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Robust Control of Wing Rock Motion

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Abstract— **In this paper, linear and nonlinear robust control strategies are proposed to suppress wing rock motion. The approaches are based on the uncertainty and disturbance estimator (UDE), which calculates and robustly cancels system uncertainties and input disturbances with appropriate filtering. In the case of a nonlinear controller, the information regarding the known part of the nonlinear plant dynamics is used by the controller, while in the case of a linear controller the terms containing the nonlinear functions are treated as additional uncertainties to the system. The algorithms provide excellent performance in suppressing the oscillations and disturbance rejection. Simulations are given to show the effectiveness of the strategies via an application to an experimentally derived delta wing rock model.**

KEY WORDS: Wing rock, uncertainty and disturbance estimator (UDE), robust control, nonlinear systems.

I. Introduction

Lightly damped or undamped rolling oscillations around the longitudinal axis at moderate to high angle of attack (AOA) exhibited by several modern high performance aircraft are commonly referred to as wing rock. Such dynamics typically possesses limit cycles, which become stable after a transient phase. In addition to being highly annoying to the pilot, wing rock can have a deteriorating effect on an aircraft performance. For some cases, wing rock is an early warning of imminent departure or spin entry. For other cases, the severity of wing rock could create inertial and kinematic coupling to cause AOA excursions and lead to loss of control. Handling qualities are clearly compromised in addition to degradation of maneuvering capabilities in terms of the maximum achievable angle of attack [1], [2].

Two different types of wing rock have been mentioned in the literature. The first type of wing rock is usually associated with low-airspeed, high-AOA flight in gusty conditions and characterized by unsteady lateral motions at moderate to high AOA. These motions show small-amplitude intermittent non-periodic roll oscillations, assumed to be a function of pilot-vehicle interaction. Flight procedures can be changed to avoid this type of wing rock without significantly affecting mission completion. The second type of wing rock is characterized by very large changes in roll angle and normally associated with high-AOA maneuvering such as in close-in air combat. For example, if a combat aircraft is incapable of tracking a target due to wing rock, significant mission accomplishment degradation is obvious. Moreover, the presence of wing rock during the approach or landing phase can have severe influence on the operational safety of the aircraft. From the stability point of view, wing rock phenomenon arises from a nonlinear aerodynamic mechanism and is associated with the nonlinear trend of roll damping derivatives, leading to hysteresis and sign changes of the stability parameters when increasing the AOA during aircraft maneuvers [3], [4]. The wing rock is usually controlled by appropriate ailerons deflection, as shown in Figure 1. Controlling wing rock is a challenge to both aircraft designers and control engineers.

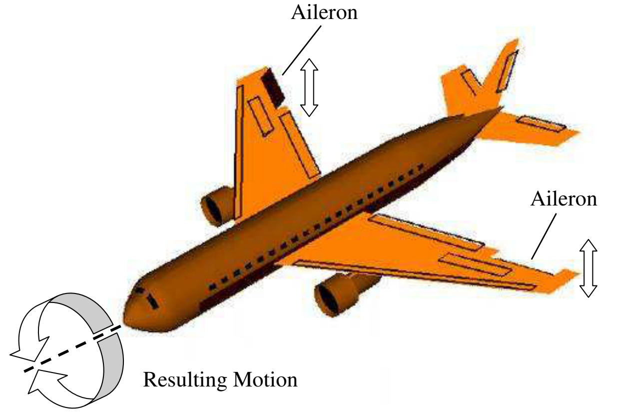

Fig. 1. Aileron deflection influence on the roll motion, modified from http://en.wikipedia.org/wiki/Aileron

Many researchers have tackled the problem of controlling wing rock motion. Adaptive feedback linearisation approaches were proposed in [5], [6], while suboptimal and optimal feedback algorithms were discussed in [7] and [8], respectively. Kalman filter based control [9] were shown to be a good candidate to solve the wing rock motion problem. Fuzzy [10], [11], fuzzy adaptive [12], and fuzzy neural [13] approaches gained popularity during the last decade. Neural network based control [14], [15] and wavelet adaptive backstepping approach [16] were also considered. Recently, several nonlinear control algorithms were shown to be suitable for dealing with wing rock [17], [18], [19].

