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Control of Wing Rock Phenomenon with a Variable Universe Fuzzy Controller

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Abstract—**Wing rock is a highly nonlinear phenomenon in which aircraft undergo limit-cycle roll oscillations at a high angle of attack (AOA). It is a challenge to design an appropriate controller, especially with modeling errors and external disturbances. The methodology of fuzzy logic control (FLC) appears very useful when a process is too complex or when an available source of information is interpreted qualitatively, inexactly, or uncertainly, but we also note that the FLC of a process under disturbances usually exhibit a tracking error when the controlled system tends to steady state. In this paper, a variable universe fuzzy control design approach is utilized to improve both tracking precision and robustness of fuzzy PD control. A switching mechanism is developed to achieve this control scheme: when the tracking error is in a large range, fuzzy PD control is used to keep fast adjustments and to reduce the error; when the tracking error is in a small range, variable universe fuzzy control is then used as a fine controller to eliminate the error. Simulation studies for the nonlinear wing-rock control show that the new control scheme is a powerful tool to improve control system performances.**

I. INTRODUCTION

Over the past twenty years, nonlinear active control in modern aircraft has been increasingly investigated. However, the control of many aircraft at a high angle of attack (AOA) is limited by the wing-rock phenomenon. Wing rock is generated by unsteady aerodynamic effects at a high AOA and is a limit cycle oscillation (LCO) in the rigid body roll model of aircraft. High-speed civil transport and combat aircraft can fly in conditions where this self-induced oscillatory rolling motion is observed. In practice, wing rock can be highly annoying to the pilot and may pose serious limitations to the combat effectiveness of aircraft [1].

The systematical approach to the study of wing rock is based on wind tunnel experimental investigations on 80^0 swept delta wing models. In these experiments, simplified triangle geometries as test models exhibit stable limit cycles and correctly reproduce the dominant effect of primary wing vortices. Based on the parameter identification of experimental data, the nonlinear mathematical models of 80^0 swept slender wings have been developed in [2-4].

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In fact, these wing-rock mathematical models are not complete roll dynamics for practical control design because aerodynamics at a high AOA is very complex. Some unmodeled uncertainties such as different configurations and sizes should be considered in these models. Furthermore, disturbance is also important factor since aircraft operate in uncertain environments.

For wing rock control, several nonlinear control schemes have been developed in [5-12]. However, most control designs focus on wing-rock suppression at a small initial roll angle, which may not applicable for the desired roll angle tracking. In [13] and [14], nine different AOAs from 25^0 to 45^0 at various initial conditions are simulated. However, they still belong to the wing-rock suppression and can track only a constant angle. It should be note that disturbances and modeling errors are not treated in all these schemes. Thus, the current wing-rock control schemes do not satisfy highly maneuverable combat aircraft needs.

The FLC has the ability to perform effectively even in situations where the information about the plants is inexact and the operating conditions are uncertain. This feature of the FLC makes it suitable for controlling plants like aircraft [12].

In [14], fuzzy PD control was designed to overcome the effects of time-varying wing rock. However, under disturbances, the fuzzy PD control usually exhibits a tracking error. Furthermore, fuzzy rules are obtained on the basis of intuition and experience, and membership functions are selected by trial and error procedure, which make the tuning of a fuzzy controller a tedious and time-consuming process. To overcome this disadvantage, rule-adaptive or self-organizing FLC is usually adopted [15-18]. The objective of these approaches is to learn how to generate and modify its control policy based on a given performance criterion. However, if the controlled system is subject to the disturbances, these learning algorithms may generate unreliable modification values and lead to incorrect rule modification. In this paper, we extend our previous work [14] to include a switching mechanism in order to utilize a variable universe fuzzy control design method for improving tracking precision and robustness of fuzzy PD

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control with disturbances. The simulations of wing-rock motion show that the proposed control scheme has good control performances such as very small tracking errors and strong robustness in the presence of modeling errors and external disturbances.

