Design of Controllers for the Stable Idle Speed in the Internal Combustion Engine

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ABSTRACT

This paper deals with control design method having anticipation delay which is proposed for the discrete nonlinear engine where system dynamics is not accurate. Due to the induction-to-power delay in internal combustion(IC) engine having abrupt torque loss, underdamping and chattering in engine idle speed becomes a serious problem and it could make drivers uncomfortable. For this reason, Three types of the closed-loop controller are developed for the stable engine idle speed control. The inputs of the controllers are an engine idle speed and air conditioning signal. The output of the controllers is an duty cycle to operate the idle speed control valve(ISCV). The proposed controllers will be useful for improving actual vehicles since these shows good test

Keywords : Idle speed control valve, PID controller, Fuzzy controller, PID type fuzzy controller, Duty cycle, Anticipation delay, Electronic control unit.

1. Introduction

Vehicle consumers feel noises and vibrations from their cars during engine warm-ups and traffic jams. Two factors from the vehicle can cause noises and vibrations. The one is the outside noises and vibrations that are transmitted to drivers, and the other is the internal ones directly delivered from the power train parts, air conditioning compressor, cooling fan, and power handle driving pump. Meanwhile, because internal noises and vibrations make the engine idle speed drop to some degree, drivers can feel uncomfortable. The internal noises and vibrations can be reduced to some degree by controlling the engine idle speed. Therefore, it is very important to obtain the optimal map table data of the electronic control unit to meet this goal. But by the aging of power train parts and the changes of the external temperature and humidity, maintaining a stable initial state of the engine is so hard that the engine idle state deteriorates. Moreover, when the disturbances due to the driving torque of air conditioning compressor and power steering pump are given to the idling engine, the electronic control unit can not make the engine idle speed to the stable mode so that this engine can be in an unstable state like stall and droop.

The disturbances which effect on the engine idle state can be explained by two factors. One of the factors is the electrical operation, and the other is the mechanical one. The electrical disturbances are the on/off operation of the cooling fan, head light lamp, etc., and the mechanical ones are mainly the torque loads by the air conditioning compressor and power handling pump. To maintain a stable engine idle state, lots of closed loop control[1-9] are studied besides the map table method of electronic control unit which is strait feedforward control. When those closed loop controls are dealt with the electrical disturbances and power steering pump, they show stable results.[8] But in the case of having the torque load of air conditioning compressor, they could not make a stable engine idle condition.

Meanwhile, the control inputs for the stable idle speed were the throttle angle of the idle speed control valve and the spark timing advance. In this paper, the controllers use only the throttle angle of the idle speed control valve when receiving the torque load of the air conditioning compressor, because controlling the spark timing advance causes the production of NOx which is harmful to human [10].

To perform a stable engine idle speed control, PID controller[11], fuzzy controller, and PID type fuzzy controller with anticipation delay are designed . To compensate for the so-called induction-to-power delay, the anticipation delay method is applied to the nonlinear engine system[12, 13] The test results of the each controllers are compared with the map method. In the experiment, the input and output(I/O) control board made by the dSPACE Inc. is used to interface with engine, and the SIMULINK by the MathWoks Inc. is used to control the engine idle speed control.

2. Controller design

Flowchart for making a stable engine idle speed mode used in the study is shown in Fig. 1. Figs. 2~4 are the block diagrams of the engine idle speed controllers developed for internal combustion engine. The input of the controllers is an engine speed ω_e (rpm), and the reference input is a desired engine speed ω_{ed} (rpm) which is set to 800rpm . The error equation between these two inputs is given by Eq. (1)

