Study and Hardware-in-the-Loop Simulation of Flight Mach Control System Based on Fuzzy Control Theory

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Abstract. An efficient and reliable flight Mach controller is specially needed for an Aircraft. A Flight Mach Fuzzy Controller (FMFC) based on modern Fuzzy control theory is designed for an Unmanned Aerial Vehicle (UAV) using a turbojet engine. The theory and process of designing control law is introduced and its control performance is optimized by changing the scaling factor. In order to evaluate the control performance, the mathematical simulation and hardware-in-the-loop simulation are carried out respectively, and the simulation results are compared. The evaluation shows good control performance to stabilize the UAV flight Mach number to the target Mach number quickly by controlling the engine work condition.

Keywords: Unmanned Aerial Vehicle · Flight Mach number · Fuzzy control · Hardware-in-the-loop simulation

1 Introduction

The Flight Mach Control System (FMCS), which controls the engine work condition to ensure that the aircraft flight according to the desired Mach number, plays an important role in the flight performance of an Unmanned Aerial Vehicle (UAV) [1]. However, because the models of aircraft trajectory and engine are incredibly complicated and strongly nonlinearized, an efficient and reliable control methodology is required [2]. Intelligent fuzzy control laws do not presuppose the strict mathematical model of the control object, different from classical model-based control approaches, and is expected to be able to flexibly handle the change of the characteristics of the control object [3]. A number of studies have already demonstrated that the fuzzy control is a feasible and flexible approach to flight control and can provide adequate control performance across the flight envelope [4–6]. In these approaches, however, the evaluation of control performance usually stays at the level of mathematical simulation without considering the factors of real products, which affects the control quality.

Hardware-in-the-loop (HIL) simulation is a technique that is used in the development and test of complex real-time embedded systems [7]. In order to be close to the

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natural processes, an effective simulation platform is built by adding some real hardware products, such as engine Electronic Control Unit (ECU), and fuel supply mechanism. These products are apparently smaller and cheaper, as compared to the complicated products which are replaced by the mathematical simulation models to avoid high costs and high risks.

In this paper, a Flight Mach Fuzzy Controller (FMFC) based on modern fuzzy control theory is designed for an UAV using a turbojet engine, considering the interconnection factor of Aircraft Flight Control System and Propulsion System. The error and error rate of flight Mach number are used as the input variables of controller, and the engine rotation speed difference is used as the output variable. The theory and process of designing control law is introduced. And the control performance is optimized by changing the scaling factor. To evaluate the control performance, a hardware-in-the-loop simulation system is built, and the result is discussed by comparing with the mathematical simulation result. The evaluation showed good control performance to stabilize the UAV flight Mach number to the target Mach number quickly.

2 Flight Mach Control System

The FMCS which uses the control algorithm to change engine condition by calculating the supply fuel, is the significant constituent part of an UAV, and its function is ensuring that the aircraft flight according to the desired Mach number from the Airborne Control Compute (ACC). The operating principle of FMCS is shown in Fig. 1.

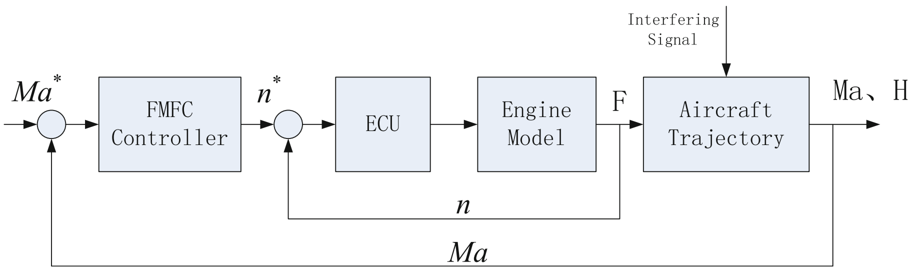


Fig. 1. Sketch map of FMCS principle

When the UAV is cruising, the ACC will calculate a target Mach number in real time and sends it to FMFC, according to the current flight condition and the subsequent flight requirements. The FMFC compares the actual flight Mach number Ma and the target Mach number Ma^*. If Ma is larger than Ma^*, the engine rotation speed n^* should be smaller to decrease the engine thrust for decelerating the UAV. On the contrary, if Ma is smaller than Ma^*, the engine rotation speed n^* should be larger to increase the engine thrust for speeding the aircraft. If Ma is the same with Ma^*, the engine rotation speed will stay its position to keep the balance of thrust and drag. When the flight Mach number drift off the scheduled variable, the FMCS will change the engine condition in good time to keep the flight Mach number to the set point needed.

