Model-based Idle Speed Control System for an Automobile Engine using an Electric Throttle System

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Abstract: Recently, it has become important to reduce the fuel consumption of automobile engines in order to reduce the amount of CO_2 emission. Reduced consumption can be achieved by reducing the idle speed. However, the idling stability at low idle speeds tends to be worse than that at higher idle speeds. Thus, more accurate idle speed control is required. In the present paper, we propose an engine model-based feedforward idle control system. The model-based control system is demonstrated to achieve better control results.

Key-Words: Idle speed control, Engine model, Feedforward control, Electric throttle system, Model-based control

1 Introduction

A reduction of the hazardous components in vehicle exhaust emissions has been desired for passenger vehicles. Recently, the additional demand for reductions of CO_2 in exhaust has become strong. Reduced the fuel by the engine system to provide better efficiency is important in CO_2 exhaust reduction. Approaches such as friction reduction by special processing of engine parts and the achievement of in-cylinder stratification thin combustion with the direct fuel injection engine [1] (DI engine) have proven highly effective. The engine torque can be freely set by electronically controlling the throttle, and the drivability of engines with strong nonlinearity can be improved greatly.

The proportion of efficiency improvement associated with idle speed control is large for the DI engine. The idling fuel consumption can be reduced by lowering the idle speed. However, when the idle rotational speed is low, the idle stability may worsen and generate engine stalls. To reduce the fuel cost, a more accurate idle speed control is needed. The idle rotational speed control discussed here is the control that prevents engine stalls and maintains a prescribed engine rotational speed. The load torque of the engine changes suddenly according to the use of in-vehicle equipment, such as the air conditioner and the headlamps, during driving under idle conditions. On the other hand, the engine torque depends on the airflow rate at the cylinder port, the fuel oil consumption, and the ignition timing. It is necessary to operate these components in manner that enables the load and the output to be balanced, and to thereby suppress changes in engine speed. The method of adaptive control [2] and the speed feedback control method [3] to control the suction system are examined as a method of achieving highly accurate idle speed control. Conformity responding to the change of the load is not good in the feedback control, which detects and feed back idle speed change.

Reference [4][5] presents several methods of controlling the idle speed regulation. Several possible solutions are including integral control, fuzzy logic control, adaptive fuzzy logic control in conjunction with Smith prediction and dynamic matrix control. However, when the amount of fuels increases from the operating limit of the ISC valve, the amount of air might be insufficient in the case of the control that operates on air mass flow rate. In these cases, the mixture ratio of the air and the fuel is not obtained stoichiometrically as 14.7. These methods increase the hazardous components contained in exhaust [5].

In the present study, a new idle rotational speed control method is proposed that uses a suction system control that does not cause exhaust gas deterioration with a new electric throttle control device. The proposed method is evaluated using an experimental car.

This system makes the best use of the feature whereby the electric throttle control device is a suction device with a large capacity and conformity and composes the control logic, the main element of which is the feedforward control. The throttle is operated by control to output the torque that corresponds to the forecast load. The idle speed can be smoothly matched to the target value by balancing the torque output and the load torque. Moreover, the steady state error can be eliminated using the feedback control.

The remainder of the present paper is organized as follows. Section 2 explains the composition and the feature of the engine control system with the electric throttle control device. Section 3 describes the engine system model necessary for the feedforward control of the idle speed and the composition of the idle speed control system. In Section 4, the effectiveness of the proposed system is evaluated by an experiment using an actual car.

2 Control structure of an engine system

Figure 1 shows the composition of the car engine control system with an electronically controlled throttle proposed herein. Previously, idle speed control was achieved in mass-produced cars by a tube that bypassed the throttle and an idle-speed-control (ISC) valve that adjusts air mass flow rate of the bypass tube. In addition, a cable connecting the accelerator pedal to the throttle was also installed. The proposed system eliminates the bypass tube, the ISC valve, and the accelerator cable, and instead uses a motor to drive the throttle butterfly. A throttle control module (TCM) drives the motor for the throttle drive with a 1-ms cycle, feeds back the throttle opening degree, and matches the throttle opening degree to the target throttle opening degree. The target throttle opening degree signal is transmitted from the electronic control unit (ECU) to the TCM every 10 ms.

A crank angle sensor is placed on the crankshaft, and the ECU obtains the engine speed (rpm) based on this measurement. In addition, input signals to the ECU include the signals from an accelerator degree sensor, air conditioner and headlamp switches, a water temperature sensor, and an O_2 sensor that detects the oxygen density of the exhaust. The output signals from the ECU include the target signals to the TCM, the pulse signal to the injectors, and the pulse signal to the igniter.

