_2\big) + \frac{(L-\bar{L})s.sign(s)}{1-d_g}\right] \\ &\quad \le s(d - Lu_2) - \left(\frac{\bar{L}-L}{1-d_g} + Lk_s|s|^{0.5}\right)|s| \\ &\dot{V} \le s(d - Lu_2) \end{aligned} \tag{9}$$

Under zero initial condition, the response to u_2 (3) is expressed by,

$$u_2(t) = \frac{1}{T}(1 - e^{-Tt})sign(s) \tag{10}$$

Inserting (10) into (9) leads to,

$$\dot{V} \le s\left(d - \frac{L}{T}(1 - e^{-Tt})sign(s)\right) \tag{11}$$

For $\dot{V}$ to become negative definite, the following conditions have to be satisfied,

$$\bar{L} > Td_m, \qquad \dot{L} = \frac{|s|}{\alpha} > T\dot{d}_m \Rightarrow \alpha < \frac{\tau}{T\dot{d}_m}, \qquad \left|\dot{d}\right| < \dot{d}_m \tag{12}$$

and this completes the proof.

To test the performance of the presented AS-SMC, it is used to control the following nonlinear perturbed system,

$$\begin{aligned} &\dot{x}_1 = x_2 \\ &\dot{x}_2 = 0.1x_2^3 + u + d, \qquad d = 0.9x_2^3 + 4\sin(4t) \end{aligned}$$

The system response and the L gain variation under the initial condition $[1\ 4]^T$ have been depicted in Fig. 1.

3. Aircraft dynamical model

An aircraft longitudinal motion is administered by the symmetric deflection of the elevators; while aileron deflection controls roll and joint rudder-aileron manages the lateral-direction (yaw) motion. The 6-degrees of freedom compact mathematical model of an aircraft is denoted by the following equations,

$$\begin{aligned} &\dot{x} = f(x,u) \\ &x = [V, \beta, \alpha, p, q, r, \varphi, \theta, \psi]^T \\ &u = [\delta_a, \delta_r, \delta_s]^T \end{aligned} \tag{13}$$

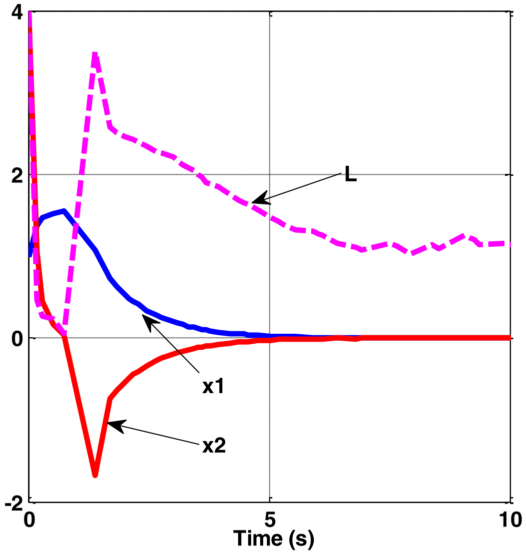

Fig. 1. The AS-SMC control of the nonlinear system and variation in the gain L.

where V(speed), β(sideslip angle), α(angle of attack), p(roll rate), q(pitch rate), r(yaw rate), φ(roll angle), θ(pitch angle) and ψ(yaw angle) are the state variables. The control surface command is delivered by u. The nonlinear roll rate and β motion equations capable of representing the unstable behavior mode of the system is given by,

$$\begin{aligned} \dot{p} &= I_{lp} C_l^{\alpha,V}(\beta, \delta_{ail,} \delta_{rud,} p, r) + I_{np} C_n + I_{yy} qr + I_{xz} pq - I_{zz} rq \\ \dot{\beta} &= f(\beta, \alpha, \theta, \varphi, p, r, V, \ldots) \end{aligned} \tag{14}$$

where the I variables (I_{lp}, I_{np}, I_{yy}, I_{xz}) are the system parameters. The nondimensional aerodynamic coefficients C's (C_n, C_l) are the time-varying nonlinear functions which are often determined experimentally and expressed by some approximate polynomials. As a result, the detailed p equation is obtained as below,

