ROBUST ADAPTIVE SLIDING MODE CONTROL FOR UAV

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Abstract

Unmanned Air Vehicles (UAV) are indispensable for various applications where human intervention is considered difficult or dangerous. However, UAV suffer from inherent instabilities in the pitch axis due to their small size and the lack of pilot feedback. A pitch axis control system based on adaptive two-phase Sliding Mode Control (SMC) for a UAV is designed and simulation results are presented. The control system is validated by comparing it with a classical PID controller in terms of input tracking and disturbance rejection properties. In both control situations, the SMC shows high performance without chattering or ripples in the response and is superior to the PID controller performance.

Keywords

reaching law, adaptive control, sliding mode control, SMC, chattering, PID, stability, UAV

1. INTRODUCTION

The theory of Sliding Mode Control (SMC) is based on the concept of varying the structure of the controller by changing states of the system to obtain a desired response [1]. Generally, a switching control action is used to switch between different structures and the system state is forced to move along the chosen manifold, called the switching manifold which determines the closed loop system behavior [2] [3]. In the recent years, considerable efforts have been put into studying the concepts of sliding mode controller design [4] [5]. Variable Structure Control (VSC) with sliding mode is a special type of control technique that is capable of making a control system very robust with respect to variations of system parameters and external disturbances and fast dynamic response. In addition, the technique provides an easy way to design the control law for plants, linear or nonlinear. The VSC has a wide range of applications like: robot control, motor control, aircraft control, spacecraft control, inertial platform, process control and other many applications.

Important contributions have been made in VSC systems; they include control of the performance of the reaching mode, reduction of chattering. Chattering occurs when the control input switches discontinuously across the boundary, and it is undesirable because it involves high control activity and may excite high frequency dynamics. To eliminate chattering, various methods are used such as: The continuation method [2] [3], the fuzzy, neural sliding mode controller [4] [5], sliding mode controller with sliding sector [6], the reaching law method [7] [8], sliding mode with unified smooth control law [9], dynamic sliding mode control and higher order sliding surface [10] [11]. In [12] Faa and Sheng use integral action and adaptive algorithm to estimate the bound of uncertainties but still we have the chattering problem. In this paper, an adaptive two phase variable structure control is presented to increase the response and control the chattering when needed, also keep the robustness at the same time.

On the other hand, unmanned aerial vehicles suffer from inherent instabilities in the pitch axis due to their small size and the lack of pilot feedback. Therefore a flight control system is needed whose primary function consists of artificial stabilization of the aircraft. This system is known as pitch axis stability augmentation system. Control augmentation systems are a common part of modern airplane control and are best characterized as a form of tracking control [13]. In this paper, a flight control system is to be designed that augments both stability and control for an UAV called Aerosonde (https://en.wikipedia.org/wiki/AAI_Aerosonde).

This control system is designed using sliding mode control technique. The performance of the control system is compared with the performance of a classical PID controller in terms of input tracking and disturbance rejection properties. The proposed technique uses two phase sliding mode control where the smoothing phase mainly controls the system in steady state and in disturbed states, while the 2nd phase is used mainly in case of disturbed states and it is autotuning phase. The proposed technique is highly robust for uncertainties and external disturbances and free of chattering.

To enhance the oscillatory dynamic stability of the aircraft, an automatic control system is necessary to provide suitable damping and natural frequencies for better aircraft responsiveness and smoother disturbance rejection. Such a control system is known as Stability Augmentation Systems (SAS). This system generally utilizes pitch rate in the control laws. The sensors commonly utilized to measure this parameter are the rate gyros. Control Augmentation Systems (CAS) are a common part of modern aircraft control and are best characterized as a form of tracking control. Therefore, to perform tasks such as precision tracking of targets, a specialized CAS is needed, known as a pitch-rate CAS. The controlled variable of such system is the pitch-rate Q, which is required to follow a pilot's joystick command. It has been found that a deadbeat response to pitch-rate commands is well suited to the task. This

doi:10.25967/490252

system is conventionally designed for the longitudinal dynamics [13].