The Uncertainty and Disturbance Estimator (UDE) strategy introduced in [20] is able to quickly estimate uncertainties and disturbances and thus provides excellent robust performance. It is based on the assumption that a continuous signal can be approximated as it is appropriately filtered. The UDE-based control strategy has been successfully extended to uncertain systems with delays in [21], [22]. Recently, the two-degree of freedom nature of UDE controllers has been

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revealed in [23], which considerably facilitates the design of the controller. In [24], the UDE strategy was adopted to formulate a robust input-output linearized controller, which was then applied to control the wing rock motion. In this paper, the UDE-based control strategy is directly applied to solving the wing rock motion problem, without going through the input-output linearisation.

The rest of the paper is organized as follows. In Section II, general linear and nonlinear UDE-based control laws for uncertain nonlinear systems with disturbances are revisited. Wing rock modeling is described in Section III, followed by the application of UDE-based control to the wing rock problem in Section IV. Conclusions are made in Section V.

II. Description of UDE-Based Control for Nonlinear Systems

Consider the nonlinear system with uncertainties and disturbances

$$\dot{\mathbf{x}}(t) = \mathbf{g}(\mathbf{x}(t),t) + \mathbf{b}(\mathbf{x}(t),t)\mathbf{u}(t) + \mathbf{f}(\mathbf{x}(t),\mathbf{u}(t),\mathbf{d}(t),t). \tag{1}$$

Here $\mathbf{x} = (x_1, ..., x_n)^T$ is the state vector, $\mathbf{u}(t) = (u_1(t), ..., u_r(t))^T$ the control input vector, $\mathbf{d}(t)$ the unpredictable disturbances vector, $\mathbf{g}(\mathbf{x}(t),t)$ the known smooth nonlinear function of the state vector and $\mathbf{f}(\mathbf{x}(t),\mathbf{u}(t),\mathbf{d}(t),t)$ the unknown smooth nonlinear function of the state vector, the control input and the unpredictable disturbances. $\mathbf{b} = \mathbf{B_1} + \mathbf{B_2}((\mathbf{x}(t),t))$ is a known nonzero control function of the state vector, where $\mathbf{B_1}$ is a constant vector and $\mathbf{B_2}$ a function of the state vector.

A linear reference model is chosen according to the desired specifications as

$$\dot{\mathbf{x}}_m(t) = \mathbf{A}_m\mathbf{x}_m(t) + \mathbf{B}_m\mathbf{c}(t). \tag{2}$$

The control objective is to force the error $\mathbf{e}$ between the states of the reference model and the states of the system

$$\mathbf{e}(t) = \mathbf{x}_m(t) - \mathbf{x}(t) \tag{3}$$

to be stable and satisfy the error dynamic equation

$$\dot{\mathbf{e}}(t) = (\mathbf{A}_m + \mathbf{K})\mathbf{e}(t), \tag{4}$$

where $\mathbf{K}$ is an error feedback gain matrix with appropriate dimensions, $\mathbf{c}(t) = (c_1(t), ..., c_r(t))^T$ is a piecewise continuous and uniformly bounded command to the system. It is worth noting that the dimension of $\mathbf{c}(t)$ does not have to be the same as that of $\mathbf{u}(t)$. This provides more freedom for the choice of $\mathbf{B}_m$.

Combining equations (1), (2), (3), and (4), then[1]

$$\mathbf{A_m x} + \mathbf{B_m c} - \mathbf{g} - \mathbf{bu} - \mathbf{f} = \mathbf{Ke}. \tag{5}$$

Hence, the control signal $\mathbf{u}$ needs to satisfy

$$\mathbf{bu} = \mathbf{A}_m\mathbf{x} + \mathbf{B}_m\mathbf{c} - \mathbf{Ke} - \mathbf{g} - \mathbf{f}. \tag{6}$$

[1]In order to simplify the exposition, the arguments of functions in the time-domain are omitted hereafter.

