Control of fuel flow-rate for a high-temperature gas trial system

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Abstract. This paper introduces the fuel supply principle of a high-temperature gas trial system (HTGTS), and gives the mathematical model of the fuel supply system. According to the problems such as time delay, time-variant parameters, interference and so on exist in the fuel supply system, the Fuzzy PID predictive (LevFuzzyPID) control algorithms are designed to realize the accurate control of the fuel flow-rate. On this basis, the simulations and experiments are carried out by using the control algorithms designed in this paper. The simulation results show that the LevFuzzyPID algorithm is superior to the traditional PID and fuzzy PID algorithm in the ability of overcoming the system’s time delay, time-variant parameters and interference, which has good control performance. The experimental results show that the control effect of the LevFuzzyPID algorithm is much better than the control effect of PID algorithm and FuzzyPID algorithm. Namely overshoot of the system by using PID algorithm and FuzzyPID algorithm are 20% and 12% respectively, but there is no overshoot in the system by using LevFuzzyPID algorithm.

1. Introduction

Supersonic combustion (SC) is an intense chemical reaction happened in supersonic airflow, and the supersonic airflow is maintained before and after combustion, which is a new field in combustion discipline. At present, research on the SC is mainly focus on the combination with ramjet. SC ramjet is a ramjet in which the fuel is burnt in the supersonic flow. Compared with the traditional ramjet, the SC ramjet has some advantages such as little air pressure loss, higher combustion efficiency and so on. However, there are still some technical problems in some aspects, which are to develop an effective fuel injection device and flame stability device with a small loss. The solutions of these problems need to be further studied the supersonic combustion. The high-temperature gas trial system (HTGTS) is a simulation device which is used to study the combustion law of the SC and test the thermal stress and strength of high-temperature specimens, so as to meet the requirement of simulation experiment of high-temperature and large heat flux density. HTGTS overcomes the disadvantages of the existing heating device which consists of quartz lamp and graphite, in the simulation capability and reliability of ultra high temperature. So, the research on the performance of HTGTS has a very important significance on the development of ramjet and the test of the thermal stress and strength of supersonic aircraft.

In the HTGTS, aviation kerosene is burnt in supersonic airflow, and the high temperature gas about 2100K is produced, then the simulation of high-temperature and large heat flux density in the stagnation region of the specimen can be achieved by acting high temperature gas on the specimen. There is no doubt that the fuel supply system is one of the most important subsystems in the HTGTS,
and the accurate control of the fuel flow-rate is the premise to guarantee the normal work of the HTGTS. Therefore, this paper analyzes the characteristics of fuel supply system, and designs a suitable control algorithm to realize the accurate control of fuel flow-rate have important practical significance on the study of supersonic combustion law and the test of the thermal stress and strength of supersonic aircraft.

For the flow-rate control strategy, the fuel supply system of the HTGTS is a system which has some characteristics such as time delay, time-variant parameters, interference and so on, and a accurate mathematical model is hardly to be established because of the existence of motor and the influence of the pure time delay which caused by the flowmeter and the long pipeline. Therefore, the research on the control strategy of the fuel flow-rate involves the study of the control strategy of the system which has time delay and time-variant parameters. Time delay is a common problem in many practical control systems, especially in the process control system. From the principle of automatic control, it can be known that the existence of time delay is very bad for the control system, which can reduce the adaptability of the controller or even fail; resulting in decreased the stability of the control system and even makes the system unstable. Therefore, how to control the system with time delay effectively is become a big difficult problem in the field of control. In recent decades, in order to solve this problem, many scholars have carried out a lot of theoretical and practical researches. Many control methods are proposed to solve this problem, and some constructive results are obtained. These methods mainly include Smith predictor and Dalin algorithm [1-2], model prediction algorithm [3-4], sliding mode control algorithm [5-6], robust control algorithm [7-8], and intelligent control algorithm [9-10].

In this paper, according to the problems such as time delay, time-variant parameters, interference and so on exist in the fuel supply system, the Fuzzy PID predictive is designed to realize the accurate control of the fuel flow-rate, and the simulations are carried out by using the control algorithms designed in this paper. The rest of the paper is as follows: ‘System descriptions and mathematical model’ section introduces the working principle of the fuel supply system and provides mathematical model of the system. The Fuzzy PID predictive control algorithms are designed and the simulation results are carried out in ‘control strategy and simulation’ section. ‘Conclusions’ section summarizes the main conclusions of the paper.