$$\begin{aligned} \dot{p} = &(0.0317q + V(0.0016\alpha - 0.0023))p \\ &+ (-0.8151q + V(-0.0071\alpha^2 + 0.0051\alpha + 0.0013))r \\ &+ 10^{-4}V^2(-5.6310\alpha^4 + 8.2890\alpha^3 - 1.2350\alpha^2 - 1.4460\alpha - 0.19800)\beta \\ &+ 10^{-5}V^2(6.7510\alpha^3 - 8.9920\alpha^2 - 1.8360\alpha + 49510)\delta_{ail} \\ &+ 10^{-6}V^2(-2.37\alpha^4 - 4.068\alpha^3 - 0.497\alpha^2 + 0.594\alpha + 4.959)\delta_{rud} \end{aligned} \tag{15}$$

which is picked from the set of equations expressing the coupled time-varying and nonlinear nature of the system detailed in [17].

3.1. Aircraft control

The simplified already implemented aircraft basic flight control law is given by [26],

$$\begin{aligned} \delta_{elev} &= (8q + 0.8\alpha)G_A(s) \\ \delta_{rud} &= \left(0.5a_y + \frac{1.1s + 6}{s + 1}r\right)G_A(s) \\ \delta_{ail} &= (-0.8p - 0.5\beta - 2\dot{\beta})G_A(s) \end{aligned} \tag{16}$$

where $G_A(s)$ is the actuator model. Based on (16), the longitudinal motion is controlled using the angle of attack, α and pitch rate, q. The directional control uses yaw rate, r, and lateral acceleration α_y. The roll rate control is initiated by feedback from the roll rate, p. However, it is recognized insufficient in handling the unmodeled coupling among variables especially when the system is perturbed by high angle of attack and /or sideslip perturbations. Thus, two extra β and $\dot{\beta}$ feedback loops are added to the control system. By this provision not only p is damped, but also β and $\dot{\beta}$ oscillations are better subdued.

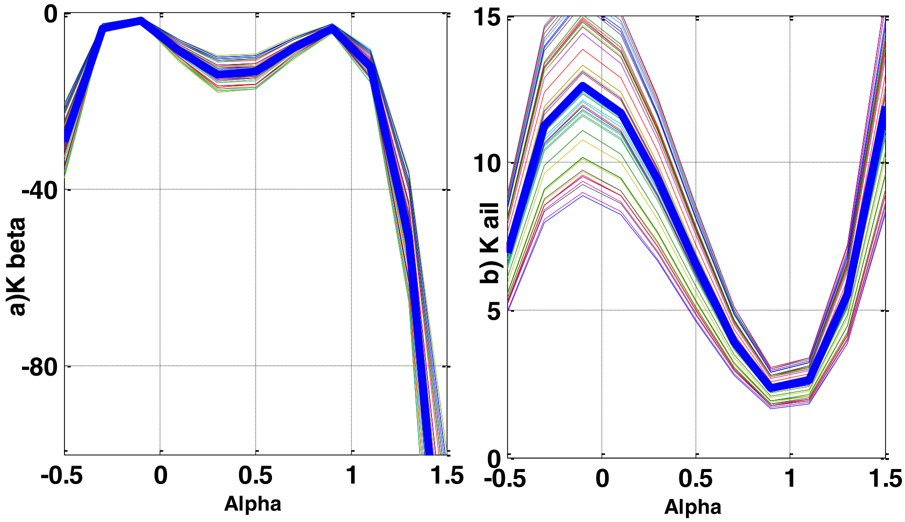

Fig. 2. Uncertain K_β and $K_{\delta ail}$ parameters of $\dot{p}$ (17).