This system controls the idle speed by the feedforward control method with the electric throttle control device. The air fuel ratio and the ignition timing are set to be optimal, as usual, at the change of load. There are two main problems in the achievement of this control system.

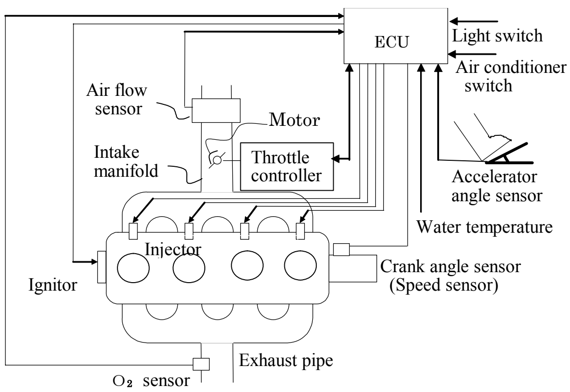

Fig.1. Engine control system

The first problem is to presume the change in the load torque according to the use of in-vehicle equipment, including the transient state in which the load changes suddenly. The second problem is to calculate the throttle opening degree in order to generate a corresponding engine torque to the load. It is therefore necessary to clarify the relationship between the change in the throttle opening degree and the engine torque.

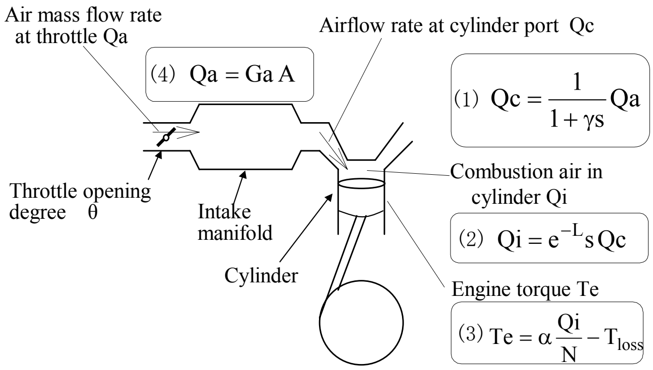

Fig.2. Engine Models

3 Composition of idle speed control

3.1 Engine system model

3.1.1 Air system and torque production model

The relationship between the throttle opening degree and the engine torque can be derived based on a theoretical formula for a gas and the theory of engine combustion [4-6]. Figure 2 shows this engine model. The throttle enters the squeezed state in idling, and the difference between the intake manifold internal pressure and the outside pressure is large at approximately 700 mmHg. Therefore, the air mass flow rate at the throttle and the opening flow area become proportional [7].

$$Qa = Ga \cdot A \quad [g/s] \tag{1}$$

Here, the relation between the opening flow area A [mm^2] and the throttle opening degree θ [deg] is decided algebraically. Ga is a constant that is peculiar to the vehicle and is 0.2445 [g/mm^2s] for the prototype vehicle in the standard condition.

Expression (2) shows the charge delay in the intake manifold, and expression (3) shows the dead time from inhalation to explosion stroke:

$$Qc = \frac{1}{1+\gamma s} Qa \quad [g/s], \tag{2}$$

$$Qi = e^{-L} s\, Qc \quad [g/s], \tag{3}$$

where Qa is the air mass flow rate at the throttle [g/s], Qc is the air flow rate at the cylinder port [g/s], and Qi is the rate of combustion of air in the cylinder. The first-order lag time constant γ in expression (2) varies with volumetric efficiency, capacity of the intake manifold, and engine speed. The dead time L in expression (3) is inversely proportional to the engine speed. The engine used in the experiment is a four-cylinder inline engine having a total piston displacement of 2,156 cc. The capacity of the intake manifold is 3,300 cc, and the caliber of the throttle is 55 mm. The abovementioned values for γ and L are obtained based on these data:

$$\gamma = \frac{174.9}{N} \quad [s], \quad L = 2.5\frac{30}{N} \quad [s], \tag{4}$$

where N [rpm] is the engine speed.