A. A nonlinear control law

The unknown term in (6), including the uncertainties and the external disturbance, can be represented as

$$\mathbf{f} = \dot{\mathbf{x}} - \mathbf{g} - \mathbf{bu}. \tag{7}$$

Hence, the unknown dynamics and disturbances can be obtained from the known dynamics of the system and the control signal. However, it cannot be directly used to formulate a control law. The UDE control strategy proposed in [20] adopts an estimation of this signal to construct control laws. Assume that $g_f(t)$ is the impulse response of a filter $G_f(s)$, whose passband contains the frequency content of $\mathbf{f}$. Then $\mathbf{f}$ can be accurately estimated from the output of the UDE as

$$\mathbf{f_{ude}} = \mathbf{f} \star g_f, \tag{8}$$

where $'\star'$ is the convolution operator. Going back to (6), the control action satisfies

$$\begin{aligned}\mathbf{bu} &= \mathbf{A}_m\mathbf{x} + \mathbf{B}_m\mathbf{c} - \mathbf{Ke} - \mathbf{g} - \mathbf{f_{ude}} \\ &= \mathbf{A}_m\mathbf{x} + \mathbf{B}_m\mathbf{c} - \mathbf{Ke} - \mathbf{g} + (-\dot{\mathbf{x}} + \mathbf{g} + \mathbf{bu}) \star g_f.\end{aligned}$$

This brings the nonlinear UDE-based control law

$$\begin{aligned}\mathbf{u} = \mathbf{b}^+ \Bigg[&\mathcal{L}^{-1}\{\frac{1}{1 - G_f(s)}\} \star (\mathbf{A}_m\mathbf{x} + \mathbf{B}_m\mathbf{c} - \mathbf{Ke}) \\ &- \mathcal{L}^{-1}\left\{\frac{sG_f(s)}{1 - G_f(s)}\right\} \star \mathbf{x} - \mathbf{g} \Bigg]\end{aligned} \tag{9}$$

where $\mathbf{b}^+ = (\mathbf{b}^T\mathbf{b})^{-1}\mathbf{b}^T$ is the pseudo inverse of $\mathbf{b}$, $G_f(s) = \mathcal{L}\{g_f(t)\}$ and $\mathcal{L}\{\cdot\}$ is the Laplace operator. The control signal has nothing to do with the unknown dynamics and disturbances. Since $\mathbf{u}$ is an approximate solution of (5), equations (4) and (5) are not always met and, when choosing the control parameters, the following structure constraint needs to be met:

$$\left(\mathbf{I} - \mathbf{bb}^+\right)(\mathbf{A}_m\mathbf{x} + \mathbf{B}_m\mathbf{c} - \mathbf{g} - \mathbf{f} - \mathbf{Ke}) = 0. \tag{10}$$

Obviously, if $\mathbf{b}$ is a square matrix and invertible, the above structural constraint is always met. If not, the choice of the reference model and the error feedback gain matrix is restricted. The unknown dynamics and disturbances also play a role in the above constraint. As shown in [20], a system in the canonical form always satisfies this constraint.

B. A linear control law

It is possible to construct a linear control law for the nonlinear system to achieve the desired performance given by the reference model. In this case, it is necessary that $\mathbf{B_1}$ is not zero. Moreover, the term $\mathbf{B_2}((\mathbf{x}(t),t))$ in $\mathbf{b}$ is treated as uncertain as well. Denote the terms in (6) that include the uncertainties, the external disturbance and the nonlinear dynamics as

$$\mathbf{h} = -\mathbf{g} - \mathbf{f} - \mathbf{B_2u} = -\dot{\mathbf{x}} + \mathbf{B_1u}. \tag{11}$$

With the UDE defined as

$$\mathbf{h_{ude}} = \mathbf{h} \star g_f, \tag{12}$$

there is

$$\begin{aligned}\mathbf{B_1u} &= \mathbf{A}_m\mathbf{x} + \mathbf{B}_m\mathbf{c} - \mathbf{K}\mathbf{e} + \mathbf{h_{ude}} \\ &= \mathbf{A}_m\mathbf{x} + \mathbf{B}_m\mathbf{c} - \mathbf{K}\mathbf{e} + (-\dot{\mathbf{x}} + \mathbf{B_1u}) \star g_f.\end{aligned}$$

This results in the following linear UDE control law, after using the Laplace transform:

$$\begin{aligned}\mathbf{U}(s) &= \frac{1}{1-G_f(s)}\mathbf{B_1}^+ [\mathbf{A}_m\mathbf{X}(s) + \mathbf{B}_m\mathbf{C}(s) \\ &\quad -\mathbf{KE}(s) - s\mathbf{X}(s)G_f(s)] \qquad (13)\end{aligned}$$

where $\mathbf{B_1}^+ = (\mathbf{B_1}^T\mathbf{B_1})^{-1}\mathbf{B_1}^T$ is the pseudo inverse of $\mathbf{B_1}$. When the filter $G_f(s)$ is strictly proper, $sG_f(s)$ is implementable and there is no need of measuring the derivative of states in both linear and nonlinear control laws.

