2015 International Conference on Industrial Instrumentation and Control (ICIC)
College of Engineering Pune, India. May 28-30, 2015

Robust Control of Wing Rock Motion under Time Varying Angle of Attack using UDE

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Abstract—**In this work, the technique of Uncertainty and Disturbance Estimator (UDE) has been employed to suppress wing rock motion in delta winged aircraft subjected to time varying angle of attack and disturbance. The time varying angle of attack introduces significant uncertainties which along with external disturbances are dynamically estimated and compensated using UDE. In addition, an observer based UDE controller has also been designed for its application to wing rock problem. Simulations have been carried out to validate the efficacy of the UDE based controllers, thus designed, for stabilization and tracking scenario.**

Keywords—**wing rock motion, time varying angle of attack, uncertainty and disturbance estimation, observer based UDE**

I. Introduction

Delta winged aircraft is generally open loop unstable in roll axis, at moderate to high angle of attacks. Wing rock [1, 2] phenomenon can be described as the oscillatory motion induced by unsteady aerodynamic effects acting on the delta wing, asymmetrically. In order to achieve maximum angle of attack and tracking accuracy in operational maneuvers, wing rock poses a serious concern for present and future aircrafts. Further this phenomenon affects the safety of the aircraft and its passengers during take-off and landing. Several theoretical and experimental studies have been performed to understand the dynamics of wing rock and to predict the amplitude and frequency of oscillation of the limit cycle. Delta wing aircraft roll dynamics can be regulated by ailerons and the 'differential aileron' is the primary control input signal for regulating roll dynamics [4].

There is continuing interest in improving the performance of present and future aircraft and missiles by increasing their high angle-of-attack capability. Therefore, the problem of wing rock needs dynamic solutions for real time scenario. In literature, various approaches have been proposed to design controllers addressing this problem. Formulation of control law based on nonlinear H_∞ approach [6], sliding mode control [7], adaptive feedback linearization [8], fuzzy logic controller [9], adaptive fuzzy control [10], uncertainty and disturbance estimation technique [3, 11, 12, 13], and design based on extended state observer [14] can be found among others.

Uncertainty and disturbance estimator (UDE) [3] is an elegant, systematic strategy in the design of robust control systems. This technique primarily 'estimates' the uncertainty and disturbance, in an integrated manner and cancels their effects. Another notable feature of this technique is that it does not require any knowledge of the uncertainty and/or the disturbance; such as their magnitude or bounds. The estimation is done dynamically and compensated. This technique has been successfully employed in the areas of aerospace and robotics [11, 15].

In current work, an attempt has been made to suppress wing rock motion under the situations of time varying angle of attack using the principle of Uncertainty and Disturbance Estimator [3]. The controller thus designed has been tested for its efficacy in stabilization and tracking requirements, in presence of parametric uncertainties and external disturbances. Additionally, an observer based UDE control has also been designed and tested for its performance under the same situations of uncertainty and disturbances. This work is organized as follows. Section II deals with wing rock modeling. Section III presents the design of UDE based controller and observer based UDE controller. Simulations and related discussions form part of Section IV. Section V concludes this work.

II. Wing Rock Model

Wing rock phenomenon is highly nonlinear in nature and there exist several approaches in literature to characterize the dynamics [1, 2]. The angle of attack is usually kept constant to develop regulators, owing to complex nonlinear behavior of the wing rock phenomenon and its qualitative dependence on the angle of attack [5]. In this work, the model presented in [14] is used for designing an UDE based controller structure for suppression of wing rock. The model is considered with time varying angle of attack and the aerodynamic coefficients at different angles of attack are interpolated smoothly using an interpolation function. To this end, considering the wing rock dynamic model of the form

$$\ddot{\phi} = -\omega_j^2\phi + \mu_1^j\dot{\phi} + b_1^j\dot{\phi}^3 + \mu_2^j\phi^2\dot{\phi} + b_2^j\phi\dot{\phi}^2 + g\delta$$

$$y = \phi \tag{1}$$

where ϕ , δ and g are respectively the roll angle, aileron deflection and the input gain, $\omega_j^2, \mu_1^j, b_1^j, \mu_2^j, b_2^j$ represent the aerodynamic coefficients at angle of attack α_j. The system coefficients appearing in (1) depend on the parameters a_i^j, which are in turn functions of angle of attack α.

