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Development Research of Methanol Fuel Engine Controller for Heat Pump based on MotoTron Platform

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Abstract

This paper develops an engine controller for practical applications based on the demand of the heat pump system for the engine. The controller is based on the MotoTron rapid control prototype platform to realize the rapid development of a methanol fuel engine controller for heat pumps with stable and reliable performance. A control system model was built in the corresponding software design platform Motohawk, and models including air intake control, fuel injection control, ignition control and speed closed-loop control based on adaptive PID algorithm were established. Afterwards, the calibration, functional verification and experimental test of the control system were carried out on the methanol fuel engine test bench. Afterwards, the calibration, functional verification and experimental test of the control system were carried out on the methanol fuel engine test bench. The results show that the developed control strategy has good performance, the engine starting process is stable and reliable, and it can be stabilized in idling conditions within 10s after starting; In the process of speed adjustment, the dynamic response of the adaptive PID algorithm is stable, without large overshoot and fluctuation, the adjustment time is less than 20s, and the speed fluctuation rate is less than 3% after stabilizing at the target speed, and it has good dynamic response characteristics.

Keywords

Engine, Heat-Pump, Control, Rapid Prototype.

1. Introduction

The engine heat pump system is an energy-saving and environmentally friendly air-conditioning device that uses an engine to drive a vapor compression heat pump to provide heating in winter and cooling in summer [1]. It has broad application prospects in the field of building heating and animal husbandry. Compared with conventional electric heat pumps, engine heat pumps have the advantages of making full use of engine waste heat, easy speed regulation, and high energy efficiency.

Methanol has similar physical and chemical properties to gasoline, and because methanol contains 50% oxygen, it can achieve clean combustion. At the same time, methanol can be produced on a large scale using coal as a raw material, with a wide range of raw materials, and the price is much lower than traditional fossil fuels such as gasoline and diesel. Therefore, methanol fuel engines have better emissions and economic benefits than gasoline engines.

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Under the same conditions, the evaporation of methanol fuel is only a quarter of the evaporation of gasoline, and as the ambient temperature decreases, the evaporation performance of methanol will become worse. And because of the lower heating value of methanol, the theoretical air-fuel ratio of methanol is only half that of gasoline. Therefore, it is necessary to develop a dedicated methanol fuel engine controller.

The functions of modern engine controllers are becoming increasingly complex. The V-process, which incorporates advanced technologies such as graphical modeling, rapid prototyping, and automatic code generation, enables R&D personnel to focus on the design of control strategies. The framework construction, model establishment, system testing and other processes in the V-process are all carried out in the same environment. The V-process allows the test link to run through the life cycle of the controller R&D, by using the rapid control prototype platform to effectively verify the function of the program. The R&D personnel can find the defects of the control strategy as early as possible, which can effectively reduce the R&D cost and R&D cycle of the controller.

The MotoTron platform is currently widely used in the field of engine controller development[2-4], but there are few researches on engine controllers for heat pumps. Compared with automobile engines, the characteristics of heat pump engines during operation fluctuate greatly, so it is impossible to directly use automobile engine controllers in heat pump system engine control.

In this paper, based on the MotoTron rapid prototyping platform, a controller for methanol fuel engines for heat pumps is designed and developed, and the controller is verified on the methanol fuel engine test bench for functional verification and control parameter calibration.

2. Heat Pump System of Methanol Fuel Engine

The working principle of the methanol fuel engine heat pump system is shown in Figure 1. The system includes a methanol fuel engine, compressor, evaporator, condenser and expansion valve. In the working cycle, the heat transfer is realized through the change of the refrigerant state.

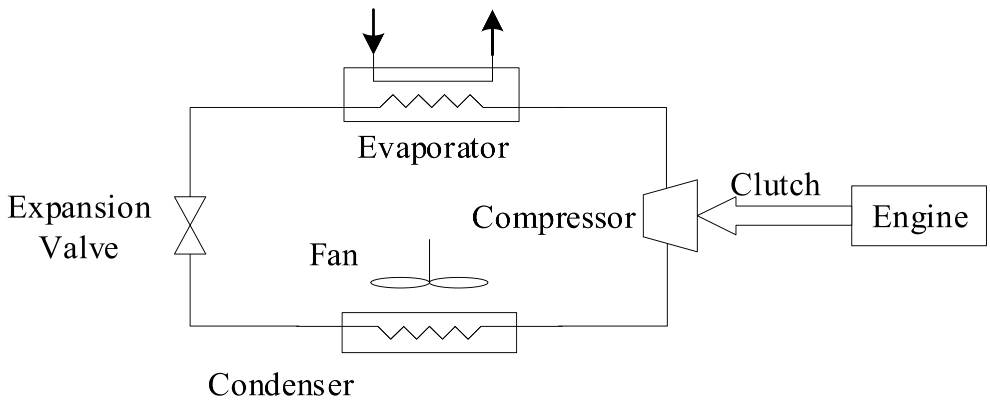

Figure 1. Working principle of heat pump system

The heat pump engine is connected with the heat pump system compressor through a clutch. The engine speed and output power directly determine the working state of the heat pump system.