As for generation torque Ti, is theoretically proportional to the air quantity filling the cylinder. The engine torque Te is the pull of the loss torque T_{loss} from the generation torque Ti:

$$Te = Ti - T_{loss} = \alpha \frac{Qi}{N} - T_{loss} \quad [\text{kgfm}] \qquad (5)$$

Here, α varies slightly depending on the air-fuel ratio and the ignition timing. It is possible to treat α as a constant as long as the optimum points are taken. Moreover, Tloss shows the tendency to increase almost in proportion to the engine speed. When the engine is idled under the no-load condition, the shaft output is 0. That is, Te is 0, and the values of Ti and Tloss correspond to Te = 0. Therefore, an air system model and a torque production model could be formulated from the throttle to the cylinder suction and combustion.

3.1.2 In-vehicle equipment load torque model

The load torque is the resistance by which the engine speed is decreased, and the engine torque is the power to increase the engine speed. The loss torque, Tloss, at the right of expression (5), is a load torque generated in the engine. In addition, there are load torques, such as electrical loads and air conditioner loads, that are generated from in-vehicle equipment outside the engine.

The electrical load is a load generated from electrical machinery and apparatus such as headlamps, defoggers, and radiator fans.

Power is discharged from the battery using electrical machinery and apparatuses. To supplement the electrical discharge, an in-vehicle dynamo increases the electric power generation. When the torque is examined from the engine side, the power generation torque becomes a load torque as the dynamo is obtaining power from the engine crankshaft.

The air conditioner load is a combination of the load by electrical machinery and apparatuses such as the capacitor fan and the indoor fan and the mechanical load. The compressor combines the belt with the engine crankshaft. Driving and stopping can be achieved by respectively connecting or disconnecting the clutch on the compressor shaft.

The abovementioned load torque T_{loss} varies with the engine speed, the water temperature, and other engine conditions. During idle driving, the change in the load torque is comparatively slow. The rotation deflection caused by this change can be canceled by the feedback control. On the other hand, the load from in-vehicle equipment changes rapidly. However, the appearance of the rapid change has reproducibility in each piece of equipment. Thus, the variation pattern for in-vehicle equipment is modeled as time series data.

The measurement results of the power generation current change for the high-beam headlamps (60 [W] × four lights = 240 [W], for four head lamps) is shown in Figure 3 by the solid line. The power generation current increases rapidly after lighting the high-beam headlamps at time 0. After the power generation current overshoots and settles to a steady-state value. The electric power generation before time 0 is the electric current required for ignition, for example, and is approximately constant during idle driving. The fundamental of the load pattern while running the high-beam headlamps based on the power generation current is shown by the dotted line of Figure 3.

Similarly, the change in the amount of power generation current associated with starting the air conditioner in shown in Figure 4. The sum of the abovementioned power generation torque and the driving torque of the compressor is taken as the air conditioner load. The clutch connects after hundreds of milliseconds when the air-conditioning switch is turned on and the compressor is driven.

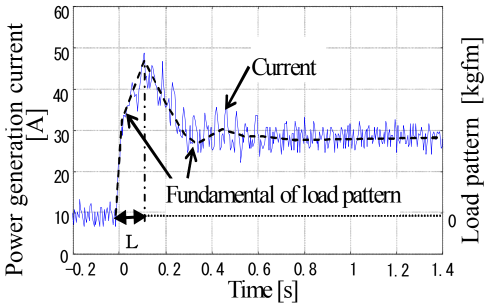

Fig. 3. Load current and load torque prototype generated by high-beam headlamps

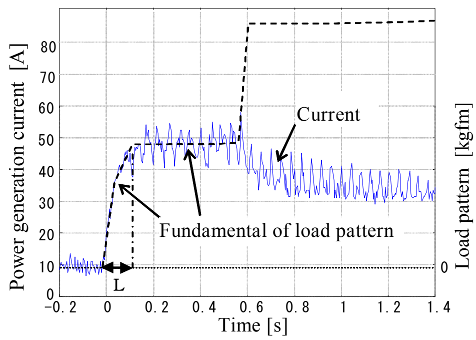

Fig. 4. Load current and load torque prototype generated by the air conditioner

The load pattern of the air conditioner load is shown by the dotted line of Figure 4. An actual load torque is obtained by multiplying a constant coefficient by this load pattern according to the vehicle characteristic.

The abovementioned load pattern is sampled, and time series data of the load torque model are composed.

3.2 Composition of idling speed control system

The engine speed does not change if the engine torque Te always corresponds to Tload, which is the total the load torque generated by in-vehicle equipment outside the engine. The constant engine speed is ideal for idle driving. That is, the sum of Tloss and T_{load} must always correspond to the combustion torque, as shown in expression (6).

$$T_{load} + T_{loss} = \alpha \frac{Qi}{N} \left(= Ti\right) \qquad (6)$$

Here, a slowly changing load like the engine internal loss can be compensated by the feedback control. On the other hand, improved idle stability can be attempted by performing feedforward control using the engine model for the load torque that changes rapidly generated by in-vehicle equipment.

