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Engine Speed Control of Excavator with PID Method

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Abstract

Distinction work task power-matching control strategy was adapted to excavator for improving fuel efficiency; the accuracy of rotate engine speed at each work task was core to excavator for saving energy. 21t model excavator ZG3210-9 was taken as the study object to analyze the rotate speed setting and control method, linear position feedback throttle motor was employed to control the governor of engine to adjust rotate speed. Improved double closed loop PID method was adapted to control the engine, feedback of rotate speed and throttle position was taken as the input of the PID control mode. Control system was designed in CoDeSys platform with G16 controller, throttle motor control experiment and engine auto control experiment were carried on the excavator for tuning PID parameters. The result indicated that the double closed-loop PID method can take control and set the engine rotate speed automatically with the maximum error of 8 rpm. The linear model between throttle feedback position and rotate speed is established, which provides the control basis for dynamic energy saving of excavator.

Keywords: *engine, PID, excavator, rotate speed, energy saving*

1. Introduction

Hydraulic excavator is the mainly earthmoving machinery,which is widely used in construction, road and agricultural engineering. While its fuel efficiency is about 30% [1], the main reason for energy loss is the load power varies periodically in large scale, which causes the fluctuation of rotate speed of engine, and then the engine can't work in high efficiency state , thus energy saving becomes a research focus.

Aiming to improve fuel efficiency, most researchers analyzed the power match problems among engine, variable displacement pump, hydraulic system and load, and finally provided a distinction work task power-matching control strategy, that is setting the maximum hydraulic system absorption power for different work task. On this basis, in order to make full use of engine power under different load state, some [2-5] tried to adjust the hydraulic absorption power and torque based on the feedback of hydraulic pressure and rotate engine speed,however, this method affected by the fluctuation of hydraulic pressure, thus the main feedback factor of the excavator control system is the engine rotate speed [6]. Adopting electronic fuel injection engine for power source can improve the fuel efficiency. Considering the fuel quality and price in China, mechanical governor engine is widely used there, the engine speed and power was adjusted by linear throttle motor, the math model between the feedback of motor position and engine speed becomes the key topic [7]. Jin Lisheng [8, 9] applied fuzzy PID method to control the speed of engine and took experiment in test bench; furthermore, Yue Yaoliang [10] provided a double PID method based on engine speed and position of motor, but there is no references about the control accuracy of engine speed and optimal PID parameters.

Before applying the distinction work task power-matching control strategy, engine speed at each work task should be set firstly. Public references are focus on only one speed of engine, the actual requirement is setting all the speed of work task firstly and then use these speed for target during working. Thus the engine speed control is the core technology for energy saving, this paper is mainly discussing on the auto-set control method of engine speed with PID method.

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2. Research Method
2.1. Engine Speed Set

Hydraulic excavator has complex working state. According to the distinction work task power-matching control strategy, excavator was divided into 10 gear engine speed for different working task, which are depended on the power requirement of hydraulic system. On this basis, the PLC control system set the maximum absorption power and torque for hydraulic system under different work task. The dividing engine speed and their govern characteristics of diesel engine curve under work was showed in Figure 1, the setting speed was the cross point between curve and engine speed axis, if the load torque becomes bigger and match speed point was not suitable, engine working point would change along with the govern characteristics line to engine external characteristics curve and was not working in high efficiency state, even more, load would cause the engine stop. Furthermore, the 10 gear engine speed is divided in H mode (heavy mode), S mode (economic mode) and L mode (light load) for different task according the required power of engine.

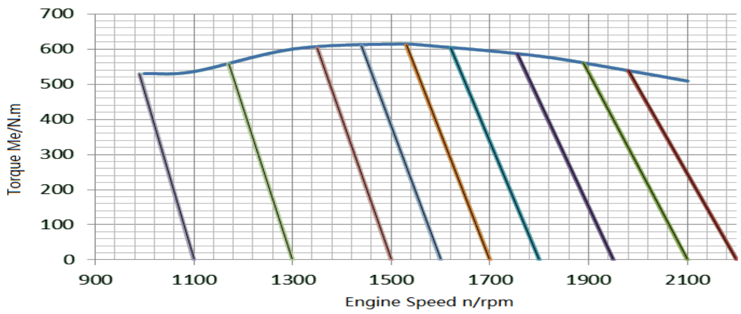


Figure 1. Govern Characteristics of Setting Engine Speed during Work

2.2. Engine Speed Control

The engine of excavator has installed variable speed governor (VSG), which can control the engine speed from low idle to maximum speed. The practicable method to control engine was adopting linear motor with a soft shaft to control the VSG to adjust the engine speed and construct the relationship between feedback of linear position and engine speed.

