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The Internal Combustion Engine Digital Prototype System based on Mountain Climbing Algorithm Design

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Abstract: In the process of highly rapid social development, environmental and energy issues have attracted more and more attention, and the concept of environmental protection and resource conservation has been deeply rooted in the hearts of people. Combustible pollution gas is an important factor causing damage to the environment. Making full use of combustible gas is of great significance to ease the current energy shortage in China, improve the ecological environment and ensure safe production. Therefore, based on the mountain climbing algorithm(MCA), the digital prototype system(DPS) of the internal combustion engine(ICE) is designed and studied in this paper. The ICE is determined as the system control object, its working principle and characteristics are analyzed, and the ICE and the actuating mechanism are respectively modeled according to the system structure. The advantages of the control strategy of this system in the prototype process of ICE are analyzed. By operating the data measured by the prototype terminal module designed, the stability time and speed fluctuation rate of the gasoline engine in the starting process and the switching process between adjacent speed ranges are obtained. The results show that the system has good steady-state performance.

1. Introduction

The use of combustible waste gas for power generation is realized by driving the generator with the gas engine, so the speed of the gas engine directly affects the frequency and quality of power generation. In view of the phenomenon that the air source concentration is unstable, it is necessary to introduce a prototype system to adjust the actual speed so that it can react in a timely manner according to the changes in the air source concentration and displacement, automatically adjust the intake volume of the valve according to the speed changes, and reduce the inlet valve opening when the speed is large; When the speed is low, increase the opening of the intake valve to minimize the influence of the change of the gas source on the speed. The speed after being adjusted by the prototype is stabilized within a certain range, so that the quality of the power generated reaches the standard. In a word, the prototype performance determines the utilization effect of combustible gas. In order to carry out systematic research, the research on the DPS of ICE is a basic part of the utilization of combustible gas, which is essential for the entire research process. This paper designs the DPS of ICE based on the MCA [1].

In the production process of some industries, a large amount of combustible waste gas will be produced. While the emission of these gases pollutes the environment, there is also a potential explosion hazard. The use of combustible waste gas for power generation depends on the gas turbine driving the generator. However, in the actual production process, the discharge and concentration of waste gas are irregular. If these unstable gases are directly supplied to the gas engine as the gas source, it will inevitably lead to unstable speed, and the power generation frequency and quality cannot meet the standard [2]. In view of this situation, the prototype system is designed to regulate the speed of the gas turbine, so that the speed is still stable within a certain range when the gas source concentration is constantly changing. Due to the large volume of the gas turbine unit and the constraints of laboratory conditions, small and medium-sized ICEs with many similarities with its structure are used to replace it. The focus of work is placed on the design of the prototype to study the prototype system of the ICE as a staged test of exhaust gas power generation technology [3].

The role of prototype system is to stabilize the speed of the controlled object within a certain range, but the concentration of exhaust gas source changes randomly, which is equivalent to that the load of ICE is constantly changing. In order to meet the demand of system speed stabilization, it is necessary to control the speed. There are three main prototype modes: automatically adjusting fuel supply with load change; changing ignition advance angle; The two methods are used together. Due to the complexity of the prototype mode involving ignition angle, the MCA is selected as the prototype control mode in this paper. The running state of machinery under various load conditions is called working condition, which is expressed by the effective power and speed generated at that time. After observing a series of running state indicators of the ICE, it can be judged whether it is running in a steady state. If the performance indicators remain stable, it is currently in a stable running state, that is, the machine is currently running in a steady state [4-5].

2. ICE DPS

2.1. Working Characteristics and System Mathematical Modeling of ICE

The reason for taking the single cylinder two-stroke ICE as the experimental object instead of the gas engine is mainly three points: first, the volume of the gas unit is huge, so it is difficult to take the laboratory as the experimental object, while the structure of the single cylinder two-stroke ICE is simpler, with smaller volume and weight; Secondly, in terms of system structure, there are similarities, both of which can be modeled mathematically through the theorem of d'Alembert, etc; For the purpose of experiment, the change of exhaust gas concentration is simulated by suddenly increasing and decreasing the load module at the crankshaft of the ICE, so the stable speed is achieved by controlling the throttle opening of the ICE to simulate the stable frequency 50Hz alternating current generated in the power generation process[6-7].