Some generic principles about how to design K and G_f can be found from [23].

III. Modeling of the Wing Rock Motion

The wing rock motion can be described by the following one-degree-of-freedom nonlinear differential equation [1], [17]:

$$I_{xx}\ddot{\phi} = T_a - T_r, \qquad (14)$$

where I_{xx} is the moment of inertia about the roll axis, T_a is the anti-rolling torque created by the ailerons deflection and T_r is the rolling torque evaluated as

$$T_r = q \cdot S \cdot b \cdot C_r, \qquad (15)$$

where q is the dynamic pressure, S is the wing surface area, b is the wing span and C_r is the rolling moment coefficient. The dynamic pressure is given by

$$q = \frac{1}{2}\rho v^2, \qquad (16)$$

where ρ is the air density and v is the airspeed. The following expression of the rolling moment coefficient was experimentally identified in [2]:

$$C_r = b_0\phi + b_1\dot{\phi} + b_2\left|\dot{\phi}\right|\dot{\phi} + b_3\phi^3 + b_4\dot{\phi}\phi^2, \qquad (17)$$

where $b_0 - b_4$ are nonlinear functions of aircraft AOA and Reynolds number (Re), which is related to the airspeed as

$$Re = \frac{\rho v L}{\mu} \qquad (18)$$

with L and μ being the wing root chord and air viscosity, respectively. Substituting (15), (16), (17) and (18) to (14), then the wing rock motion can be described as

$$\ddot{\phi} + a_0\phi + a_1\dot{\phi} + a_2\left|\dot{\phi}\right|\dot{\phi} + a_3\phi^3 + a_4\dot{\phi}\phi^2 = \frac{1}{I_{xx}}T_a, \quad (19)$$

with

$$a_i = \frac{q \cdot S \cdot b \cdot b_i}{I_{xx}}, \quad i = 0, ..., 4,$$

which are also nonlinearly dependent on AOA and Re as well as on the aircraft dimensions and environmental conditions. They are normally determined experimentally.

When there is an additive input disturbance (such as wind gusts) of the form $\mathbf{d} = \begin{pmatrix} 0 \\ d \end{pmatrix}$ and model parameters uncertainty of the form $a_i = a_{in} + \Delta a_i,\ i = 0, ..., 4$ and with $b_n = I_{xx}^{-1}$, the wing rock dynamics (19) can be reformulated into the form of system (1) with $x = \begin{pmatrix} \phi & \dot{\phi} \end{pmatrix}^T$ and

$$\begin{aligned}\mathbf{g} &= \begin{pmatrix} \dot{\phi} \\ g_2 \end{pmatrix}, \\ \mathbf{b} &= \begin{pmatrix} 0 \\ b_n \end{pmatrix}, \\ \mathbf{f} &= \begin{pmatrix} 0 \\ f_2 \end{pmatrix}, \qquad (20)\end{aligned}$$

where

$$\begin{aligned}g_2 &= -a_{0n}\phi - a_{1n}\dot{\phi} - a_{2n}\left|\dot{\phi}\right|\dot{\phi} - a_{3n}\phi^3 - a_{4n}\dot{\phi}\phi^2, \\ f_2 &= -\Delta a_0\phi - \Delta a_1\dot{\phi} - \Delta a_2\left|\dot{\phi}\right|\dot{\phi} - \Delta a_3\phi^3 \\ &\quad -\Delta a_4\dot{\phi}\phi^2 + \Delta b \cdot T_a + d.\end{aligned}$$

Consider an aircraft with an 80° delta wing with $L = 479mm$, $b = 169mm$ and $I_{xx} = 1.0117 \times 10^{-3} kg \cdot m^2$ from [2]. According to the free-to-roll experiments described in [2] on the delta wing for $AOA = 25° \sim 45°$and $v = 15 \sim 40$ m/s, corresponding to $Re = 486000 \sim 1290000$, the coefficients $a_0 - a_4$ were determined and are shown in Figure 2. Apparently, these parameters vary a lot.