2. MATHEMATICAL MODEL OF A UAV

Dynamic equations that govern aircraft motion were developed in many papers and a lot of previous work to obtain an in-depth understanding of the mechanics involved from first principles. Various transformation matrices were created for the purpose of elegantly converting between the reference frames. Kinematic equations are responsible for translating linear and angular velocities to position and attitude over time. Finally, forces and moments acting on the aircraft were identified; the six degrees of freedom (6DoF) equations of motion are responsible for modeling the dynamics of any rigid body given the forces and moments that act on it as in Figure 1.

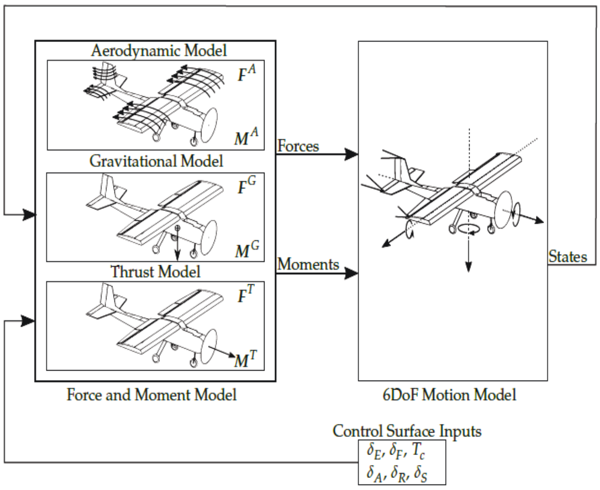

FIGURE 1. Dynamics of UAV

These equations are driven by the combined force and moment models shown on the left-hand side of Figure 1. Aircraft states are then fed back to the force and moment block, which in turn determines the future of the states as the system propagates forward in time. The thrust command and control surface inputs are fed into the thrust and aerodynamic force and moment models to manipulate the system as desired. Now that the core fundamentals of a non-linear aircraft model have been established, we will focus on the development of a linearized aircraft model. A linear aircraft model is required so that well-developed, linear systems analysis techniques can be used to gain insight into the aircraft's natural modes of motion, which will assist in the design of an effective flight control system [14]. According to the aerodynamic stability and control derivatives associated to the Aerosonde UAV [13], the nonlinear aircraft model is linearized about the trim condition straight and level flight: ($V_T = 25\frac{m}{s}$, $h = 300m$, $\emptyset = 0$) . The resulting linear model is then decoupled into longitudinal and lateral directional plants. The longitudinal plant model is given as follows:

$$\begin{bmatrix}\dot{U}\\ \dot{W}\\ \dot{Q}\\ \dot{\theta}\end{bmatrix} = \begin{bmatrix}-0.2368 & 0.5319 & -1.2158 & -9.8100\\ -0.5665 & -4.4286 & 24.3798 & -0.4856\\ 0.4310 & -4.7929 & -5.1089 & 0\\ 0 & 0 & 1 & 0\end{bmatrix}\begin{bmatrix}U\\ W\\ Q\\ \theta\end{bmatrix} + \begin{bmatrix}0.3504\\ -2.5231\\ -34.8697\\ 0\end{bmatrix}[\delta_e]$$

$$C = [0 \quad 0 \;\; 1 \quad 0] \tag{1}$$

U is the forward speed, W is the normal speed, Q is the pitch rate, θ is the pitch attitude and δ_e is the elevator deflection.