$$\begin{aligned}
\omega_j^2 &= -c_1 a_1^j \\
\mu_1^j &= c_1 a_2^j - c_2 \\
b_1^j &= c_1 a_3^j \\
\mu_2^j &= c_1 a_4^j \\
b_2^j &= c_1 a_5^j
\end{aligned} \tag{2}$$

The constants c_1 and c_2 are given by the physical parameters of a delta wing used in wind tunnel experiments. The values of parameters a_i^j for various angles of attack are referred from Table 1 [14]. A smooth, time varying model of wing rock that depends on angle of attack can be built by considering an interpolation function [14]

$$P_j(\alpha) = \frac{e^{-(\frac{\alpha-\alpha_j}{s_j})^2}}{\sum_{l=1}^{7} e^{-(\frac{\alpha-\alpha_l}{s_l})^2}} \tag{3}$$

where α_j and s_j are centers and spreads whose values are referred from Table 2 [14]. Due to paucity of space the Table 1 and 2 of [14] are not being reproduced. Following the approach made in [14], the wing rock model for varying α can be written in state space form as

$$\begin{aligned}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= \sum_{j=1}^{7} P_j(\alpha)\left(-\omega_j^2 x_1 + \mu_1^j x_2 + b_1^j x_2^3 + \mu_2^j x_1^2 x_2 + b_2^j x_1 x_2^2\right) + g\delta \\
y &= x_1
\end{aligned} \tag{4}$$

with the states defined as $x_1 = \phi$ and $x_2 = \dot{\phi}$. Assuming the angle of attack (α) to vary according to an external dynamic system

$$\begin{bmatrix} \dot{\alpha}_1 \\ \dot{\alpha}_2 \end{bmatrix} = \begin{bmatrix} 0 & 25 \\ -25 & -10 \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \alpha_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 500 \end{bmatrix} + \begin{bmatrix} 0 \\ 62.5 \end{bmatrix} r \tag{5}$$

where $\alpha_1 = \alpha$ and r is the command input taking values between -1 and $+1$. The system described in (5) is assumed to represent the effects of the aircraft when the pilot commands are input as r [5].

The angle of attack, in the present work, is assumed to vary between 15 to 25° such that the qualitative behavior of (4) changes periodically as α becomes smaller or larger than 19.5°. Then a robust controller is designed, initially assuming both roll angle and roll rate to be available; followed by a situation when only roll angle is available, to ensure suppression of wing rock motion and also tracking of desired roll command.

III. UDE BASED CONTROLLER

As stated before, the technique of Uncertainty and disturbance estimator (UDE) has proved itself to be a powerful robust control strategy when the characteristics and bounds of uncertainties and disturbance are not available. This technique has already been employed on control of wing rock motion in [12, 13]. However in the current work, the same technique is employed on a model referred in [14] which is different from the model used in [12, 13]. The design of UDE based control law has been carried out in two different forms. The first form has been derived assuming both roll angle and roll rate are available. The second form employs an UDE based observer following an assumption that only roll angle is available for feedback.

A. UDE Control Law

Consider the dynamics given in (1) and (4), which is re-written as

$$\begin{aligned}
\ddot{\phi} &= \sum_{j=1}^{7} P_j(\alpha)\left(-\omega_j^2\phi + \mu_1^j\dot{\phi} + b_1^j\dot{\phi}^3 + \mu_2^j\phi^2\dot{\phi} + b_2^j\phi\dot{\phi}^2\right) + g\delta + d' \\
y &= \phi
\end{aligned} \tag{6}$$

In practice the accurate model describing a system is rarely available. Hence it becomes necessary to account for the modeling inaccuracies and errors. Accordingly by letting $\omega_j^2 = \hat{\omega}_j^2 + \Delta\omega_j^2$, $\mu_1^j = \hat{\mu}_1^j + \Delta\mu_1^j$, $b_1^j = \hat{b}_1^j + \Delta b_1^j$, $\mu_2^j = \hat{\mu}_2^j + \Delta\mu_2^j$, $b_2^j = \hat{b}_2^j + \Delta b_2^j$ where $\hat{\omega}_j^2, \hat{\mu}_1^j, \hat{b}_1^j, \hat{\mu}_2^j, \hat{b}_2^j$ are the nominal values of the aerodynamic coefficients and the Δ terms being their associated uncertainties. Following the same logic, the input gain is g is taken as $g = \hat{g} + \Delta g$. To this end, the dynamics of (6) can be written as

$$\ddot{\phi} = \sum_{j=1}^{7} P_j(\alpha)\left(-\hat{\omega}_j^2\phi + \hat{\mu}_1^j\dot{\phi}\right) + \hat{g}\delta + d \tag{7}$$

where

$d = \sum_{j=1}^{7} P_j(\alpha)\left(-\Delta\omega_j^2\phi + \Delta\mu_1^j\dot{\phi} + b_1^j\dot{\phi}^3 + \mu_2^j\phi^2\dot{\phi} + b_2^j\phi\dot{\phi}^2\right) + \Delta g\delta + d'$.

