Fuzzy modeling to instruction steering of aircraft and simulation of pilot-aircraft closed loop system

Xiongzhiguo, Dongxinmin
Engineering Institute of the Air Force Engineering University
Department of Aerial Automation, the Engineering Institute of the Air Force Engineering University, Xi'an, China, 710038
email: xiongzhiguo430@sina.com Tel: 029-4397400

***Abstract* — When autopilot is not on or malfunctioning or pilot wants to control the aircraft via joystick directly, instruction steering system can lighten the burden of pilot greatly, by the help of which pilot will finish flying control task more easily and reliably than with the assistance of conventional aircraft instrument.**

This paper firstly introduces the structure and common theory of instruction steering system, and discusses the basic algorithm of fuzzy modeling. Afterwards, the rule of pointer deflection is designed based on fuzzy modeling method. The detailed procedures are presented in the paper. Lastly, we conduct the modeling to pilot-aircraft closed system, and compared with autopilot, the dynamic process of pilot-aircraft closed loop system is simulated in the altitude holding state of this type aircraft.

***Index Terms* — instruction steering, fuzzy modeling, pilot-aircraft closed loop system**

Ⅰ. Introduction

A certain type of medium size jet aircraft equip with autopilot system which has the following functions: attitude and course hold; altitude hold; manipulating ascend, descend and synchronized turn of the aircraft. The pilot will not be involved in controlling the craft when autopilot is working. The output of the autopilot system controls the craft and completes the flying tasks. If autopilot is not on or malfunctioning or pilot wants to control the aircraft via joystick directly, he can only do that in virtue of conventional aircraft instrument and his own flying experience without the assistance of instruction steering system. Under such condition, on one hand, pilot will have subjective randomness, so that he will not achieve accurate optimized flying, and on the other hand, the pilot will get tired both physically and mentally, so that there will be potential danger after long time flying. If we install an instruction steering system, so that pilot can exert control accordingly simply by tracing the pointer deflection of instruction indicator. In this case, the burden of pilot will be greatly reduced, and accurate designing of the rule of pointer deflection can help the pilot to achieve better controlling effect.

Ⅱ. The structural analysis of instruction steering system

Instruction steering is a fundamental working mode that is adopted widely in the flight control system of third-age fighter, for example SU-27, F-16. In this working mode, pilot can gain a pleasure of his own volitional revelation by control the aircraft directly and independently [1]. Instruction steering means that while the connection between autopilot or automatic control system and aircraft operation system is cut off, in different flying states, instruction steering system works out steering amount of joystick on pitching and deflect direction according to the instruction of external system and movement information of aircraft itself. And it will show the results on the indicator or instruction instrument livingly, vividly and directly. Pilot, according to the pointer of instruction instrument, could make the aircraft reach a required standard movement state by steering joystick.

For the study of this paper, the structure of instruction steering system is shown in Fig1.

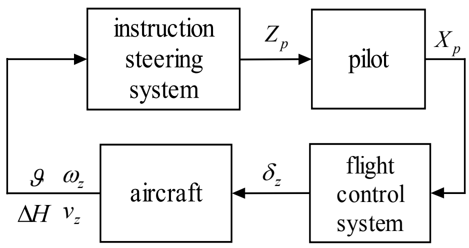

Fig 1. Structural figure of instruction steering system

where ϑ、ω_z、ΔH、v_z are the movement parameters aircraft outputs. Respectively, they are angle of pitch, pitch rate, deviation of altitude, longitudinal velocity. Z_p is deflection amount of longitudinal pointer. X_p is the longitudinal output of pilot on joystick. δ_z is longitudinal deflection amount of steer engendered by flight control system.

In different working mode, the input of instruction steering system is the instruction of external system and the movement parameters value of aircraft itself. And the output of it is amount of pointer deflection. All of above show on instruction indicator. We just make a study of the state of altitude hold. Consider that aircraft's lateral character is balanced, thus pilot only needs to conduct longitudinal operation. Therefore, we just consider the deflection of longitudinal instruction pointer. There are 4 inputs of instruction steering system, ϑ、ω_z、ΔH、v_z , and the output Z_p ,which is about equal to be longitudinal steering amount of joystick. Because we don't involve in lateral operation, so lateral instruction pointer doesn't deflect. Please consult the reference 1 for the illustration of instruction instrument deflection.

Based on fuzzy theory, we design the pointer deflection rule of instruction steering system. Also, pilot-aircraft closed loop system is simulated in the working mode of altitude hold, and the control effect of instruction steering system is compared with autopilot in the same working mode.