Figure 5 shows a block diagram of the composition of the control system that combines this feedback control with the feedforward control.

The manipulated variable of the feedback control and the feedforward control is air mass flow rate at the throttle. The required air mass flow rate at the throttle is converted into the throttle opening degree using expression (1) and the relationship between the throttle opening degree and the area, and the target throttle opening degree is requested.

A general PID control is used for the feedback control. When the change in the load is gradual, stable driving can be achieved.

In the feedforward control, the combustion torque Ti is increased to become ΔTi = Tload when the load of Tload increases, and ΔQa (increment of the air mass flow rate at throttle) is obtained as follows. The increment of the combustion air in the cylinder, ΔQi, should increase to maintain the target engine speed and the control system design is theoretically obtained as follows:

$$\Delta Qi = \frac{T_{load}}{\alpha} No \qquad (7)$$

Here, No is the target engine speed in the control system design. To achieve ΔQi, ΔQc is obtained by as

$$\Delta Qc = e^{L} s\, \Delta Qi \qquad (8)$$

Here, ΔQc is the increment of airflow rate at the cylinder port. The right side of expression (8) is the increment of the combustion air in the cylinder after time L.

In the feedforward control, it is necessary in order to forecast load Tload(t+L) after time L and to calculate ΔQc for ΔQi(t+L). The control block that achieves this is "Time series data selection" and "Stroke dead time compensation and air mass flow rate conversion" in Figure 5. First, the swiching-on of the equipment is detected in the "Time series data selection" block, and the time series data of load pattern ΔPL of the pertinent equipment is selected. Load torque Tload(t+L) (= ΔPL(t+L)) generated by the equipment after L s from the present time t is obtained from ΔPL in the "Stroke dead time compensation and air mass flow rate conversion" block in order to increase the engine torque that corresponds to Tload(t+L) by using expression (7), ΔQi(t+L), i.e., ΔQc(t), is obtained. Here, L is the value at which No = 700 [rpm] is substituted for N in expression (4).

The increment of air mass flow rate at the throttle (ΔQa) is increased as follows in order to increase ΔQc in expression (8):

$$\Delta Qa = \left(1 + \gamma s\right)\Delta Qc \qquad (9)$$

This ΔQa is theoretically needed as a manipulated variable of the feedforward control and is obtained in the "Charge delay compensation" block according to expression (9).

The details of the composition of the proposal control system were shown above. If the equipment, such as the air conditioner compressor, starts after time L after switching on the equipment, it is possible to make the engine torque balance the load torque at any time by this control.

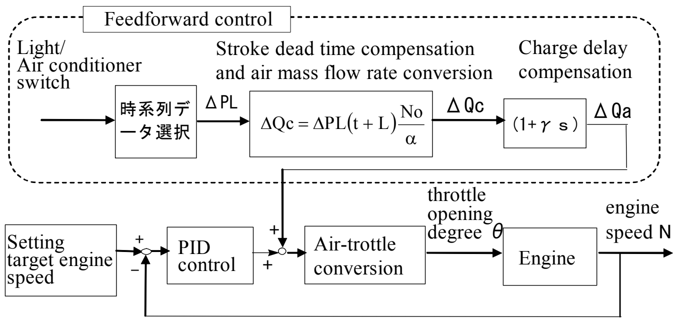

Fig.5. Block diagram of the idle speed control system

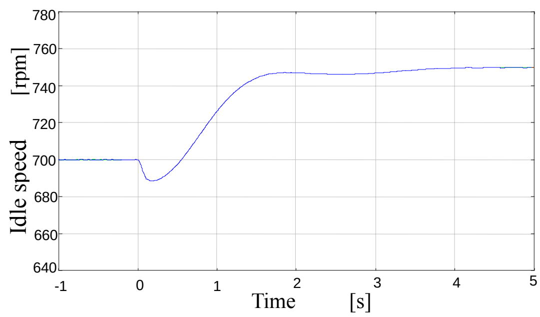

Fig.6. Simulation results

The engine speed response by this control to the lighting of the high-beam headlamps is that the load torque increases immediately after the headlamps are confirmed to have been switched on. The target engine speed smoothly increases the idle up to 750 [rpm] from 700 [rpm] under the no-load condition after lighting the headlamps according to the control specifications of a commercially available vehicle. Figure 6 shows the results. The engine speed decreases once by approximately 10 [rpm] between approximately 100 [ms] from the throttle operation to the increase of the engine torque after headlamp lighting at time 0.