The control target engine of this system is the DK15C four-stroke PFI gasoline engine produced by Dongfeng Sokon. This engine is a naturally aspirated inline four-cylinder engine. Table provides the Basic parameters of the engine.

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Table 1. Basic parameters of the engine

Item	Content
Bore(mm)	75
Stroke(mm)	84.8
Displacement volume(L)	1.5
Compression ratio	10.5
Rated power(kW)	80
Rated speed(r/min)	6000
Maximum torque (N·m)	140

3. Overall Scheme Design of Control System

The heat pump control system is divided into a heat pump subsystem controller and an engine subsystem controller according to functions, and the two work in coordination.

The heat pump subsystem controller adjusts the compressor working status in real time according to user needs and changes in external conditions. The heat pump subsystem controller calculates and sends the compressor target speed to the heat pump engine subsystem controller, and the heat pump engine subsystem controller adjusts the engine speed in real time.

3.1 The Overall Structure of the Engine Controller

Figure 2 is a schematic diagram of the overall structure of the engine subsystem controller based on the MotoTron platform. The input signal of the engine controller mainly includes the crankshaft position signal, the camshaft position signal, the throttle position signal, the cooling water temperature signal and the lambda sensor signal. The sensor signal is collected through the hardware port and processed by the controller circuit and then input to the microcontroller interface. After the microcontroller calculates and processes the collected sensor signal, it outputs a control signal to the actuator through the drive signal output port. The signal output of the controller includes four-cylinder fuel injection signal, four-cylinder ignition signal, throttle motor drive signal and methanol fuel pump drive signal.

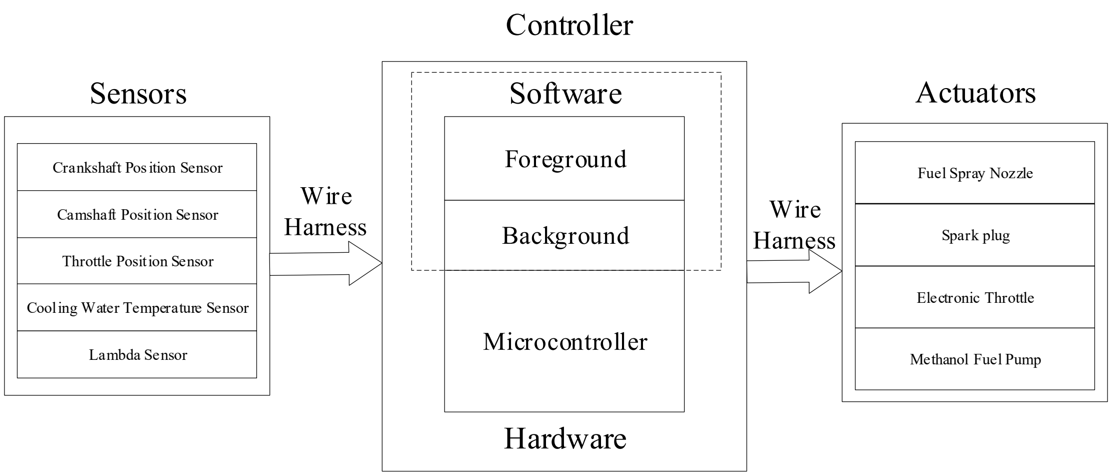

Figure 2. The overall structure of the control system

3.2 MotoTron Platform

This system uses the MotoTron platform 112Pin rapid prototyping controller (ECM-5554-112-0904). This rapid prototyping controller uses Freescale's 32-bit microprocessor MPC5554, with rich

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interface resources, the maximum calculation frequency can reach 80Mhz, and the working voltage is 9-16V. The controller can provide high and low peak current mode peak-hold mode fuel injector drive output, with TTL (Transistor-transistor logic) level ignition drive signal output function. The controller also has three high-speed CAN (Controller Network Area) channel interfaces and one RS-485 serial channel interface.

The rapid prototyping controller based on the MotoTron platform is composed of hardware circuits and software programs. The hardware circuit includes a central processing unit module, a power supply module, an input signal acquisition module, an input signal processing module and an output signal drive module, etc. The software program includes the foreground program and the background program. The background program mainly includes functional modules such as controller model selection, interrupt trigger cycle selection, CAN communication parameter setting and CCP protocol parameter setting, etc. The background program does not allow users to rewrite, and the user can configure the basic software function parameters of the rapid prototyping controller through the corresponding modules. The foreground program is the user's main control strategy program. The system mainly includes working condition judgment, fuel injection control, ignition control and speed closed-loop control.