TABLE 1. Characteristics of longitudinal stability

mode	eigenvalues	ε	ω_n
Short period	$-4.77 + 10.8j$	0.403	11.8
phugoid	$-0.119 + 0.554j$	0.211	0.567

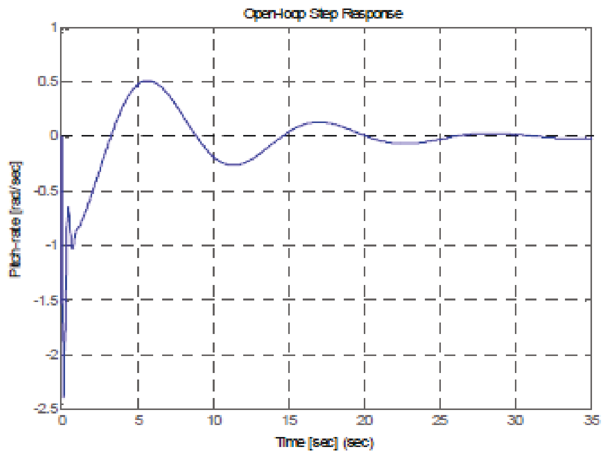

FIGURE 2. Open-loop response of pitch rate to a step in the elevator

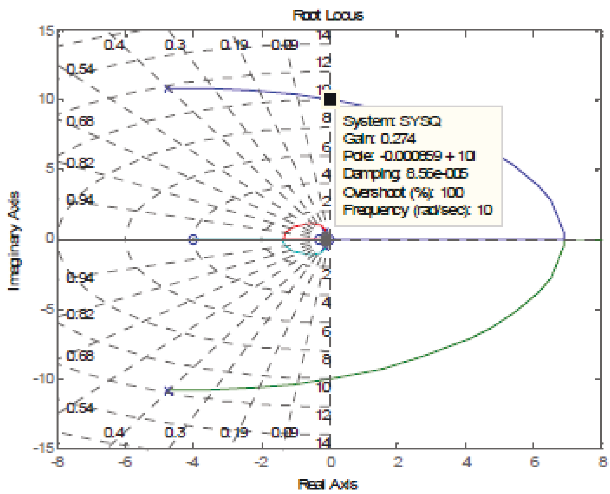

FIGURE 3. Root locus for the open-loop

With reference to Table 1, the eigenvalues of longitudinal state matrix reveal that there are two sets of complex poles; the low frequency lightly damped set, called phugoid mode, mainly affects pitch attitude θ and forward speed U, and the high frequency well damped set called short period mode, mostly affects the transient responses in normal speed W and pitch rate Q. The uncontrolled open-loop step response of the pitch rate to the elevator input is shown in Figure 2. The step response confirms that the system is lightly damped, and the root locus plot shows that the system goes unstable quickly as the gain exceeds 0.274 as we can see these in Figure 3.

3. ADAPTIVE SLIDING MODE CONTROLLERS

Consider the n[th] order linear time invariant system with m inputs given by

$$\dot{x}(t) = Ax(t) + Bu(t) \quad (2)$$

Where $A \in R^{nxm}$ and $B \in R^{nxm}$ with $1 \leq m \leq n$.Without loss of generality it can be assumed that the input distribution matrix B has full rank. Define a switching function s: $\mathrm{R} \to \mathrm{R}^{\mathrm{m}}$ to be

$$s(t) = Cx(t) \quad (3)$$

Where $C \in R^{n\times m}$ and S is of full rank and let C be the hyperplane defined by

$$C = \{x \in R^n : Cx(t) = 0\} \quad (4)$$

Suppose $u(s(t), x(t))$ represents a variable structure control law where the changes in control strategy depend on the value of the switching function. It is natural to explore the possibility of choosing the control action and selecting the switching strategy so that an ideal sliding motion takes place on the hyperplane, i.e. there exists a time $t_s$such that

$$s(t) = Cx(t) = 0 \text{ for all } t \succ t_s \quad (5)$$

Suppose at time $t = t_s$ the systems states lie on the surface s and an ideal sliding motion takes place. This can be expressed mathematically as $Cx(t) = 0$ S and $\dot{s}(t) = Cx(t) = 0$ for all $t \succ t_s$. Substituting for $\dot{x}(t)$ from (2) gives