Afterwards, the balance of torque recovers, and the target engine speed is promptly realized.

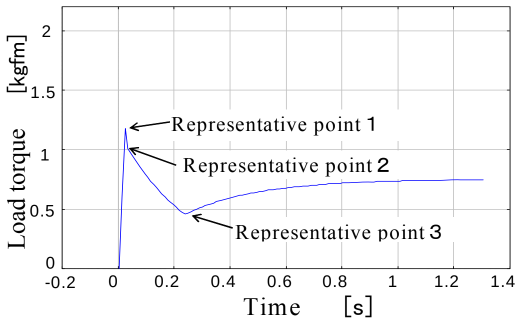

Fig.7. Load torque pattern generated by high-beam headlamps

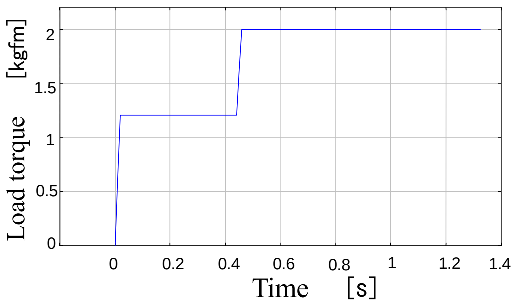

Fig.8. Load torque pattern generated by the air conditioner

4 Setting of load pattern and control performance evaluation

The idling speed control system shown in Section 3 is evaluated with a practical vehicle. Evaluation experiments were conducted on the idle stability under the load generated by the high-beam headlamps (60 [W] × four lights = 240 [W] for four headlamps), which is a typical electrical load, and the load that includes the driving of the machinery. The prototype car was obtained by adding an electronically controlled throttle, a TCM, and an ECU to a commercially available model of car.

In order to approximate a practical vehicle condition, the high-beam headlamps load pattern and the air conditioner load pattern obtained experimentally, as shown in Figures 3 and 4, are converted. For instance, the torque necessary to maintain the engine speed when lighting the high-beam headlamps is obtained. The proportionality coefficient of the electric power generation and the power generation torque is obtained according to this torque and the amount of the power generation current after lighting the headlamps, and the previously measured value of the basic load pattern (Figure 3) is converted. Next, the modeling error is absorbed by choosing a representative point where the externals of a basic pattern are retained, observing the response of an actual engine speed, and adjusting the value of the representative point by hand several times. It is possible to smoothly supplement the representative points. Figure 7 shows the load pattern that is eventually obtained. The absorption of the error is adjusted with respect to the air conditioner based on the basic load pattern (Figure 4).