4. Design of the Control Model

4.1 Model of Working Phase Judgment and Synchronization

The control strategy of fuel injection timing and ignition timing is one of the difficulties in the development of engine controllers. The controller realizes the judgment of the engine working phase by collecting, processing and calculating the crankshaft position signal and the camshaft position signal. The relative position relationship between the crankshaft and camshaft of the controlled engine of this system is shown in Figure 3.

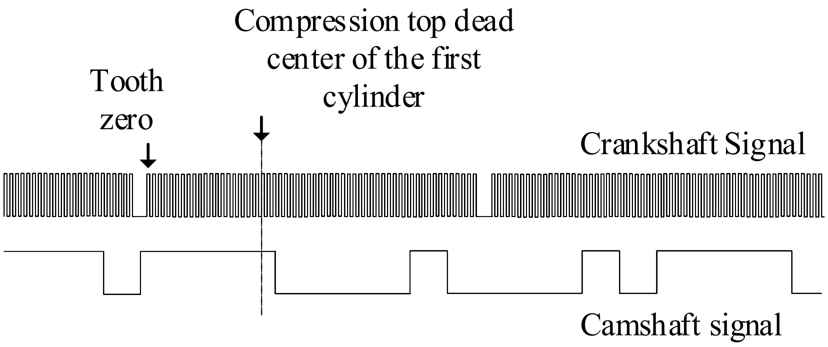

Figure 3. The relative position relationship between the crankshaft signal and the camshaft signal

Motohawk, the programming platform corresponding to the MotoTron rapid prototyping controller, encapsulates the phase determination and synchronization functions in the Encoder Definition module. The user configures parameters such as crankshaft signal type, camshaft signal type, and position compensation angle of compression top dead center in the module. The background program can automatically complete the judgment and synchronization of the engine's working phase.

After setting the signal type of the engine crankshaft and camshaft in the Encoder Definiton module, the synchronization program will use the detected crankshaft tooth missing signal position as the synchronization point according to the configured signal type. The synchronization program detects the phase of the camshaft signal at the synchronization point to determine the top dead center position.

In the Motohawk synchronization program, the synchronization state variable is defined, and the output value of the variable is the synchronization state. Developers can use the Encoder State Get module to read the state variable to the host computer display interface. The synchronization status switch is shown in Figure 4.

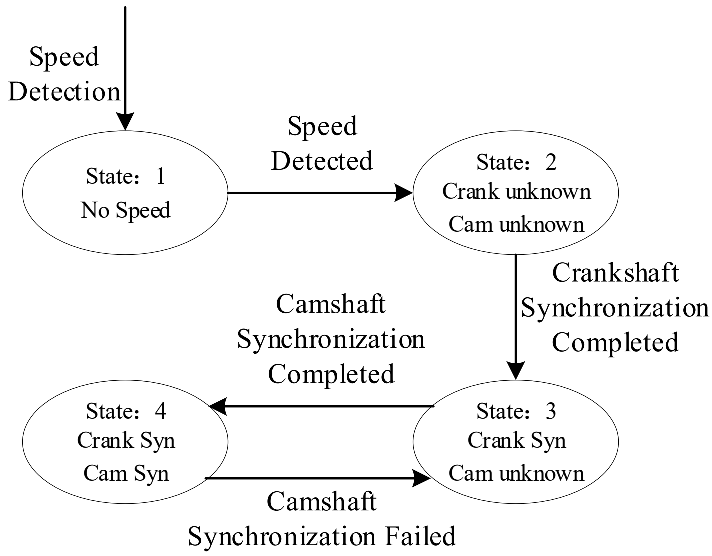

Figure 4. Synchronization algorithm state switching

The Motohawk synchronization algorithm is designed with four states: Zero-speed, Waiting for synchronization, Crankshaft synchronization and Synchronization success.

Zero-speed state, that is, state 1 as shown in the figure. At this time, the controller is in the power-on state, but the speed signal is not detected. Usually, when the engine speed is lower than 60r/min, it is considered that the speed is not detected.

Waiting for the synchronization state, that is, in the state 2 shown in the figure, the algorithm detects the speed signal at this time, but the system has not yet completed synchronization.

The crankshaft synchronization state, that is, the state 3 shown in the figure, the synchronization program has completed the crankshaft synchronization, but the camshaft signal is not detected or the camshaft signal is not synchronized.

