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A Performance Improvement in Idle-Speed Control System with Feedforward Compensation for the Alternator Load Current

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ABSTRACT

It is well-known that decreasing idle speeds is one of the ways to reduce fuel consumption. On the other hand, it is also well-known that even slight fluctuations of the idle speed cause unpleasant vibrations of the vehicle when this speed is set at low values. Therefore, it is important to create idle-speed control (ISC) systems that undergo less idle-speed fluctuations with respect to various load disturbances, in order to reduce fuel consumption without giving rise to unpleasant vibrations.

The first topic of this paper is a linearized model which derives a new feedforward compensation method for reducing idle-speed fluctuations caused by load distrubances for specific electric loads. The second concerns the control results of our ISC system using this feedforward compensation. The final topic is a discussion of the validity of the parameter values used in the feedforward compensation.

FOR IMPROVEMENTS OF AUTOMOTIVE ENGINE PERFORMANCE, the following items immediately suggest themselves : high power, high fuel economy, high response, and low vibration of the vehicle. Many investigators have been engaged in such improvements. Recently, of all these improvements, fuel economy has again attracted attention, because it will also be able to reduce the greenhouse effects of carbon dioxide.

For improving fuel economy, there are several approaches: (1) decreasing frictional losses in engines, (2) improving combustion in engines, and (3) decreasing fuel consumption in a given driving mode. Reducing idle speed are obvious means of decreasing fuel consumption, because the fuel consumed while idling makes no contribution to work done by the engine. On the other hand, it will be readily recalled that decreasing idle speeds often causes not only degradation of idling stability, but also unpleasant vibrations of the vehicle caused by large fluctuations of idle speed under slight load disturbances. Therefore, the technical issues of decreasing idle speed fluctuations are important to satisfy the requirements of both fuel economy and good driveability. As candidates to solve this issue, idle-speed control (ISC) systems are appropriate.

Unfortunately, the degree of control achieved by current commercially-available ISC systems is still unsatisfactory. Therefore, many investigators have been making efforts to improve the control provided by ISC systems. For examples, Takahashi et al. have discussed the application of modern control theory to ISC systems.(1)* Osawa et al. have also proposed the application of an adaptive control scheme to ISC.(2) Despite these efforts, it seems that no remarkable progress in the control provided by ISC systems is to be found in the literature. Quite apart from the issue of fuel economy, there is another important reason for reducing the excursions of idle speed from the nominal value. Recently, automobiles have been equipped with many kinds of electrical equipment and as a result, every electrical load variation can cause idle-speed fluctuations. As noted previously, such electrical load variations will cause unpleasant vibrations for those in the vehicle.

In this paper, we propose an ISC system which can greatly reduce idle-speed fluctuations caused by various electrical load variations. Our ISC system manipulates air-flow rates both proportionally to the load currents of alternators and their derivatives. We show theoretically that this feedforward manipulation of air-flow rates results in a significant reduction of transient idle-speed fluctuations. Then, we confirm experimentally that this ISC system shows the expected characteristics. We finally

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* Number in parentheses designate references at the end of the paper

discuss the agreement of both proportional and derivative gains between theory and experiment.

DERIVATION OF IDLE SPEED DYNAMICS, INCLUDING THE ALTERNATOR

Despite the great influence that alternators can have on idle-speed dynamics, there have been few papers discussing alternator dynamics and linking them with engine-speed dynamics while idling. Therefore, we start our discussion with a review of alternator and engine-speed dynamics. For simplicity, we confine our discussion to the frequency domain.

First we derive the dynamics of an alternator. Figure 1 shows the equivalent circuit of an alternator. The instantaneous relations among field current I_f〔A〕, load current I_a〔A〕, induced voltage E〔V〕 and required torque T〔Nm〕 are represented by the following equations.(3)

$$E = P\ M\ \omega_m\ I_f \qquad [\mathrm{V}] \tag{1}$$

$$T = P\ M\ I_f\ I_a \qquad [\mathrm{Nm}] \tag{2}$$

where P is the polar number, M is mutual inductance〔H〕, N is engine speed〔rpm〕, α_p is pulley ratio, and ω_m is mechanical angular speed ($= \pi N \alpha_p / 30$). By taking deviations of various physical quantities from an equilibrium state in Eqs. (1) and (2) and normalizing by equilibrium value, we obtain the follwoing equations.