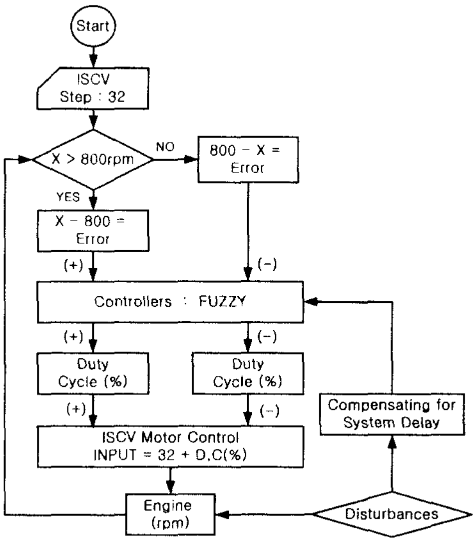

Fig. 1 Flowchart of engine idle speed control

$$e(t) = \omega_e(t) - \omega_{ed} \tag{1}$$

Meanwhile, the output of the controllers is the desired duty cycle DC_{des} (%), which is the input signal of the idle speed control valve. The disturbance of the engine is the torque load of the air conditioning compressor that is applied by the on/off operation of the air conditioning switch.

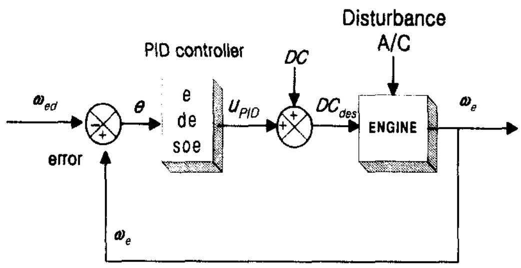

Fig. 2 Schematic diagram of PID controller

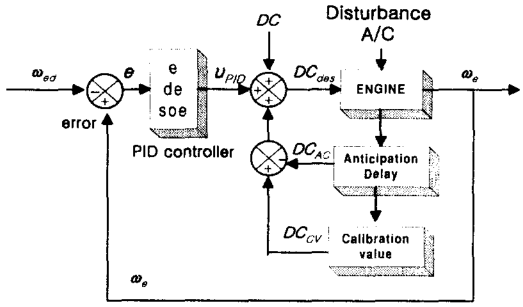

Fig. 3 Schematic diagram of PID controller with anticipation delay.

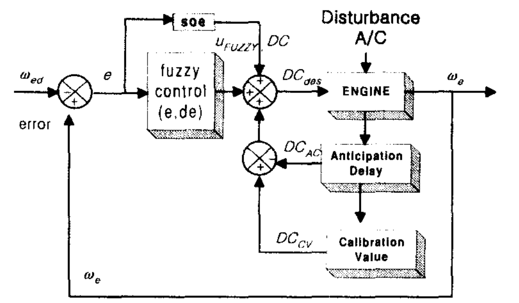

Fig. 4 Schematic diagram of PID-type fuzzy controller with anticipation delay.

2.1 PID Controller

The equation of PID controller using the error has the form as Eq. (2).

$$u(t)_{PID} = K_P[e(t) + \frac{1}{T_i}\int_0^t e(\tau)d\tau + T_d \frac{de(t)}{dt}] \quad (2)$$

where K_P denotes the proportional gain, T_i is the integral time, and T_d represents the derivative time. The block diagram shown in Fig. 2 represents the straightforward feedback control structure to solve the control problem. The u_{PID} represents the output value calculated from the PID controller, DC is the basic duty cycle given to the idle dc motor to maintain the stable engine idle speed 800rpm after the spark ignition, and DC_{des} is the desired duty cycle. Therefore, the desired duty cycle is defined by Eq. (3).

$$DC_{des} = DC + u_{PID} \quad (3)$$

2.2 PID Controller(with anticipation delay)

The block diagram of PID controller having anticipation delay is shown in Fig. 3. The anticipation delay compensates for the delay time which makes the rise time of the system worse. In the internal combustion engine, the delay time can be composed of two. One is the induction delay time(D1) which is the lag between the opening of idle bypass air duct and the inflowing of the air mass into the combustion chamber, and the other is the power delay time(D2) due to the action of the intake stroke, the compression stroke, and action of the power stroke, before each cylinder produces torque. The delay time D1 is empirically estimated as 0.8sec and D2 is as 0.2sec finally from the transient test data. By compensating D1 and D2, the transient control of the engine idle speed is performed before the operation of the air conditioning compressor. DC_{AC} denotes the compensating duty cycle of the torque load of compressor which is calculated by anticipation delay. DC_{CV} is the correction duty cycle which is given to the compensating duty cycle DC_{AC} 1sec later. The overshoot of the engine idle speed due to the compensating duty cycle can be controlled by the correction duty cycle DC_{CV} . Therefore, the desired duty cycle is described in Eq. (4).