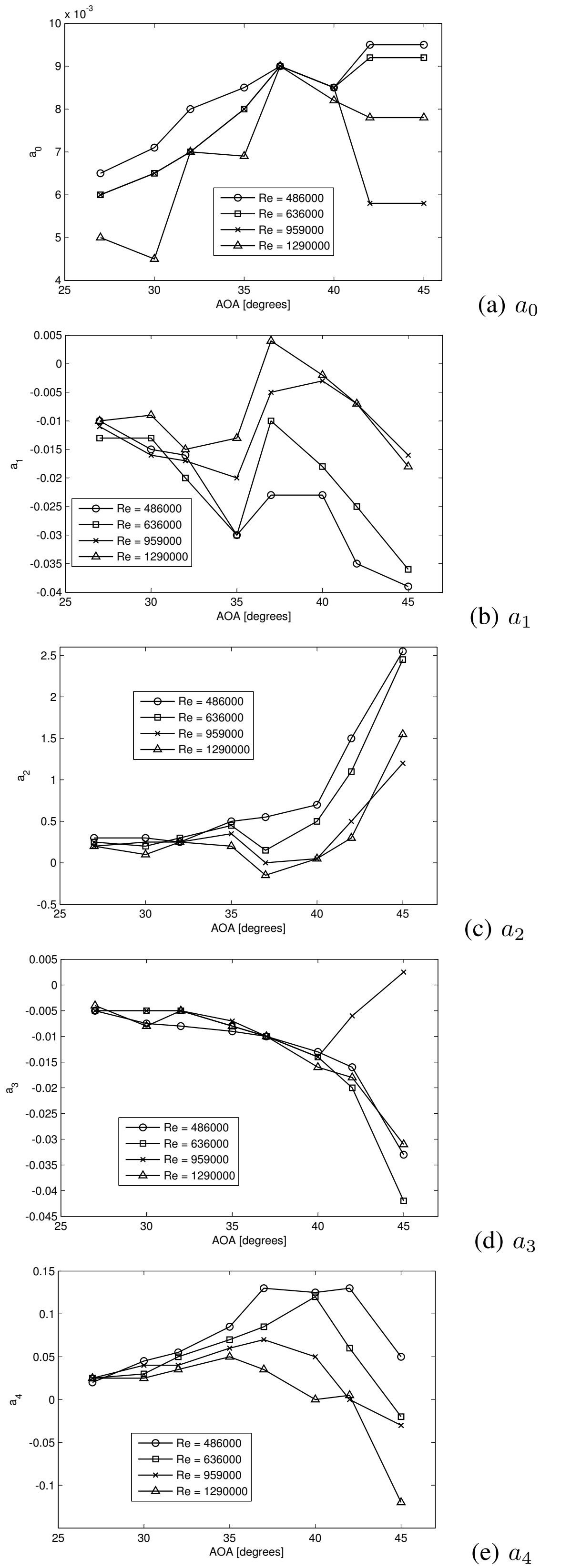
It is well known that an uncontrolled wing rock motion results either in limit cycle oscillations or in unstable divergence depending on the initial condition [13]. This is shown in Figures 3 with two different initial conditions. In the case of initial conditions of $\mathbf{x_0} = \begin{pmatrix} 35 \times 10^{-3} rad \\ 0\, rad/sec \end{pmatrix}$, the wing rock motion results in limit cycle oscillations as shown in Figure 3(a). Step changes of Reynold number and angle of attack affect the oscillation characteristics but do not cause divergence. In the case of initial conditions of $\mathbf{x_0} = \begin{pmatrix} 35 \times 10^{-3} rad \\ 52 \times 10^{-3}\, rad/sec \end{pmatrix}$, the wing rock motion results in roll angle divergence as shown in Figure 3(b). Hence, appropriate control strategies should be developed to avoid these.

