Original Research Article

Research on engine speed control based on Tuna Swarm Optimization

ABSTRACT

Accurate control of engine speed can effectively improve fuel economy and comfort. Currently, the commonly used PID parameter setting methods for engine speed control include Ziegler-Nichols method and gradient method, etc. Although they have good performance in parameter setting, they still have shortcomings such as slow response to the control process and long stability time. In this paper, the tuna swarm optimization is used to adjust the PID parameters, and the optimized results are compared with the traditional setting results. The experimental results show that under the same test conditions, the response speed can be reduced by 3.2-6.2s, the maximum overshoot can be reduced by 0.5%-5%, and the maximum steady-state error can be reduced by 0.6%-0.8%.The tuna swarm optimization has an obvious effect in PID parameter optimization of engine speed control, which provides a theoretical basis for the application of other group optimization algorithms in PID parameter optimization of engine speed control.

Key words: Tuna swarm optimization, speed control, PID，internal combustion engine

1. INTRODUCTION

Precise control of engine speed can effectively improve fuel economy, reduce pollutant emissions, and obtain a better driving experience. However, in the process of engine operation, influenced by fuel characteristics and working condition changes and other factors, the engine speed will usually fluctuate greatly, which has a great impact on driving experience and fuel consumption. Therefore, how to achieve accurate control of engine speed is the focus of engine control system research.

At present, PID control and adaptive control are commonly used in engine speed control[1],predictive control[2],sliding mode variable structure control[3]and so on. Adaptive control, predictive control and sliding mode variable structure control are better when the control system is relatively simple, and the reliability and stability of the practical application will decrease with the complexity of the control system. However, the engine speed control system is very complex, and the reliability and stability of the control algorithm are very high, so PID control is still widely used in the practical application.

PID control has the advantages of simple principle, easy to implement, wide application, independent control parameters, simple parameter selection, convenient adjustment and so on. And in theory, it can be proved that PID controller is an optimal control for the typical process control objects ——"first-order lag + pure lag" and "second-order lag + pure lag" control objects. PID regulation is an effective method for dynamic quality correction of continuous system. Its parameter setting method is simple and its structure change is flexible (such as PI adjustment, PD adjustment, etc.). For a long time, PID controller has been used by the majority of technical personnel and field operators, and has accumulated a lot of experience.

The performance of PID control is directly related to the optimization and setting of proportion, integral and differential coefficients. Currently, the commonly used PID parameter setting methods include Ziegler-Nichols method and gradient method, etc. Although they have a good performance in parameter setting, However, there are some shortcomings such as strong dependence on worker experience, sensitivity to initial value, slow response to control process, long stability time and the need for a lot of calibration to determine PID parameters[4-7].With the deepening of the research of swarm intelligence algorithm in recent years, more and more swarm intelligence algorithms have been applied in the process of PID parameter optimization. Therefore, it is of great significance to study modern intelligent PID control. Through the research and analysis of different group intelligent optimization algorithms. In this paper, the tuna swarm optimization is used to optimize the fractional PID parameters in the closed- loop control of engine speed.

2. TUNA SWARM OPTIMIZATION

2.1 Algorithm Overview

The tuna swarm optimization (TSO) was proposed by Lei Xie et al in 2021.Inspired by the cooperative foraging behavior of natural tuna populations, TSO mainly includes spiral foraging and parabolic foraging. The tuna swarm optimization has the characteristics of fast convergence speed and high accuracy in the single objective problem, which has been applied to many industries, but there are relatively few researches on PID parameter optimization.

2.2 Principle of algorithm

2.2.1 Algorithm initialization

As a kind of swarm algorithm, tuna swarm optimization algorithm is similar to other swarm optimization algorithms. It starts the optimization process by uniformly and randomly generating initial populations in the search space. The mathematical formula (1) of tuna swarm optimization algorithm initialization is as follows.

$$X_i^{\mathrm{int}} = rand \cdot (ub - lb) + lb,\ i = 1,2,\cdot\cdot\cdot,NP \qquad (1)$$

Where, X_i^{int} is the initial position of the ith individual, ub and lb is the upper and lower bound of the search space respectively. This boundary condition can be set in the program, NP is the number of tuna population, which can also be set in the program. This value mainly affects the optimization speed of the tuna population optimization algorithm, and is a random vector in uniformly distributed [0,1].