3 Flight Mach Fuzzy Controller

The static and dynamic characteristics performance of the FMCS depends largely on the performance of the FMFC. The fuzzy control system is a digital and intelligent control system, with a kind of feedback closed loop structure, the composition heart of which is an intelligent fuzzy controller [7]. The design major components of the FMFC include the pretreatment, the fuzzification, the rules, the inference engine and the defuzzification, as shown in Fig. 2.

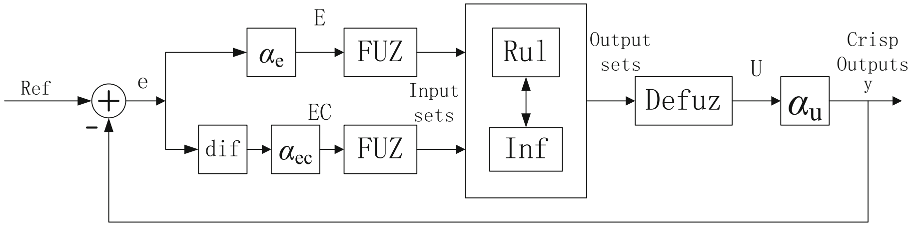


Fig. 2. FMFC structure

3.1 Pretreatment and Fuzzification

The pretreatment means deciding the input and output variables to the inference part, and quantifying these variables to form the fuzzy space [8]. The FMFC consists of double inputs and single output. The Mach number error $e = Ma - Ma^*$ and error rate $\Delta e = (Ma - Ma^*)/T$ are chosen as the input variables, where T is the control cycle time. The output of the fuzzy inference part is used as an engine rotation speed difference $\Delta n = n - n^*$. For simplicity, the same quantization domains are used for all control variables: {−6, −5, −4, −3, −2, −1, 0, 1, 2, 3, 4, 5, 6}.

This fuzzification determines the corresponding degree of each variable within the associated membership function [8]. Seven fuzzy subsets same for all control variables are chosen: (NB, NM, NS, Z0, PS, PM, PB},

where

NB = negative big,
NM = negative middle,
NS = negative small,
Z0 = zero,
PS = positive small,
PM = positive middle,
PB = positive big.

Two triangular fuzzy membership functions are used to determine the membership of fuzzy linguistic values decided by the input (Fig. 3) and output (Fig. 4). In Fig. 3, the initial values of indexes {a, b, c, d, e, f} are set as {−0.06, −0.04, −0.02, 0.02, 0.04, 0.06} according to the experience. In fact, these values play an important part in the performance of FMFC and need to be optimized. More details about the optimization will be discussed in Sect. 4.2.

3.2 Fuzzy Rules and Inference

The inference manages all the operations specified by the fuzzy rules with their logical operators, and aggregates the outputs of these fuzzy rules as the fuzzified output [8]. Two types of usual methods to determine the fuzzy control rules exist in the literature: the synthetic reasoning and the experience induction [9]. In this paper, the experience induction method is adopted to obtain a total of 49 if-then rules that cover the complete input/output space as Table 1. The experience is extracted from the Mach number control process described in Sect. 2, utilizing a strategy resembles to that of a classic PD controller since the rules are predicated on errors and error rates. Examples of the rules in Table 1 are:

R1: if e is NB and Δe is NB, then Δn is PB;
R2: if e is NM and Δe is NM, then Δn is PB.