IV. UDE-based control of wing rock motion

Assume that the nominal values of the coefficients $a_0 \sim a_4$ are chosen as $a_{0n} = 7 \times 10^{-3}$, $a_{1n} = -0.02$, $a_{2n} = 0.25$, $a_{3n} = -0.01$ and $a_{4n} = 0.05$. In addition, the moment of inertia about the roll axis was measured incorrectly as $I_{xx} = 2 \times 10^{-3} kg \cdot m^2$ and an external input disturbance $d(t) = 2.5 \times 10^{-4} \sum_{k=0}^{\infty} (1(t - 100k) - 1(t - 50 - 100k))$ is applied to the system. The reference model is chosen as the second order system

$$\begin{pmatrix} \dot{\phi}_m \\ \ddot{\phi}_m \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ -\omega^2 & -2\xi\omega \end{pmatrix} \begin{pmatrix} \phi_m \\ \dot{\phi}_m \end{pmatrix}.$$

Here, $\mathbf{c}(t) = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$ because the control objective is to suppress the wing rock dynamics and the desired steady-state



(a) a_0

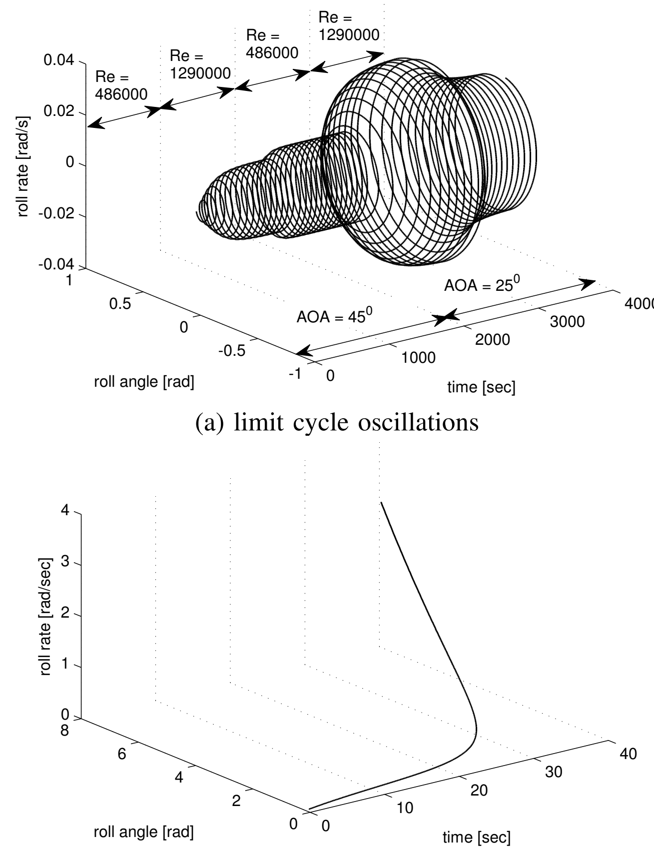
(b) a_1

(c) a_2

(d) a_3

(e) a_4

Fig. 2. The coefficients a_0, ..., a_4 corresponding to different AOA and Reynolds number Re from [2]



(a) limit cycle oscillations

(b) divergence

Fig. 3. Uncontrolled wing rock dynamics

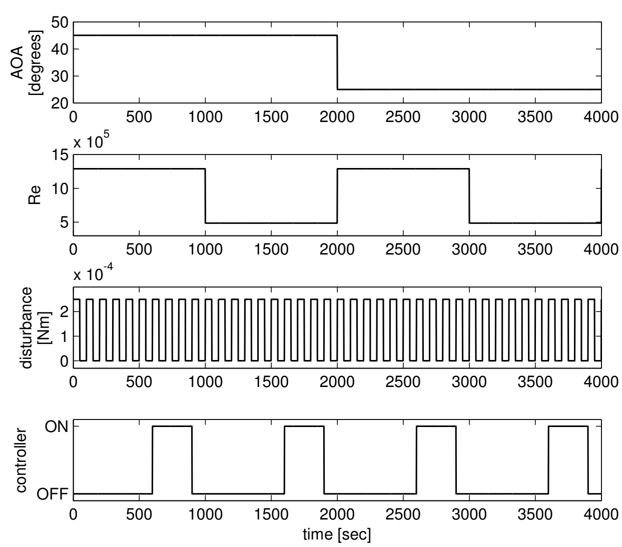


Fig. 4. Change of the operating conditions during the simulations

operating point for the system states $\begin{pmatrix} \phi_m \\ \dot{\phi}_m \end{pmatrix}$ is $\begin{pmatrix} 0 \\ 0 \end{pmatrix}$.