Ⅲ. The design of pointer deflection rule

A. Introduction to the basic ideas of design

In the working mode of instruction steering, pilot acts just as an executive plant that has the tracing capability. So the control law of instruction instrument has great similitude with automatic control system or autopilot. Therefore, in modern flight leading system, instruction system should work the same way with flight control system as possible as it could. Thus, pilot could make a choice between automatic flight and flying with assistance of instruction steering system. This paper is based on this essential thought to design the rule of pointer deflection.

Because aerodynamic derivatives of aircraft change greatly with the atmospheric parameter, for example altitude, Mach number, etc, aircraft model has great uncertainty in different states. Thus the design of flight controller is fairly complicated. When we use regular controller, the selection of controller parameters depends on large amounts of experiments and usually we have to make a compromise although the construction of controller is easy to be ascertained. In addition, when different pilots conduct different flight task, the requirements to flight controller have a great change. In the study of this paper, namely, the flight controller is the rule of pointer deflection.

In order to adapt to the complicated conditions mentioned above, we choose the method of fuzzy modeling to the controller, trying to design the desired rule. The controller based on fuzzy modeling has expendable capability, which can attain an excellent performance through more valid training. But this need collect more representative data through a great deal of flying trial.

B. The algorithm of Fuzzy modeling

A Fuzzy system model usually contains fuzzy algorithm R; a group of discrete finite fuzzy input space U; a set of discrete finite fuzzy output space E and the whole fuzzy subset of P which model defines. It could be shown as follows: M(R,E,U,P) [2]. Consider a example of a SISO system, we suppose the input and output space are respectively divided into the class of $m(e_1, e_2, \cdots e_m)$ and $n(u_1,u_2,\cdots u_n)$, their corresponding fuzzy subset being A_1, A_2, $\cdots A_m$ and B_1, B_2, $\cdots B_n$。 The fuzzy rules of system described by conditional expression is shown as follows:

R_r: if $e(t-k_1) = A_i$ and $u(t-k_2) = B_j$

then $u(t) = B_r$

$(i= 1, 2, \cdots, m;\ j=1, 2, \cdots, n;\ r=1, 2, \cdots, k)$

where $e_i \in E$, $u_j \in U$ ($i=1, 2, \cdots m; j=1, 2, \cdots n$), A_i and $B_j \in$ P. Fuzzy subset of the output is obtained by fuzzy reasoning based on fuzzy rules. Then we can calculate the exact value of output through defuzzification. Generally speaking, the number K of fuzzy rules of reflects the complexity of fuzzy algorithm. If the requirements for accuracy are higher, m and n have to be bigger. Thus, the amount of fuzzy rules will increase, resulting in more complicated fuzzy algorithm. In actual system design, we have to choose the way that splits the difference.

Fuzzy modeling is applied to complicated unknown objects. The solution for fuzzy modeling is shown as following steps: gather experimental data of input and output from system; train the fuzzy system to attain desired performance speciation; derivate final fuzzy model. The model built in this way could apply to any scheduled situation, and more the training data is, more accurate the model will be. We could design the rule of pointer deflection by using the fuzzy model of Sugeno fuzzy model[3,4].

C. The selection of fuzzy model

The model developed is a fuzzy system with 4 inputs and single output. That is, there are 5 spaces that could be studied: angle of pitch（ϑ）、pitch rate（ω_z）、deviation of altitude（ΔH）、longitudinal velocity（v_z）、amount of deflection of longitudinal pointer（Z_p）。

In case of the overabundance of training parameter, we make 3 fuzzy variables respectively for each of the four inputs: small-size(N), middle-size(Z), large-size(P). And we regard "gbellmf"[5] as membership function. "gbellmf" membership function which has 3 parameters: a, b, c is shown in Eq(1):

$$f(x,a,b,c)=\frac{1}{1+\left|\frac{x-c}{a}\right|^{2b}} \tag{1}$$

Define the output variable of Sugeno is the linear function of the input. So the relation between input and output could be shown in Eq.(2):

$$Z_p = K_\vartheta \vartheta + K_\omega \omega_z + K_{\Delta H}\Delta H + K_v V_z + K \tag{2}$$

where coefficient K_ϑ、K_ω、$K_{\Delta H}$、K_v and constant variable K are the parameters of Sugeno model which needs to be ascertained. Because there are 4 inputs, and each of them has 3 fuzzy sets, so this fuzzy system has 81 rules in all. And each of the rules has 5 parameters, so the final fuzzy rule has 81×5 parameters to be ascertained altogether. Training the system we could obtain a 81×5 matrix which includes the unknown parameters of this fuzzy system. Each row corresponds to each fuzzy rule and the 5 column corresponds to K_ϑ、K_ω、$K_{\Delta H}$、K_v and constant variable K.