$$C\dot{x}(t) = CAx(t) + CBu(t) = 0 \text{ , for all } t \geq t_s \quad (6)$$

Suppose the matrix C is designed so that the square matrix CB is nonsingular, in practice this is easily accomplished since B is full rank and C is a free parameter. The equivalent control, written as u_{eq} is defined to be the unique solution to the algebraic equation (6) as:

$$u_{eq}(t) = -(CB)^{-1}CAx(t) \quad (7)$$

This represents the control action which is required to maintain the states on the switching surface. The ideal sliding motion is then given by substituting the expression for the equivalent control into equation (2) which results in a free motion

$$\dot{x}(t) = (I - B(CB)^{-1}C)Ax(t) \quad (8)$$

For all $t \geq t_s$and $Cx(t_s) = 0$

It can be seen from equation (8) that the sliding motion is a control independent free motion which depends on the choice of sliding surface s although the precise effect is not apparent readily. A convenient way to shed light on the problem is to first transform the system into a suitable canonical form. In this form the system is decomposed into two connected subsystems, one acting in $R(B)$ and the other in $R(C)$, which is referred to as regular form. The second step is to design the sliding surface $\mathrm{s(t)} = \mathrm{Cx(t)}$, then a discontinuous control function:

$$u = \begin{cases} u^+, \text{if } S(x) > 0 \\ u^- \text{if } S(x) < 0 \end{cases} \quad (9)$$

is designed to move the trajectory of system (13) to the surface (3), and to keep it on the surface thereafter. The following well-known condition of the existence of sliding mode must be met in the vicinity of the sliding surface:

$$S(x)\dot{S}(x) < 0 \quad (10)$$

A discontinuous control law (9) can be designed in various formats as:

- additional input in the form:

$$u = u_{eq} + \Delta u \quad (11)$$

- The reaching law approach, it directly specifies the dynamics of the switching function. Let the dynamics of the switching function be specified by the differential equation [16]:

$$\dot{s} = -Q \operatorname{sgn}(s) - Kf(s) \quad (12)$$

Where gains Qand Kare diagonal matrices with positive elements, and

$$\operatorname{sgn}(s) = [\operatorname{sgn}(s_1) \ldots\ldots.\operatorname{sgn}(s_m)]^T \quad (13)$$

$$f(s) = [f_1(s) \ldots\ldots f_2(s)]^T \quad (14)$$

$$s_i f_i > 0 \text{ when } s_i \neq 0, i = 1..\text{to}\ldots m$$

Equation (12) is called the reaching law. Various choices of Qand Kspecify different rates for s and yield different structures in the reaching law. These laws can be applied [13]:

1) The constant rate reaching law

$$\dot{s} = -Q \operatorname{sgn}(s) \quad (15)$$

Then the sliding condition of (3) is guaranteed. The main disadvantage of the conventional VSC is the drastic change of the control signal across the sliding surface, which leads to chattering in the digital implementation this chattering may damage the system to be controlled. The larger the magnitude of Q, the more sever the chattering will be, if Q is too small, the reaching time will be too long.

2) The saturation reaching law

$$\dot{s} = -Q\operatorname{sat}(s(x)/\varphi) \quad (16)$$

3) The constant plus proportional rate reaching law

$$\dot{s} = -Q \operatorname{sgn}(s) - Ks \quad (17)$$

4) The power rate reaching law

$$\dot{s}_i = -k_i|s_i|^\alpha \operatorname{sgn}(s) \quad (18)$$

Where$0 < \alpha < 1$, and$i = 1..\text{to}\ldots m$

But still we have the tern (K sgn(s)) which is high robust to uncertainties and load disturbance but cause the chattering problem, so if we can control the gain Kto have effect when the system is disturbed and minimize theKin the steady state we can solve the chattering problem. The parameter variations of the system are difficult to measure and the exact value of the external load disturbance is also difficult to know in advance for practical applications in industry [13]. The adaptive algorithm used here is used to estimate the rate of change of the upper bound of uncertainties and load disturbance.