In the synchronization state, that is, state 4 as shown in the figure, the crankshaft signal and the camshaft signal are synchronized.

In practical applications, engine control requires high fault tolerance and reliability for the controller's synchronization function. Therefore, the synchronization program stipulates that the state 3 or state 4 is collected in two consecutive cycles before the synchronization is considered successful.

After the synchronization is successful, the controller can control the fuel injection timing and ignition timing according to the crankshaft position signal. The judgment program defaults that the first rising edge (or falling edge) detected after missing teeth is the top dead center position. The actual top dead center position of the engine is 60°CA-120°CA after missing teeth, and the Encoder TDC (Top Dead Center) Offset module needs to be called to set the actual dead center position. After the setting is completed, by inputting the ignition timing to the Spark Sequence module and inputting the fuel injection timing to the Injection Sequence module, the phase judgment program can automatically control the fuel injection ignition timing.

4.2 Judgment of Working Conditions

According to the state requirements of the heat pump system for the engine, the working state of the engine is divided into four types: stop condition (STALL), start condition (CRANK), idle condition (IDLE) and operating condition (RUN).

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The logic of the engine working condition judgment is complicated. Usually, the engine controller uses the accelerator pedal position signal and the speed signal to judge the engine working condition. However, in order to simplify the speed closed-loop control algorithm for the heat pump engine, the accelerator pedal is removed. The controller judges the current working state of the engine according to the engine speed and the demand state signal sent by the heat pump subsystem controller. The engine controller sets the demand state flag StateR through the received demand state signal. The variable values 0, 1, 2, 3, 4 correspond to the demand state stop, start, idle, run and fault respectively. The working condition judgment algorithm judges the current working state according to the value of the demand state flag variable and the current speed. The working condition judgment algorithm is shown in Figure 5.

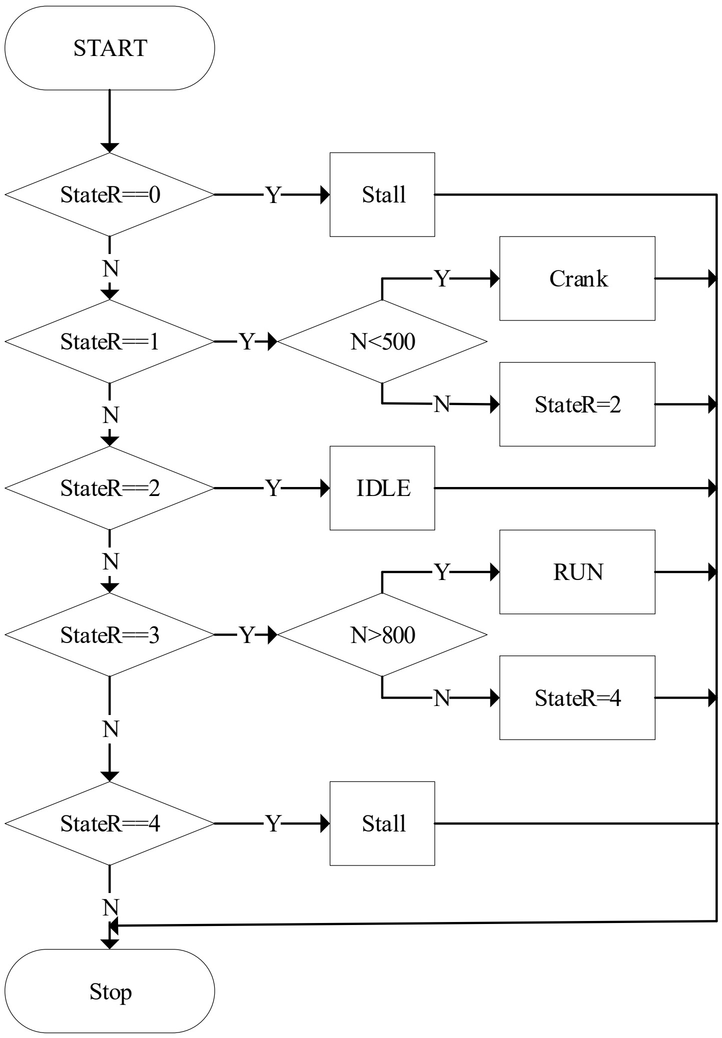

Figure 5. Working condition judgment

Simulink provides a relatively simple Stateflow flow diagram, which can easily and conveniently realize the conversion between the logical relations of the working state of the engine. The Stateflow logic diagram of the engine working state is shown in Figure 6.