$$DC_{des} = DC + u_{PID} + DC_{AC} + DC_{CV} \quad (4)$$

2.3 PID type fuzzy controller

The block diagram of fuzzy controller with anticipation delay shown in Fig. 4 has a fuzzy algorithm. Fuzzy logic is a convenient way to map an input space to an output space. The characteristic of fuzzy logic is that this can model nonlinear functions of arbitrary complexity. Because most fuzzy logic control routines have relied upon heuristic information based on operators' experience to design the rule base, one can make the system to a stable condition. To design the fuzzy logic controller, we have to define the input/output variables of the system, and make the membership function to these variables and the fuzzy control rules to construct the basic knowledge.

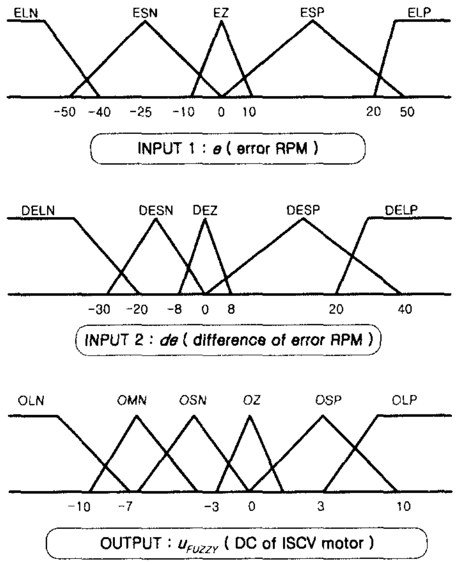

Fig. 5 Membership function of input and output

In this study, the Max-Min composition in Fig. (4) as the one of the inference methods is used to obtain the output of the controller by the linguistic fuzzy rules and membership functions. Mamdani's fuzzy inference method is adapted on the fuzzy inference process. Applying the inference results to the defuzzification algorithm leads to the output of the controller. The center of gravity method is used in the defuzzification algorithm and has the form as Eq. (5)

$$Y = \frac{\sum Y_i \bullet \mu_B(y_i)}{\mu_B(y_i)} \quad (5)$$

where, Y : Output of defuzzification

Y_i : Quantification value of membership function
$\mu_B(y_i)$: Membership function of fuzzy set

As you can see in Fig. 4, the input variables of the controller are composed of the error $e(t)$ and the change of the error $de(t)$. Membership functions of these inputs are chosen at each linguistic variables. The sum of error $soe(t)$ is added to the controller to improve the steady-state error. This is called as the PID type fuzzy controller because the calculation method is as same as PID control. The input and output relationship of the fuzzy controller is shown in Eq. (6).

$$R(t): e(t)\times soe(t)\times de(t) \Rightarrow u_{FUZZY} \tag{6}$$

where $R(t)$ represents the related matrix of (t) *th* rule. The membership functions of input and output applied in this study is shown in Fig. 5. The output of PID type fuzzy controller is denoted by u_{FUZZY} and the desired duty cycle of PID type fuzzy controller is designed as Eq. (7).

$$DC_{des} = DC + u_{FUZZY} + DC_{AC} + DC_{CV} \tag{7}$$

3. Experimental configuration

A schematic diagram of experimental system setup is presented in Fig. 6. For the purpose of controlling the engine idle speed, I/O control board(DS 1103) by the dSPACE cooperation has been used in the test. Input signals to the control board are composed of hall sensor signal, cooling water and engine oil temperature, ambient temperature, and air conditioning control signal(on/off).

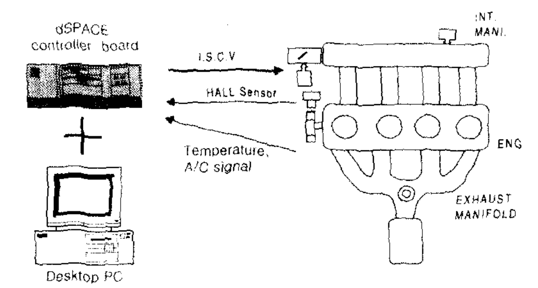

Fig. 6 Schematic diagram of experimental system setup.