II. WING-ROCK DYNAMICS

The differential equation describing the wing rock is given by [3, 5]

$$\ddot{\phi} = (\rho U_\infty^2 Sb / 2I_{xx})C_l + u \tag{1}$$

where ϕ is the roll angle, ρ is the density of air, U is the freestream velocity, S is the wing reference area, b is the chord, I_{xx} is the mass moment of inertia, and C_l is the roll moment coefficients, then written as

$$C_l = b_0 + b_1\phi + b_2\dot{\phi} + b_3|\dot{\phi}|\dot{\phi} + b_4\phi^3 + b_5\phi^2\dot{\phi} \tag{2}$$

The aerodynamic parameters b_i are nonlinear functions of the AOA.

Substituting (2) in (1), we have

$$\ddot{\phi} + a_0\phi + a_1\dot{\phi} + a_2|\dot{\phi}|\dot{\phi} + a_3\phi^3 + a_4\phi^2\dot{\phi} = u$$

(3)

where the parameters a_i are nonlinear functions of the AOA and is relative to free-to-roll experiment conditions [17].

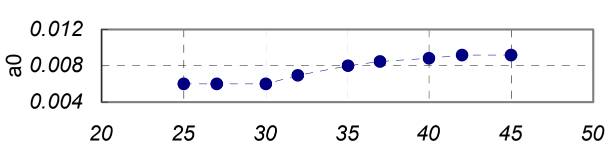
A typical set of coefficients a_i (at Reynolds number=636000) is illustrated in Fig. 1. To illustrate the behaviors of wing rock, the uncontrolled wing-rock motion at the small initial conditions $(\phi, \dot{\phi}) = (0.5^0, 0)$ is demonstrated in Fig. 1

As we have previously seen, because the model of complete aircraft roll dynamics is quite difficult to obtain as well as aircraft at high AOAs is operated in uncertain environments, the control model of wing rock should include a disturbance term d (modeling errors + external disturbances). The wing-rock control system for 80_0 swept back wing is then modified by

$$\ddot{\phi} + a_0\phi + a_1\dot{\phi} + a_2|\dot{\phi}|\dot{\phi} + a_3\phi^3 + a_4\phi^2\dot{\phi} = u + d \tag{4}$$

III. FUZZY PD CONTROL

We will briefly present our previous work [14] to design a fuzzy PD controller. The fuzzy control design procedure usually includes three parts: fuzzification, fuzzy rule base, and defuzzification. The structure of fuzzy PD control is shown in Fig. 3, where *e(t)* is the error signal defined by $e(t) = xd(t) - y(t)$, *xd(t)* is a reference signal, *y(t)* is the system output, and *u(t)* is the output of the controller.



