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Improved adaptive control for wing rock via fuzzy neural network with randomly assigned fuzzy membership function parameters

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ABSTRACT

Two stable adaptive fuzzy-neural control schemes within the indirect and direct frameworks are proposed to suppress the wing rock occurring at high angles of attack. In the two control strategies, a fuzzy neural network (FNN) with any bounded nonconstant piecewise continuous membership function is used to approximate the system nonlinear dynamics and external disturbances. Differently from the existing techniques, the parameters of the fuzzy membership functions are determined based on the recently developed fuzzy-neural algorithm named online sequential fuzzy extreme learning machine (OS-Fuzzy-ELM) where the fuzzy membership function parameters need not be adjusted and could randomly be generated according to any given continuous probability distribution without any prior knowledge. This simplifies the design of the controllers. Furthermore to ensure stable control performance, the tuning laws of the consequent parameters are derived using the projection algorithm and Lyapunov stability theorem. The merits of the proposed control schemes lie in the simplicity, robustness and stability, which manifests they can be applied for online learning and real-time control. In order to evaluate the performance of the proposed two control schemes, a comparison between a neural control, a fuzzy control and a fuzzy-neural control is carried out on various initial conditions. Results indicate the performance of the proposed controllers is superior using the randomly assigned fuzzy membership function parameters.

1. Introduction

Modern high-performance fighters are operating at high angles of attack to capture the maximum maneuverability and controllability. However, serious lateral directional stability problems have been encountered at high angles of attack. One frequently encountered instability is the limit-cycle roll oscillation called wing rock that is a highly nonlinear aerodynamic phenomenon. Some researchers have performed several theoretical studies to understand the dynamics of wing rock and to predict the amplitude and frequency of oscillation of the limit cycle [1–3,12]. The onset of wing rock may cause a loss of stability in the lateral/directional mode due to the large amplitudes and high frequencies of the rolling oscillations. This severely constrains the manoeuvring envelope of the high-performance fighters. Therefore, suppression of wing-rock motion is a very important task. To achieve the goal, some nonlinear control strategies including nonlinear optimal feedback control [10], the adaptive control based on the feedback linearization [11] and the robust H_∞ control [18] have been used to suppress the wing rock. An essential characteristic of these controllers is their model dependence, i.e., the need for full knowledge of the nonlinear dynamics *a priori*. It has been shown in [9,19] that an aircraft's wing rock is a complex, uncertain, and time-varying nonlinear system, and therefore its precise analytical modeling is unavailable. This will bring significant difficulties to the design of these controllers.

Recently an Extended State Observer (ESO) based robust control design [8] is proposed for suppressing the wing rock motion by employing the ESO to estimate the uncertainty. An advantage of the method is that it neither requires accurate plant model nor any information about the uncertainty. Besides, some researchers have turned to intelligent control as a means of explicitly accounting for nonlinear control problems [6,13,23,27–33]. Fuzzy logic system is one of the popular intelligent control methods that can provide knowledge-based heuristic controllers for ill-defined and complex systems without requiring a complete analytical model of dynamic systems. In the design of fuzzy logic controllers, the selection of appropriate parameters of fuzzy membership functions

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existing in the premise part of fuzzy rules is an important issue as the change of fuzzy membership functions may alter the performance of the fuzzy controller significantly [9]. Many researchers [21,24] have constructed model-free fuzzy logic based controllers to suppress the oscillation of wing rock. In these methods the parameters of fuzzy membership functions are determined by uniformly partitioning the fixed universe of the input variables, which lacks the online learning ability to deal with the uncertainties and time-variations under the large angle of attack. By applying a variable universe technique to modify the premise parameters of the fuzzy system, a reinforcement adaptive fuzzy controller using a fuzzy logic system is proposed for suppressing or tracking wing rock phenomena [9]. In the variable universe, the universe of the fuzzy sets can change along with changing of the input variable using a contraction–expansion factor. This method can improve the interpolation precision of fuzzy systems, but the improvement of the performance largely relies on the contraction–expansion factor chosen by trial-and-error.

By incorporating the fuzzy logic into a neural network, the fuzzy neural network (FNN) possesses an inherent structure suitable for online learning and reconstructing complex nonlinear mappings, which provides an effective mechanism for the control of wing rock. The authors [15] have addressed the wing rock problem using the FNN and a sequential growing and pruning learning algorithm for FNN, called as Extended Sequential Adaptive Fuzzy Inference System (ESAFIS). Although ESAFIS can determine the proper number of fuzzy membership functions during learning, fuzzy membership function parameters are determined according to the novelty of incoming data which requires many control parameters to be tuned and in the case of non-optimal values, the control performance may be low. Another deficiency of ESAFIS is the utilization of one specific type of fuzzy membership function (Gaussian) and not any type. In addition, there is no strict theory to guarantee the universal approximation for ESAFIS. This cannot provide justification in applying ESAFIS to almost any nonlinear system control problems. Lastly, in the control approaches based on ESAFIS, the knowledge of bound on uncertainties is necessary for successful design of the controller.