2.2.2 Spiral foraging

Spiral foraging is one of the main foraging methods of tuna schools, which chase prey by forming tight spirals. In addition to chasing prey, schools of tuna exchange information with each other. Each tuna is sequenced and closely connected, so neighboring tuna can share information with each other. Based on the above principles, the mathematical formula (2) of spiral foraging strategy is as follows:

$$X_i^{t+1} = \begin{cases} \alpha_1 \bullet \left(\mathrm{X}_{\mathrm{best}}^{\mathrm{t}} + \beta \bullet \left| X_{best}^t - X_i^t \right|\right) + \alpha_2 \bullet X_i^t, \ i = 1, \\ \alpha_1 \bullet \left(\mathrm{X}_{\mathrm{best}}^{\mathrm{t}} + \beta \bullet \left| X_{best}^t - X_i^t \right|\right) + \alpha_2 \bullet X_{i-1}^t, \ i = 2,3,\cdots NP, \end{cases} \tag{2}$$

$$\alpha_1 = a + (1 - a) \bullet \frac{t}{t_{\max}}, \tag{3}$$

$$\alpha_2 = (1 - a) - (1 - a) \bullet \frac{t}{t_{\max}}, \tag{4}$$

$$\beta = e^{bl} \bullet \cos(2\pi b), \tag{5}$$

$$l = e^{3\cos(((t_{\max} + 1/t) - 1)\pi)}, \tag{6}$$

X_i^{t+1} is the ith individual of the t+1 iteration, $\mathrm{X}_{\mathrm{best}}^{\mathrm{t}}$ is the current best individual (food), α_1 and α_2 is the weight coefficient controlling the movement trend of the individual to the best individual and the previous individual, a is a constant, used to determine the extent to which the tuna follows the best individual and the previous individual in the initial stage, t indicates the current number of iterations, $t_{\max}$ indicates the current number of iterations. b is a random number evenly distributed between 0 and 1. When the optimal individual cannot find food, blindly following the optimal individual foraging is not conducive to group foraging. Therefore, in order to enable each individual to have better spatial search capabilities, a reference point for spiral search needs to be provided to generate a random coordinate in the search space, thus enabling TSO to have better global exploration capabilities. The specific mathematical model (7) is described as follows:

$$X_i^{t+1} = \begin{cases} \alpha_1 \bullet \left(\mathrm{X}_{\mathrm{rand}}^{\mathrm{t}} + \beta \bullet \left| X_{rand}^t - X_i^t \right|\right) + \alpha_2 \bullet X_i^t, \ i = 1, \\ \alpha_1 \bullet \left(\mathrm{X}_{\mathrm{rand}}^{\mathrm{t}} + \beta \bullet \left| \mathrm{X}_{\mathrm{rand}}^{\mathrm{t}} - X_i^t \right|\right) + \alpha_2 \bullet X_{i-1}^t, \ i = 2,3,\cdots NP, \end{cases} \tag{7}$$

Where, $\mathrm{X}_{\mathrm{rand}}^{\mathrm{t}}$ is a randomly generated reference point in the search space. Tuna swarm optimization are typically explored extensively globally at an early stage, then gradually transitioned to precise local exploitation. Therefore, with the increasing number of iterations, TSO gradually changes the reference point of spiral foraging from random individuals at the beginning to optimal individuals. In summary, the final mathematical model of spiral foraging strategy (8) is as follows:

$$X_i^{t+1} = \begin{cases} \begin{cases} \alpha_1 \bullet (\mathrm{X}_{\mathrm{best}}^{\mathrm{t}} + \beta \bullet \left| X_{best}^t - X_i^t \right|) + \alpha_2 \bullet X_i^t, i = 1, \\ \alpha_1 \bullet (\mathrm{X}_{\mathrm{best}}^{\mathrm{t}} + \beta \bullet \left| X_{best}^t - X_i^t \right|) + \alpha_2 \bullet X_{i-1}^t, i = 2,3, \cdots NP, \end{cases} & if rand \ge \dfrac{t}{t_{\max}} \\ \begin{cases} \alpha_1 \bullet (\mathrm{X}_{\mathrm{rand}}^{\mathrm{t}} + \beta \bullet \left| X_{rand}^t - X_i^t \right|) + \alpha_2 \bullet X_i^t, i = 1, \\ \alpha_1 \bullet (\mathrm{X}_{\mathrm{rand}}^{\mathrm{t}} + \beta \bullet \left| \mathrm{X}_{\mathrm{rand}}^{\mathrm{t}} - X_i^t \right|) + \alpha_2 \bullet X_{i-1}^t, i = 2,3, \cdots NP, \end{cases} & if rand < \dfrac{t}{t_{\max}} \end{cases} \tag{8}$$

2.2.3 Parabolic foraging

Tuna will choose parabolic cooperative foraging in addition to spiral foraging. Tuna form a parabola with the target food as a reference to the Z-point.Tuna find the target food by searching around the parabola. The two foraging methods of tuna are carried out according to probability allocation, and if the probability of choice for both foraging methods is 1/2, both methods are carried out simultaneously, the specific mathematical model is described below.

$$X_i^{t+1} = \begin{cases} X_{best}^t + rand \bullet (X_{best}^t - X_i^t) + TF \bullet p^2 \bullet (X_{best}^t - X_i^t), if rand < 0.5, \\ TF \bullet p^2 \bullet X_i^t, if rand \ge 0.5, \end{cases} \tag{9}$$

$$p = (1 - \frac{t}{t_{\max}})^{(t/t_{\max})}, \tag{10}$$

Where, TF is a random number with a value of 1 or −1.

2.2.4 Tuna swarm optimization flow

In order to find their target prey, tuna usually use two foraging strategies to forage cooperatively. First, an initial population will be randomly generated in the whole search space, and then in the process of continuous iteration, each individual will choose to regenerate the position in the search space according to the probability Z, or randomly choose one of the two foraging strategies. In the whole process of algorithm optimization, each individual of TSO is constantly updated and changed, and finally reaches the optimal result, and then returns the optimal individual after optimization and the corresponding fitness value. The flow chart of the algorithm drawn according to the characteristics of spiral and parabolic foraging of tuna is shown in Figure 1.