It can be inferred that d is the lumped uncertainty which represents the combined effect of uncertainties and external disturbances, if any. Now, assuming both ϕ (roll angle) and $\dot{\phi}$ (roll rate) are available, the control law that will provide robust performance in presence of uncertainties is defined as

$$\delta = \frac{1}{\hat{g}}\left(\delta_a + \delta_d + v\right) \tag{8}$$

where

$$\delta_a = -\sum_{j=1}^{7} P_j\left(\alpha\right)\left(-\hat{\omega}_j^2\phi + \hat{\mu}_1^j\dot{\phi}\right) \tag{9}$$

By defining tracking error $e(t) = \phi(t) - \phi^*(t) = y(t) - y^*(t)$, with $\phi(t)$ being actual state and $\phi^*(t)$ being reference state, the outer loop control v is chosen as

$$v = \ddot{y}^* - k_1\dot{e} - k_0 e \tag{10}$$

which results in an error dynamics of the form $\ddot{e}+k_1\dot{e}+k_0 e=0$, in the absence of uncertainties. The values of gains k_1 and k_0 are chosen such that they satisfy the desired performance specifications. Substituting (8) in (7) leads to

$$\ddot{\phi}=\delta_d+d+\nu \tag{11}$$

and consequently

$$d=\ddot{\phi}-\delta_d-\nu \tag{12}$$

Proceeding on the lines of [3], considering $\hat{d}$ to be an estimate of d and related by $\hat{d}=G_f(s)d$ with $G_f(s)=\dfrac{1}{(1+s\tau)}$ as the first-order filter, can be written as

$$\hat{d}=(\ddot{\phi}-\delta_d-\nu)G_f(s) \tag{13}$$

Taking $\delta_d=-\hat{d}$ and solving for δ_d leads to

$$\delta_d=-(\ddot{\phi}-\nu)\left(\frac{G_f(s)}{1-G_f(\mathrm{s})}\right) \tag{14}$$

Substituting for $G_f(s)$ and simplifying for δ_d gives

$$\delta_d=-\frac{\dot{\phi}}{\tau}+\frac{1}{\tau}\int \nu dt \tag{15}$$

Finally substitution of (9) and (15) in (8) and simplifying gives the UDE control law as

$$\delta(UDE)=\frac{1}{\hat{g}}\left(-\sum_{j=1}^{7}P_j(\alpha)\left(-\hat{\omega}_j^2\phi+\hat{\mu}_1^j\dot{\phi}\right)-\left(\frac{\dot{\phi}}{\tau}\right)+\frac{1}{\tau}\int \nu dt+\nu\right) \tag{16}$$

The resulting control law requires plant states which includes first order time derivative of output y which is $\dot{\phi}$. A situation may arise wherein only the roll angle is available for implementation. Under such circumstances requirement to estimate the unavailable state, in the present case roll rate, is inevitable. An UDE based observer design is presented in the next sub-section to address this requirement.

B. Observer based UDE Control Law

In the proposed work, an observer is employed to design a robust controller to meet the requirement of obtaining the roll rate i.e. $\dot{\phi}$, in situations when only roll angle is available. First, an alternate form of UDE based controller using the actual states is proposed followed by observer design to estimate the states. To this end, re-writing the dynamics of (6) as

$$\ddot{y}=\left[\hat{a}\bar{y}+(a-\hat{a}\bar{y})+(g-\hat{g})\delta\right]+\hat{g}\delta+d' \tag{17}$$

where $a=\sum_{j=1}^{7}P_j(\alpha)\left(-\omega_j^2\phi+\mu_1^j\dot{\phi}+b_1^j\dot{\phi}^3+\mu_2^j\phi^2\dot{\phi}+b_2^j\phi\dot{\phi}^2\right)$, $\bar{y}=\begin{bmatrix}\phi & \dot{\phi}\end{bmatrix}^T$ and $\hat{a}=\left[\sum_{j=1}^{7}P_j(\alpha)(-\hat{\omega}_j^2) \quad \sum_{j=1}^{7}P_j(\alpha)(\hat{\mu}_1^j)\right]$. The parameter d' represents the effect of external disturbances, if any. Defining lumped uncertainty d as $d=(a-\hat{a}\bar{y})+(g-\hat{g})\delta+d'$, the system of (17) can be written as