The objective of the present work is to develop the simple and improved adaptive fuzzy-neural control strategies within the indirect and direct frameworks for the wing rock problems by circumventing the deficiencies suffered from the ESAFIS. As a first step in achieving the objective, an FNN with any bounded nonconstant piecewise continuous membership function in a unified framework is used to approximate the system nonlinearities and uncertainties. Then the parameters of any fuzzy membership functions are determined by the OS-Fuzzy-ELM algorithm [17] developed based on the ELM [4,5]. In OS-Fuzzy-ELM, the parameters of the fuzzy membership functions need not be adjusted during learning and could be randomly generated according to any given continuous probability distribution without any prior knowledge about the target function. This simplifies the controller design process and also avoids tuning many control parameters in ESAFIS. Besides, it has been shown in our recent work [16] that with the fuzzy membership function parameters chosen randomly, the FNN with any bounded nonconstant piecewise continuous membership function can work as a universal approximator. To remove the requirement of a priori knowledge about the bound on uncertainties, the estimated value which is tuned based on the adaptive laws derived from the Lyapunov stability theorem and the projection algorithm is used for the controller design.

The performance of the proposed fuzzy-neural controllers is evaluated by comparing with a neural controller using RBF network, a fuzzy controller based on TS fuzzy system and a fuzzy neural controller using ESAFIS at various initial conditions. Simulation results demonstrate that the proposed control schemes achieve superior control performance for suppressing the wing rock with the randomly assigned fuzzy membership function parameters.

Table 1
Coefficients of rolling moment with angle of attack α.

α	a_1	a_2	a_3	a_4	a_5
15.0	−0.01026	−0.02117	−0.14181	0.99735	−0.83478
21.5	−0.04207	−0.01456	0.04714	−0.18583	0.24234
22.5	−0.04681	0.01966	0.05671	−0.22691	0.59065
25.0	−0.05686	0.03254	0.07334	−0.35970	1.46810

The rest of the paper is organized as follows. Section 2 introduces the dynamic model of the wing rock under consideration and the control objective. Section 3 describes the theoretical foundation of designing the proposed controllers, that is a brief review about the OS-Fuzzy-ELM algorithm together with the structure of a five-layer FNN. The proposed indirect and direct adaptive fuzzy-neural control schemes are introduced in Section 4. Convergence and stability of the proposed controllers are proven using the Lyapunov theory and Barbalat's lemma. Section 5 presents the simulation results and analysis in controlling the wing-rock system between various control methods. Section 6 shows the conclusions from this study.

2. Wing rock dynamics and control objective

In this study, a nonlinear mathematical model for wing rock of 80° slender delta wings [12] is considered. The dynamics of the wing rock system is a complex nonlinear function related with the roll angle ϕ, roll rate $\dot{\phi}$ and the angle of attack α. By choosing the state vector $\mathbf{x} = [x_1, x_2] = [\phi, \dot{\phi}]$, the wing rock dynamics can be written in the following state variable form:

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= f(\mathbf{x}) + u + d \end{aligned} \tag{1}$$

where d is the disturbance, u is the control input of the system. $f(\mathbf{x})$ is assumed to be bounded real continuous nonlinear function and given as,

$$f(\mathbf{x}) = -\omega^2\phi + \mu_1\dot{\phi} + b_1\dot{\phi}^3 + \mu_2\phi^2\dot{\phi} + b_2\phi\dot{\phi}^2 \tag{2}$$

The coefficients in the above equation are given by the following relations:

$$\begin{aligned} &\omega^2 = -Ca_1, \qquad \mu_1 = Ca_2 - D, \qquad \mu_2 = Ca_4, \\ &b_1 = Ca_3, \qquad b_2 = Ca_5 \end{aligned} \tag{3}$$

These various coefficients are dependent on the variables C, D and the dimensionless aerodynamic parameters a_1 to a_5. C is a fixed constant and equal to 0.354. D is the damping coefficient and fixed as 0.0001. Variables a_1 to a_5 are nonlinear functions of the angle of attack α and presented in Table 1.

The values of the coefficients in Eq. (2) could be obtained for any angle of attack according to any interpolation method. According to [12], the observed onset angle where μ_1 is zero corresponding to the onset of wing rock is "19–20 deg". The aim of the present study is to suppress the wing rock, i.e., maintain the 80° delta wing model at zero roll angle (ϕ) and zero roll rate ($\dot{\phi}$) condition.

Defining $\dot{\mathbf{x}} = [\dot{x}_1, \dot{x}_2]$, Eq. (1) can be further written in the following state-space form,

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{b}f(\mathbf{x}) + \mathbf{b}u + \mathbf{b}d \tag{4}$$

where

$$\mathbf{A} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, \qquad \mathbf{b} = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \tag{5}$$