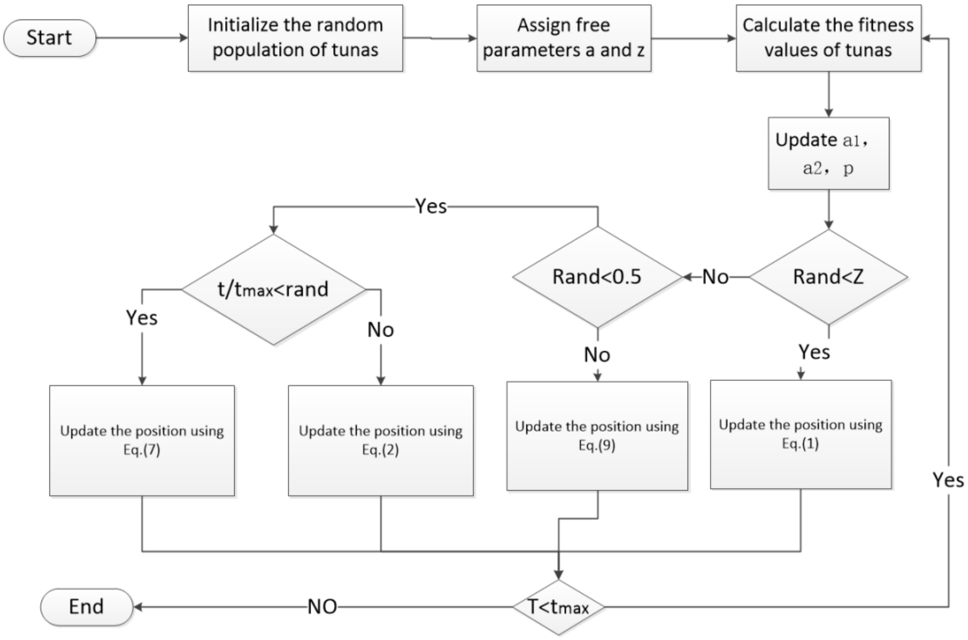


FIG. 1 Tuna swarm optimization flow chart

As shown in Figure 1, first of all, the random population of tuna ($i = 1,2,3,\cdots NP,$) is initialized and the free parameters a and z are assigned, when ($t < t_{\max}$) , calculate the fitness value of tuna, update the position of X_{best}^{t} , α_1 α_2 , p , if ($rand < z$) Then, formula (1) is used to update position X_i^{t+1} ; When ($rand \geqslant$z) and ($rand < 0.5$), if (t/$t_{\max}$ < $rand$), then use formula (7) to update position X_i^{t+1} ,($\frac{t}{t_{\max}} \geq rand$), then use formula (2) to update position X_i^{t+1} ,if ($rand$ ≥0.5), use formula (9) to update position X_i^{t+1} . Finally, the optimal individual X_{best}^{t} is returned to end the optimization process, and the optimal PID parameter value is output.

3. EXPERIMENTAL SYSTEM

3.1 Hardware system

The experimental bench is a 4-cylinder gasoline engine, and the basic parameters are shown in Table 1.The engine controller adopts V-shaped development mode. The development platform is MotoTron 112-pin ECM-5554-112-0904, The platform has a sealed shell design and a better anti-interference circuit design, can work in the ambient temperature -40℃ to +105℃, vibration noise is large in the harsh environment. MotoTron platforms have been tested for humidity, thermal shock, salt spray, solution performance, anti-wetting, electromagnetic interference, mechanical shock, vibration and other professional automotive tests before delivery. They can operate normally in harsh environments and are well suited for engine controller product development in automotive, Marine and non-road applications. which is based on the microcontroller chip MPC5554 developed by Freescale company. The chip is a microcontroller chip specially designed for the development of the engine control system, which can meet the requirements of the engine control system for complex real-time control.

Table 1. Engine parameters

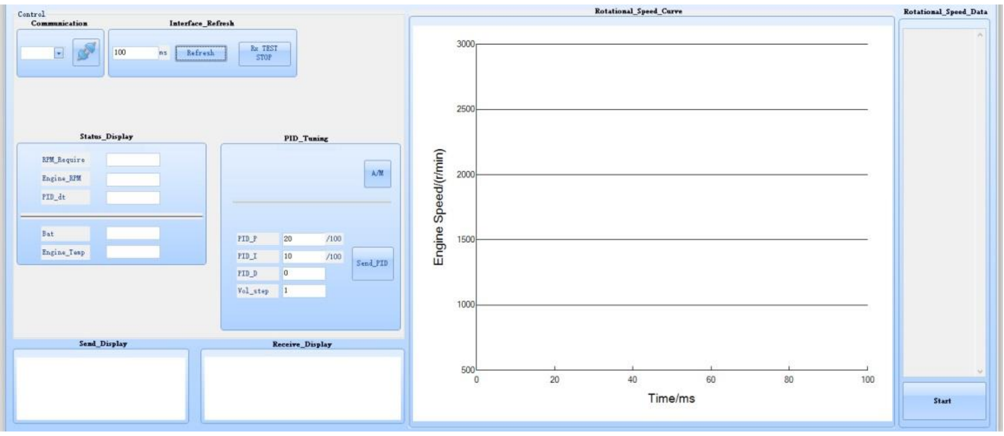
project	parameter
cylinder diameter /mm	75
Stroke /mm	84.8
displacement /L	1.5
compression ratio	10.5
rated power /KW	80
Rated speed/(r/min)	6000
Maximum Torque/(N·m)	140