3.2. Roll aerodynamic uncertainty

To differentiate the variable couplings and un-modeled dynamics from the rest of the model, Eq. (15) is rewritten as below,

$$\begin{aligned} \dot{p} &= K_p(\alpha)p + K_\beta(\alpha)\beta + K_{ail}(\alpha)\delta_{\text{ail}} + \text{d}(.) \\ d(.) &= 0.0317qp - 0.8151qr + K_r(\alpha)r + K_{rud}(\alpha)\delta_{\text{rud}} \end{aligned} \tag{17}$$

where *d(.)* is the total perturbation. To analyze the system uncertainty, a set of random systems by applying 30% tolerance to the coefficients of (17) is generated. The variation in K_β versus α has been portrayed in Fig. 2(a) and the variation of K_{ail} has been depicted in Fig. 2(b), which is more or less compatible with 30% tolerance applied.

Now, the prime question here is to what extent the randomness applied to the parameters of (17) affects the system response. From the viewpoint of robust design and practical implementation, the response tolerance has to be minimized and the flight stability has to be secured.

4. AS-SMC roll control design

To start the AS-SMC design, the basic control law configuration is valued and a weighted combination of p and β is formed as a new control variable,

$$z = p + w\beta \tag{18}$$

Indeed the sliding mode control based on just p feedback cannot provide the desired result as it is also understood before, in the basic control law design (16). By combining $\dot{p}$ (17) and $\dot{\beta}$ (14), the z dynamical equation is obtained,

$$\dot{z} = a_0 z + b_0\delta_{ail} + \Delta_0 + d(.), \qquad |d(.)| < \delta \tag{19}$$

where 0 subscript refers to the nominal values and positive δ is the uncertainty bound.

Remark: Only the roll related aerodynamic parameters are exposed to the uncertainty.
Assumptions 1: The basic controller stabilizes the nominal system states including β [26].
Assumptions 2: The initial conditions are within the region of attraction of the basic control law [26].

Except for the $a_0 w\beta$ term, the rest of the $w\dot{\beta}$ dynamics are collected in Δ_0, since the uncertainty is only applied to the roll aerodynamic parameters (Assumption 1), otherwise, other control loops have to be redesigned similarly.

Considering the stability of the β loop (Assumption 2), the p variable asymptotical stability is achieved if the following error function is forced to zero by some appropriate control action,

$$e = z - z_0 = p - p_{trim} + w(\beta - \beta_{trim}) \tag{20}$$

To apply AS-SMC, the sliding surface given below with the relative order one is utilized,

$$s = e - e(0) + \lambda \int e(t)dt \tag{21}$$

The sliding surface (21) is designed such that the initial state is on the sliding surface (reaching phase free). The choice of λ determines the speed of sliding on the sliding surface to reach the equilibrium point which higher value of λ corresponds to faster settling time. The aileron equivalent control signal stabilizing the nominal system is obtained using $\dot{s}$, assuming the aileron deflection limit is not violated, as below,

$$\begin{aligned} &\dot{s} = \dot{e} + \lambda e = 0 \quad for \quad t > 0 \\ &\dot{s} = a_0 e + b_0 \delta_{ail} + \Delta_0 + d(.) + \lambda e, \quad |d(.)| < \delta \\ &u_0 = -b_0^{-1}\left(a_0 e + \Delta_0 + \widehat{d} + \lambda e\right) \end{aligned} \tag{22}$$

where $\hat{d}$ is a rough estimate of d which even may be taken to be zero, $\hat{d} = 0$. Due to uncertainty in d, maintaining robust response requires a complementary switching SMC signal to administer the existing tolerance. This is achieved by the following adaptive super twisting second-order switching law copied from (3) and (4),

$$\begin{aligned} &u_s(s) = -{b_0}^{-1} L\left[k_s |s|^{1/2} sign(s) + u_1\right] \\ &\dot{u}_1 = -T u_1 + sign(s) \\ &\dot{L} = \begin{cases} \frac{1}{\alpha}|s| & s\dot{s} > 0, \quad |s| > c_1 \\ -\gamma & s\dot{s} < -c_2 \\ 0 \ or - \frac{\gamma}{10} & else \end{cases} \qquad L_{\min} < L \le \bar{L} \end{aligned} \tag{23}$$