$$\ddot{y}=\hat{a}\bar{y}+\hat{g}\delta+d \tag{18}$$

To address the issue of uncertainties the control δ is augmented as

$$\delta=\frac{1}{\hat{g}}(\delta_a+\delta_d+\nu) \tag{19}$$

where

$$\delta_a=-\hat{a}\bar{y} \tag{20}$$

Following the same procedure as in sub-section III.A, defining tracking error $e(t)=\phi(t)-\phi^*(t)=y(t)-y^*(t)$, where $\phi(t)$ is the actual state and $\phi^*(t)$ is the reference state. The outer loop control ν is chosen as

$$\nu=\ddot{y}^*-k_1\dot{e}-k_0 e \tag{21}$$

δ_d is that part of control which cancels the effect of uncertainties, non-linearities and external disturbances, obtained in the same lines as in sub-section III.A

$$\delta_d=-\frac{\dot{\phi}}{\tau}+\frac{1}{\tau}\int \nu dt \tag{22}$$

It is reiterated here that actual states are used in evaluation of δ_a, δ_d and ν. Final substitution of (20), (21) and (22) in (19) and further simplifying, an alternate form of UDE based controller can be expressed as

$$\delta(UDE1)=\frac{1}{\hat{g}}\left(-\hat{a}\bar{y}-\left(\frac{\dot{\phi}}{\tau}\right)+\frac{1}{\tau}\int \nu dt+\nu\right) \tag{23}$$

Eq.(23) clearly calls for $\dot{\phi}$. In case this is not available for implementing the derived control, a natural solution is to observe or estimate the same using an observer. Proceeding further, to estimate the output derivative, i.e. $\dot{\phi}$, an observer is designed by re-writing the system of (7) in phase variable state space form as

$$\begin{aligned}\dot{y}_1&=y_2\\ \dot{y}_2&=\sum_{j=1}^{7}P_j(\alpha)\left(-\hat{\omega}_j^2 y_1+\hat{\mu}_1^j y_2\right)+\hat{g}\delta+d\end{aligned} \tag{24}$$

by defining the state vector x_p as $x_p=\begin{bmatrix}y_1 & y_2\end{bmatrix}^T=\begin{bmatrix}\phi & \dot{\phi}\end{bmatrix}^T$. The system of (24) is written compactly as

$$\begin{aligned}\dot{x}_p&=A_p x_p+B_p\delta+B_d d\\ y_p&=C_p x_p\end{aligned} \tag{25}$$

where

$$A_p=\begin{bmatrix}0 & 1\\ \sum_{j=1}^{7}P_j(\alpha)(-\hat{\omega}_j^2) & \sum_{j=1}^{7}P_j(\alpha)(\hat{\mu}_1^j)\end{bmatrix};B_p=\begin{bmatrix}0\\ \hat{g}\end{bmatrix};B_d=\begin{bmatrix}0\\ 1\end{bmatrix}$$

and $C_p=\begin{bmatrix}1 & 0\end{bmatrix}$. Due to the presence of the uncertainty, the conventional Luenberger observer will not be able to provide accurate state estimation for the plant of (25). In view of this, a Luenberger like observer of the following form is proposed as

$$\dot{\hat{x}}_p = A_p\hat{x}_p + B_p\delta + B_d\hat{d} + L\left(y_p - \hat{y}_p\right)$$
$$\hat{y}_p = C_p\hat{x}_p \qquad (26)$$

where $L = \left[l_1 \quad l_2\right]^T$ is the observer gain vector. The observer needs the uncertainty estimate i.e., $\hat{d}$ which is same as present in (18). Therefore the uncertainty estimated by UDE controller is used in observer (26), resulting in an observer based UDE controller. The UDE based control law using the observed/ estimated states can be expressed as

$$\delta\left(UDE + OBS\right) = \frac{1}{\hat{g}}\left(-\tilde{a}\bar{y} - \left(\frac{\dot{\hat{\phi}}}{\tau}\right) + \frac{1}{\tau}\int v\,dt + v\right) \qquad (27)$$