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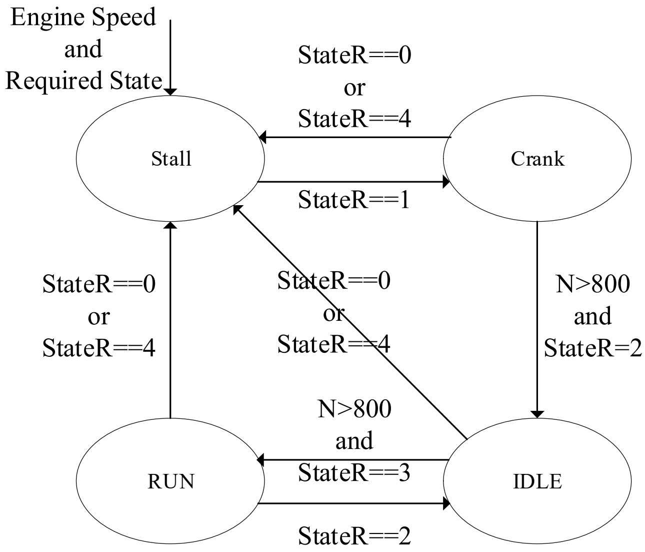

Figure 6. Working condition switching

4.3 Model of Methanol Fuel Injection

Engines have different methanol fuel injection strategies under different operating conditions, which are mainly divided into open-loop control strategies and closed-loop control strategies.

The open-loop control strategy is usually used for start-up conditions. The controller obtains the injection timing and fuel injection quantity by querying the MAP map through the collected speed and intake manifold pressure. The open-loop control strategy is simple in logic, and the system responds quickly, but its accuracy and real-time performance are poor, and it cannot respond to changes in the engine's state in real time.

A feedback system is added to the closed-loop control strategy, and the controller indirectly obtains the concentration state of the mixture in the cylinder according to the collected sensor values. The controller corrects the fuel injection quantity in the next cycle according to the obtained mixture concentration, so that the in-cylinder mixture is closer to the theoretical air-fuel ratio. The closed-loop control strategy is more complex than the open-loop control strategy, but more appropriate control parameters can be selected according to the actual operating conditions to output the control signal, which effectively improves the power and economy of the engine.

The controller calculates the air quality entering the cylinder by collecting the signals of the intake air pressure sensor and the intake air temperature sensor. According to the ideal state equation, the ideal air quality entering the cylinder in the cycle is Equation (1).

$$m_a = \frac{PV\eta}{RT} \tag{1}$$

Where P is the pressure of the intake manifold (Pa); V is the cylinder volume (L); T is the intake temperature (°C); R is the ideal gas constant; η is the charging efficiency (%).

The charging efficiency η represents the ratio of the air mass actually sucked into the cylinder to the gas mass that fills the working volume of the cylinder in the theoretical state. It is related to engine speed and intake pressure, and is obtained by querying the map chart calibrated by the engine test bench.

The air-fuel ratio is the ratio of the mass of air entering the cylinder to the mass of fuel, Therefore, the ideal fuel mass injected into the cylinder can be calculated from the air-fuel ratio A/F as Equation (2).

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$$m = \frac{m_a}{\frac{A}{F}} = \frac{PV\eta}{\frac{RTA}{F}} \tag{2}$$

From this, the basic cycle injection pulse width can be obtained as Equation (3).

$$D_b = \frac{m}{\Delta m} = \frac{PV\eta}{\frac{\Delta mRTA}{F}} \tag{3}$$

The injection pulse width obtained in the above equation is obtained under ideal conditions. In the actual use of the engine, it is necessary to add a correction coefficient to improve the accuracy of control.

The actual injection pulse width D can be calculated by Equation (4).

$$D = D_b(1 + K_{AT} + K_C + K_{AFs} + K_{AFl}) + D_U \tag{4}$$

Where D_b is the basic fuel injection pulse width; K_{AT} is the intake air temperature correction coefficient; K_C is the start-up correction coefficient; K_{AFs} is the short-term correction coefficient of air-fuel ratio closed-loop control; K_{AFl} is the long-term correction coefficient of air-fuel ratio closed-loop control; D_U is the battery voltage correction pulse width.

The air-fuel ratio closed-loop control strategy uses the oxygen sensor signal to feedback control the fuel injection volume. The lambda sensor used by the controlled target engine cannot accurately measure the concentration of the mixture in the exhaust, but indicates the rich-lean state of the mixture through the jump of the signal near the theoretical air-fuel ratio. The adjustment of fuel injection quantity adopts a PI controller-based scheme, The working principle is shown in Figure 7.