where α, γ, c_1, c_2, and k_s are some positive numbers with system-dependent appropriate values. L_{min} and $\bar{L}$ are the lower and the upper bound of the time-varying adjustable gain L. Applying both continuous and switching control laws and following the stability proof line given in (9) leads to,

$$\begin{aligned} &V = \tfrac{1}{2}s^2 + \tfrac{1}{2}\alpha(L - \bar{L})^2 \\ &\dot{V} = s(a_0 e + b_0(u_0 + u_s) + \Delta_0 + d + \lambda e) + \alpha(L - \bar{L})\dot{L} \\ &\dot{V} = s\left(d - \hat{d} - L u_1 - L\left[k_s |s|^{1/2} sign(s)\right]\right) + (L - \bar{L}) s.sign(s) \\ &\dot{V} \le s(e_d - \tfrac{L}{T}(1 - e^{-Tt}) sign(s)), \qquad e_d = \left|d - \hat{d}\right| \\ &\dot{V} \le s(e_d - \tfrac{L}{T}(1 - e^{-Tt}) sign(s)) \end{aligned} \tag{24}$$

For the system asymptotic stability, Eq. (24) has to become negative definite, which is satisfied under the following conditions,

$$\begin{aligned} &\delta_{ail-LB} < u_0 + u_s < \delta_{ail-UB} \\ &\bar{L} > \max(e_d) T, \qquad \alpha < \frac{\tau}{T \max(\dot{e}_d)} \end{aligned} \tag{25}$$

5. Simulations

The system (1) with parameters reported in [17] is simulated in SIMULINK and a set of 50 random systems with 30% tolerance in the parameters are generated. Then the basic controller and the proposed AS-SMC are employed to control the set of random systems. The working point is the one used in [26] for studying the unstable falling leaf phenomena as below,

$$\begin{aligned} &x = [V \quad \beta \quad \alpha \quad p \quad q \quad r \quad \varphi \quad \theta \quad \psi]^T \\ &x_{Trim} = [106.5 \quad 0 \quad 20 \quad -1 \quad 2 \quad 2.5 \quad 35 \quad 19 \quad 0]^T \end{aligned}$$

The aileron deflection angle bound (−25° to 45°) is also applied [26].

Four test scenarios are defined by introducing initial condition perturbations to the angle of attack and sideslip: 1) high α and high β, 2) high α and medium β, 3) medium α and high β, 4) medium α and medium β. The initial conditions are taken within the attraction region of the basic controller (Assumption 2) since just the controllers' response robustness is examined.

In the first test, high $\alpha = 80$ and $\beta = 50$ perturbations are introduced through the following initial condition,

$$x_{Initial} = [106.5 \quad 50 \quad 80 \quad 24 \quad 2 \quad 3 \quad 60 \quad 19 \quad 0]^T$$

The system responses have been depicted in Fig. 3. The responses with lower variance are the outcome of using the suggested AS-SMC controller. The response tolerance is so much low as if no uncertainty has been applied to the system parameters. This is also true for the other system states. Once the control reaches the sliding surface the system becomes insensitive against disturbances because it won't be able to leave it; so SMC is robust only in the sliding phase; however,