Consider the system:

$$\dot{x}(t) = f(x) + Gu(t) + r(t) \quad (19)$$

$$r(t) = \Delta f(x) + \Delta Gu(t) + d(t) \quad (20)$$

Where $d(t)$ is the external disturbance (unknown); $\Delta f(x,t)$ is the model error (unknown); $f(x)$ is known and $\Delta f(x)$ is unknown but bounded as: $|\Delta f(x)| \leq F$; and the disturbance $d(t)$ has also the upper bound D. In this way, with conventional VSC as given by (15) and the system as in (19), if $Q \geq \eta + D + F$

Where η is positive constant, the sliding condition of (10) is guaranteed.

If we do not know the upper bounds F or D, r(t) becomes unknown, assuming that it is bounded as:

$$|r(t)| < E \quad (21)$$

Where E is unknown but bounded positive constant.

In [12] the following adaptive algorithm for computing the rate of change of the upper bound (E) is given as:

$$\dot{\hat{E}}(t) = \frac{1}{\alpha}|s(t)CB| \quad (22)$$

Where $\alpha > 0$ and is denoted as adaptation gain. So the modified adaptive law becomes:

$$u = u_{eq} + \hat{E}(t)\,\mathrm{sgn}(s) + Kf(s) \quad (23)$$

or using the reaching law as:

$$\dot{s} = -\hat{E}(t)\,\mathrm{sgn}(s) - Kf(s) \quad (24)$$

To satisfy equation.(10), we put $f(s) = s$ then:

$$s\dot{s} = s(-\hat{E}(t)\,\mathrm{sgn}(s) - Ks) = -s\hat{E}(t)\,\mathrm{sgn}(s) - Ks^2$$

$\because \hat{E}(t) \geq 0, K \geq 0$, so, equation (10) is satisfied.

By using this modified adaptive law, the term Kf(x) is the smoothing term and grantees the fast response in transient and steady state while the adaptive term $\hat{E}(t)\,\mathrm{sgn}(s)$ satisfies high robustness in disturbed states.

4. SIMULATION AND RESULTS

Firstly, we design a PID controller with a Genetic Algorithm (GA). Parameters are tuned using a genetic algorithm optimization technique under constraints of performance specifications.

$$G_c(s) = K_p + \frac{K_i}{s} + K_d s$$

The GA PID parameters obtained are $K_p = 1.486, K_i = 62.06, K_d = 0.0423$ and the corresponding step response is shown in Figure 4 with load disturbance occur at time $t = 1$ s . Figure 5 shows the control input (elevator deflection) which is band limited to 90 degrees to a unit step and change in the disturbance, applied directly at the plant output.

Secondly, to design a sliding mode controller, we start with designing the sliding surfaces as:

$s = Ce + \dot{e}$, $e = Q_d - Q$

and the equivalent control is determined from $\dot{s} = 0$.

According to (15), we have the conventional VSC as:

$u = u_{eq} + Q\mathrm{sgn}(s)$

and from equations (17) and (22) the proposed adaptive two phases sliding mode controller:

$u = u_{eq} + \hat{E}(t)\mathrm{sgn}(s) + Ks$

We choose the design parameters as: $C = 10$, $Q = 1.5, K = 0.5, \alpha = 10^3$.

In the simulation, the response of the conventional SMC to a unit step and disturbance applied at $t = 1$ s is shown in Figure 6 and in Figure 7 the control input (elevator deflection) has a chattering problem at $t = 1$ s.