2. System descriptions and mathematical model

2.1. System descriptions
Due to the range of temperature control in the HTGTS is larger (200-1700℃), therefore, the fuel flow-rate must be adjusted in a wide range, and the adjustable range of the fuel flow-rate is about 0.2 L/min to 6.67 L/min. In order to meet this requirement, this paper presents a complex flow-rate control solution in the design of the fuel supply system. Namely uses variable frequency pump to achieve the control in case of large flow-rate is required, and uses proportional throttle valve to achieve the control in case of small flow-rate is required. In this way, it is possible to ensure that achieve the wide range regulation of flow-rate in the case of minimizing the loss of system energy.

The principle of the fuel supply of the HTGTS is shown in figure 1; it can be seen from figure 1 that it consists of the fuel supply subsystem and the control subsystem. The fuel supply subsystem includes two fuel circuits; the main fuel circuit and the secondary fuel circuit. Each fuel circuit consists of variable frequency driver (VFD), motor, pump, proportional valve, pipelines, solenoid valves, gear flowmeter (GF), etc. It adjusts the flow-rate of the aviation kerosene feeding to the combustor. The control subsystem adopts high reliability programmable logic controller (PLC) as field controller and industrial personal computer (IPC) as remote controller. PLC is used to carry out the functions of starting and stopping of the pump group, pollution alarm and pressure, level monitoring, etc; IPC is used to realize the control algorithm and the precise control of fuel flow-rate.
2.2. Mathematical model

Because the structure and working principle of the two fuel circuits are identical, so it only need to establish the mathematical model for one of the fuel circuits, and here the main fuel circuit is chosen. In addition, the fuel supply system is mainly work in pump-control mode. Therefore, this paper establishes the model and discusses the flow-rate control strategy in pump-control mode.

It can be seen from the working principle of the fuel supply subsystem that the model of the fuel supply subsystem includes VFD, motor, fixed volumetric pump and fuel circuits. The transfer function between the fuel flow-rate $q$, and the VFD input voltage $u$ can be obtained by referring literature [11].

\[
G(s) = \frac{q(s)}{u(s)} = \frac{b_0}{a_2 s^2 + a_1 s + a_0} \tag{1}
\]

where

\[
b_0 = \frac{1}{60} K_i K_f K_m D_p \\
a_2 = \frac{\pi}{30} J_t C_p L \\
a_1 = \frac{\pi}{30} J_t + K_3 L + \frac{\pi}{30} J_t C_p R + C_p L (K_3 + \frac{\pi}{30} B_t) \\
a_0 = 0 + C_p R_0 (K_3 + \frac{\pi}{30} B_t) + K_3 R
\]

\[
K_1 = \frac{3 m_p}{2 \pi R_m} K_i; \quad K_2 = \frac{m_p^2}{40 \pi R_m}; \quad K_3 = \frac{D_p^2}{120 \pi \eta_m}; \quad R = R_e + R_h;
\]

As the gear flowmeter in the actual system has a time delay with $\tau$ seconds, the actual flow-rate $q_{in}$ obtained in the controller lags behind the theoretical flow-rate $q_t$. It can be expressed as

\[
q_{in}(s) = q_t(s)e^{-\tau s} \tag{2}
\]

![Diagram](image)

**Figure 1.** The principle of the fuel supply of the HTGTS.

| Table 1. Model parameters of fuel supply subsystem |
|-----------------|-------|-----------------|-------|
| Symbol          | Value | Symbol          | Value |
| $\rho$ (Kg $\cdot$ m$^{-3}$) | $7.8 \times 10^2$ | $R$ / $\Omega$ | $7.56$ |
| $J_t$ (kg $\cdot$ m$^2$)     | $0.054$ | $l$ / m        | $12$  |
| $B_t$ (N $\cdot$ m $\cdot$ s $\cdot$ rad$^{-1}$) | $0.045$ | $d$ / m        | $0.01$ |
| $C_p$ (m$^3$ $\cdot$ Pa $\cdot$ s$^{-1}$)   | $9.25 \times 10^{-11}$ | $C_\delta$ | $0.6$ |
| $\mu$ (N $\cdot$ s $\cdot$ m$^{-2}$) | $2.34 \times 10^{-3}$ | $m_p$ | $3$ |
| $D_s$ (m$^3$ $\cdot$ r$^{-1}$)    | $21.1 \times 10^4$ | $\eta_m$ | $0.87$ |
| $A_i$ / m$^2$                  | $8.478 \times 10^6$ | $\tau$ / s    | $3$   |