The engine idle speed is calculated from the hall sensor, and K-type thermocouples are used to measure the temperatures. Meanwhile, the cooling water temperature is measured in the outlet of engine cooling circulation system. The output signals from the control board are for driving the dc motor of the idle speed control valve, and these signals are composed of close pulse, open pulse, and 12volts as shown in Fig. 7. By the way, an additional power supply is installed to give stable gain value to the system. The same type of idle actuating sensor is used to give constant idle air mass to the combustion chamber. Intake air mass 1.0~2.0*l*/sec is needed to maintain the engine idle speed mode, and 3.4~3.50*l*/sec is also needed at the start of spark ignition. Unless the disturbance is applied to the engine, the basic duty cycle to keep engine idle speed to 800rpm is set to close 32% and open 68% separately.

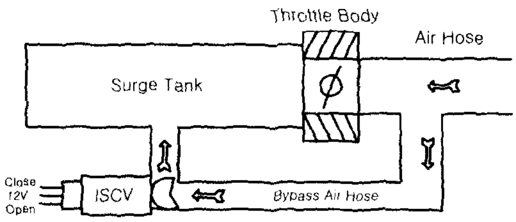

Fig. 7 Schematic diagram of air mass flow in the intake system of engine.

The engine displacement of test vehicle is 1800cc and the operating cooling water temperature is around 81 Celsius that is the driving temperature of the low fan motor to maintain the constant test condition. A desk top PC(cpu: pentium-3) is used for the real time fuzzy control of the engine idle speed mode instead of changing the EPROM data directly. The other map table data of electronic control unit except for the idle speed map is loaded to the engine control, and the input signals to the I/O control board(DS 1103) are extracted from the pin assembly of the electronic control unit for the convenient test.

4. Experimental results

Fig. 8 shows the changes of the engine idle speed, air conditioning(A/C) on/off signal voltage, and the desired duty cycle of test vehicle due to the compressor torque load by the consumer's operation. The data of the air conditioning signal and duty cycle have been multiplied by 100 and 10 times separately for the sake of comparison. When switch is on, the voltage of signal is up from 0volts to 5volts. When the switch is off, the voltage of signal downs from 5volts to 0 volts. Torque loss by the compressor occurs when the air conditioning switch is pressed on. At this point, the basic duty cycle 32% is kept constantly because of no control.

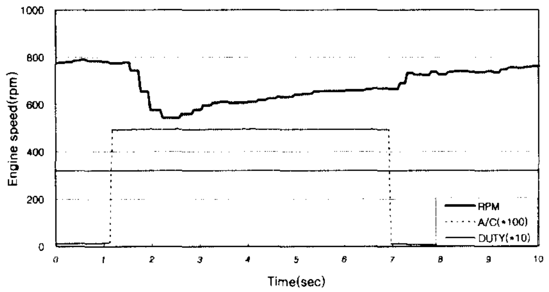

Fig. 8 The rpm change under A/C load (no control).

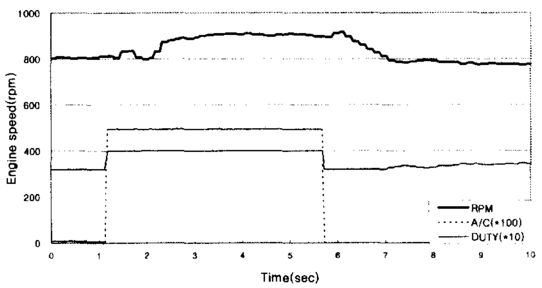

Fig. 9 The rpm change under A/C load (map table).

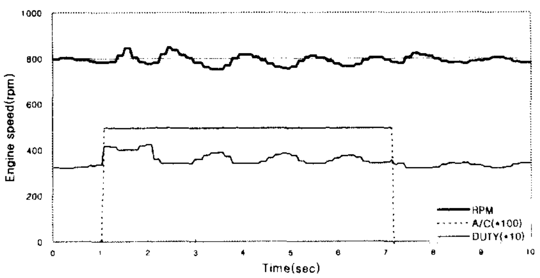

Fig. 10 The rpm change under A/C load (PI control with anticipation delay).