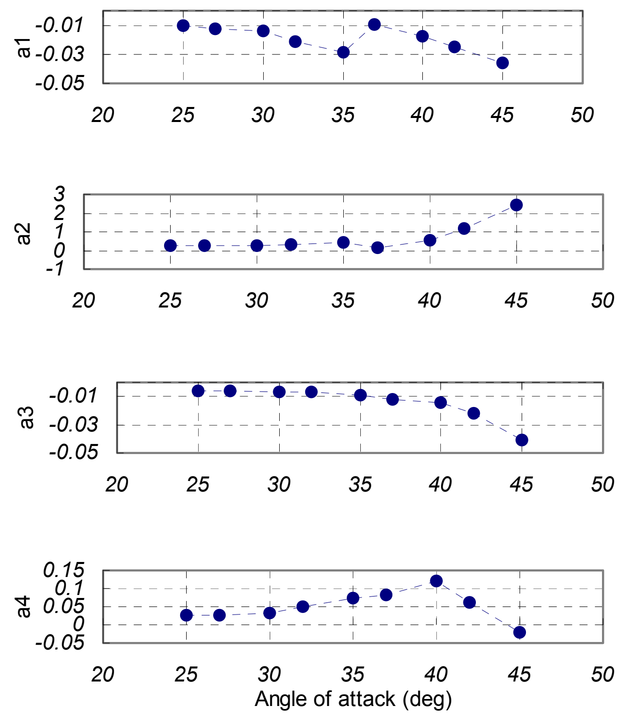


Fig. 1 The coefficients a_i in the analytical model

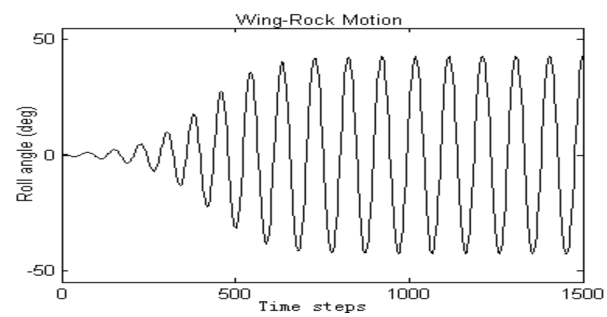


Fig. 2 Typical time history of wing rock

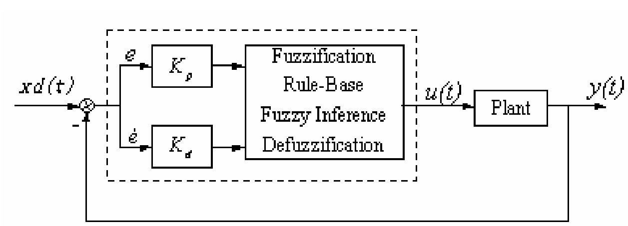
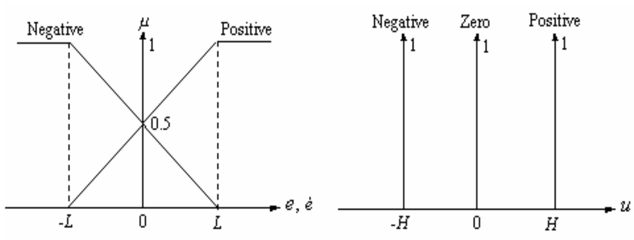


Fig. 3 Fuzzy PD control

A. Fuzzification

The two control inputs are the error *e(t)* and the error rate $\dot{e}(t)$; the one control output *u(t)* is fed to the controlled plant. Membership functions are shown in Fig. 4. Both *e(t)* and $\dot{e}(t)$ have two membership values: positive and negative, while *u(t)* is a singleton output membership function and has three membership values: positive, negative and zero.

Let $X_i = [-L \quad L]\,(i = 1,2)$ be the universes of input variables *e(t)* and $\dot{e}(t)$. To employ the same membership function on the two inputs, two scaling factors K_P and K_d are introduced to magnify input variable values. Let $Y = [-H \quad H]$ be the universe of output variable *u(t)*; According to the output range of *e(t)* and *u(t)*, designers can determine the above constants L and H.



(a) Inputs *e(t)* and $\dot{e}(t)$ (b) Output *u(t)*

Fig. 4 Membership functions

B. *Fuzzy Rule Base*

Based on the defined membership functions, the corresponding fuzzy rule-base is specified as follows:

R1: IF e(t)=*ep* AND $\dot{e}(t)$=*rp* THEN output=*op*

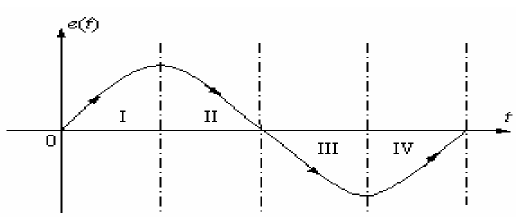
R2: IF e(t)=*ep* AND $\dot{e}(t)$=*rn* THEN output=oz

R3: IF e(t)=*en* AND $\dot{e}(t)$=*rn* THEN output=*on*

R4: IF e(t)=*en* AND $\dot{e}(t)$=*rp* THEN output=*oz*

where *ep* is denoted as a positive error, *en* is a negative one, *rp* is the rate of positive error, *rn* is the rate of negative one, *op* is a positive output, *oz* is a zero one, and *on* is a negative output.