3.2 Software System

The engine speed closed-loop control program is written using the MatLab/Simulink/Motohawk tool. Motohawk is a fast control system development tool developed by Woodward Company. Based on the MATLAB/Simulink development environment, it allows developers to quickly create control models. The developed control model can be seamlessly connected from the development stage to the finished product stage. Motohawk not only has the advantages of MATLAB/Simulink, such as clear model structure and fine simulation, but also modularizes the function of the engine control system, greatly improving the readability and portability of the control program. Motohawk packages some basic engine functionality into functional modules that developers can invoke to configure the functionality, and the underlying software automatically generates the functional code. Such as engine information and synchronization configuration module (Encoder Definition), CAN send/receive module, Look-up Table module, etc.By calling the function module in Motohawk, calling the hardware interface and communication module, In MATLAB/Simulink combined with logic operation module to develop the control model, so as to achieve the control system development of functional model building, calibration and experimental verification work[8].

3.3 System monitoring software

The monitoring software of this system is developed based on Visual Studio, which can modify the parameters of fractional PID in the closed- loop control of engine speed. The software interface is shown in Figure 2.



Interface_Refresh: 100 ms

PID_P: 20 /100

PID_I: 10 /100

PID_D: 0

Vol_step: 1

FIG. 2 PID parameters modify the upper computer

The communication setting of the upper computer is connected to the computer by USB interface, and the interface is refreshed and set for 100ms. The status display interface can display the target speed and real-time speed in real time, and the data display function is set below. The PID debugging interface can modify the PID parameters in real time, and the speed acquisition function is also set on the right side of the upper computer. It can not only display the speed curve in realtime, but also collect the speed change value.

4.XPERIMENTAL ANALYSIS

4.1 Tuna swarm optimization model simulation test

Write the tuna swarm optimization model based on MatLab/Simlink. First, write the tuna swarm optimization optimization program using MatLab script to initialize the tuna swarm optimization, including the setting of the number of optimization variables, the setting of the size of the tuna group, the setting of the maximum iteration, etc; Secondly, the tuna swarm optimization optimization model is written by Simlink, as shown in Figure 3 below, to determine the transfer function between the optimization objective and the actuator. The accuracy of the transfer function will have a great impact on the quasi determination and feasibility of the tuna optimization algorithm. The optimization objective of this study is the engine speed, and the actuator is the accelerator pedal. In order to make the transfer function obtained more accurate, the calibration is carried out on the engine test bench. The engine bench speed was read by the upper computer, the gas pedal voltage was measured by oscilloscope, and the transfer function was determined by the least square fitting method. Finally, modify the variable name that needs to be passed into the Simlink program in the MatLab script program to keep consistent with the variable in Simlink.

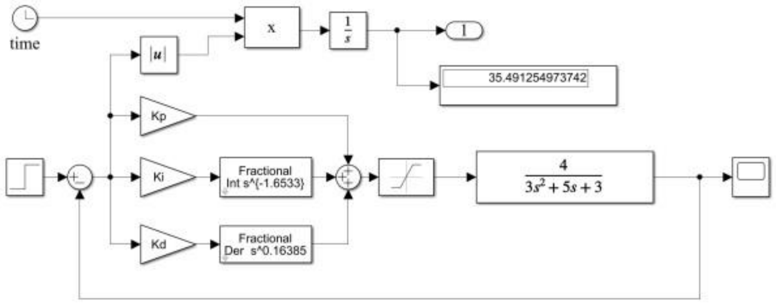


FIG. 3 Tuna swarm optimization model

In order to verify the feasibility of the algorithm, an input signal is given in the tuna swarm optimization model, the initial value is set as 1000r/min, and the final value is set as 1500 r/min, which is used to simulate the process of the engine speed rising from 1000r/min to 1500 r/min. The simulation results are obtained as shown in FIG. 4. At the fourth iteration, the target speed of 1500 r/min has been reached, there is no obvious overshoot and the steady state is good. Therefore, the values of 'P', 'I' and 'D' optimized by the tuna swarm optimization can be used in the closed-loop control of engine speed.