As you can see from Fig. 8, the drop of engine speed abruptly occurs 0.6sec later after the switch is pressed on. After the engine speed reaches to the 550rpm, it turns back slowly. This value of rpm loss is equivalent to the torque loss 10Nm of the air conditioning compressor. Meanwhile, the engine speed is recovered by removing the torque load of the compressor. The change of engine idle speed controlled by the map table of the electonic control unit is illustrated in Fig. 9. When the air conditioning switch is pressed on, the anticipation delay method is operated simultaneously, but the abrupt and steady overshoot of the engine idle speed(920rpm) has occurred because of the feedforward map control. Nevertheless, the map method is the best way to control the engine idle speed in the test vehicle so far. Moreover, we can feel more unstable engine idle speed state according to the aging of the powertrain parts and unexpected noises.

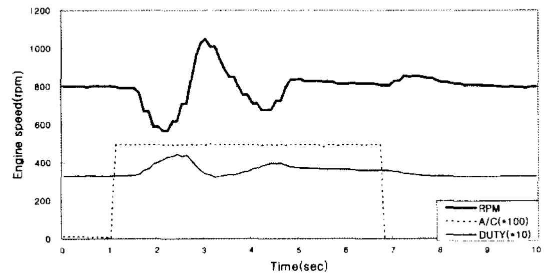

Fig. 11 The rpm change under A/C load (PID control).

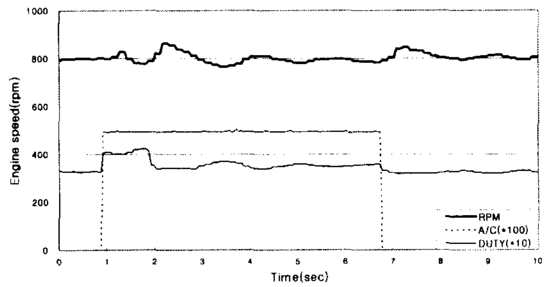

Fig. 12 The rpm change under A/C load (PID control with anticipation delay).

The change of the engine idle speed controlled by a closed loop algorithm(PI control with anticipation delay) is demonstrated in Fig. 10. the PI controller changes the desired duty cycle (from the test results, the range is from 32% to 42%) to compansate for the torque loss of the compressor. In this study, three types of closed loop controller are designed, and the changes of the engine idle speed are compared with each controller.

4.1 Test result of PID control

Fig. 11 shows the change of the engine idle speed controlled by the PID algorithm without the anticipation delay. The engine idle speed starts to down 0.6sec later after the air conditioning switch is pressed on, and the duty cycle compansation to the compressor is performed. The delay time of the air mass flow from idle speed control valve to combustion chamber has not been considered in this controller. Initial torque loss by the compressor has occurred in the engine idle speed mode. The maximum rpm drop is observed at the range of 580rpm. But as the torque of the air conditioning compressor is unloaded, the engine idle speed mode has become a stable codition. By the way, the Ziegler-Nichols tuning method[11] was used to determine the propotional gain(P), integral gain(I), and delivative gain(D). And each gains are P : 0.0068, I : 0.001, and D : 0.1.

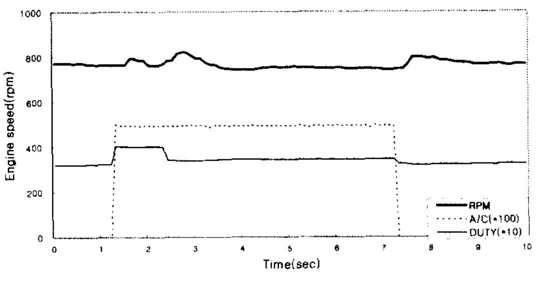

Fig. 13 The rpm change under A/C load (fuzzy control with anticipation delay).

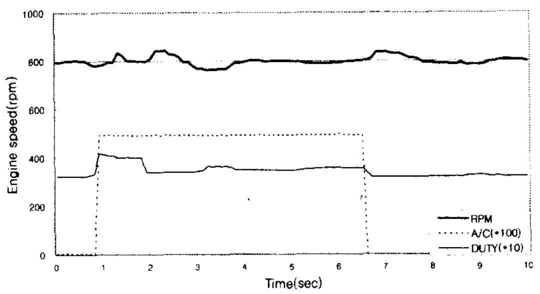

Fig. 14 The rpm change under A/C load (PID type fuzzy control with anticipation delay).