The reason for establishing these rules can be explained with Fig. 5, assuming the error output for wing rock is an approximate sinusoidal wave. We note that for the case of suppressing wing rock (*xd=0*) one has the relationship $e(t) = xd(t) - y(t) = -y(t)$ and $\dot{e}(t) = -\dot{y}(t)$.



	I	II	III	IV
Input $e(t)$	>0	>0	<0	<0
Input $\dot{e}(t)$	>0	<0	<0	>0
Output $u(t)$	**op**	**oz**	**on**	**oz**

Fig. 5 The four different phases of output signal

1) For Rule 1: In phase I, the condition $ep = e > 0$ implies that $y < 0$ and the condition $rp = \dot{e} > 0$ implies that $\dot{y} < 0$. In this case, the controller should drive the system output upward. We let output = **op**.

2) For Rule 2: In phase II, the condition $ep = e > 0$ implies that $y < 0$ and the condition $rn = \dot{e} < 0$ implies that $\dot{y} > 0$. In this case, the controller will automatically perform the expected task, i.e., to drive the system output toward zero. That is, the controller needs not to take any action. For this reason, we set output = **oz**.

Similarly, we can explain the rules *R3* and *R4*.

Fuzzy inference is the process of formulating the mapping from a given input to an output by using fuzzy logic. We consider *Max-Min* composition with Mamdani implication for the four fuzzy rules with two antecedents.

C. *Defuzzification*

Defuzzification is a process to convert the fuzzy set obtained from an inference mechanism into a single value. Perhaps the most popular defuzzification method is the centroid calculation, which returns the center of area (COA) under the curve. All possible input combinations (ICs) of '*e*' and '$\dot{e}$' are shown graphically in Fig. 6. The control rules (*R1~R4*), the membership functions, and the IC regions are used to evaluate an appropriate fuzzy control law with respect to each region [20].

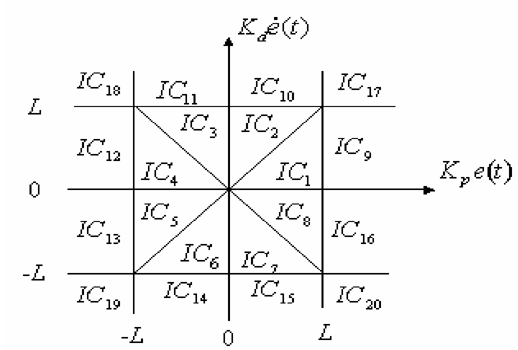


Fig. 6 Regions of possible input combinations (ICs)

On the other hand, a PD control law can be described by $u(t) = K_p e(t) + K_d \dot{e}(t)$, which is a plane passing through the system origin in the input-output space, i.e., it is of linear regulation law. However, the fuzzy PD controller is a piece-wise quadratic surface passing through the origin in the space, in which the whole surface can approximate a nonlinear regulation law. Thus, its whole merit is much better than the PD controller.

IV. THE FUZZY CONTROL WITH SWITCHING MECHANISM

A. *Control Scheme*

To improving the tracking precision of wing rock control as well as the robustness of fuzzy PD control under disturbances, a variable universe fuzzy control approach will be employed, which can be thought of as a fine controller. Thus, a switching mechanism will be introduced.