Chose the model parameters listed in table 1, and took them into the equation (1) and corrected the time constants according to large inertia of the flowmeter in the actual system, and then turned unit of the flow-rate to L/min, so the open-loop transfer function of flow-rate can be obtained.

\[
G(s) = \frac{1155}{1.24s^2 + 680s + 617} \tag{3}
\]
3. Control strategy and simulation

3.1. Calculation of fuel flow-rate
Because the accurate control of fuel flow-rate is to achieve precise control of the gas temperature of the system, it is necessary to determine the setting value of the fuel flow-rate according to the target temperature, that is, to get the input value of the fuel flow-rate control system. According to the working principle of the system, the demand of the fuel flow-rate is closely related to the gas target temperature, the air flow-rate value, the inlet temperature and the combustion efficiency. Therefore, the approximate setting value of fuel flow-rate can be determined according to the above parameters, and then the adjustment can be made according to the actual situation. The calculated formula of the setting value of fuel flow-rate can be obtained by reference [12]. It can be expressed as

$$m_f = \frac{m_a(t_{i_a} - t_{i_0})}{\eta_i H_s - H_f + H_0} \quad (4)$$

where $m_a$ is the air flow-rate; $t_{i_a}$ is the inlet air enthalpy; $t_{i_0}$ is the outlet gas enthalpy; $\eta_i$ is the combustion efficiency; $H_s$ is the calorific value of the fuel; $H_f$ and $H_0$ is the isothermal combustion enthalpy difference.

3.2. Fuzzy PID predictive control
The Fuzzy PID predictive (LevFuzzyPID) algorithm is a compound algorithm which integrates the advantages of Fuzzy algorithm, PID algorithm and predictive algorithm. The basic principle of the LevFuzzyPID algorithm is that improves system’s robustness by using Fuzzy algorithm, improves system’s steady state precision by using PID algorithm, eliminates system’s time delay by suing predictive algorithm, so as to reach a satisfactory control effect. The LevFuzzyPID algorithm is implemented in three steps. In the first step, a Levinson predictor is designed to determine the output value of the future $d$ steps from the historical data of the process output. Next, the error is computed by comparing the predicted value that is fed back against the reference signal. Based on the computed error and the PID gain parameters that are updated by the fuzzy algorithm in real time, the final step determines the output of the PID algorithm. In literature [13], the author has made a detailed introduction of LevFuzzyPID algorithm, this paper will not repeat it, and only uses it to achieve the accurate control of fuel flow-rate.

Takes the model of fuel flow-rate which presented in the above section as the control simulation object, the simulation studies are carried out by using the PID algorithm, the Fuzzy PID algorithm and the LevFuzzyPID algorithm respectively in MATLAB. In simulation, the control cycle is 1s, the input of the controller is the step signal of 2.5L/min, the predictive step of the LevFuzzyPID algorithm is 5, the order number of Levinson predictor is 6, the optimum predictive parameters are \{1.1159, 1.1159, 0.0826, 1.1159, 0.0826, 0.00086\}. In order to compare the simulation results of three algorithms, the simulation results of three control algorithms were drawn on a same figure 2 as shown in figure 2. It can be seen from figure 2, a larger overshoot, about 15% is appeared when conventional PID algorithm is used because of there is pure time delay in the system, and the overshoot is much larger than the overshoot which in the other two control algorithms. In addition, the adjusting time of the PID algorithm is about 30 s, which is slower than the adjusting time of Fuzzy PID algorithm and LevFuzzyPID algorithm. It can be also found in figure 2 that the adjusting time of LevFuzzyPID algorithm and Fuzzy PID algorithm has small difference, is about 15 s and 18 s respectively, but there are overshoot in the system when Fuzzy PID algorithm is used, because the effect of prediction, LevFuzzyPID algorithm can effectively overcome the adverse impact of the time delay on the controlled object, and realize the fast, without overshoot control of fuel flow-rate. In short, the LevFuzzyPID algorithm has gotten a satisfactory control effect, and its control quality is better than conventional PID algorithm and Fuzzy PID algorithm.
Simulation comparative results are carried out by using conventional PID algorithm, Fuzzy PID algorithm and LevFuzzyPID algorithm respectively in the case of the pure time delay in system is increased from 3s to 5s and other simulation conditions are not changed, as shown in figure 3. It can be seen from figure 3, the increase of the time delay can cause the system appears larger overshoot, the overshoot of the conventional PID algorithm is about 36%, the overshoot of Fuzzy PID algorithm is about 30%, the overshoot is the smallest when the LevFuzzyPID algorithm is used, and the overshoot is about 23%. It can be seen that in the ability to overcome the pure time delay, the performance and quality of the LevFuzzyPID algorithm is superior to the conventional PID algorithm and Fuzzy PID algorithm.