2.1.1. Working Principle

The first is the intake process. As the name implies, the ICE will suck in the mixture; The second is the compression process, in which the inhaled mixture is compressed, and then the gas temperature and pressure will rise, preparing for the next process; The third is the combustion work process. The temperature and pressure of the mixture increase with the compression process. If the gas is ignited, it will rapidly burn and expand. The internal air pressure rises sharply, pushing the piston to move from top to bottom, driving the connecting rod to move so that the crankshaft rotates, completing the conversion from internal energy to mechanical energy. The fourth process is the exhaust process. The exhaust valve is opened to discharge the burnt exhaust gas, and the piston then returns to the top dead center from bottom to top, resetting the piston for the next intake and completing the work cycle [8].

2.1.2. Operating Characteristics

The role of prototype system is to stabilize the speed of the controlled object within a certain range, but the concentration of exhaust gas source changes randomly, which is equivalent to that the load of ICE is constantly changing. In order to meet the demand of system speed stabilization, it is necessary to control the speed. There are three main prototype modes: automatically adjust the fuel supply with the load change; Change ignition advance angle; The two methods are used together. Due to the complexity of prototype mode involving ignition angle, this paper selects the mode of adjusting throttle opening (automatic fuel supply) as the prototype control mode [9-10].

The running state of machinery under various load conditions is called working condition, which is expressed by the effective power and speed generated at that time. After observing a series of running state indicators of the ICE, it can be judged whether it is running in a steady state. If the performance indicators remain stable, it is currently maintained in a stable running state, that is, the machinery is currently operating in a steady state.

The change of many parameters including ICE and load will directly or indirectly affect the transformation between different working conditions of ICE. When the ICE system is in the same load resistance torque curve state, the greater the throttle opening, the higher the speed, and the torque decreases;

In the actual work of the ICE, the load will often change. When the load increases, the speed of the ICE will decrease. After a dynamic transition process, it will finally reach stability; In the same way, when the load is weakened, the speed must be accelerated. After the transition phase, it will eventually become stable. In the research and daily application of this topic, the fundamental reason why the ICE can not reach a stable speed is that the load is constantly changing, resulting in unstable speed. To solve this problem, prototype system needs to be introduced, which can help the ICE system to reach a stable working state more smoothly and quickly from the transition period. The experiment also proves that the dynamic characteristics of the ICE with prototype system have been significantly improved [11].

2.2 Control Demand Analysis

The prototype system can be seen as a single closed loop control system. The actual speed measured by the speed measurement module in the set speed domain is difference, and the deviation obtained is the input of the controller. Under the influence of the ICE working condition change and sudden load change, the controller needs to select an appropriate control algorithm, output the control quantity, and submit it to the stepping element to adjust the ICE speed, and finally maintain it within the given interval [12-13].

It can be seen from the analysis that the working conditions of the ICE are complex and the parameters of the stable speed transition period change frequently. After mathematical modeling, the system belongs to a high-order control system. Therefore, the selection of control strategy is particularly important. It is necessary not only to meet the requirements of high-order systems for control accuracy, but also to ensure that the system can maintain stability in the case of frequent switching of working conditions and sudden changes in parameters. A prototype strategy with strong robustness, excellent dynamic characteristics and high adaptability is required. The control process is shown in Figure 1.