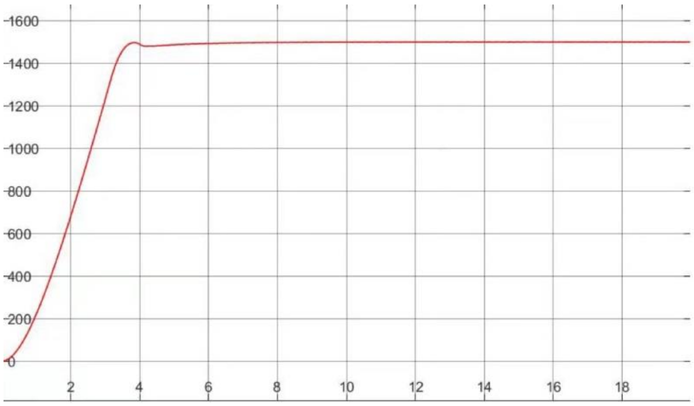


FIG. 4 Simulation results

4.2 Experimental Analysis

The feasibility of tuna swarm optimization in PID parameter optimization was verified by simulation test, and then tested on real engine bench. Through the upper computer input PID parameters obtained by method of gradient and the PID parameters optimized by the tuna swarm optimization, the speed change from the idle speed of 900 r/min first increased to 1200 r/min, then increased to 1500 r/min, and finally decreased from 1500 r/min to 900 r/min. Through the speed acquisition function on the right side of the upper computer, the speed value is collected, and then the speed curve is drawn to directly describe the influence of different PID parameters on the engine speed change process. The speed data obtained through experiments are drawn as shown in FIG.5.

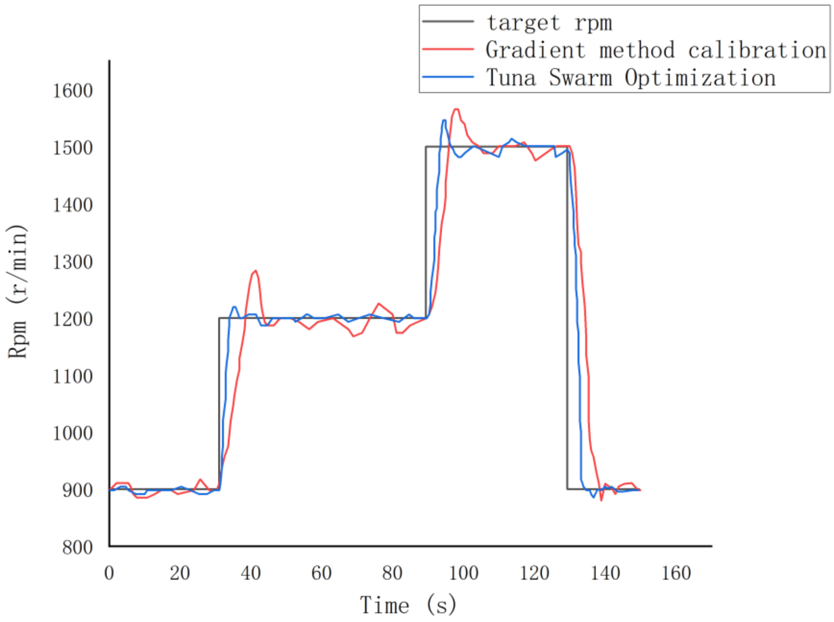


FIG. 5 Result analysis

FIG.5 shows that PID parameters optimized by the tuna swarm optimization have better effects in the engine bench test. When the engine speed increases from 900 r/min to 1200 r/min, the response speed decreases by 5.5s, the maximum overkill decreases from 7% to 2%, and the maximum steady-state error decreases from 2% to 1.2%.When the engine speed increases from 1200r/min to 1500 r/min, the response speed decreases by 6.2s, the maximum overshoot decreases from 4.3% to 3.1%, and the steady-state maximum error decreases from 1.7% to 1.3%.The process in which the engine speed decreases from 1500r/min to 900 r/min reduces the response speed by 3.2s, the maximum overshoot decreases from 2.2% to 1.7%, and the maximum steady-state error decreases from 1.2% to 0.5%.