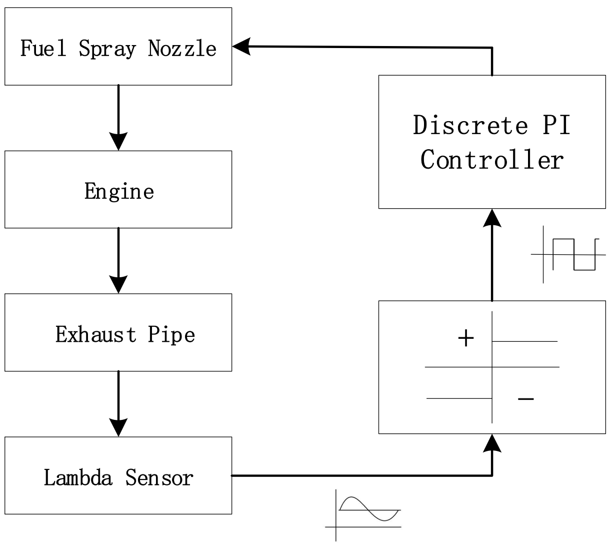

Figure 7. The principle of air-fuel ratio closed-loop control

The feedback signal of the lambda sensor has only two states, suppose the output characteristic of the sensor is:

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$$e(n) = \begin{cases} -1 & V_s > V_{s_r} \\ 1 & V_s < V_{s_r} \end{cases} \tag{5}$$

Where $e(n)$ is the comparison state of the mixture concentration and the theoretical air-fuel ratio; n is the discrete time point label; V_s is the oxygen sensor output voltage; V_{s_r} is the sensor reference level when the mixture concentration is at the theoretical air-fuel ratio[5].

The expression of the short-term correction coefficient K_{AFs} is shown in the Equation (6).

$$K_{AFs} = e(n-1) + K_p e(n) - K_p \frac{\tau_i - T_s}{\tau_i} e(n-1) \tag{6}$$

Where K_p is the constant of proportionality; τ_i is the delay time of system transmission; T_s is the sampling period.

The change of the long-term correction coefficient K_{AFl} of the air-fuel ratio closed-loop control is a qualitative change formed by the control system based on the change of the short-term correction coefficient.When the short-term correction coefficient K_{AFs} cannot return to the vicinity of the zero position within a certain period of time, the control system calculates the long-term correction coefficient under this working condition by weighting the average of the short-term correction coefficients in the period to make the short-term correction value return to zero.

4.4 Model of Ignition Control

The engine adopts a fixed ignition advance angle during the starting process, and the ignition advance angle is corrected according to the cooling water temperature after the engine is successfully started and enters the idling condition. When the water temperature is low, the controller makes a greater correction to the ignition advance angle to overcome the greater frictional resistance caused by the low oil viscosity.

The ignition advance angle under engine operating conditions is open-loop control and is affected by engine speed and intake pressure. The ignition advance angle under running conditions is obtained according to the minimum ignition advance angle when the maximum torque is calibrated under each steady-state operating condition in the engine bench test.

The ignition drive signal can be generated by calling the ignition drive module (Spark Sequence) that comes with Motohawk. The module has two built-in ignition signal control modes: angle control mode and time control mode.

In the angle control mode, the input is the crank angle corresponding to the time when the primary coil is energized and the energizing time, while in the time control mode, the crank angle corresponding to the time when the primary coil is energized and the time when the primary coil is energized are input to the module. The moment of power-off of the primary coil, that is, the ignition advance angle is calculated by the underlying program.

The angle control mode can ensure the accurate control of the energizing time of the primary coil, and it is adjustable. However, in this mode, due to the calculation deviation of the crankshaft angle under the high-speed engine condition, the ignition signal of some cycles may be missing, resulting in the fluctuation of the engine speed. The calculation of the power-off moment in the time control mode is naturally guaranteed by the algorithm, and the deviation of the control of the ignition advance angle is also within the acceptable range, so the time control mode is selected to control the ignition drive signal output.

4.5 Model of Heat Pump System Variable Refrigerant Flow

For the engine heat pump system, when the ambient temperature and system load change, the variable capacity needs to be adjusted in time. The refrigerating capacity of the compressor has a certain proportional relationship with the rotational speed, and the energy loss exists in the traditional adjustment methods such as start-stop, suction throttling and hot gas bypass. Therefore, the capacity adjustment method with variable compressor rotational speed has good economy.

Compared with the capacity adjustment of the electric heat pump, the premise of the variable capacity adjustment of the engine heat pump system is to ensure the effective control of the engine speed under various working conditions. Generally, the engine controller obtains the driver's torque demand according to the accelerator pedal opening signal, and adjusts the electronic throttle opening to control the working speed and output torque of the engine. The accelerator pedal is removed from the heat pump engine subsystem, so the controller adjusts the opening of the electronic throttle according to the demand speed signal sent by the heat pump subsystem controller to complete the closed-loop control of the engine speed.