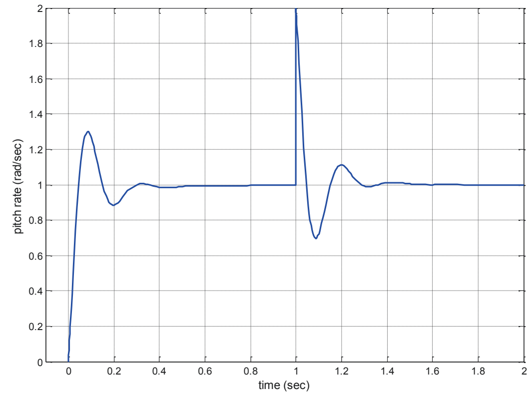

FIGURE 4. Step response for GA PID Controller

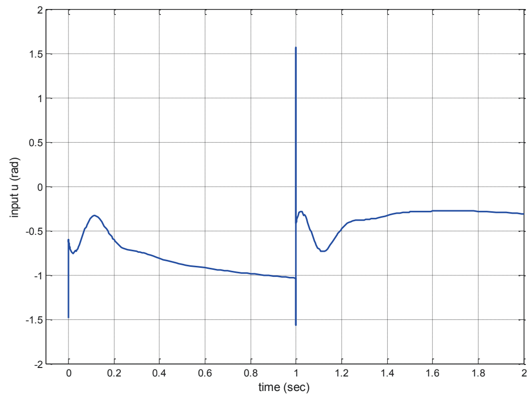

FIGURE 5. Control input elevator deflection for GA PID Controller

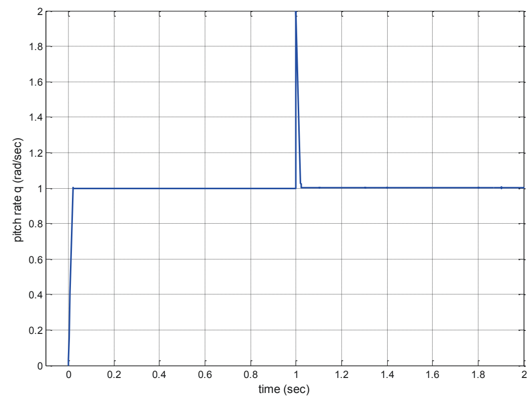

FIGURE 6. Step response for conventional SMC

The step response with the proposed controller is shown in Figure 8 and Figure 9, the robust control performance of the proposed adaptive sliding mode controller in both commands tracking and load disturbance shows no chattering phenomena and no ripples in the output response and shows high performance in nominal case as well as in the disturbed case. Simulation of the three controllers in the presence of wind affecting the aircraft is shown in Figure 10. As we can see, a good performance is achieved with our proposed controller.

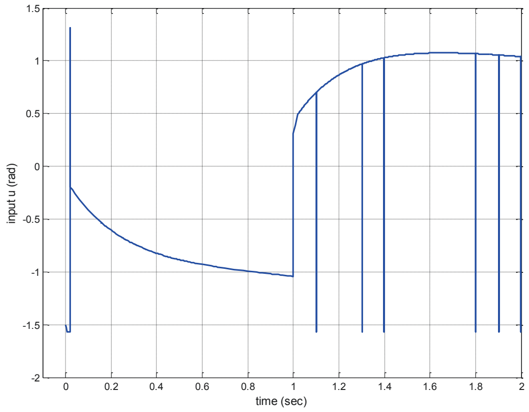

FIGURE 7. Control input elevator deflection for conventional SMC

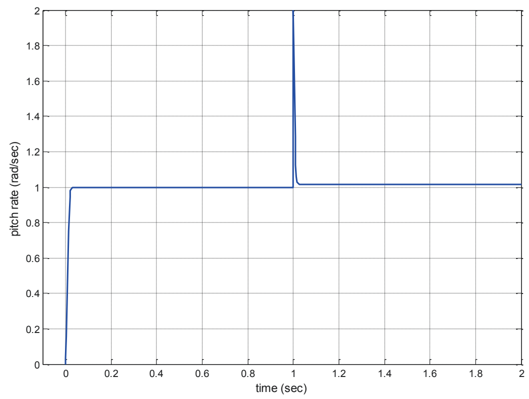

FIGURE 8. Step response for adaptive SMC

In the simulation, the response of conventional SMC to a unit step and disturbance applied at $t = 1$ s is shown in Figure 6 and in Figure 7 the control input (elevator deflection) witch it has a chattering problem.