Figure 3. Simulation comparative results when pure time delay changed.

In order to compare the anti-disturbance capability of the three algorithms, 0.2V voltage disturbance is added to the system at 40s in the simulation and other conditions are not changed. Simulation comparative results are carried out by using conventional PID algorithm, Fuzzy PID algorithm and LevFuzzyPID algorithm respectively, as shown in figure 4. It can be seen from figure 4 that the three control algorithms have the ability to suppress disturbance, namely when a disturbance is added, the overshoot is appeared, and the system is restored to normal after a period of time. But the overshoot of the system by using LevFuzzyPID algorithm and Fuzzy PID algorithm is less than the overshoot of the system by using conventional PID algorithm, and the recovery time of the system by using LevFuzzyPID algorithm and Fuzzy PID algorithm is quicker than the recovery time of the system by using conventional PID algorithm. It can be known that the Fuzzy PID algorithm and LevFuzzyPID algorithm are superior to the conventional PID algorithm in the ability of anti-disturbance.
Figure 4. Simulation comparative results when disturbance is added.

In order to verify the ability of the controller to overcome the time-variant parameters,Simulation comparative results are carried out by using conventional PID algorithm, Fuzzy PID algorithm and LevFuzzyPID algorithm respectively in the case of the model parameter $a_1$ of the system is increased from 680 to 1200 and other conditions are not changed, as shown in figure 5. It can be seen from figure 5 that when model parameter of the system is increased, the overshoot of the system is increased. When the PID algorithm is used, the maximum overshoot is about 20%, and the overshoot is about 5% when the Fuzzy PID algorithm is used, and the overshoot is about 1% when the LevFuzzyPID algorithm is used. It can be known that the LevFuzzyPID algorithm is superior to the conventional PID algorithm and Fuzzy PID algorithm in the ability to overcome time-variant parameters.

Figure 5. Simulation comparative results when model parameter is changed.

4. Experimental result
Takes the fuel flow-rate of the fuel supply system as control target and the experimental result is carried out by using the traditional incremental PID control algorithm, FuzzyPID and LevFuzzyPID algorithm, respectively. In the experiment, firstly, the fuel flow-rate was adjusted to 2.0L/min, then the fuel flow-rate was set to 2.5 L/min, and the experimental result was obtained.

In order to compare the experimental results which carried out by using various algorithms more intuitive, the experimental results with different algorithms were drawn on the same figure. Figure 6 is the comparison of experimental results of PID, FuzzyPID and LevFuzzyPID algorithm; the results show that the control effect of the LevFuzzyPID algorithm is much better than the control effect of PID algorithm and FuzzyPID algorithm. Namely overshoot of the system by using PID algorithm and FuzzyPID algorithm are 20% and 12% respectively, but there is no overshoot in the system by using LevFuzzyPID algorithm.
Figure 6. The experimental comparative results of PID, FuzzyPID and LevFuzzyPID.

5. Conclusions
This paper introduces the fuel supply principle of a high-temperature gas trial system, and gives the mathematical model of the fuel supply system. According to the problems such as time delay, time-variant parameters, interference and so on exist in the fuel supply system, the LevFuzzyPID control algorithms are designed to realize the accurate control of the fuel flow-rate. On this basis, the simulations are carried out by using the control algorithm designed in this paper. It can be seen from the simulation results, the LevFuzzyPID algorithm is superior to the conventional PID algorithm and FuzzyPID algorithm in aspects of the ability to overcome time delay, time-variant parameters and interference. It can be seen from the experimental results, the experimental results are in agreement with the simulation results, which verify the validity of the simulation. When uses the LevFuzzyPID algorithm to achieve the control of the fuel flow-rate, the control effect is the best, FuzzyPID algorithm are followed, and PID controller is the worst. Namely, there is no overshoot when LevFuzzyPID algorithm are used, but the overshoot is 12% when FuzzyPID algorithm is used, and the overshoot is 20% when PID algorithm is used.

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