There are normally 10 pre-setting engine speeds dividing by the work task due to power requirement of different task, PLC control system automatically controls the linear motor to adjust the GSV to match the setting speed and record the feedback position of linear motor in the auto set mode. During the working mode of excavator, the PLC controls the linear motor to reach the record position, which decides the work power of excavator. Thus the position feedback of linear motor and its accuracy is key to the match performance of engine and hydraulic.

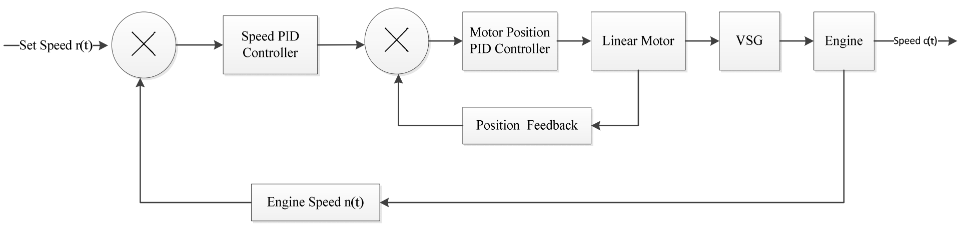


Figure 2. Double PID Control Model for Engine Rotation Speed of Excavator

In the auto set mode of PLC control system, the excavator was starting with no load and the variable displacement pump was shut to the minimum flow. The setting engine speed were the maximum speed shown in Figure 1, which were the cross point between governing characteristic curve and speed axis. PID, fuzzy PID, ANN and their cross algorithms were mostly used in industry control. Consider the capability of PLC; PID method was employed to control the engine speed. In order to construct the relationship between linear motor and engine speed, the feedback of motor position and engine speed were set at the input of PID control mode. Figure 2 shows the double PID control model for engine speed, there are two PID loops, one is for controlling linear throttle motor and the other is for controlling engine speed.

2.3. Experiment Method

Experiment machine is the 21 ton excavator ZG3210-9, which was produced by Sinomarch, China. The engine type is Cummins 6BTA5.9-C (112KW@1950rpm), Linear motor with 60mm displacement and 6N.M torque is produced by Yongqing Ltd.co, China. The connection between linear motor and engine GSV was shown in Figure 3. The linear throttle motor has throttle rod and soft shaft, the throttle rod was employed to connect GSV, and the soft shaft was employed to connect throttle rod and motor. As shown in Figure 3, when PLC control the motor to extend or retract, the soft shaft can adjust the GSV to control the engine speed from low to high speed.

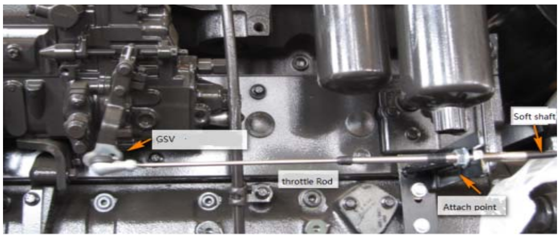


Figure 3. Connection of Speed Governor and Throttle Linear Motor

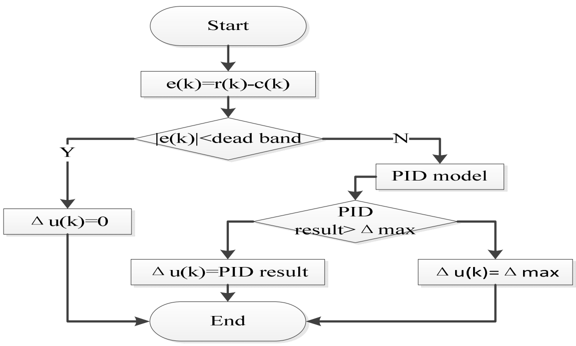


Figure 4. Incremental PID Method with Dead Band Zone and Maximum Increment Limit

Experiment method: (a) Construct control system of throttle motor with Hersmor G16 PLC in CoDeSys 2.3, take motor control experiment and auto-set engine speed experiment; (b) Construct the parameters monitor system based on LabVIEW and USB/CAN(Sys Tec, German) converter, online tune the PID parameters according to the monitor system. The sample frequency of the feedback position of motor in PLC is 1kHz, the CAN bus data sending cycle is 0.2s.