The proposed controller is shown in Figure 8 and Figure 9, the robust control performance of the proposed adaptive sliding mode controller in both commands tracking and load disturbance, no chattering phenomena, no ripples in output response and high performance in nominal case or disturbed case. Simulation of the three controllers in the presence of wind affecting the aircraft is shown in Figure 10, as we can see the good performance of our proposed controller.

In the proposed controller, the time response can be increased by increasing the gain K with no effect on chattering and robust performance. From all these figures, we note that the proposed controller has a faster response and has no ripples when compared to the conventional variable structure technique. Also, the proposed technique is free of chattering in the steady state and undisturbed state. For the modified technique, the robustness can increased by controlling α, if we chose α to be very large, the modified technique is reduced to one phase conventional variable structure technique.

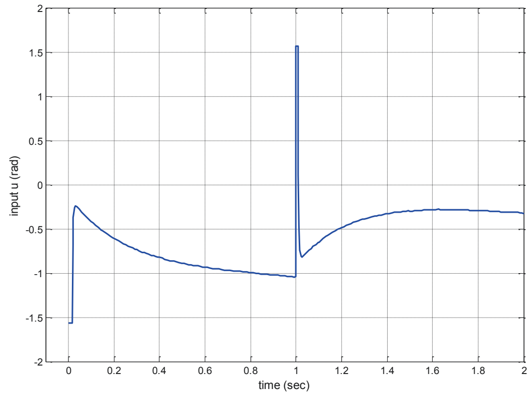

FIGURE 9. Control input elevator deflection for adaptive SMC

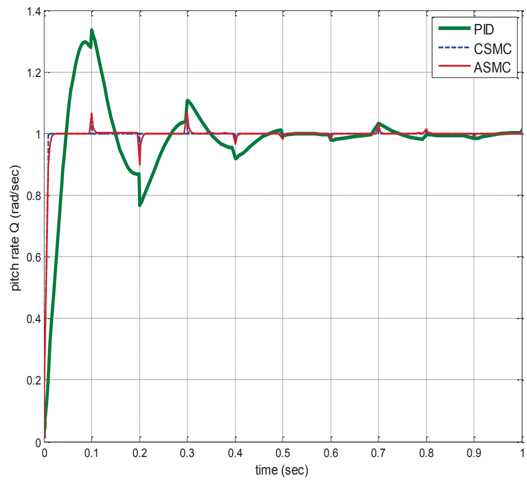

FIGURE 10. Step response in presence of wind acting on the UAV

5. CONCLUSIONS

In this paper we investigate an adaptive two-phase sliding mode controller to control the pitch axis of a UAV which has a fast response and high robustness for uncertainties and external disturbances. The proposed technique uses two phases, where the smoothing phase mainly controls the system in steady state and in disturbed states, while the 2nd phase is used mainly in case of disturbed states and it is the adaptive phase. Using the proposed technique, it is shown that the sliding mode controller becomes a more practical one. In this paper, a flight control system is designed that augments both stability and control for the Aerosonde UAV. This control system is first designed using the classical Z-N tuning algorithm for PID controllers, which showed bad behavior. The PID parameters are then optimized using

GA optimization technique under performance specifications. Next, the control system is designed using SMC technique and is compared with the performance of the PID controller. Although for the two techniques, the design objectives were satisfied including good tracking and disturbance rejection, the SMC has better performances for tracking and robustness.

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