In Fig. 8, the new control strategy is proposed in order to control second-order nonlinear systems, for example, wing-rock motions. In principle, in the initial control phase the tracking error is usually large, i.e. $|e| > e_0$, where e_0 is a switch threshold given by designers; the task of the control system is now to reduce the large tracking error. We can use fuzzy PD control with fixed membership functions to achieve required fast adjustments. When the system tends to the steady state and has a small error, the control system is then switched to a fine fuzzy controller to eliminate the error.

A. *Variable Universe Fuzzy Control*

A variable universe fuzzy controller is used as a fine fuzzy controller and its structure is the same as the fuzzy PD control except the different gains K_P and K_d as well as the variable universes L and H. The reason for using different gains K_P and K_d in the controller is to reduce overshoot and to make the system stable when the tracking error is small, the K_P should be selected small but the K_d is selected large. For simplicity, Let the new gains are $K_{PF} = K_P / m$ and $K_{dF} = m \times K_d$, where m is a constant and $m > 1$. Based on these

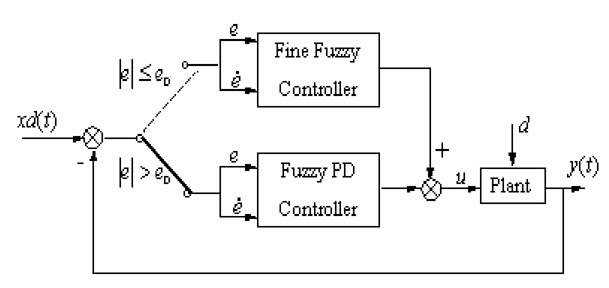


Fig. 8 Integrate fuzzy controller

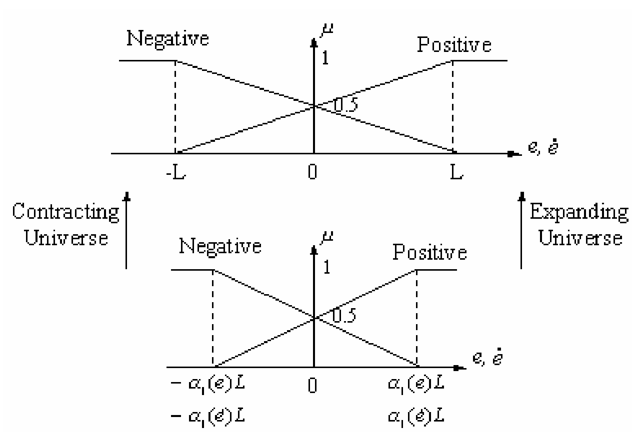


Fig. 9 Contracting/expanding universe L

new gains, the variable universe technology is then used to modify parameters L and H, but the control rules will not be changed.

A so-called variable universe means that some universes, (for example, X_i and Y) can respectively change along with changing of variables $e(t)$, $\dot{e}(t)$ and $u(t)$, denoted by [21]

$$X_1(e) = [-\alpha_1(e)L \quad \alpha_1(e)L] \tag{5}$$

$$X_2(\dot{e}) = [-\alpha_2(\dot{e})L \quad \alpha_2(\dot{e})L] \tag{6}$$

and

$$Y(u) = [-\beta(u)H \quad \beta(u)H] \tag{7}$$

where $\alpha_1(e)$, $\alpha_2(\dot{e})$ and $\beta(u)$ are called contraction-expansion factors of the universes X_i and Y, respectively. Being relative to variable universes, the original universes X_i and Y are naturally called initial universes. Fig. 9 illustrates this variable universe idea.

Now the issue is how to select $\alpha_1(e)$, $\alpha_2(\dot{e})$ and $\beta(u)$ to further reduce the tracking error. Generally, a function α: $X \to [0,\ 1]$, $e \to \alpha_1(e)$ and $\dot{e} \to \alpha_2(\dot{e})$ is called a contraction-expansion factor on $X_i = [-L, L]$ if it satisfies the following axioms [21]:

1) Duality: $\forall e \in X_1$, $\forall \dot{e} \in X_2$, $\alpha_1(e) = \alpha_1(-e)$ and $\alpha_2(\dot{e}) = \alpha_2(-\dot{e})$.