3.Engine Control System Design of Excavator

3.1. PID Control Method

The digital PID method is developed from the analog PID from Equation (1).

$$G(s) = \frac{U(s)}{E(s)} = K_p\left(1 + \frac{1}{T_I s} + T_D s\right) \quad (1)$$

In Equation (1), $G(s)$ is the PID controller transfer function, $E(s)$ is error transfer function, $U(s)$ is the output of the PID controller, K_P is proportional coefficient, T_I is integration time, T_D and is the derivative time.

In order to apply PID method into PLC controller, it needs to convert the PID method from analog type to digital type. Incremental PID method was shown in the following equation.

$$\Delta u(k) = K_P[e(k)-e(k-1)] + K_I[e(k)-2e(k-1)+e(k-2)] = K_P e(k) + K_I e(k) + K_D[\Delta e(k) - \Delta e(k-1)] \quad (2)$$

In Equation (2), k indicates the k^{th} sample cycle, $e(k)$ is the error between the set value and actual value at this sample cycle $\Delta u(k)$ is the incremental PID output of $u(k)$, K_P, K_I and K_D are the parameters of PID model. As is from Equation (2), the output of PID $\Delta u(k)$ is also depending on the sample cycle, smaller sample cycle would increase the load of PLC, larger sample cycle would decrease the sensitivity of PID controller, thus there needs a suitable control cycle of PID method. According to the characteristic of engine GSV and linear throttle motor, the PID control cycle was set at 0.05 s, improve the PID method of Equation (2) with dead band, the improved incremental PID flow chart was shown in Figure 4, The incremental output $\Delta u(k)$ is depended on the dead band value and the incremental max value $\Delta \max$, PID parameters are tuned online in both motor position control loop and engine speed control loop.

3.2. Control Circuit

In the engine speed auto set experiment, the input signals are the engine speed select potentiometer, linear throttle motor position sensor, engine speed sensor, the output signals are the direction of throttle motor and the control voltage for motor. All the input signal are the resistance signal and could be input the AI (Analog Input, 10bit AD) port of G16 PLC, the output of motor direction are connecting to the DO (Digital Output) port of G16, the motor control voltage is connected to the PWM (Pulse Width Modulation) port of G16. The engine speed sensor is connected to the PI(Pulse Input) port of G16 and the number of gear teeth of engine flywheel is 127, thus the speed need to use the pulse number PI to divide the gear theeth number. The control circuit is shown in Figure 5.

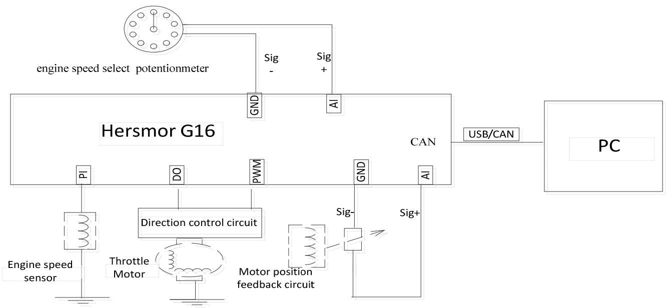
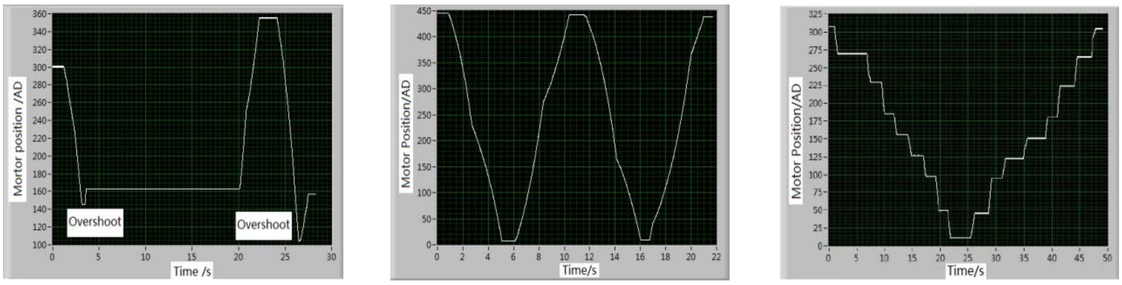