where $\bar{y} = \left[\hat{\phi} \quad \dot{\hat{\phi}}\right]^T$ and v is defined as $v = \ddot{y}^* - k_1(\dot{\hat{\phi}} - \dot{\phi}^*) - k_0(\hat{\phi} - \phi^*)$ using observation error as $e_o(t) = \hat{\phi}(t) - \phi^*(t) = \hat{y}(t) - y^*(t)$. It must be noted that $\hat{\phi}(t)$ and $\dot{\hat{\phi}}(t)$ are the estimated states derived from the observer. The stability analysis of UDE and observer based UDE controller for wing rock motion has been dealt, in detail in [12, 13] and hence omitted.

IV. Simulation Results

The performance of the proposed UDE and UDE+OBS controllers in wing rock suppression is evaluated with fixed and time varying angle of attacks under two situations. Firstly, the evaluation is carried using the control law given by (16) where actual states are assumed to be available. Next, performance evaluation is carried out with observed states using the control strategy given in (27).

Simulations were carried out considering the constant values in (2) as taken from [14] as $c_1 = 0.354$, $c_2 = 0.001$ and $\hat{g} = 1.5$. Initial conditions for plant dynamics are assumed as $\left[\phi \quad \dot{\phi}\right]^T = \left[20° \quad 0\right]^T$. For simulations, a settling time of 4 s and damping ratio of 0.8 are considered [14], to achieve desired error dynamics and controller gains k_1 and k_0 are accordingly chosen which works out to be 2 and 1.5625. Time constant of first order filter τ is taken as 0.01. The aerodynamic coefficients in (2) are calculated by considering parameters a_i^j corresponding to $\alpha = 21.5°$ from Table 1 of [14] and are kept same. Simulations are carried out using control law formulated in (16) in stabilization scenario keeping α constant and results are given in Fig.1. The same is verified in tracking scenario with reference roll angle trajectory [14] as

$$\phi^*(t) = 20\sin(0.4\pi\, t)\ \text{deg} \qquad (28)$$

and the results are presented in Fig. 2. From the figures it is evident that UDE based control law is able to perform efficiently in controlling the wing rock motion as well as in meeting tracking requirements. Next, simulations were carried out using (16) keeping initial conditions and all other parameters same, with time varying angle of attack and considering an external disturbance [14] of the form

$$d' = 0.6141\phi + 1.2099\dot{\phi} - 0.0513\phi^2\dot{\phi} + 0.035\phi\dot{\phi}^2 + 0.0135\dot{\phi}^3 \qquad (29)$$

The angle of attack variations are simulated using the dynamics of (5), in which the command input r varies between -1 to +1 for every 0.5s. The initial conditions in (5) are considered as $\left[20° \quad 0\right]^T$. It may be noted that under this condition of varying angle of attack (which introduces

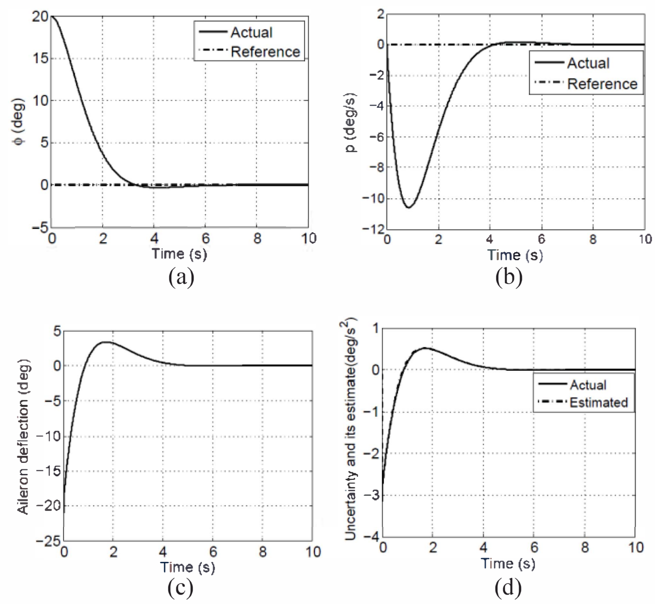

Fig. 1.Performance of UDE based controller with constant angle of attack for stabilization: (a) Roll angle (b) Roll rate (c) Aileron deflection (d) Uncertainty estimation