2) Near Zero: $\alpha_1(0) = \varepsilon_1 > 0$ and $\alpha_2(0) = \varepsilon_2 > 0$ (ε_1 and ε_2 is a very small real constant).

3) Monotonicity: α_1 and α_2 is strictly monotonically increasing on [0, L].

4) Normality: $\alpha_1(\pm L) = 1$ and $\alpha_2(\pm L) = 1$.

For fuzzy controller with two input variable and one output variable, the following contraction-expansion factors are suggested:

$$\alpha_1(e) = \varepsilon_1 + (|e| / L)^{\tau_1} \tag{8}$$

$$\alpha_2(\dot{e}) = \varepsilon_2 + (|\dot{e}| / L)^{\tau_2} \tag{9}$$

As for the output variable, the contraction-expansion factor $\beta(u)$ of the output variable can be expressed as:

$$\beta(e, \dot{e}) = (\alpha_1(e)\alpha_2(\dot{e}))^{\tau_3} \tag{10}$$

where $0 < \tau_1, \tau_2, \tau_3 \le 1$ and ε_1, ε_2 >0 is a very small constant, for example, taken as $\varepsilon_1 = \varepsilon_2 = 0.001$.

B. *Switching Control Law*

The proposed fuzzy control scheme is composed of the fuzzy PD controller and the variable universe fuzzy controller, which can be expressed as

$$u(t) = \begin{cases} u_{fine}(t) & |e| \le e_0 \\ u_{fuzzy}(t) & |e| > e_0 \end{cases} \tag{11}$$

where $u_{fine}(t)$ is defined as follows:

in IC_1, IC_4, IC_5, and IC_8,

$$u_{fine}(t) = \frac{L(\alpha_1(e)K_{PF}\,e(t) + \alpha_2(\dot{e})K_{DF}\,\dot{e}(t))}{2(2\beta(e,\dot{e})H - K_p|e(t)|)}$$

in IC_2, IC_3, IC_6, and IC_7,

$$u_{fine}(t) = \frac{L(\alpha_1(e)K_{PF}e(t) + \alpha_2(\dot{e})K_{DF}\dot{e}(t))}{2(2\beta(e,\dot{e})H - K_p|\dot{e}(t)|)}$$

$$= \frac{\beta(e,\dot{e})H + K_{DF}\dot{e}(t)}{2} \quad \text{in } IC_9 \text{ and } IC_{16},$$

$$= \frac{\beta(e,\dot{e})H + K_{PF}e(t)}{2} \quad \text{in } IC_{10} \text{ and } IC_{11},$$

$$= \frac{-\beta(e,\dot{e})H + K_{DF}\dot{e}(t)}{2} \quad \text{in } IC_{12} \text{ and } IC_{13},$$

$$= \frac{-\beta(e,\dot{e})H + K_{PF}e(t)}{2} \quad \text{in } IC_{14} \text{ and } IC_{15},$$

$$= \beta(e,\dot{e})H \text{ or } -\beta(e,\dot{e})H \quad \text{in } IC_{17} \text{ or } IC_{19},$$

$$= 0 \quad \text{in } IC_{18} \text{ and } IC_{19}.$$

$u_{fuzzy}(t)$ is similarly defined by $\alpha_1(e) = \alpha_2(\dot{e}) = \beta(e,\dot{e}) = 1$ and m=1.

V. SIMULATION RESULTS

In this section, we will describe the application of the proposed control scheme to wing-rock control and compare the simulation results of two control schemes, the fuzzy PD control and the proposed control scheme.

1) For the fuzzy PD control, we select $L = \pm$ 0.7rad, K_P =1, K_D =0.3, and $H = \pm 20$, respectively.