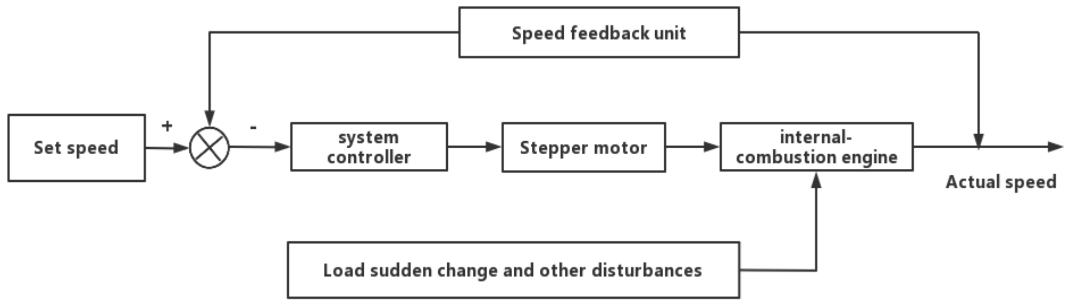

Figure 1. Block diagram of internal computer control system

2.2.1. System Control Strategy Selection

When the ICE starts or stops or the load suddenly changes, a very large speed deviation will occur. The integral accumulation of the prototype system due to excessive output error will lead to a large overshoot. The integral separation PID can cancel and introduce the integral link according to the speed deviation, weaken the excessive overshoot, and improve the system stability [14]. The working state of ICE belongs to a time-varying process, and the real-time change of load is also nonlinear. A set of fixed PID parameters cannot meet the requirements of the whole process. The fuzzy idea is introduced to adjust the correction value of PID coefficient in real time, so as to obtain the value most consistent with the real-time working condition, so that the whole process has better real-time response[15-16].

2.2.2 Digital PID Control

The basic idea of PID control is to take the deviation between the given and the actual quantity as the input, and the three links and their parameters constitute the decision quantity. According to the actual system, the parameters of the three links are linearly combined to complete the adjustment of the passive object. The classic system is shown in Figure 2.

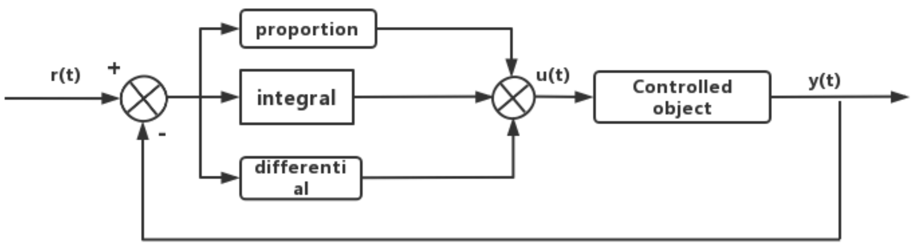

Figure 2. Schematic diagram of classical PID control system

According to the three requirements of "fast, stable and accurate" of the control system, it is necessary to balance the relationship between the three parameters P, I and D, make them cooperate and interact with each other, and set the optimal linear combination to serve the system, so as to meet the control optimization requirements [17-18].

3. Application of Hill Climbing Algorithm to DPS of ICE

3.1. MCA

The MCA can be said to be the most basic and simple optimization algorithm. The variable step size MCA improves the step size on the basis of the traditional MCA Speed disturbance value with variable step size is adopted. Specifically, it is necessary to increase the wind speed when the wind speed changes rapidly.

3.2. Mathematical Model of ICE based on MCA

In the preheating stage, if the load is constant and there is no other disturbance, the ICE will run in a stable condition, and the speed, torque and other performance parameters will reach a stable state. Among its many components, the crankshaft is an indispensable part, which is responsible for converting the force of the mechanical linkage into torque, outputting torque through its own structure, and driving other components to operate. Therefore, when a given load is in a stable state, the crankshaft speed is usually used as an important reference to weigh the mechanical stable working condition. If the load changes or is affected by disturbance, the system resistance torque will change. If the output torque of the ICE cannot maintain balance with the change amount generated by the resistance torque within a certain period of time, a torque difference will occur, which will change the angular speed of the crankshaft. Therefore, when the output torque Ma is equal to the resistance torque Md, it can be maintained in a stable working condition. According to d'Alembert's theorem, the motion equation of the ICE is:

$$J\frac{d\omega}{dt}=N_d-N_c \tag{1}$$

in formula (1), J is the value of the moment of inertia converted to the crankshaft; ω Is the angular velocity of the crankshaft; Md is the output torque of ICE; Mc is the resistance moment. Use Taylor series to calculate the change value of output and resistance moment. In order to facilitate the calculation, according to the minimum deviation mechanism, the second order and above items are omitted. Equation (2) can be written as:

$$T_a\frac{d\varphi(t)}{dt}+T_g\varphi(t)=K_q\beta(t-\delta)-K_\mu\lambda(t) \tag{2}$$