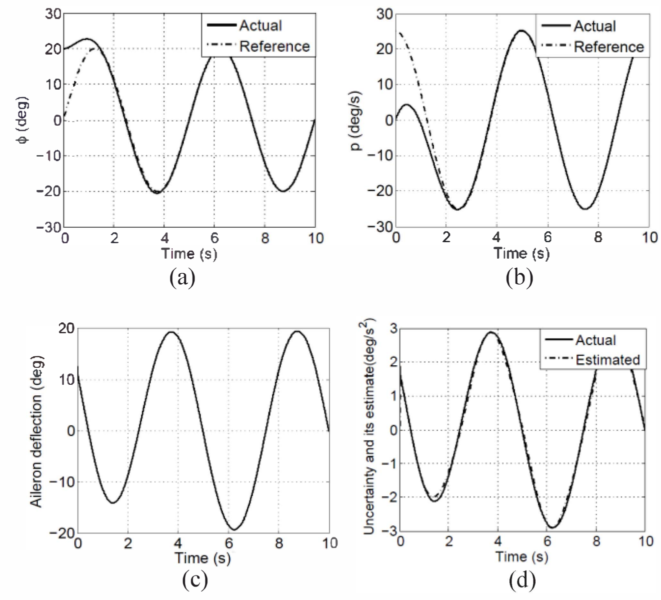

Fig. 2.Performance of UDE based controller with constant angle of attack for tracking: (a) Roll angle (b) Roll rate (c) Aileron deflection (d) Uncertainty estimation

significant uncertainties), the control δ_a is evaluated for $\alpha = 21.5°$. The results for stabilization scenario are given in Fig. 3. Also, tracking of the desired roll command as in (28) is verified and the results are presented in Fig. 4. These figures also validate the efficiency of the proposed controller in presence of time varying angle of attack and external disturbance. Inspite of significant uncertainties and disturbance the controller is able to perform well to meet stabilization and tracking requirements thus proving itself to be robust. The uncertainty estimation was also found to be satisfactory in this situation.

Further, assuming the non-availability of $\dot{\phi}$ simulations were carried using control given in (27), with observer initial conditions as $\hat{x}_p(0) = [20° \quad 0]$. To test the efficacy of this controller, time constant of first order filter τ is chosen as 0.01. The nominal values for aerodynamic coefficients $-\hat{\omega}_j^2$ and $\hat{\mu}_1^j$ in (24) are chosen corresponding to angle of attack $\alpha = 21.5°$ referred from Table 1 [14]. Pole placement technique was followed to calculate observer gain vector L by placing observer poles at $[-150, -150]$. Simulations were then carried

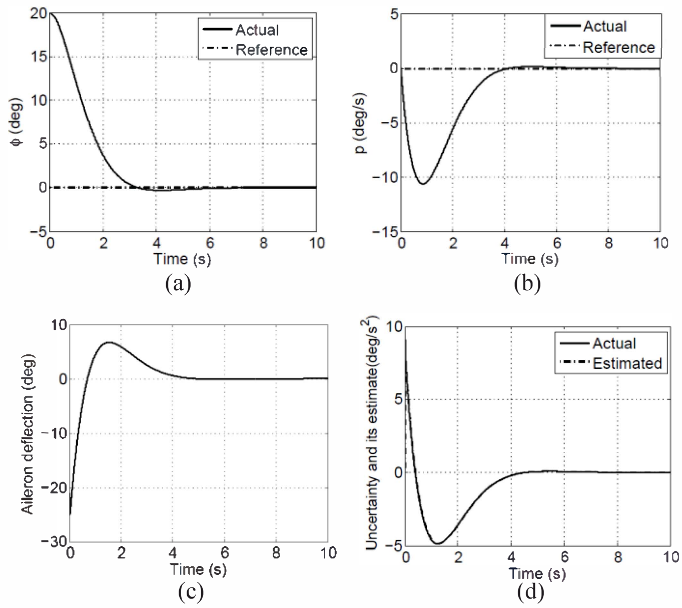

Fig. 3.Performance of UDE based controller with varying angle of attack and external disturbance for stabilization: (a) Roll angle (b) Roll rate (c) Aileron deflection (d) Uncertainty estimation