D. Training the model

Because of the restriction of experiment, we only choose the input and output data in the state of altitude hold of instruction steering when initial altitude deviation is ±100m as the basis of training data. Finally, 662 pairs of sampling data in 3 different flight states are chosen to train fuzzy system selected.

After training, membership functions of 4 inputs are shown in Fig.2. There are 81 rules in all described as follows:

If:

K_ϑ=i, K_ω=j, $K_{\Delta H}$=u, K_v=v

Then:

$$Z_p = K_\vartheta \vartheta + K_\omega \omega_z + K_{\Delta H}\Delta H + K_v V_z + K$$

where i, j, u and v are fuzzy variables which belong to input space, and each of K_ϑ、K_ω、$K_{\Delta H}$、K_v、K is the row of parameters matrix of fuzzy rules obtained by training.

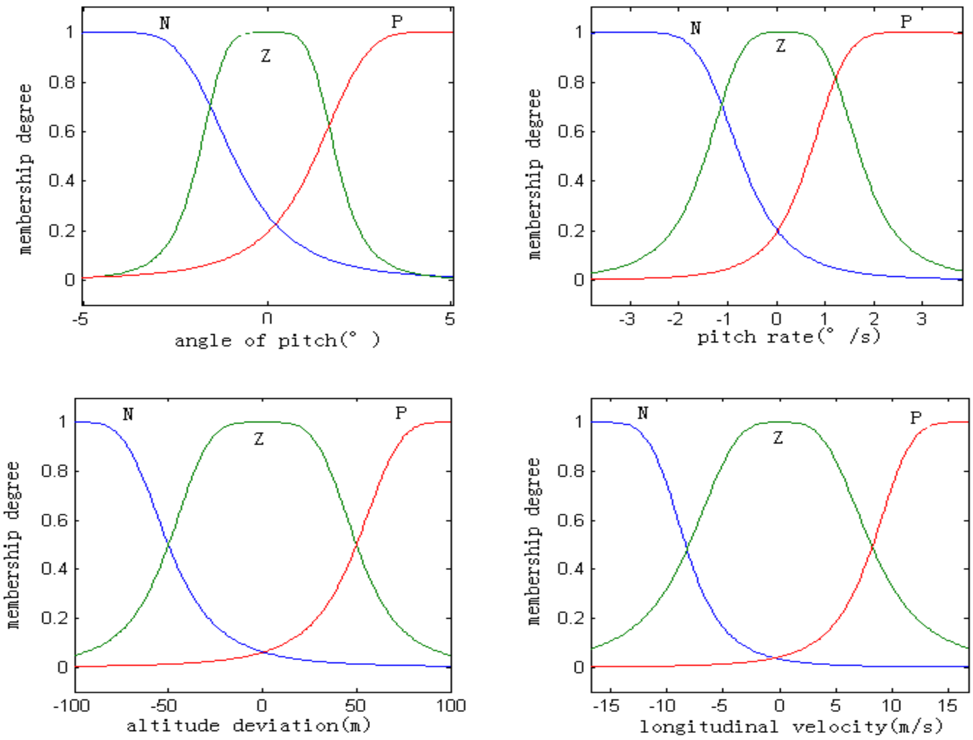

Fig .2 The membership function of 4 inputs

Ⅳ. Simulation of pilot-aircraft closed loop system

A. The pilot model

The establishment of pilot model is the basis of the study of pilot-aircraft closed loop system. The widely applied pilot models include: optimum control model[6]; structure model[7]; fuzzy control model etc. The aim of our study is to enhance accuracy of the pilot's control on the aircraft, and to lighten the burden of pilot, so the requirements to pilot is low. Therefore, it is enough to use McRuer transfer function model[8].

The common format of McRuer transfer function model is shown as follows:

$$Y_p = K_p e^{-\tau s} \frac{T_L s + 1}{(T_I s + 1)(T_N s + 1)}$$

where K_p is equivalent of pilot gain, whose value is between 1 and 100; τ is the delay of pilot's response, whose value is between 1 and 100; T_N is inherent first-order delay of nerve and muscle, about0.2s; T_L and T_I are lead and lag compensated time constant respectively. In different working mode, and as far as different pilots is concerned, these parameters values are variable in above field.