Figure 5. Engine Speed Control Circuit of Excavator

4. Results and Analysis

4.1. Linear Throttle Motor Control Experiment

The experiment result indicated that the range of motor position of AD converter value is among 0 to 610 from the limit of extend and retract without connecting to the engine GSV; after installing on the excavator and connecting to the GSV, the range of throttle motor position was limited by the GSV displacement, the motor position feedback of AD convert value is among 0 to 450. In order to construct a common control method for different linear throttle motor, scale the range the AD value of motor position to 0~1000, and set the dead band of motor position PID loop is 5, maximum increment $\Delta \max$ at each PID control cycle is 100, take the online experiment to tune the parameters of K_P, K_I and K_D. The online tuning experiment result is shown in Figure 6. When the PID parameters combination is not suitable, the result indicated that the motor position feedback would overshoot the set value point, after several trials, suitable PID parameters were got and the set value and actual value result were shown in Figure 6(b) and (c). The result indicated that with the PID controller the motor could reach the set point without overshoot, and the optimal PID parameters is (5, 0.5, 0.6).



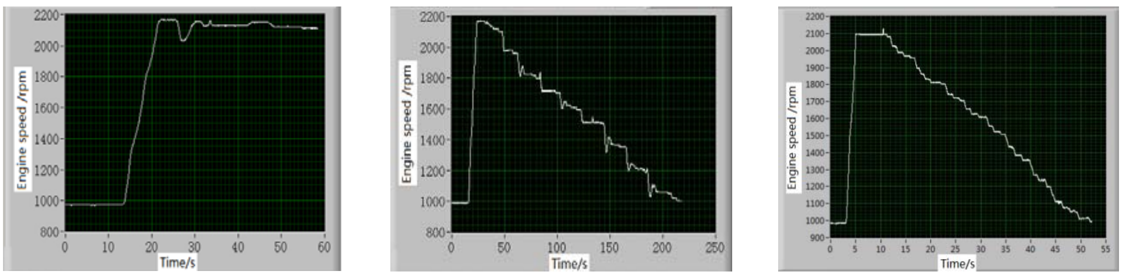
(a) Not suitable parameters (b) Suitable parameters (c) Multi target control result

Figure 6. Result of Throttle Position PID Control Experiment

4.2. Engine Speed Auto Set Control Experiment

In the engine speed auto set control mode, there are 10 working engine speeds and 1 for auto-idle engine speed. In order to get the corresponding motor position of the setting speed, two PID loops were employed, one is the motor position PID loop and the other is engine speed PID loop. Before ascertaining the relationship between motor position and engine speed, the PLC controller should acquire the maximum and minimum limit of engine speed and motor position AD value, then the PLC would automatic get the required motor position value and record under the setting engine speed with PID control method.

The linear throttle motor has the worm-gear-drive mechanism to reduce the speed of motor and convert to the soft shaft displacement. Thus, there has inter-lobe clearance between gears, which would cause control error of engine speed. According the motor and engine characteristics, the dead band of engine speed PID loop is set as 10rpm, and maximum incremental $\Delta \max$ is 150rpm and online tuning the PID parameters of engine PID loop.



(a) Control cycle is too long (b) Not suitable PID parameters (c) Suitable PID parameters

Figure 7. Engine Speed Control Result Based on Speed and Throttle Motor Position with Segment-PID Method

Result of engine speed auto set experiment was shown in Figure 7, if the PID control cycle was 0.1s or bigger, the PID control result shows that the engine speed adjustment curve is too slow like Figure 7(a). During the experiment, the engine PID control cycle was set at 0.05s.

If the PID controller has only one target and one judge error, the result would like shown in Figure 7(b), engine speed would overshoot at the set speed. Thus for higher accuracy and based on the error value, the PID control loop was improved into two segment. One control segment is set the error target at 50rpm, and set the dead band to 25rpm; another control target is set the error below 50 rpm and the dead band is 10rpm, the PID control result was shown in Figure 7(c), it indicated that the control curve of engine speed was more stable and without overshoot. The speed curve has two separated stage, one is changing from about 980rpm to 2086 rpm, in this stage, the PLC control system adjusts the linear throttle motor displacement from 0 to maximum value, and the PLC would get the range of engine speed motor position feedback AD converter value. The other stage is the engine speed curve changes from maximum to minimum value, this stage is the engine speed auto set mode, and the PLC system automatically control the motor and GSV reach the setting speed. With the two segment PID control method, it indicated that the PID control result is more stable and faster.