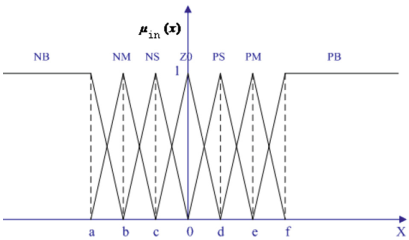


Fig. 3. Input membership function

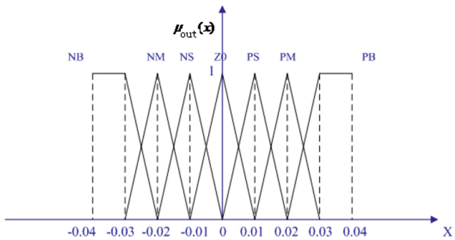


Fig. 4. Output membership function

Table 1. The fuzzy rules

Δn / e	NB	NM	NS	Z0	PS	PM	PB
NB	PB	PB	PB	PB	PM	PS	Z0
NM	PB	PB	PM	PM	PS	Z0	Z0
NS	PB	PM	PM	PS	Z0	Z0	NS
Z0	PM	PS	PS	Z0	NS	NS	NM
PS	PS	Z0	Z0	NS	NM	NM	NB
PM	Z0	Z0	NS	NM	NM	NB	NB
PB	Z0	NS	NM	NB	NB	NB	NB

For implication functions and the compositional rules of inference, Mamdani's minimum-operation is utilized. Then, the expression of the new membership function is obtained as follows:

$$\mu_c(\Delta n) = [w_1 \wedge \mu_{PB}(\Delta n)] \vee [w_2 \wedge \mu_{PB}(\Delta n)] \tag{1}$$

where

$$w_1 = \mu_{NB}(e) \wedge \mu_{NB}(\Delta e) \tag{2}$$

$$w_2 = \mu_{NM}(e) \wedge \mu_{NM}(\Delta e) \tag{3}$$

3.3 Defuzzification

The resulting fuzzy set is defuzzified to yield a crisp value. The popular defuzzification method used within the Mamdani defuzzification block is weighted average method [9], which can be calculated for a discrete membership function as follows:

$$\Delta n = \frac{\sum_{j=1}^{k} \mu_{C_j}(w_j) w_j}{\sum_{j=1}^{k} \mu_{C_j}(w_j)} \tag{4}$$

At last, the target engine rotation speed n^* of the next $T + 1$ can be obtained according to Eq. (5).

$$n^* = n + \alpha_u \Delta n \tag{5}$$

Where, n is the engine rotation speed of the present T, α_u is the scaling factor of the output.

4 Simulations

In this part, the FMFC control performance is examined for the flight Mach number control process in a complex system that is built according to Fig. 1. The mathematical simulation and hardware-in-the-loop simulation are carried out respectively. The goal is to test the ability of the control system to stabilize the UAV flight Mach number.

4.1 Mathematical Simulation

Validation of the FMFC is done on the test platform built according to Fig. 1, consisting of the FMFC, the ECU model, the engine model and the aircraft trajectory model. The function of ECU model is calculating the supply fuel flow to the engine according to the target engine rotation speed n^* from FMFC. The engine model and the aircraft trajectory model that is built to simulate the steady state operation of the UAV are complex, and can calculate accurately the parameters that consist of flight Mach number, flight altitude, engine rotation speed and thrust. The platform and all the models are written in *C#* language.

The simulation is assumed to take place at a typical flight condition of Mach 0.72 at 5 km altitude that the engine rotation speed is 85% of the maximum speed as shown in Table 2 Example A. The UAV needs to be accelerated to Mach 0.8. Whereafter, the FMFC activates and assumes the control authority.

Table 2. Simulation conditions

Parameter	Symbol	Example A	Example B
Altitude (km)	H	5	8
Mach number	Ma	0.72	0.716
Engine rotation speed	$n/n_{\max}$	85%	85%
Target mach number	Ma^*	0.8	0.65
Control cycle time (s)	T	5	5

The simulation result is shown in Fig. 5. The maximum overshoot is 0.1 for Mach number. It can be clearly learned that the controller has performed a good work for controlling the Mach number to achieve and stabilize the target. Although a long period of oscillations are observed before reaching the stable target because the initial values of the variables membership is not reasonable that is needed to be optimized.