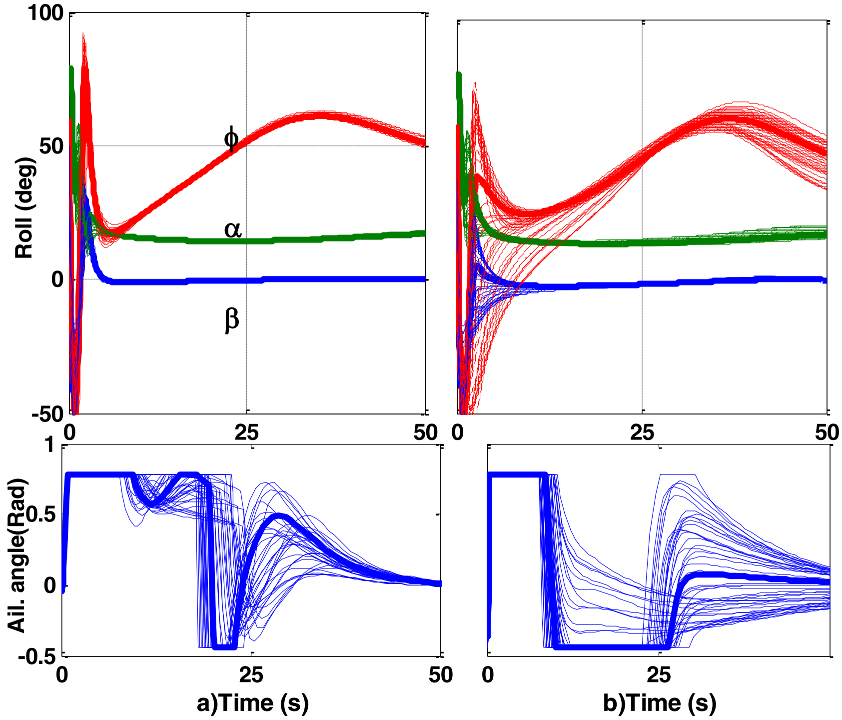

Fig. 3. The system response robustness under high α and β perturbations using (a) AS-SMC versus (b) the basic controller.

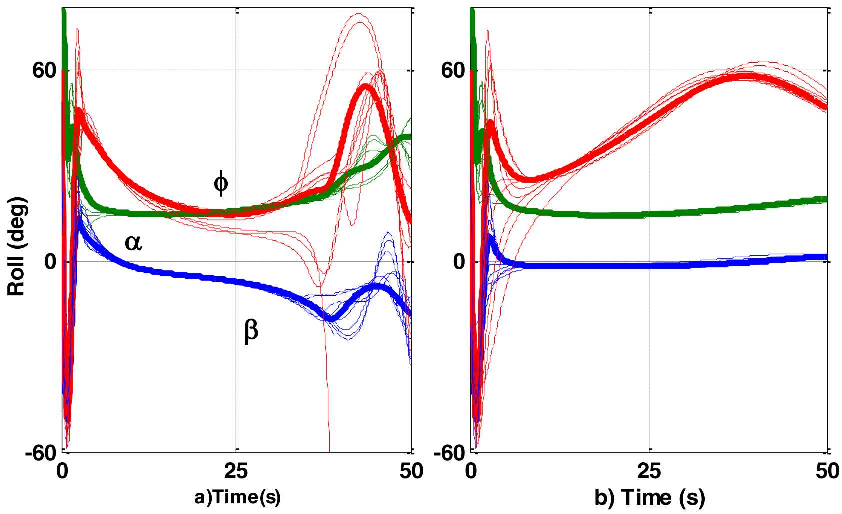

Fig. 4. The AS-SMC behavior using $w = 0$ with a) $\lambda = 2$ and b) $\lambda = 0.1$.

where the sliding surface satisfies the initial condition forced by (21); the reaching phase is eliminated and overall robustness is achieved [24]. The system response can be compared with using fuzzy sliding mode [17], where the simpler tuning and design procedure is the advantage here. Since the initial condition is within the attraction region of the basic controller (Assumption 2), the basic controller system remains stable but the response tolerance is poor.

The system response where p is used in place of z ($w = 0$) with $\lambda = 2$ (fast sliding speed) leads to flight failure as shown in Fig. 4(a). However, where $\lambda = 0.1$ (slower sliding speed) is employed the stability is again restored Fig. 4(b). Thus, for the robust adaptive second-order sliding mode roll control design, it is not enough to stands on just p feedback, using β is also necessary. In other words, defining the sliding surface based on z extends the size of the system attractor.