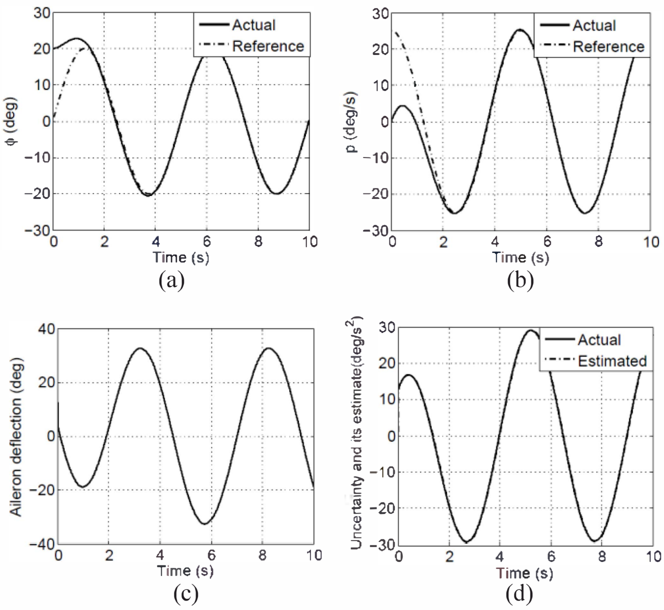

Fig. 4.Performance of UDE based controller with varying angle of attack and external disturbance for tracking: (a) Roll angle (b) Roll rate (c) Aileron deflection (d) Uncertainty estimation

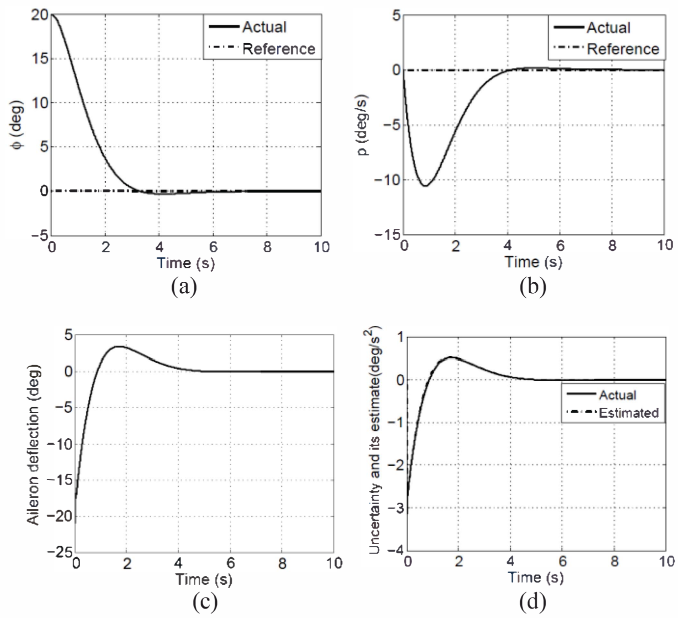

Fig. 5.Performance of observer based UDE controller with constant angle of attack for stabilization: (a) Roll angle (b) Roll rate (c) Aileron deflection (d) Uncertainty estimation

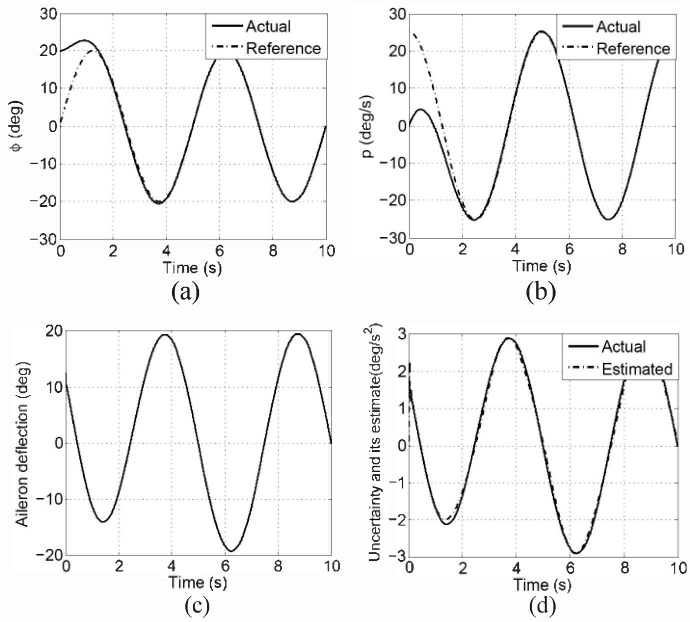

Fig. 6.Performance of observer based UDE controller with constant angle of attack for tracking: (a) Roll angle (b) Roll rate (c) Aileron deflection (d) Uncertainty estimation