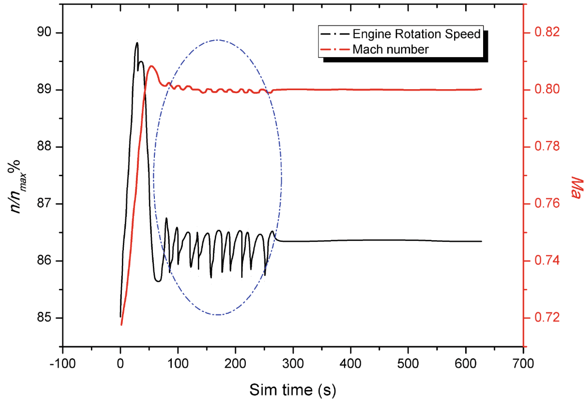


Fig. 5. Result of mathematical simulation

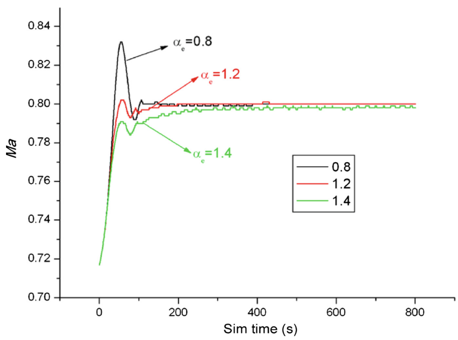
4.2 Optimization

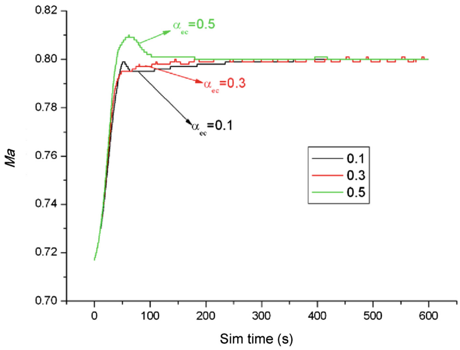
In order to improve the controller performance, the control variable scale factors (α_e, α_{ec} and α_u) are adjusted as the optimization parameters to modify the membership function of the all variables. Figure 6 shows the effect of the scale factors to the control performance. The smaller α_e or the bigger α_u gives rise to the oscillation and overshoot, while the bigger α_{ec} leads to overshoot only.

The objective function of the optimization is defined in Eq. (6).

$$J = \min\left(\int_{0}^{t_z} |e(t)|dt\right) \quad (6)$$

Where, t is the simulation time, and $e(t)$ is the error of Mach number to the target Mach number. According to the optimization results, it is probable to achieve good control performance when the scales are chosen as $\alpha_e = 1.29, \alpha_{ec} = 0.31$, and $\alpha_u = 0.9$. The results contrast before and after the optimization is shown in Fig. 7. The contrast shows that the time response is quick and overshoots are tiny.