5.CONCLUSIONS

1. In this paper, the tuna swarm optimization is used to optimize PID parameters, which can effectively solve the shortcomings of traditional PID parameter setting, such as strong dependence on worker experience, sensitivity to initial value, slow response to control process, long stability time and large amount of calibration.

2. Through simulation and experimental tests, it is concluded that the PID parameters optimized by tuna swarm optimization can reduce the response speed by 3.2-6.2s, the maximum overkill by 0.5%-5%, and the maximum steady-state error by 0.6%-0.8% in the practical application, which has a significant effect in the closed- loop PID parameter optimization of engine speed control.

3. This paper proposes to use tuna swarm optimization algorithm to optimize closed-loop PID parameters of engine speed, which can provide experience reference for the application of other swarm intelligent optimization algorithms in the closed-loop PID parameters of engine speed, and expand the application field of swarm optimization algorithm.

REFERENCES

[1] Tomizuka M, Horowitz R. Model reference adaptive control of mechanical manipulators[C]//Proc. IFAC Symp. Adaptive Systems in Control and Signal Proc. 2014: 27-32.

[2] Xiao Lingfei, Huang Xianghua. Adaptive Nonlinear Predictive Control for Turboshaft Engine [J]. Aerodynamics Chinese Journal of Mechanical Mechanics, 2012, 27(5): 1194-1200.Xiao L F, Huang X H. Adaptive Nonlinear Predictive Control for Turboshaft Engines [J]. Journal of Aerospace Power, 2012, 27 (5) : 1194-1200.

[3] Miao San-Guang, Xie Shou-Sheng, Zhang Bo, et al. Adaptive Global Fast Non-Singular Terminal Sliding Mode Control for Aero-Engine [J]. Journal of Aerospace Power, 2013, 28(11): 2634-2640.Miao D G, Xie S S, Zhang B, et al. Aeroengine adaptive global fast non-singular Terminal sliding mode control [J]. Journal of Aerospace Power, 2013, 28(11): 2634-2640.

[4] Li Yue, Sun Jianguo. Multi-objective Optimization PID Control of aero Engine based on Genetic Algorithm [J]. Journal of Aerospace Power, 2008, 23(1): 174-178.Li Y, Sun J G. Multi-objective optimal PID control of Aeroengine Based on genetic algorithm [J]. Journal of Aerospace Power, 2008,23 (1): 174-178.

[5] Li Qiuhong, Sun Jianguo, Zhou Jichao. Improved Genetic Algorithm for PID Control Parameter Optimization of Aero Engine [J]. Journal of Nanjing University of Aeronautics and Astronautics, 2006, 38(2): 162-165.Li Q H, Sun J G, Zhou J C. Improved genetic algorithm for optimization of aeroengine PID control parameters [J]. Journal of Nanjing University of Aeronautics and Astronautics, 2006, 38 (2):162-165.

[6] Li S, Sun J. Application of genetic algorithm to solving nonlinear model of aeroengines[J]. Chinese Journal of Aeronautics, 2003, 16 (2) : 69-72.

[7] Cao Zhisong, Piao Ying. Optimization of Aero Engine PID Control Parameters Based on Hybrid Genetic Algorithm [J]. Journal of Aerospace Power, 2007, 22(9): 1588-1592.

[8] FU Gongrou. Heat pump with methanol fuel engine control system research [D]. University of north China water conservancy and hydropower, 2022. The DOI: 10.27144 /, dc nki. GHBSC. 2022.000513.