$$\Delta E^* = \Delta I_f^* + \Delta N^* \tag{3}$$

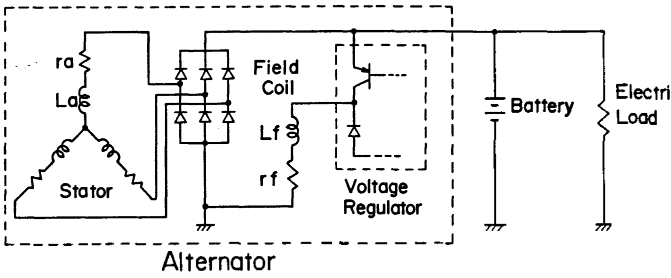
$$E_o = \frac{\pi P M \alpha_p}{30} N_o\ I_{fo} \qquad [\mathrm{V}]$$

$$\Delta T = T_o\,(\Delta I_f^* + \Delta I_a^*) \tag{4}$$

$$T_o = P\ M\ I_{ao}\ I_{fo} \qquad [\mathrm{Nm}]$$

where Δ means deviations from their equilibrium values, subscript o their equilibrium values, and superscript * the values normalized by them, respectively.

The field circuit is represented by a series connected resistance and inductance. The relation between excited voltage E_r〔V〕 and I_f is obtained by Laplace transformation as shown in Eq.(5).



$$\Delta E_r^* = (1 + s\,\tau_f)\,\Delta I_r^* \tag{5}$$

$$\tau_f = \frac{L_f}{r_f} \qquad [\mathrm{s}]$$

equivalent inductance : L_f 〔H〕
equivalent resistance : r_f 〔Ω〕

The relation among E, I_a and load voltage V〔V〕 is also represented by a series connected resistance and inductance. But the equivalent inductance of stators can be neglected. Therefore, we derive the following simple equation.

$$\Delta E^* = \Delta I_a^* + \Delta V^* \tag{6}$$

Generally, the terminal voltage V is regulated to a constant voltage, typically 14〔V〕, by controlling the field current. As is well-known, this control of the field current is performed by modulating the pulse width of the current. Therefore, strictly speaking, the action of the voltage regulator cannot be expressed by a block diagram. However, for simplification, it is assumed that terminal voltage ΔV is in proportion to field current ΔI_f and that an effective gain K_f is so defined. We have also approximated the control action by a simple feedback loop, because our primary object is to derive the overall dynamics of the alternator, not to derive the strict dynamics of the voltage regulator itself. From the above equations, the alternator dynamics shown in Fig. 2 can be easily derived.

Next, we derive the dynamics of engines. We have already described this derivation.(4-6) Therefore, only the results of our papers are cited here.

$$\Delta \dot{G}_a^* - \Delta N^* = \Delta P_b^*\,(1 + s\,\tau_a) \tag{7}$$

$$\Delta T_e = K_p \exp(-sL)\,\Delta P_b^* \tag{8}$$

$$\Delta N^* = \frac{\Sigma\, T_j}{K_d\,(1 + s\,\tau_d)} \tag{9}$$

where $\dot{G}_a$ is air-flow rate〔kg/s〕 through a throttle valve, P_b manifold absolute pressure〔Pa〕, N engine speed〔rpm〕, T_e brake torque〔Nm〕, L dead time〔s〕, and T_j torque disturbance〔Nm〕 for engines, respectively. The time constants τ_a and τ_d and other related parameters are defined by the following equations:

$$\tau_a = \frac{120\ V_m}{\eta_{vo}\ N_o\ V_h} \qquad K_p = \frac{\Delta T_e}{\Delta P_b} P_{bo}$$

$$K_d = \frac{c\,\pi}{30} N_o \qquad \tau_d = \frac{J}{c}$$

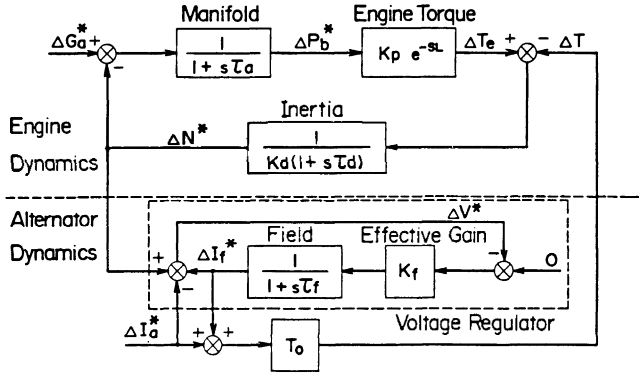


Fig. 2 Idle-Speed Dynamics, Including Alternator

where Vm is manifold volume $[m^3]$, V_h stroke volume $[m^3]$, η_v volumetric efficiency, J mement of inertia $[kgm^2]$, and c resistance coefficient [kgm], respectively.