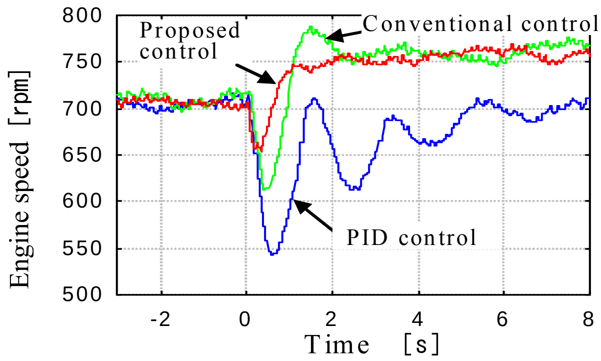

Fig.9. Experimental result for the high-beam headlamps

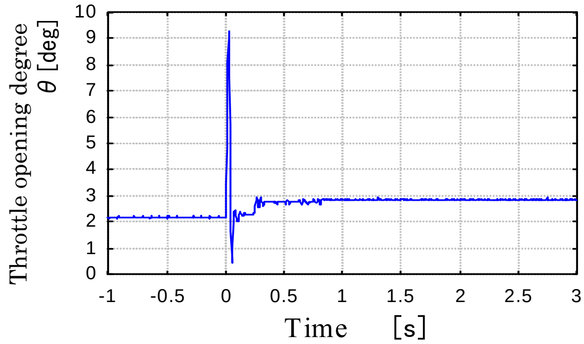

Fig.10. Throttle angle upon turning on the high-beam headlamps

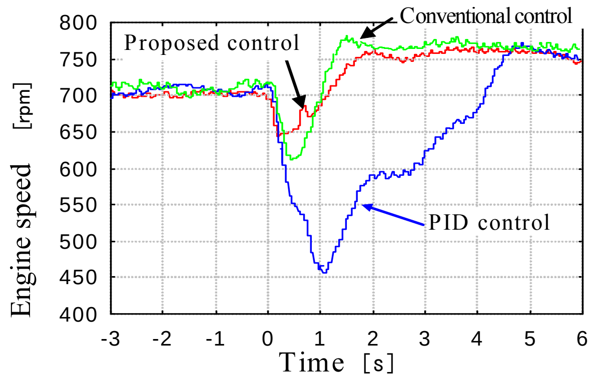

Fig.11. Experimental results for the air conditioner

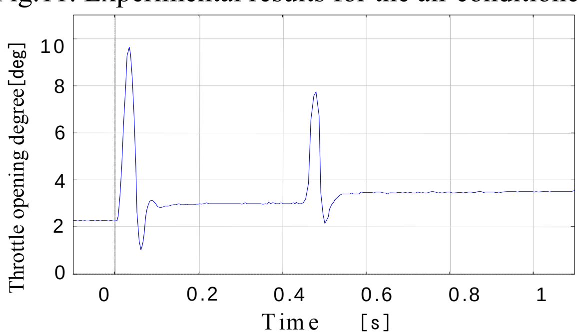

Fig.12. Throttle angle upon starting the air conditioner

Figure 9 shows the air conditioner load pattern that is eventually obtained. Each load pattern also retains the outline of the basic pattern.

The idle stability is confirmed with the abovementioned load pattern set to the controller. The target engine speed rises smoothly up to 750 [rpm] from 700 [rpm] at idle under the no-load condition like simulation results (Fig.6). The following three types of control systems are evaluated by the comparative experiment: the proposal control systems, a PID control system, and a conventional control system. The conventional control system is a method of adding the slight fixed throttle opening degree to the manipulated variable of PID control when in-vehicle equipment is used. The response of a usual control method corresponds to the response of the control that increases the air mass flow rate at throttle, which flows to the bypass pipe when the load torque changes in the system with a conventional machine type throttle.

Figures 9 and 10 show the experimental results for the lighting of the high-beam headlamps. The light is turned on at time 0. Figure 9 shows the engine speed response. When the change in the engine speed after lighting the high-beam headlamps is compared, the change in engine speed approaches the target engine speed promptly in the proposed system, as compared with PID control and the conventional control method. If the decrease in engine speed immediately after switching on the headlamps and the amount of overshoot of the engine speed at the time of recovery are considered, the proposed method provides an improvement of approximately 30% compared to the conventional control method. Figure 10 shows the change in the throttle opening degree of the proposed system. The throttle is opened wide and quickly upon lighting the headlamps, and sufficient air is provided in the intake manifold. In addition, the engine torque is increased quickly.

Figures 11 and 12 show the experimental results of for starting the air conditioner. The switch is turned on at time 0. Figure 11 shows the engine speed response. In the proposed system, the engine speed variation associated with the air conditioner load is improved by approximately 30% compared to the conventional control method. A comparatively large decrease in engine speed does not occur, even though there is a slight engine speed change before and after starting the air conditioner compressor (0.56 [s]). Figure 12 shows the change in the throttle opening degree for the proposed system. The throttle twice opens widely and closes, because the electrical load increases first with the startup of the air conditioner and later with the load generated by the compressor. The abovementioned experimental results indicate that the load pattern can be set to absorb the modeling error. Moreover, for typical electrical and air conditioner loads, the control performance of the proposed system is confirmed to be superior to conventional system.

5 Conclusion

In the present paper, an idling speed control system that includes feedforward control was demonstrated using an engine model based on a theoretical gas formula. The proposed system adopts an electronically controlled throttle with fast operation and large capacity as a means of adjusting the air mass flow rate at the throttle. As a result, the proposed system provides highly accurate rotation control, even considering the problem of controlling the air system, where the response is slow. In addition, the idle stability when the high-beam headlamps and the air conditioner are used was evaluated using an actual car. When the engine speed variation associated with equipment use was evaluated, an improvement in idle stability of approximately 30% could be confirmed compared with conventional control methods used in currently available vehicles.

The approach by this control sets the target torque of the engine. The above-mentioned results are advantageous from the viewpoint of torque control. In the future, the development of overall driving force control of the vehicle will be examined.

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