2) For the proposed control scheme, we select $e_0 = 0.02$ rad, L=± 0.7rad, m=4, K_P =1/4, K_d =0.3*4, and H =±20, respectively. The other parameters are chosen as $\tau_1 = 0.9$, $\tau_2 = \tau_3 = 0.1$, $\varepsilon_1 = 0.001$, and $\varepsilon_2 = 0.001$.

We are interesting in the following two problems related to wing-rock control with disturbances.

1) Suppressing control: maintain the wing-rock outputs at zero roll angle $(\phi \approx 0)$ and zero roll rate $(\dot{\phi} \approx 0)$.

2) Tracking control: make the output roll angle follow a known time-varying trajectory xd(t).

Assume desired trajectories are xd(t)=10^0+5^0sin(0.01πt) or xd(t)=10^0. The disturbances $d = 1.5\sin(2\pi t) + \sin(5\pi t)$ or d =2 are used to evaluate the robustness of control schemes. Let $(\phi_0, \dot{\phi}_0) = (2^0, 0)$ at AOA =32.5^0 and the uncontrolled system have some limit cycles; and then the controller at t =1000 time steps is activated. The following five cases are selected for comparing the performance of two controllers.

Case 1:Suppressing control with xd(t)=0 and d=0

The output responses for both controllers are quite similar, as shown in Fig. 10. The simulation results show that the tracking errors are all close to zero.

Roll angle ϕ (deg)

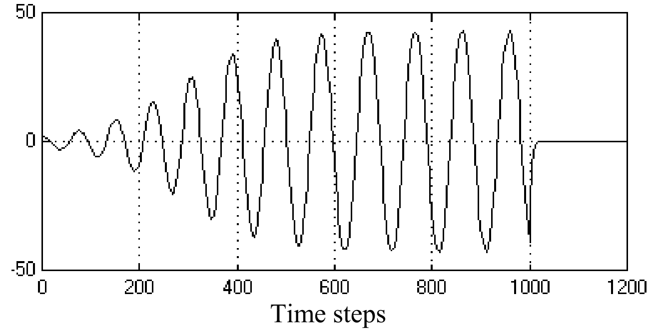


Fig. 10 Wing-rock suppression

Roll angle ϕ (deg)

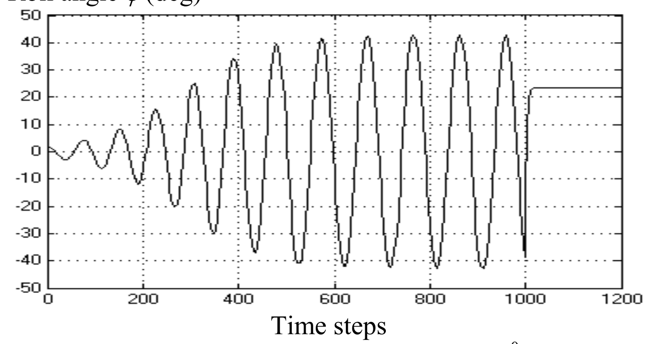


Fig. 11 Wing-rock tracking control (xd(t)=10^0) with d=2

Case2: Tracking control: xd(t) =10^0 and $d = 0$

The tracking error with the fuzzy PD control for tracking *xd(t)*=10^0 is less than 0.01^0 while the tracking error for the proposed controller is less than 0.0002^0.

From the above *Cases 1* and *2*, both the controllers have the good and almost same performance if wing rock is not subjected to the disturbances.

