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Extended state observer based robust control of wing rock motion

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ABSTRACT

In this paper, a new design based on the Extended State Observer (ESO) technique for the robust control of wing rock motion of slender delta wings is proposed. The wing rock motion dynamics with varying angle of attack is significantly uncertain. The ESO is employed to simultaneously estimate the state and the uncertainty. The estimated uncertainty is used to robustify an Input–Output Linearization based controller designed for the nominal system. Closed loop stability of the overall system is established. The notable feature of the proposed design is that it neither requires accurate plant model nor any information about the uncertainty. The effectiveness of the ESO in estimation of the uncertainties and states and in regulating the rolling motion in the presence of significant uncertainties and un-modeled servo and sideslip dynamics is illustrated by simulation. Lastly, the efficacy of the proposed design is demonstrated by comparing its performance with some well-known existing designs.

1. Introduction

Wing rock motion is a concern for combat aircraft because it may have adverse effects on maneuverability, tracking accuracy, and operational safety. Unsteady aerodynamic effects at high angle of attack generate wing rock phenomenon in case of slender delta wing aircraft and is a complicated aerodynamic phenomenon, characterized by self-induced limit-cycle roll oscillations. The maneuvering envelope of an aircraft exhibiting this behavior gets seriously restricted because the maximum incidence angle is often limited by the onset of wing rock before the occurrence of stall [25]. Since high performance aircraft have mission requirements for operating at high angles of attack, the control of wing rock motion is of significant importance.

The wing rock motion needs to be controlled as it causes maneuver limitation ranging in severity from degradation in tracking effectiveness to loss of control. There are three possible approaches to suppress or prevent wing rock [1] such as reshaping the airframe configuration, by adopting maneuver limiting and by employing stability augmentation or automatic flight control system of which the last one has become the most effective method for attaining strong resistance to wing rock without degrading maneuverability. However, as the dynamics of the wing rock phenomenon change nonlinearly with the angle of attack, the problem of designing controllers that are robust against changes in angle of attack coupled with presence of system uncertainties and external disturbances pose a great challenge. In literature one can find application of various theories towards designing controllers for regulating the wing rock motion. Formulations based on nonlinear H_∞ approach [25], feedback linearization [20], adaptive control [3,27], optimal control [1,19,26], variable phase control [17], sliding-mode fuzzy neural network based design [18], variable structure model reference adaptive control [2], and design based on uncertainty and disturbance estimation technique [35] are some examples to mention.

In general in the designs appeared in literature, some issues need attention. Owing to the complex nonlinear behavior of the wing rock phenomenon and its dependence on the angle of attack, usually the controllers have been designed by considering a fixed angle of attack. In some cases, the controllers are tested at other angles of attack to prove robustness of the designs. Requirement of availability of an accurate mathematical model for designing controller is another concern. For example, the designs based on feedback linearization need accurate mathematical model, a requirement which is hard to meet in practice. In some approaches, such as the designs based on variable structure control or Lyapunov theory, usually the knowledge of bound on uncertainty and disturbances is necessary for successful design of the controller. Lastly, the issue related to tackling external disturbances is often ignored in the designs.

In this work, an Extended State Observer (ESO) based robust control design is proposed for suppressing the wing rock motion with time-varying angle of attack. To address the issues of uncertainties and external disturbances, an ESO is designed and integrated with the Input–Output Linearization (IOL) controller to

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achieve robustness. The design is relatively less dependent on the availability of accurate mathematical model and also does not need any information such as bound or any other characterization of the uncertainties and disturbances. The resulting design essentially follows the principle of the well-known Active Disturbance Rejection Control (ADRC) technique. The basic idea in ADRC is to estimate the effect of unknown plant dynamics, uncertainties and disturbances using an ESO and to actively compensate for the same in the control law in real-time. In general, the ADRC approach [9,13,31] consists of tracking differentiator also referred to as profile generator or reference generator, an ESO and a PD controller. Although originally, the components of ADRC were presented in the nonlinear set up, i.e., nonlinear tracking differentiator, nonlinear ESO and nonlinear PD control, extension of the ADRC with linear ESO and PD control [40] designated as LARDC have also been widely studied and reported in the literature. The work presented here employs Input–Output Linearization (IOL) approach for designing the wing rock motion controller. The IOL control has been robustified by using the ESO. The resulting controller design, in essence, results into ADRC employing ESO and PD control and therefore, follows the principle of ADRC in linear set-up. Numerical simulations are carried out and the results are presented to demonstrate efficacy of the design.