Where, Ta is the acceleration time constant of ICE; φ (t) Is the speed of the ICE; β (t) Is the opening angle of the mechanism for controlling the fuel supply; τ Is ignition delay time of ICE; λ (t) Is an external disturbance; Tg is the self stability coefficient of ICE; K η Is the throttle opening correction coefficient; K μ Is the disturbance correction coefficient. The Laplace transformation of equation (2) is as follows:

$$T_a\phi(s)s+T_g\phi(s)=K_\eta e^{-\tau s}H(s)-K_\mu\Lambda(s) \tag{3}$$

Where, φ (t) Laplace transform for pairs; H (s) is a pair β (t) Laplace transform of.

4. Design of DPS for ICE based on MCA

4.1. DPS Design

The purpose of this topic is to complete the prototype of the ICE through the designed DPS, and then realize the speed stabilization. After selecting the prototype strategy of this system, it is necessary to design a suitable system platform for testing.

The basic idea of the system design is: first, a speed is given, and the speed detected by the speed detection module is different from the given value. The obtained deviation is the input of the system. The control quantity is obtained by using the integral separation fuzzy PID control strategy, which is handed over to the execution module. The throttle opening is adjusted according to the control quantity to achieve the speed adjustment, so that the actual speed is stabilized within the set range. Figure 3 is the prototype system structure block diagram.

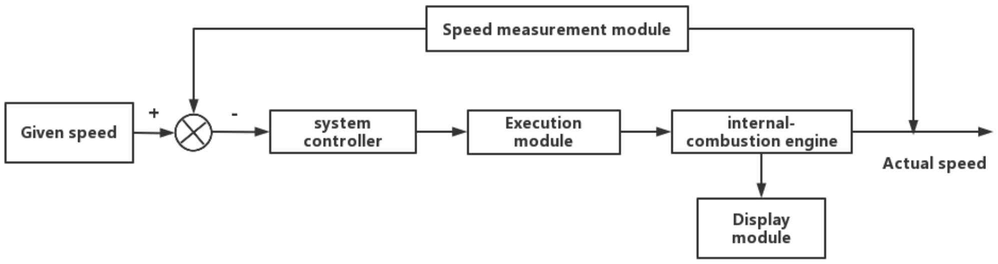

Figure 3. Structure block diagram of speed governing system

4.2. Structural Platform Design

In this paper, 1E34F gasoline engine is selected as the experimental object. 1E34F gasoline engine is often used in mowing and irrigation fields. The main structure is composed of a base plate and two side plates, which are made of solid steel with the intention of increasing the weight to stabilize the gasoline engine. The screw holes on the two side panels can be connected with the original screw holes on the gasoline engine housing. The screws with moderate length and matching hole diameters are used to fit the side panel with the engine body, which not only fix the engine body, but also facilitate disassembly to prevent the internal parts of the gasoline engine from being damaged and cannot be replaced.

The actuator selected in this paper is a stepping motor, and the size of the motor bracket is designed according to the size of the selected stepping motor. The two structures can fit each other. The function of nylon block is to block the rotation of the crankshaft of the gasoline engine. Adding nylon block is equivalent to increasing the load of the gasoline engine. The addition or removal of this module can be used to simulate the disturbance. The tray is used to place nylon blocks. In order to achieve speed detection, a six hole speed code plate is made. The inner side of the code plate is the same as the outer part of the crankshaft. Welding the two together can not only achieve synchronous rotation with the crankshaft to complete speed detection, but also keep the speed code plate at a certain distance from the oil tank to prevent collisions. The L-shaped bracket is the fixed bracket of the speed sensor, which can be fixed by screws. The position of the speed sensing module can exactly correspond to the position of the speed measuring hole after the code plate is welded.