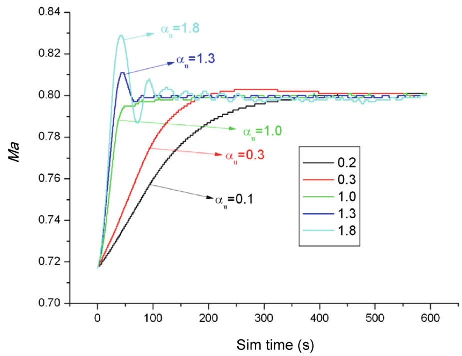


Fig. 6. (a)–(c) Three scale factors effect

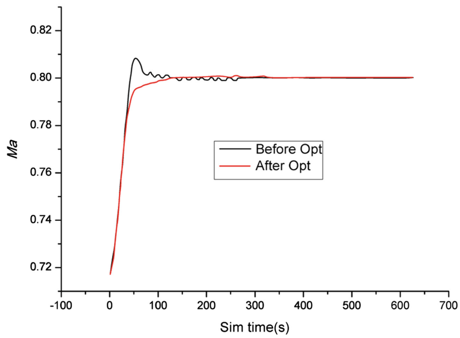


Fig. 7. Contrast before and after optimization

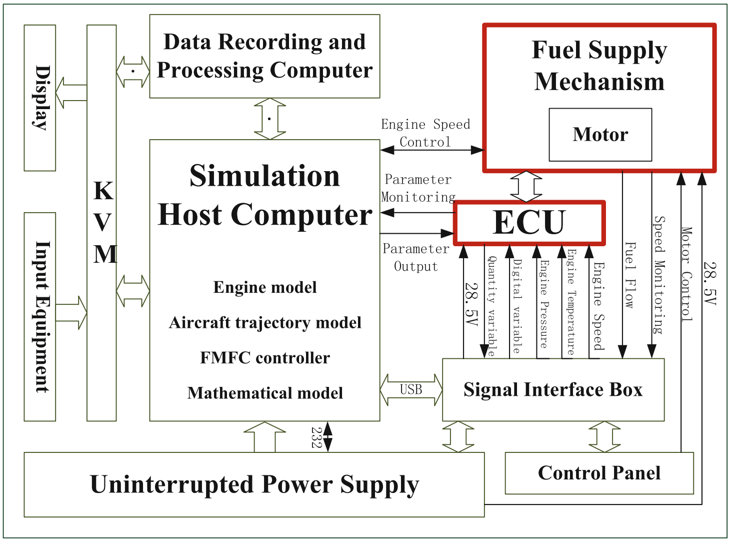


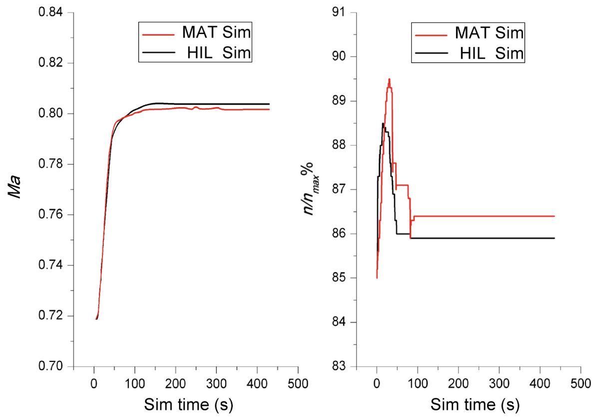
Fig. 8. HIL system architecture diagram (the bold solid frames are real products)

4.3 Hardware-in-the-Loop Simulation

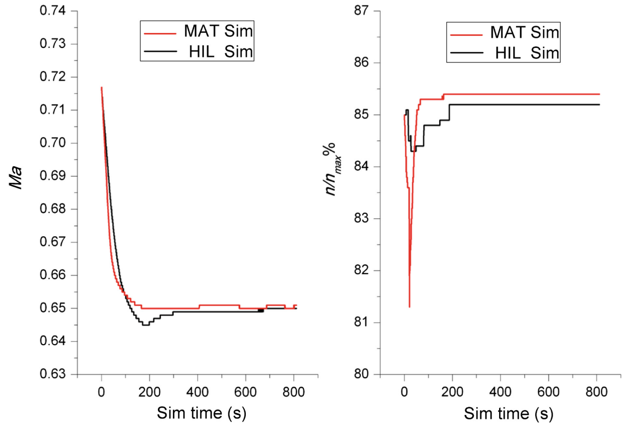
The Hardware-in-the-loop simulation system is built on the basis of mathematical simulation by replacing partial mathematical models with real products [10, 11]. The system consists of Electronic Control Unit (ECU), Fuel Supply Mechanism (FSM), Simulation Host Computer (SHC), Data Recording and Processing Computer (DRPC), Signal Interface Box (SIB), and Uninterrupted Power Supply (UPS), as shown in Fig. 8. The FSM is one of a series of actuators that the ECU controls on an internal combustion engine to ensure optimal engine performance. These two real products work together to achieve the fuel supply function of the engine, by reading values from a multitude of parameters within the engine model, interpreting the data using the complex control algorithms, and adjusting the engine actuators. The Engine model, aircraft trajectory model, FMFC controller and the other related mathematical models run on the SHC computer.