Equations (7)-(9) give the engine-speed dynamics as shown in Fig. 2 (the upper parts). Therefore, the overall dynamics of idle-speed including an alternator are given by the block diagram in Fig. 2.

Figure 2 readily suggests the mutual interactions between an engine and an alternator. Suppose that the engine speed is decreased from its original equilibrium value by any load ($\Delta N^* < 0$). This means a reduction of the terminal voltage ($\Delta V^* < 0$). Therefore, the regulator will increase its field current so as to keep the terminal voltage constant ($\Delta I_f^* > 0$). This causes a torque increase (ΔT) and it reduces the engine speed. That is, there is qualitatively a visible reduction in engine friction effect when using an alternator. Beside this qualitative understanding of the alternator action, we can derive a control strategy for imrpoving control results of ISC systems as shown below. For this purpose, we derive a relation among ΔN^*, $\Delta \dot{G}_a^*$ and ΔI_a^*. Assuming that the effective gain K_f is large enough for practical use and the deadtime L small enough, we can easily obtain the following relation using the block diagram in Fig. 2.

$$\Delta N^* = \frac{K_p\,\Delta\dot{G}_a^* - 2\,T_o\,(1+s\,\tau_a)\Delta I_a^*}{K_p+K_d-T_o+s(\tau_a(K_d-T_o)+K_d\,\tau_d)+s^2\,\tau_a\tau_d K_d} \qquad (10)$$

From Eq.(10), the following useful results are obtained.

(1) If we can control air-flow rates so as to maintain the following equation, we can always make $\Delta N^* = 0$ for any variation of load current ΔI_a^*.

$$\Delta\dot{G}_a^* = \frac{2\,T_o}{K_p}\,(1 + s\,\tau_a)\,\Delta I_a^* \qquad (11)$$

That is, in order to reduce idle-speed fluctua- loads, we must control intake air flow rates according to both the proportional and derivative of the currents. This feedforward compensation is the theoretical basis of our ISC system.

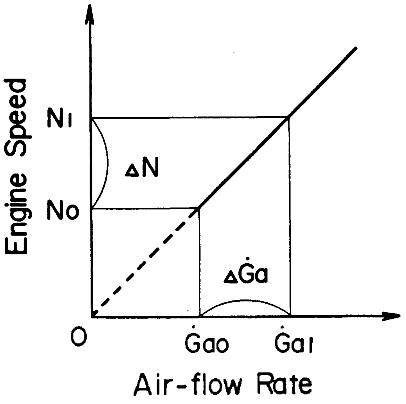
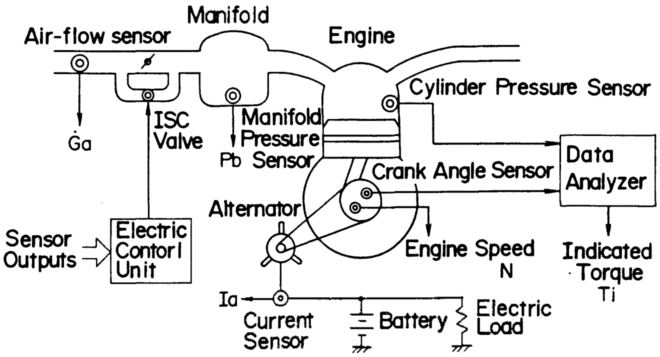


Fig. 3 Relation between Engine Speed and Air-Flow Rate

(2) In Eq.(10) the torque T_o caused by the current of the alternator always appears in the form of the difference $K_d - T_o$. This implies the alternator effectively decreases the friction K_d of engine. Therefore, alternators degrade idle stability. In other words, idle stability will be different according to alternator characteristics for a given engine. As a special case, the variation of idle speed ΔN^* is equal to the variation of air-flow rate $\Delta\dot{G}_a^*$, when T_o is equal to K_d. Then we obtain the relation as shown in Fig. 3. It should be noted that the relation between engine speeds and air flow rates is represented by a straight line which passes through the origin.

DETERMINATION OF CONTROL PARAMETERS FOR ISC SYSTEM

In order to design ICS system with the feedforward compensation formulated in Eq.(11), we must determine the values of parameters T_o,



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