In the second test, the initial condition,

$$x_{Initial} = [106.5 \quad 20 \quad 80 \quad 9 \quad 2 \quad 8 \quad 35 \quad 19 \quad 0]^T$$

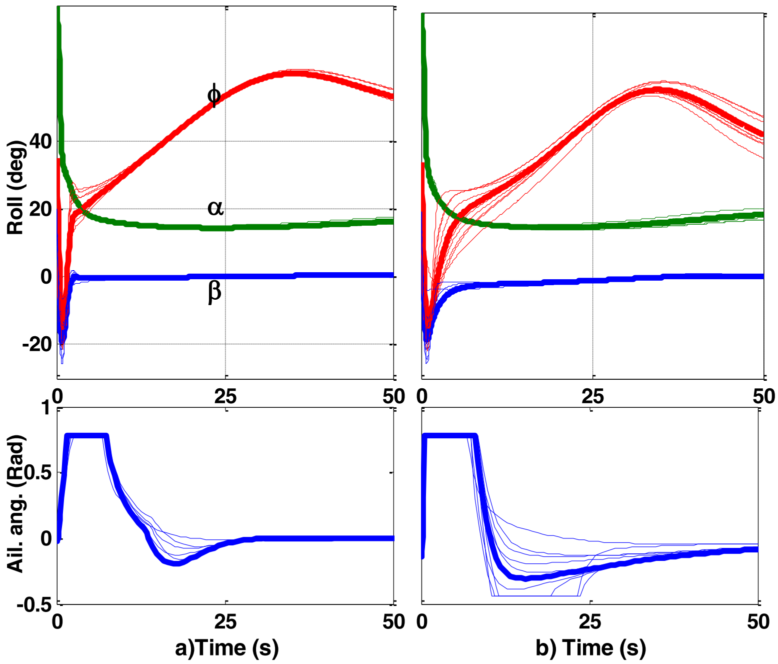

Fig. 5. The system response robustness under high α and medium β perturbations using (a) AS-SMC versus (b) the basic controller.

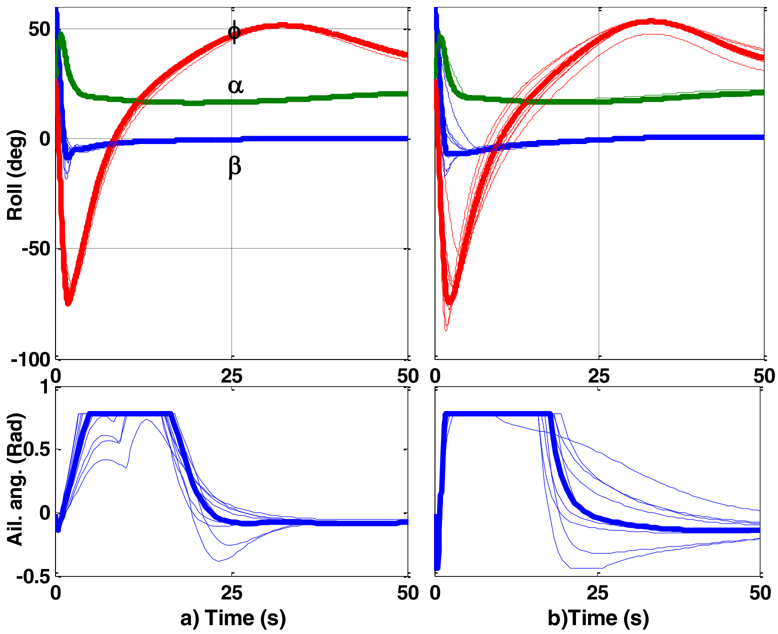

Fig. 6. The system response robustness under medium α and high β perturbations using (a) AS-SMC versus (b) the basic controller.

is employed reflecting high α and medium β perturbation. The responses of both methods have been exhibited in Fig. 5. More coherencies in the response (robustness) of AS-SMC are visible from the figure. Therefore, it is realized that the proposed method outperforms the basic design. Moreover, less input control fluctuation is another salient point of the proposed approach.

The initial condition for the third test is as below,

$$x_{Initial} = [106.5 \quad 60 \quad 30 \quad 25 \quad 25 \quad 20 \quad 25 \quad 0 \quad 0]^T$$

corresponding to the medium α and high β perturbation. The system responses have been portrayed in Fig 6. Similar conclusion is obtained again, i.e. better performance of random systems.