The controller calculates the required throttle opening according to the difference between the required target speed and the actual speed, and obtains the actual opening through the collected signal of the throttle position sensor. Based on the dynamic difference between the target opening and the actual opening, the controller uses the adaptive PID control algorithm to output the pulse width modulation (PWM) signal in real time to control the opening of the throttle drive motor control valve to achieve closed-loop control of the speed.

During the working process of heat pump engines, the dynamic and static characteristics fluctuate greatly, and the traditional PID control is difficult to meet the control requirements. Therefore, the improved adaptive PID control algorithm is selected for closed-loop control of the speed.

PID controller is a linear controller, based on dynamic error of the controlled object proportional, integral, differential control. The classical position PID algorithm is shown in the Equation (7).

$$u(t) = K_p e(t) + K_i \int e(t)\,dt + K_d \frac{de(t)}{dt} \tag{7}$$

Where K_i is the integral constant; K_d is a differential constant.

The Equation (8) and Equation (9) are incremental PID control algorithm.

$$\Delta u(k) = u(k) - u(k-1) \tag{8}$$

$$\Delta u(k) = K_p\big(e(k) - e(k-1)\big) + K_i e(k) + K_d\big(e(k) - 2e(k-1) + e(k-2)\big) \tag{9}$$

Adaptive PID control algorithm on the basis of incremental PID, by creating adaptive controller real-time tuning PID controller parameters. Equation (10) for parameter self-tuning of adaptive PID controller.

$$\begin{cases} K_p = K_{p_0} + \Delta K_p \\ K_i = K_{i_0} + \Delta K_i \\ K_d = K_{d_0} + \Delta K_d \end{cases} \tag{10}$$

Where K_{p_0}, K_{i_0} and K_{d_0} are the initial values of PID controller parameters; ΔK_p, ΔK_i and ΔK_d are real-time correction values of adaptive controller

The adaptive PID control algorithm is shown in Figure 8.

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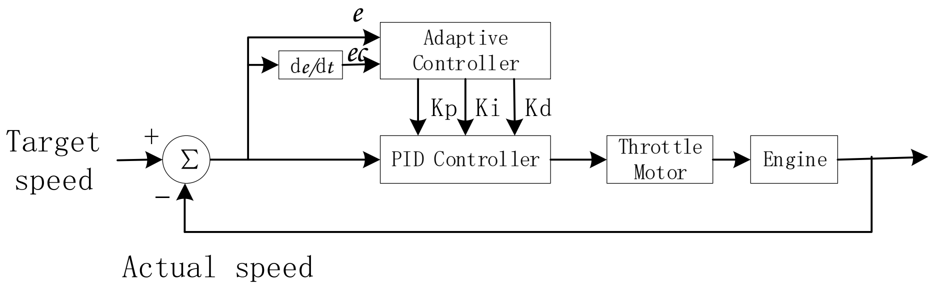

Figure 8. Algorithm of adaptive PID control

5. Functional Verification and Experimental Testing

After many times of algorithm design and optimization, the calibration and experimental test of the control parameters carried out on the modified methanol fuel engine bench.

Engine starting control is a difficult point in engine control strategy, which involves working condition judgment, fuel injection control, ignition control, throttle control and other functions. Figure 9 is the starting test results of engine controller for heat pump. The results show that the engine starts successfully, the initial speed stability is good, and quickly stabilizes to idle speed; Due to the low cooling water temperature, the correction coefficient of cooling water temperature is too large, resulting in a slightly higher idle speed than the normal idle speed; Due to the existence of start-up correction coefficient, the initial injection pulse width is large. After the start-up is successful, the injection volume is well attenuated to the idle oil volume.