out to show the performance in stabilizing roll angle, with constant α and results are presented in Fig. 5. Also, simulations were carried out for tracking scenario with reference trajectory as (28) and results are given in Fig. 6. The results show that the designed controller utilizing observed / estimated states is able to give satisfactory performance comparable with the Figs. 3 and 4. Next, simulations were carried out with time varying α, in presence of an external disturbance d' (29). Fig. 7 gives exhibits the stabilization performance of the proposed observer based UDE controller, while Fig. 8 showcases the ability of the observer based UDE controller for tracking requirements. Once again, Figs. 5 till 8 prove the robustness of the proposed observer based UDE controller. Further the capability of the proposed control law employing UDE in estimating the uncertainties and disturbances can be easily inferred from Sub-Fig (d) of Figs 1 till 8.

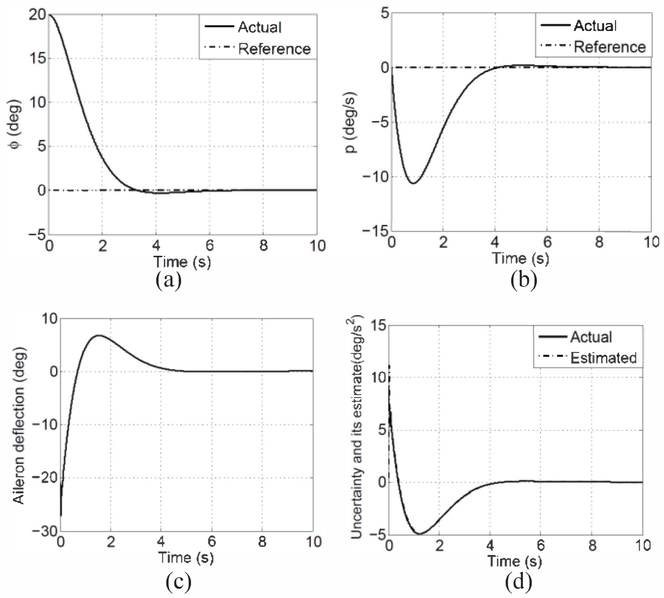

Fig. 7.Performance of observer based UDE controller with varying angle of attack and external disturbance for stabilization: (a) Roll angle (b) Roll rate (c) Aileron deflection (d) Uncertainty estimation

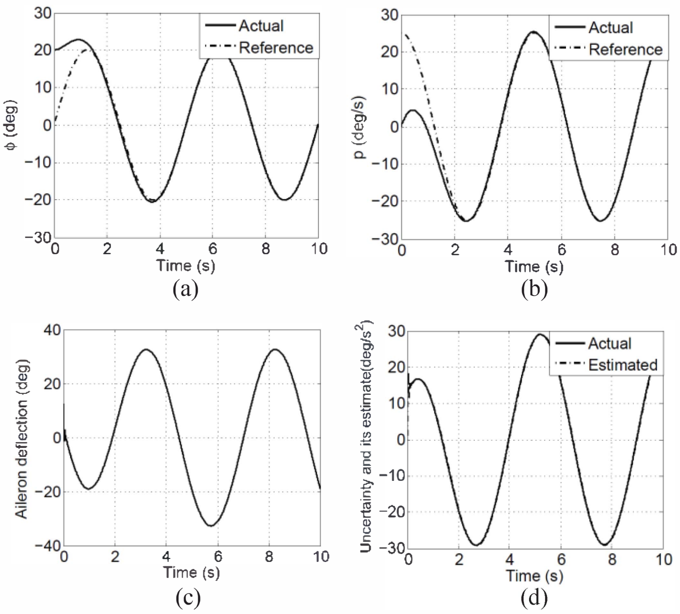

Fig. 8.Performance of observer based UDE controller with varying angle of attack and external disturbance for tracking: (a) Roll angle (b) Roll rate (c) Aileron deflection (d) Uncertainty estimation

V. CONCLUSION

In this work, the problem of wing rock motion under time varying angle of attack was addressed by designing controllers based on UDE. Design of observer based UDE control has also been accomplished for the said problem. Inspite of the presence of significant uncertainties due to varying angle of attack and disturbances, the controllers thus designed using UDE approach have proved themselves to be robust. Simulation results have also validated the robustness of the UDE based controllers under uncertainty and disturbances in meeting the stabilization and tracking requirements.

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