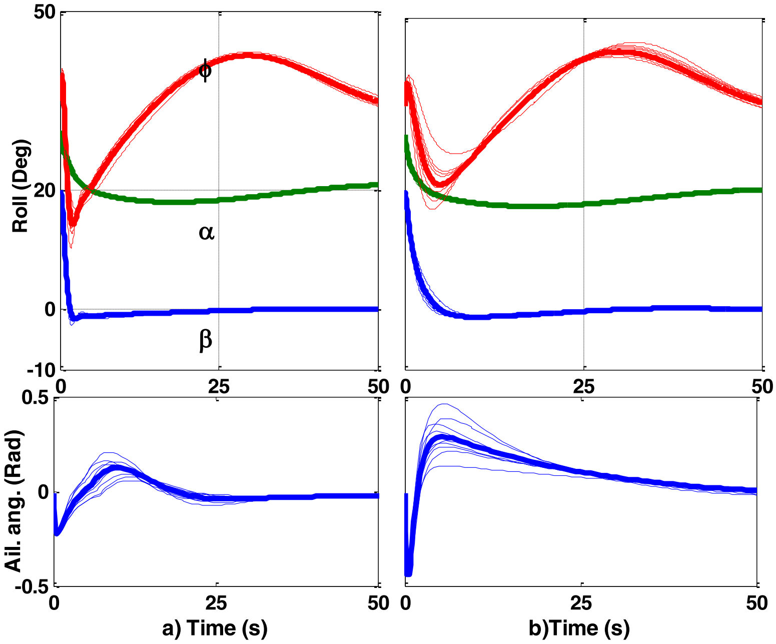

Fig. 7. The system response robustness under medium α and β perturbations using (a) AS-SMC versus (b) the basic controller.

Lastly, the initial condition representing medium α and β perturbation is applied,

$$x_{Initial} = [106.5 \quad 20 \quad 30 \quad 30 \quad 20 \quad 3 \quad 35 \quad 10 \quad 0]^T$$

The roll state responses and the required control efforts have been exhibited in Fig. 7. By comparing the roll responses, it is easily verified that the proposed controller provides superior performance. Moreover, the task is achieved with very low control efforts. The algorithm outcome under other working points within the region of attraction also proves the validity of the findings.

In overall, the results indicate that the basic controller serves its task moderate even under a low angle of attack flight execution with respect to the AS-SMC design.

6. Conclusion

In this paper, a robust aircraft roll control design is investigated to deliver low tolerance system responses. The system is nonlinear with un-modelled dynamics and subjected to strong coupling and initial condition perturbations. In this respect, (1) an AS-SMC design is developed and its stability proof is provided (2) It is reformulated for an aircraft roll dynamics control by taking a linearly weighted p and β variables as the sliding surface variable (3) The reaching phase is bypassed by introducing an appropriate sliding surface (4) Large 30% aerodynamic parameter uncertainty and initial conditions perturbations are applied and the response tolerances are observed. The results indicate that the proposed controller provides lower tolerance responses (performance robustness) than the behavior of the basic controller under various simulation scenarios.

Declaration of Competing Interest

None.

Acknowledgments

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.compeleceng.2019.106536.