4.3. Experimental Data and Analysis

According to the national machinery industry standards, the prototype performance indicators of gasoline engines used for generators are shown in Table 1.

Table 1. Prototype performance index

Speed regulation performance		Stable speed regulation rate (%)	Speed fluctuation rate (%)	Speed stabilization time (s)
Purpose	General	≤10	≤3	--
	For generator	≤6	≤1.5	≤7

Stable prototype ratio refers to the percentage of the ratio between the difference between the no-load stable speed and the full load steady speed and the given speed when the accelerator is fixed at the calibration position; Speed stabilization time refers to the transition time from the original shape of the system to the given speed; The speed fluctuation rate refers to the ratio of the difference between the maximum speed and the minimum speed measured within a certain time and twice the given speed value. The test of the system is mainly aimed at the steady-state performance index under the condition of no sudden load change, so the research is carried out around the two parameters of speed stability time and speed fluctuation rate.

Due to the high speed of the system, the basic task of speed regulation is to accurately measure the real-time value of the speed. After the oscilloscope measurement, it is found that the speed measurement module can better capture the speed signal. When the speed is 4500r/min, the measured waveform remains normal. Another important part of the prototype process is that the stepping motor operates the throttle cable to adjust the fuel supply. The 28BYJ-48 stepping motor selected for this system has a relatively small volume and torque. I was worried that the torque generated by the rotation is too small to pull the throttle cable, but the actual test found that the torque of this motor is large enough to provide the torque required to drag the throttle cable.

In order to facilitate the analysis, the simulation calculation results and test results of the main performance parameters are further processed to calculate the error between the simulation value and the test value, as shown in Table 2 below.

Table 2. Error between experimental and calculated results (unit:%)

Speed(r/min)	Load(%)	Power(kW)	Fuel consumption rate	Pressure after intercooling	Temperature after intercooling	Exhaust pressure before vortex	Front row temperature of vortex
1300	100	1.024	0.195	1.064	0.314	1.190	0.908
	75	1.021	1.623	1.863	0.633	2.649	0.494
	50	0.463	2.330	3.704	0.977	3.676	4.486
	25	0.932	1.326	3.419	0.984	4.762	1.625
2200	75	0.651	1.703	1.860	1.592	4.583	4.756
	50	1.630	1.873	4.082	0.317	2.232	2.609
	25	0.868	0.910	2.548	0.631	3.825	5.657

It can be seen from the table that the calculation errors of power, fuel consumption rate, intercooling temperature, etc. in the simulation results are small, and their errors are all within 2%; The error of intercooling after pressure, exhaust pressure before turbine and exhaust temperature before turbine fluctuates greatly, but still within 5%. Therefore, the error between the calculated results and the original engine test results is small through test verification, and the simulation model can be used to predict the comprehensive performance parameters of the engine.

5. Conclusion

In order to meet the requirement of working stability of ICE, the research of DPS is indispensable, which will affect the accuracy and rapidity of speed regulation and ensure its safe operation. This paper introduces the development history of prototype and the research status of DPS at home and abroad, analyzes the working principle of ICE and the mathematical model of the system, and selects the appropriate control strategy based on its operating characteristics; Design and build a test platform to complete prototype testing. Finally, the prototype terminal module is designed and tested. Through the operation of the setting button and the gasoline engine, the performance indicators of the gasoline engine in the process of starting and the change of the set speed value are measured, indicating that the steady-state characteristics of the system can meet the requirements. In this prototype system design, because the design of some modules is not reasonable enough and the overall consideration is still not comprehensive enough, the sudden load test has not been realized. In the future experiments, more appropriate ways must be considered to suddenly add and reduce the load on the controlled object.

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Data Availability

Data sharing is not applicable to this article as no new data were created or analysed in this study.

Conflict of Interest

The author states that this article has no conflict of interest.

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