In order to suppress the wing rock within $10sec$ without overshoot, $\xi = 1$ and $\omega = 0.2\pi$ are chosen. The error feedback gain is set to $\mathbf{K} = \mathbf{0}$ and the low-pass filter is selected as $G_f(s) = \frac{1}{s+1}$.

When a nonlinear control law is preferred, the information regarding the nominal values of the coefficients $a_0 \sim a_4$ is

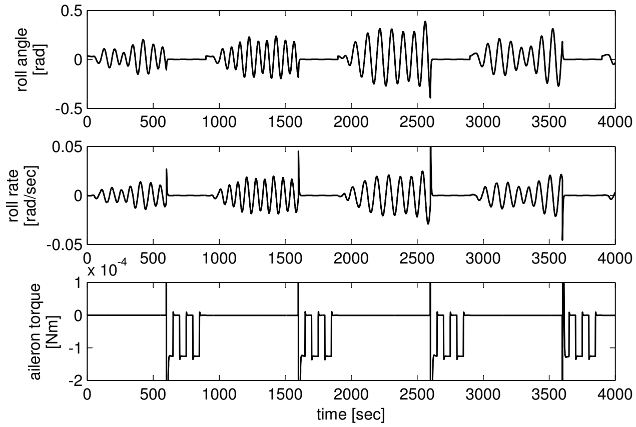


Fig. 6. Simulation results with the linear controller

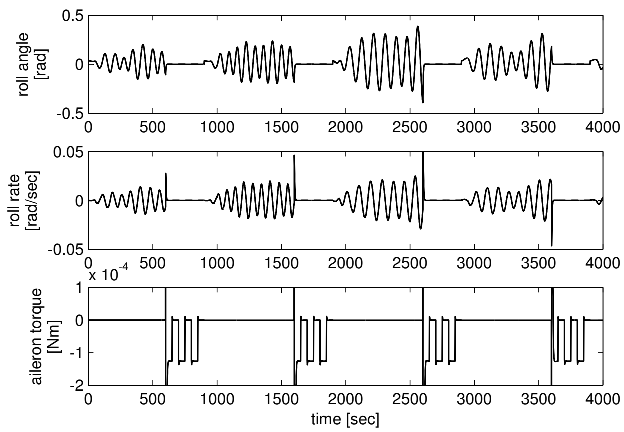


Fig. 5. Simulation results with the nonlinear controller

used and the nonlinear control law is derived according to (9). If this information is absent or a linear control law is preferred, a linear control law can be derived according to (13).

According to (9) and (13), the nonlinear and linear control laws are

$$\begin{aligned} u(t) &= -b_n^{-1}\left(g_2(t) + \omega^2 x_1(t) + \omega^2 \int_0^t x_1(t)dt \right. \\ &\qquad \left. + x_2(t) + 2\xi\omega x_2(t) + 2\xi\omega \int_0^t x_2(t)dt\right), \end{aligned}$$

where $x_1 = \phi$ and $x_2 = \dot{\phi}$, and

$$U(s) = -b_n^{-1}\left[(1+\frac{1}{s})(\omega^2 \hat{x}_1 + 2\xi\omega\hat{x}_2) + \hat{x}_2\right],$$

respectively. Note that $\hat{x}_1$ and $\hat{x}_2$ are the corresponding variables in the Laplace domain of x_1 and x_2. The control approaches were verified by simulations. During the simulations the controller was periodically turned on and off to demonstrate the differences between controlled and uncontrolled motions. The operating conditions were also changed during the simulations, as shown in Figure 4, to better demonstrate the performance of the controller under different operating conditions. The simulation results with both control laws are shown in Figures 5 and 6, respectively. Both approaches demonstrated excellent results while the nonlinear controller slightly outperforms the linear one because of the additional information used.

V. Conclusions

In this paper, the uncertainty and disturbance estimator (UDE) based control has been applied to the problem of wing rock motion. Both linear and nonlinear control strategies have been developed. The proposed algorithms have demonstrated excellent performance in suppressing the wing rock oscillations.

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