References

[1] Sun H, Chen Y-H, Zhao H. Adaptive robust control methodology for active roll control system with uncertainty. Nonlinear Dyn 2018;92:359–71.
[2] Seyedtabaii S. New flat phase margin fractional order PID design: perturbed UAV roll control study. Rob Auton Syst 2017;96:58–64.
[3] Seyedtabaii S, Zaker S. Lateral control of an Aerosonde facing tolerance in parameters and operation speed: performance robustness study. Trans Inst Meas Control 2019;41:2319–27.
[4] Seyedtabaii S. A modified FOPOID versus H∞ and µ synthesis controllers: robustness study. Int J. Control, Autom. Syst 2019;17:639–46.
[5] Tran TT, Gonzalez OR. Backstepping-based control methodology for aircraft roll dynamics. Proc Instit Mech Eng Part I 2019. doi:10.1177/0959651819860294.
[6] Andrievsky B, Kudryashova EV, Kuznetsov NV, Kuznetsova OA, Mokaev TN, Tomashevich S. Simple adaptive control of aircraft roll angle, suppressing the wing rock oscillations. J| MESA 2019;10:373–86.
[7] Qi P, Zhao X, Wang Y, Palacios R, Wynn A. Aeroelastic and trajectory control of high altitude long endurance aircraft. IEEE Trans Aerosp Electron Syst 2018;54:2992–3003.
[8] Zhang Z, Ye D, Xiao B, Sun Z. Third-order sliding mode fault-tolerant control for satellites based on iterative learning observer. Asian J Control 2019;21:43–51.
[9] Sathiyavathi S. Design of sliding mode controller for magnetic levitation system. Comput Electr Eng 2019;78:184–203.
[10] Nemati M, Seyedtabaii S. Fault severity estimation in a vehicle cooling system. Asian J Control 2019. doi:10.1002/asjc.2155.
[11] Lhachimi H, Sayouti Y, El Kouari Y. Optimal improvement of direct power control strategy based on sliding mode controllers. Comput Electr Eng 2018;71:637–56.
[12] Swathi K, Kumar GN. Design of intelligent controller for reduction of chattering phenomenon in robotic arm: a rapid prototyping. Comput Electr Eng 2017. doi:10.1016/j.compeleceng.2017.12.010.
[13] Wang Y, Karimi HR, Shen H, Fang Z, Liu M. Fuzzy-model-based sliding mode control of nonlinear descriptor systems. IEEE Trans Cybern 2018;49:3409–19.
[14] Ding S, Li S. Second-order sliding mode controller design subject to mismatched term. Automatica 2017;77:388–92.
[15] Seyedtabaii S, Velayati A. Adaptive optimal slip ratio estimator for effective braking on a non-uniform condition road. Automatika 2019;60:413–21.
[16] Mobayen S, Tchier F. A novel robust adaptive second-order sliding mode tracking control technique for uncertain dynamical systems with matched and unmatched disturbances. Int J Control, Autom Syst 2017;15:1097–106.
[17] Seyedtabaii S, Delavari M. The choice of sliding surface for robust roll control: better suppression of high angle of attack/sideslip perturbations. Int J Micro Air Vehicles 2018;10:330–9.
[18] Muñoz F, González-Hernández I, Salazar S, Espinoza ES, Lozano R. Second order sliding mode controllers for altitude control of a quadrotor UAS: real-time implementation in outdoor environments. Neurocomputing 2017;233:61–71.
[19] Shi S, Xu S, Zhang B, Ma Q, Zhang Z. Global second-order sliding mode control for nonlinear uncertain systems. Int J Robust Nonlinear Control 2019;29:224–37.
[20] Hess RA, Peng C. Design for robust aircraft flight control. J Aircr 2017;55:875–86.
[21] Zhang J, Yan J, Yang L, Mou Y. Robust IFNTSN–ESO control design for aircraft subject to parameter uncertainties. Int J Aeronaut Space Sci 2019. doi:10.1007/s42405-019-00201-5.
[22] Raj K, Muthukumar V, Singh SN, Lee KW. Finite-time sliding mode and super-twisting control of fighter aircraft. Aerosp Sci Technol 2018;82:487–98.
[23] Muñoz F, Espinoza ES, González-Hernández I, Salazar S, Lozano R. Robust trajectory tracking for unmanned aircraft systems using a nonsingular terminal modified super-twisting sliding mode controller. J Intell Robot Syst 2019;93:55–72.
[24] Ferrara A, Incremona GP. Design of an integral suboptimal second-order sliding mode controller for the robust motion control of robot manipulators. IEEE Trans Control Syst Technol 2015;23:2316–25.
[25] Laghrouche S, Liu J, Ahmed FS, Harmouche M, Wack M. Adaptive second-order sliding mode observer-based fault reconstruction for pem fuel cell air-feed system. IEEE Trans Control Syst Technol 2015;23:1098–109.
[26] Chakraborty A, Seiler P, Balas GJ. Susceptibility of f/a-18 flight controllers to the falling-leaf mode: linear analysis. JGuidance Control Dyn 2011;34:57–72.

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