The change of the engine idle speed cotrolled by the PID algorithm having the anticipation delay method is shown in Fig. 12(P:0.0048, I:0.001, D:0.09). Pressing the air conditioning switch on, the compensated duty cycle 8% which is adaptive control value of the delay time and the torque inertia of compressor is given to the idle speed control valve. The correction duty cycle is also added to the nonlinear system 1sec later, and this leads to the stable cotrollability of the initial engine idle speed condition. The drop of the engine idle revolution appears to be 20rpm 0.4sec later after the compressor torque is given, but the desired engine idle speed is maintained immidiately by the compensation method for the duty cycle. The time period of the residual osillation is 1.5sec and the range of the idle speed change is from 760rpm to 860rpm.

4.2 Test result of fuzzy control

The change of the engine idle speed cotrolled by the fuzzy algorithm having the anticipation delay method is shown in Fig. 13. The two inputs of a fuzzy controller are the error of engine idle speed and the change of the error. The fuzzy logic shows more stable controllability on reducing the residual oscillation, but fuzzy controller has a steady state error 50rpm to the reference input 800rpm.

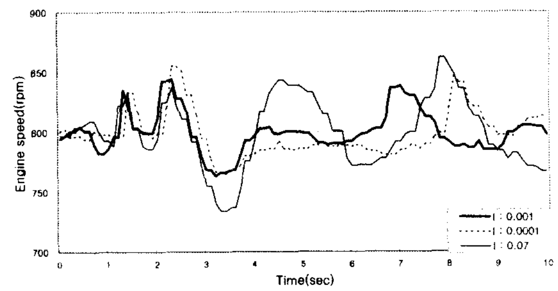

Fig. 15 The rpm changes of PID type fuzzy controlsystem according to I-gains.

4.3 Test result of PID type fuzzy control

Fig. 14 is the test results by PID type fuzzy controller with anticipation delay. The PID type fuzzy controller has additional integral item of the error(I : 0.001) besides the two inputs. The PID type fuzzy controller removes the steady state error and reduces the residual oscillation. The range of the idle speed change is from 770rpm to 840rpm. The PID type fuzzy controller makes the engine idle speed mode more stable than previous controllors.

The comparison graph of idle speed change according to I-gains is illustrated in Fig. 15. The range of the idle speed change has increased by choosing higher I-gain(0.07), and shows the resonance beyond some I-gain values. Meanwhile, the steady state error has occurred at the small I-gain(0.00001).

5. Conclusions

When the internal combustion engine in the idle speed mode receives the abrupt torque disturbance from the external driving sources, the engine idle speed mode becomes unstable. Particularly, as the abruptly loaded mechanical torque due to the air conditioning compressor is given to the engine, the stall and droop at the engine idle speed mode can be detected. In a situation like this, three types of closed loop controllers have been designed to compare with the map table control of the electronic control unit. And the conclusions are as below

1. The PID type fuzzy controller showed the most stable controllability on the engine idle speed control(770-840rpm) among the proposed three types of controller. And the fuzzy controller had more stability on the control of a residual oscillation than the PID controller, but fuzzy controller itself didn't remove the steady state error.
2. The conventional PID controller without the anticipation delay method made the engine idle condition more unstable than the map method of the electronic control unit. The engine idle speed downed to maximum 580rpm due to the air conditioning compressor and sometimes showed an engine stall.
3. The PID controller with an anticipation delay showed the stability on the internal combustion engine having disturbance. The change of engine idle speed ranged from 760rpm to 860rpm so that this type of controller showed better test results than the map table making the engine idle speed up to 920rpm.
4. The anticipation delay method was robust to the transient idle speed changes resulting from the fast movement of the solenoid valve controlling the air mass flows in the intake manifold.
5. The controllers proposed in this study can be used in the commercial vehicle for the improvement of the consumer's comfort and fuel economy.

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