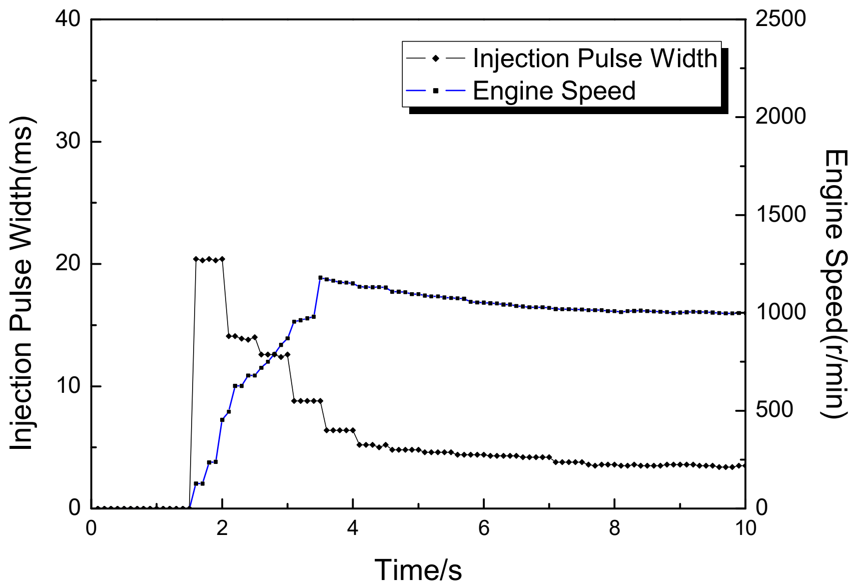

Figure 9. Results of engine start test

The engine for heat pump needs to adjust the speed of the engine in real time during operation to meet the power demand of the heat pump system for the compressor. Figure 10 is the test result of speed control in variable capacity regulation. The results show that after the target speed changes, the engine has good dynamic response characteristics. The adjustment process is less than 20 s, and the speed fluctuation rate after stability is not more than 3 %.

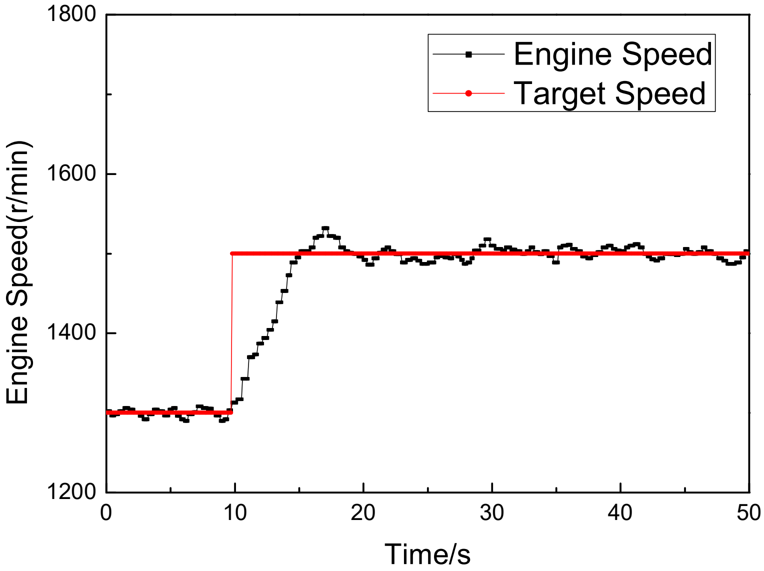

Figure 10. Results of speed adjustment test

6. Conclusion

(1). The control system of methanol fuel engine for heat pump is designed and developed by using the mature hardware and perfect underlying software program provided by MotoTron rapid prototyping platform. The platform has high engineering application value, which can effectively reduce the difficulty of control system development and shorten the development cycle.

(2). The control strategies of the developed control system mainly include synchronization and condition judgment, air intake control, fuel injection control and throttle control. The engine start test shows that the control strategy has good performance, stable and reliable engine start, no overshoot, and can be stabilized at idle condition within 10 s.

(3). The heat pump system needs the real-time variable speed (load) operation of the engine. In the variable capacity adjustment process of the heat pump system, the dynamic response process of the adaptive PID is stable, and there is no large overshoot and fluctuation. The adjustment time is less than 20 s, and the speed fluctuation rate is less than 3 % after the target speed is stable, which has good dynamic response characteristics.

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References

[1] M.T. Wang, H.W. Liu, B.H. Zhang, Simultaneous control of engine speed and evaporator superheat for gas engine-driven heat pump system, CIESC Journal, vol. 67 (2016) No.10, p.4309-4316.

[2] H. Zhang, C.L. Wang, J.L. Zhang, C.L. Yin, Development of a Gasoline Engine Controller Based on MotoTron, Journal of Shanghai Jiaotong University, vol. 48 (2014) No.06, p.845-849.

[3] C. Ke, Y. Huang, Z.F. Zhao, et al Development of Two-stroke Kerosene Engine Controller Based on MotoTron Platform, Journal of Aerospace Power, vol. 35 (2020) No.04, p.832-843.

ISSN: 2414-1895 DOI: 10.6919/ICJE.202201_8(1).0087

[4] W.C. Lu, H.Y. Gao, X. Meng, et al Design and Experimental Study of ETC Control System Based on MotoTron Platform, Chinese Internal Combustion Engine Engineering, vol.31 (2010).No.06, p.59-64.

[5] F.J. Zhang, Y. Huang, Y.S. Ge, L.J. Hao, Y.B. Sun, A Study of A/F Ratio Close Loop Control System Ruled by Adaptive Reference Voltage of EGO Sensor, Chinese Internal Combustion Engine Engineering, (2002) No.05, p.64-71+75.