2. Wing rock dynamics

Owing to its highly nonlinear characteristics, various approaches have been presented to model the wing rock phenomena [6,11,14,22,23]. In [23], the models presented in [6] and [22] are used with varying angle of attack scenario and the authors have proposed an interpolation function which interpolates smoothly the aerodynamic coefficients with corresponding angles of attack. Further, it is shown that the interpolated values are in close proximity to the coefficients at different angles of attacks as given in [22]. In this work, the model presented in [23] is used for designing an ESO based robust controller for suppression of wing rock motion. To this end, the equations governing the wing rock dynamics are given by

$$\begin{aligned}\ddot{\phi} &= -\omega_j^2\phi + \mu_1^j\dot{\phi} + b_1^j\dot{\phi}^3 + \mu_2^j\phi^2\dot{\phi} + b_2^j\phi\dot{\phi}^2 + g\delta \\ y &= \phi \end{aligned} \tag{1}$$

where ϕ, δ, and g represent the roll angle, aileron deflection and input gain respectively, ω_j^2, μ_1^j, μ_2^j, b_1^j, b_2^j are the values of aerodynamic coefficients at angle of attack α_j. Relations for the system coefficients appearing in (1) are

$$\begin{aligned}\omega_j^2 &= -c_1a_1^j \\ \mu_1^j &= c_1a_2^j - c_2 \\ b_1^j &= c_1a_3^j \\ \mu_2^j &= c_1a_4^j \\ b_2^j &= c_1a_5^j \end{aligned} \tag{2}$$

where the coefficients depend on the parameters a_i^j, which in turn are functions of the angle of attack α. The values of the parameters a_i^j for various angles of attack are given in Table 1. In order to build a smooth, time-varying model of the wing rock that depends on angle of attack, the following interpolation function has been proposed

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

where the centers α_j and spreads s_j are as given in Table 2.

Table 1
Parameters for the coefficients in the wing rock model.

α	a_1^j	a_2^j	a_3^j	a_4^j	a_5^j
15	−0.01026	−0.02117	−0.14181	0.99735	−0.83478
17	−0.02007	−0.0102	−0.0837	0.63333	−0.5034
19	−0.0298	0.000818	−0.0255	0.2692	−0.1719
21.5	−0.04207	0.01456	0.04714	−0.18583	0.24234
22.5	−0.04681	0.01966	0.05671	−0.22691	0.59065
23.75	−0.0518	0.0261	0.065	−0.2933	1.0294
25	−0.05686	0.03254	0.07334	−0.3597	1.4681

Table 2
Centers and spreads for wing rock interpolation.

j	1	2	3	4	5	6	7
α_j	15	17	19	21.5	22.5	23.75	25
s_j	1.5	1.5	1.5	2.0	1	1	1

With $x_1 = \phi$, $x_2 = \dot{\phi}$ the time-varying wing rock model can be written in state space form as

$$\begin{aligned}\dot{x}_1 &= x_2 \\ \dot{x}_2 &= \sum_{j=1}^{7}\rho_j(\alpha)\big(-\omega_j^2x_1 + \mu_1^jx_2 + b_1^jx_2^3 + \mu_2^jx_1^2x_2 + b_2^jx_1x_2^2\big) + g\delta \\ y &= x_1 \end{aligned} \tag{4}$$

It is assumed that the angle of attack, α, varies according to an exogenous dynamical 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 that can take values between -1 and $+1$. This system has been chosen without a basis on physical aircraft dynamics, but it could represent the effects of the aircraft itself which receives the pilot's commands through the input r.

In [22], the authors have analyzed that the wing rock model has a stable focus at the origin for the angle of attack α less than $19.5°$. For higher angles, the origin becomes an unstable equilibrium and limit cycle behavior is observed. For example, simulations results for an angle of attack of 21.5 degrees with initial conditions of $\phi(0) = 20$ deg and $p(0) = 0$ deg/s are given in Fig. 1 from where it can be observed that the roll angle history exhibits oscillatory motion and the limit cycle behavior. In the present work, it is considered that the angle of attack varies between 15 to $25°$ so that the qualitative behavior of (4) changes periodically as α becomes smaller or larger than $19.5°$. The control objective is to design a robust controller using only roll angle feedback such that the wing rock motion is suppressed and the roll angle is regulated to zero confirming the imposed specifications.

3. Extended state observer

As real plants are usually affected by significant uncertainties and unmeasurable external disturbances, disturbance rejection or compensation has become an important problem for high performance control system design. A great deal of effort has been devoted to address this issue and consequently number of methods/approaches have been proposed to robustify systems in presence of the uncertainties and disturbances [4,12,21,32,41].

One well-known approach that can be used in designing robust control systems is the Extended State Observer (ESO) [8,37,40,44]. The ESO can estimate the uncertainties along with the states of the system enabling disturbance rejection or compensation. In [37], a comparison study of the performances and characteristics of