Two Simulation Examples (A and B) are carried out to test the performance of the FCFC controller. The condition of example A is the same with that in Sect. 4.1. The simulation of example B is assumed to take place at a flight condition of Mach 0.716 at 8 km as shown in Table 2.

The comparison results of mathematical simulation and the hardware-in-the-loop simulation in the same condition are shown in Fig. 9. It can be clearly learned that the controller has performed an excellent work for the tracking task, and the results of mathematical simulation and the hardware-in-the-loop simulation are almost the same. The relative error of the stabilized final Mach number defined as θ in Eq. (7) is less than 2%, while the engine rotation speed are quite different that is especially for example B, as represent in Fig. 9(b). The result of hardware-in-the-loop simulation is more hysteretic and stable, which is because the system has delayed effect benefit from



(a) The Simulation Example A



(b) The Simulation Example B

Fig. 9. Comparison of mathematical simulation and hardware-in-the-loop simulation

adding the real products, and the ECU has more detailed algorithm to calculate the fuel flow than mathematical simulation model.

$$\theta = \frac{\max(|e(t)|)}{Ma^{*}} \times 100\% \tag{7}$$

5 Conclusions

Flight Mach Fuzzy Controller (FMFC) based on modern fuzzy control theory is designed for an UAV using a turbojet engine, and the control performance is optimized by changing scaling factor. A hardware-in-the-loop simulation system is built to evaluate the control performance, and the relative error of the stabilized final Mach number is less than 2%, meaning that the controller has performed an excellent work for the tracking task.

This study indicates that, although the flight condition for the UAV is complicated and changeable, the FMFC controls the flight Mach to the target Mach number quickly. This conclusion is proved by the test including the mathematical simulation and hardware-in-the-loop simulation.

In the future, the work is expected to integrate the FMFC with the roll, Angle of attack and Angle of sight controller using fuzzy logic concept, and create more realistic hardware-in-the-loop simulation environment.

References

1. Purnachander, D.: Aircraft dutch roll control by fuzzy logic controller. Int. J. Latest Trends Eng. Technol. **3**(5), 38–46 (2015)
2. Ross, I.M., Fahroo, F.A.: Perspective on methods for trajectory optimization. In: AIAA Paper 2002, p. 4727 (2002)
3. Suratia, P., Patel, J., Rajpal, R.: FPGA based fuzzy logic controller for plasma position control in ADITYA Tokamak. Fusion Eng. Des. **87**(11), 1866–1871 (2012)
4. Erginer, B., Altug, E.: Design and implementation of a hybrid fuzzy logic controller for a quadrotor VTOL vehicle. Int. J. Control Autom. Syst. **10**(1), 61–70 (2012)
5. Hector, G., Qian, G., Jiang, C.S.: Fuzzy terminal sliding-mode control for hypersonic vehicles. J. Intell. Fuzzy Syst. **33**(3), 1831–1839 (2017)
6. Jan, B., Frantisek, D., Pavol, F., Daniela, P.: Autonomous flying with quadrocopter using fuzzy control and ArUco markers. Intell. Serv. Robot. **10**(3), 185–194 (2017)
7. Lijun, Z., Yingyue, X.: Application of normalized LCF method in flight/propulsion controller design. Acta Aeronaut. et Astronaut. Sin. **21**(3), 267–269 (2000)
8. Kevin, M.P., Yurkovich, S.: Fuzzy Control. Tsinghua University Press, Beijing (2001)
9. Jantzen, J.: Foundations of Fuzzy Control: A Practical Approach, 2nd edn. Wiley, Hoboken (2013)
10. Kai-long, C., Shou-sheng, X., Jin-hai, H.: Semi-physical simulation experiment system of fuel integration control system for turbofan engine. J. Propul. Technol. **28**(4), 422–427 (2007)
11. Zheng, W., Wu, G., Xu, G.: Adaptive fuzzy sliding-mode control of uncertain nonlinear system. In: 3rd International Conference on Management, Education, Information and Control, pp. 707–711 (2015)