However, in this paper, we mainly consider the feasibility of designing the controller using fuzzy modeling. And the key to accuracy of our fuzzy modeling is the training data. So, as for our study, an invariable pilot model is acceptable. The final adopted pilot model is shown as follows:

$$Y_p = e^{-0.2s} \frac{2s + 1}{3.5s + 1}$$

B. The aircraft movement model

Simulation is conducted according to 3 flying states of this type aircraft. The states are shown in Form.1. Changing angle of pitch results in speed of ascend and descend, thus altitude deviation can be amended. The changing speed of angle of pitch are faster than that altitude deviation is amended, so the dynamic process of angle of pitch is described by short period equation in this paper. Suppose that wind speed is zero, aircraft equations are shown in Form.2 according to 3 flying states, where ω_z is pitch rate; v_z is longitudinal velocity; δ_z is longitudinal deflection angle of steer; ϑ is angle of pitch.

Form.1 The flying states

State	h（m）	M	v（m/s）
1	600	0.4	135
2	4000	0.5	162
3	8000	0.8	246

Form.2 The involved longitudinal equation of aircraft

State	ω_z / δ_z	v_z / ϑ
1	$\frac{-4.4s-4.84}{s^2+2.77s+5.001}$	$\frac{148.5}{57.3s+63.05}$
2	$\frac{-3.27s-3.139}{s^2+2.415s+4.808}$	$\frac{155.5}{57.3s+55.01}$
3	$\frac{-5.3s-5.512}{s^2+2.65s+7.773}$	$\frac{255.8}{57.3s+59.59}$

C. Simulation of pilot-aircraft closed loop system

Suppose that initial height deviation is 100m, we neglect other constant disturbance and conduct closed loop system simulation according to 3 conditions individually. Simulation results are shown in Fig3 and Fig4. Fig3 shows the dynamic process of altitude deviation and angle of pitch. Fig4 shows the dynamic process of longitudinal deflection angle of steer. They correspond to 3 states in ordinal sequence. In the figures, real line shows dynamic processes that instruction steering system amends deviation. While broken line shows dynamic processes that autopilot system eliminates deviation.

D. The simple analysis of simulation results

Dynamic processes of altitude deviation show that control effect of instruction steering system corresponds to autopilot system. For instruction steering system, the dynamic processes of angle of pitch and deflection angle of steer are not very good enough. This is mainly caused by restriction of experimental data and lack of training to fuzzy system, which also result in that adaptability of instruction steering system is not good enough. Therefore, from the figures, the control effect of designed instruction steering system is not so good as autopilot system. In theory, control law of autopilot is only a compromise design aiming to all kinds of situation. That is to say, it could not ensure to achieve satisfied control effect under all sorts of unknown disturbance. Therefore, the control effect of instruction steering system that adopts fuzzy design could surpass that of autopilot. For this, data for training needs to be optimized, and fuzzy model needs to be trained further in order to perfect rule of control. Generally speaking, scheme of instruction steering system is feasible when the aircraft is in the state of altitude hold.