Table 1. Engine Speed Control Result (unit: rpm)

Speed select	Target speed	Result 1	Result 2	Result 3	Average	Error
1	1050	1048	1056	1048	1051	1
2	1200	1196	1201	1204	1200	0
3	1350	1360	1355	1360	1358	8
4	1500	1503	1509	1503	1505	5
5	1600	1605	1607	1608	1607	7
6	1700	1707	1703	1705	1705	5
7	1800	1799	1802	1795	1799	1
8	1950	1953	1957	1955	1955	5
9	2086	2081	2081	2089	2084	2
10	2086	2077	2092	2088	2085	1

Table 1 was the result of target and auto set engine speed under three experiment, the 10 engine speed value is set as 1050, 1200, 1350, 1500, 1600, 1700, 1800, 1950, 2100, 2200rpm, as from the result of Figure 7(c), it indicated that the maximum speed is less than 2100rpm, because the range of engine speed is among 980 and 2086, thus the PLC would auto change the set engine speed 2100 and 2200rpm to 2086rpm. From the result of Table 1, it indicated that the maximum error is 8rpm, which is meeting the control error band of 10rpm.

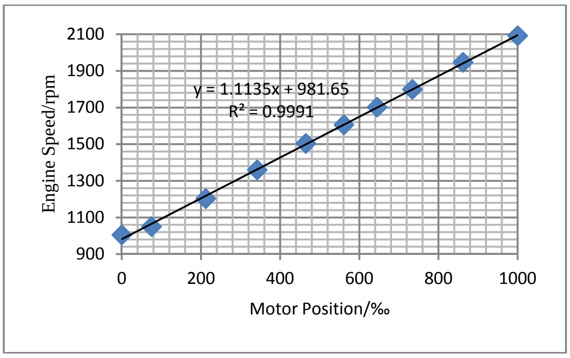


Figure 8. Curve between Throttle Position and Engine Speed

Figure 8 shows the relationship between the engine speed and the feedback of motor position, compared to Table 1, Figure 8 added a minimum engine speed at 980rpm and its corresponding motor position. It indicated that the relationship between motor position and engine speed is linear, and the correlation coefficient is 0.9991, which indicated that each point of engine speed select potentiometer is corresponding to the engine from 980 to 2086rpm. Thus the PLC control system could add more working task if the excavator needs and set the engine power and the hydraulic absorption torque.

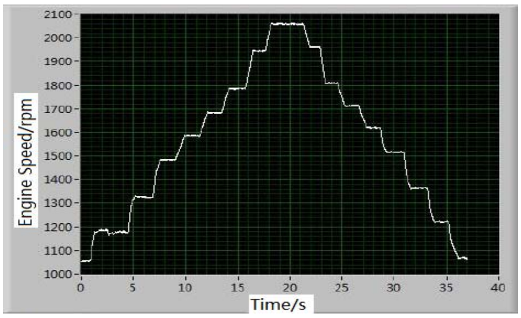


Figure 9. Engine Speed Following with Throttle Switch

Figure 9 was the result between the engine speed select potentiometer and engine speed; it indicated that the engine speed is following the change of potentiometer. Due to the worm-gear-drive mechanism of linear throttle motor and its clearance of extend and retract is different, the engine from low to high and from high to low is different at the same speed select potentiometer value, furthermore, if the their need higher accuracy of engine speed, the auto set mode of PLC should consider the speed increase and decrease direction to record the motor position to reduce the different clearance of linear motor between extend and retract.

5. Conclusion

On the basis of analyzing the engine speed auto set control function of excavator, excavator control system based on Hersmor G16 was designed, and the application of PWM to drive linear motor was more stable and accuracy.

Improved incremental PID control method was employed to control the linear throttle motor and online PID parameters tuning experiment indicated that the optimization PID parameters combination is (5, 0.5, and 0.6).

Segment PID method was employed to auto set the requirement engine speed, the result indicated that the improved control method has higher accuracy with the maximum error of 8rpm and total less than 60s auto set control time.

It is a good method to solve the difference of linear throttle motor and engine GSV displacement by scaling the AD converter value of the extend and retract limit of motor position feedback to the range of 0 and 1000. Experiment result indicated that the relationship between motor position and engine speed is linear, which provides the control basis for dynamic energy saving of excavator.

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