Case3: Tracking control: xd(t)=10^0 *and* $d = 2$

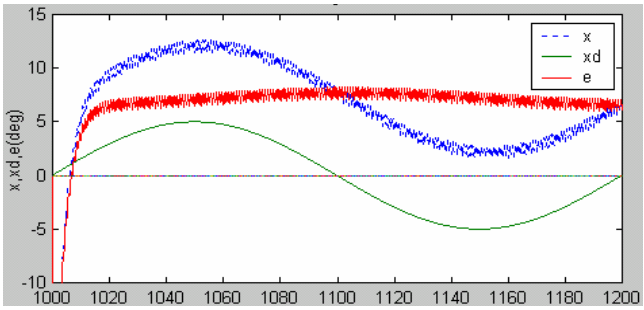
In this case, the tracking error of the fuzzy PD control for tracking desired trajectory xd(t)=10^0 under the constant disturbance d=2 is about 13.355^0, as shown in Fig. 11, while the proposed controller has a tracking error less than 0.061^0.

Case4: Tracking control: xd(t)=10^0+5^0sin(0.01πt) *and* $d = 1.5\sin(2\pi t) + \sin(5\pi t)$

The tracking error of the fuzzy PD control under the disturbance $d = 1.5\sin(2\pi t) + \sin(5\pi t)$ is in the range $\pm 1.1^0$, but the proposed control scheme with a tracking error is less than -5×10^{-4}.

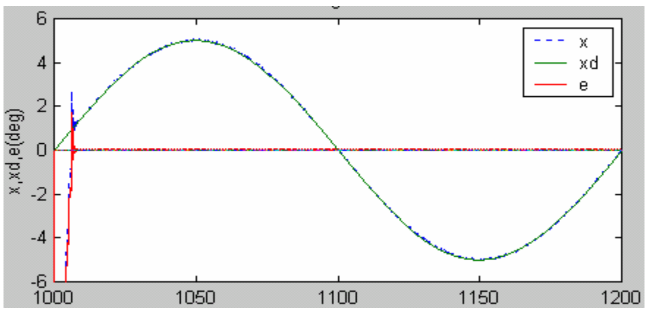
Case 5: Tracking control: xd(t)=5^0sin(0.01πt) *and complex disturbances* $d = 1 + 1.5\sin(2\pi t) + \sin(5\pi t)$

The tracking error of the fuzzy PD control for tracking desired trajectory xd(t)=5^0sin(0.01πt) under the *compound* disturbance $d = 1 + 1.5\sin(2\pi t) + \sin(5\pi t)$ is about 8.1^0. The tracking error of the proposed scheme is in the range from 0.1^0 to -0.05^0, as shown in Figs. 12a and 12b.



Time steps

Fig. 12a The tracking error of the fuzzy PD controller with $xd(t)=5^0\sin(0.01\pi t)$ and $d=1+1.5\sin(2\pi t)+\sin(5\pi t)$



Time steps

Fig. 12b The tracking error of the proposed controller with $xd(t)=5^0\sin(0.01\pi t)$ and $d=1+1.5\sin(2\pi t)+\sin(5\pi t)$

From the above *Cases 3-5*, when the plant has external disturbances, the new control scheme has much better tracking performance with much smaller tracking errors, disturbance rejection than the PD controller. Besides, we should mention that ε_1 and ε_2 are important factors, which affect tracking precision and computing speed.

VI. CONCLUSIONS

A variable universe fuzzy control scheme is utilized for improving the nonlinear wing-rock motion tracking precision and robustness under constant or time-varying disturbance environments. A switching mechanism is thus introduced. First, the fuzzy PD controller is used to keep fast adjustment and to reduce the large tracking error; when the tracking error is in the small range, the variable universe fuzzy controller is then used as the fine controller to eliminate the small tracking error. In this case, the wing-rock control mathematical model is allowed to have modeling errors and external disturbances. Most importantly, the developed controller can easy be design with four-rule fuzzy PD controllers and with the simple and stable variable universe strategies even though its robustness is lack of rigorous proof.

The wing-rock motion system is applied to evaluate the proposed control scheme. The five-case simulation results show that 1) if the wing-rock system is not subjected to the disturbances, two controllers have almost the same performance; 2) if the control system has modeling errors and external disturbances, the proposed control scheme has much better tracking performance, disturbance rejection, and robustness than the fuzzy PD control.

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