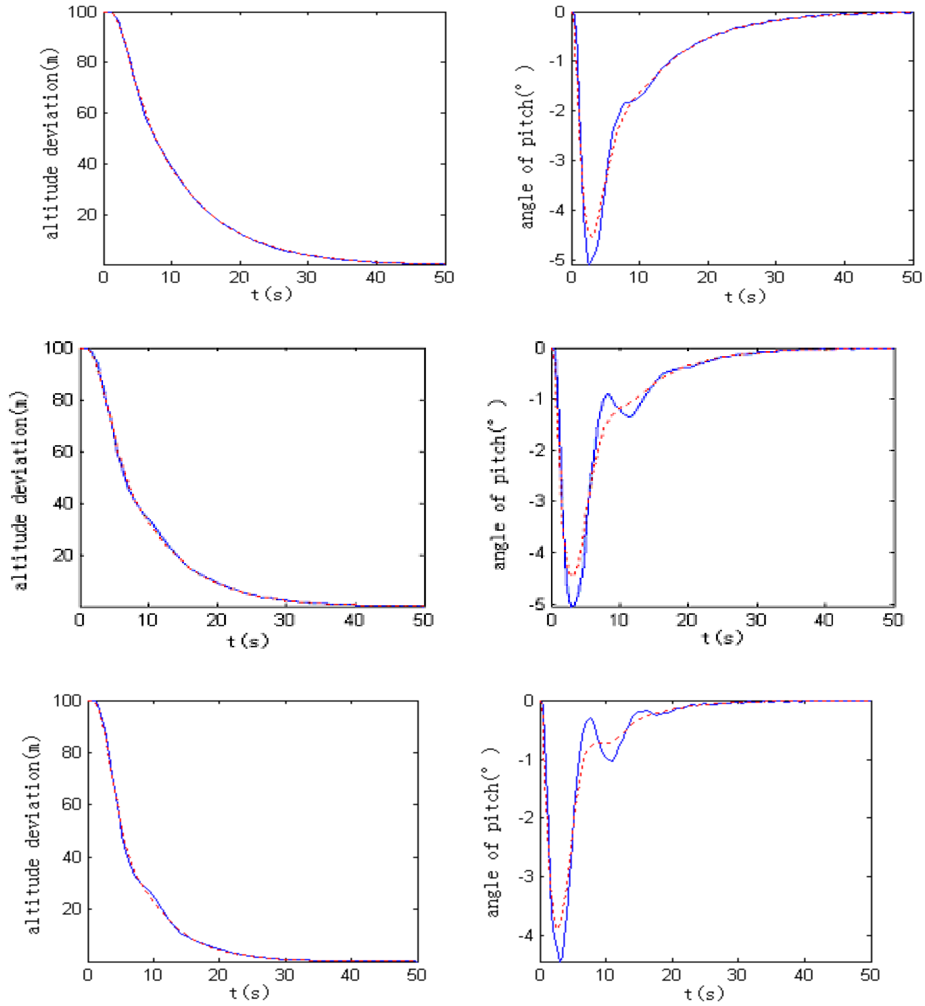

Fig.3. Dynamic processes of the closed loop system (the state 1, 2 ,3 from top to bottom)

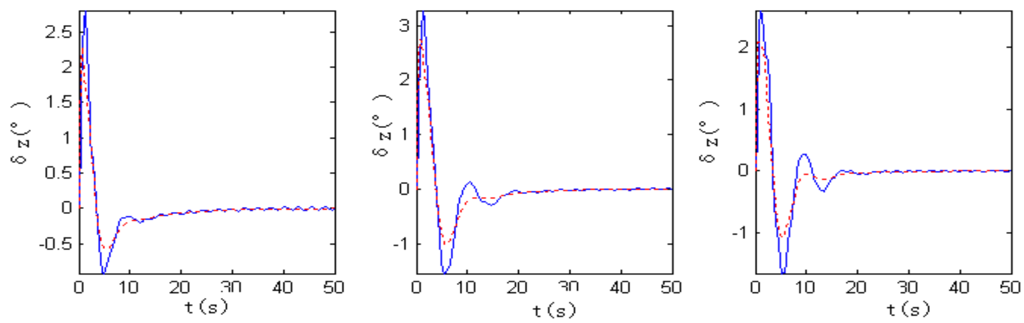

Fig 4. Dynamic processes of δz (the state 1, 2 ,3 from left to right)

V Concluding remarks

The key of designing the instruction steering system is to obtain the rule of pointer deflection. It can turn to many design scheme of flight control law for help, for example, flight automatic control system, autopilot system, etc. From the simulation results in this paper, we can see that it is feasible to build the rule of pointer deflection by fuzzy modeling, with the help of the training data which the autopilot system outputs in many kinds of states and conditions. In the working mode of altitude hold, the pilot-aircraft system developed by this way can complete the set flying control task very well.

Lastly, we must point out that as described in above sections, we treat the pilot model as an invariable model, however, the fact is the pilot model is variable along with different pilots and different flying tasks. Namely, the system robust stability is neglected in our study. Therefore, it still needs further study on how to perfect this scheme.

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Brief introduction of authors:

Xiong Zhiguo received the B.E. degree in navigation, guidance and control from the Engineering Institute of the Air Force Engineering University, Xi'an, China, in 2000. He is currently pursuing the M.S. degree in the same specialty. His research interests are in the field of pilot model, pilot-aircraft system and flight control.

Dong Xinmin received the Ph.D. in mechanics and electronics from the Xi'an Jiaotong University, China, in 1991. He is currently a professor of the Engineering Institute of the Air Force Engineering University. His recent research focuses on pilot-aircraft systems and the flight control.