Proceedings of the 9th WSEAS International Conference on Applied Mathematics, Istanbul, Turkey, May 27-29, 2006 (pp466-470)

Low Fuel Consumption Control Scheme Based on Nonlinear Optimzation for Engine and Continuously Variable Transmission

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Abstract: - The environment has recently led to very severe regulations on fuel consumption and exhaust emissions. I propose a scheme to minimize rate of fuel consumption for a direct fuel injection engine used by combination with a continuously variable transmission. Target values for the engine and the transmission which minimizes fuel consumption ensuring driving performance is calculated based on the nonlinear optimization method. The engine and the transmission are controlled cooperatively.

The simulation in the acceleration test and the 10-15 mode tests showed that the proposed method is effective to achieve low fuel consumption ensuring driving performance.

Key-Words: - Direct fuel injection engine, Continuous variable transmission, Driving performance, Fuel consumption, Nonlinear optimization, Simulation test

1 Introduction

A direct fuel injection engine control system that reduces fuel consumption has recently attracted attention. Because it burns fuel under very lean conditions so that the theoretical heat efficiency is improved and fuel consumption reduced.

Another way to reduce fuel consumption is to have the engine run around an optimal fuel consumption point. This is achieved by cooperative control of the engine and a continuously variable transmission (CVT).

This paper proposes a new engine-transmission cooperative control scheme based on nonlinear optimization for DI engine and CVT. The scheme incorporates driving torque demand control in which the target driving torque is calculated based on the degree to which the accelerator is depressed. Fuel consumption is optimized by minimizing the specific fuel consumption characteristics under various restrictions, including the achievement of target driving torque. These characteristics are previously formulated as a function of engine running conditions. As a result of optimization, target values for an engine and transmission, such as target air-fuel ratio and target gear ratio can be calculated and controlled by tracking. Under this scheme, the application of dynamic fuel consumption characteristics enables the optimization of fuel consumption in the transient condition as well as in the static condition.

2 A driving torque demand control scheme for DI engine and CVT

2.1 Concept of Low Fuel Control

Fuel consumption can be improved by using an engine with a continuously variable transmission and operating an engine around a low fuel consumption point [1]. Figure 1 shows an example of specific fuel consumption characteristics of a multi point fuel injection system (MPI). Fuel consumption is minimized at only one point. If we operate the engine only at this point, however, the driving performance is not satisfied because the driving torque to be generated for each vehicle speed is limited. To ensure the proper driving performance, the desirable driving torque is calculated according to the degree the accelerator is depressed. The engine and transmission are controlled cooperatively to minimize fuel consumption ensuring the target driving torque. This is called driving torque demand control [2]. A ‘drive by wire’ structure using the electric throttle control device was adopted for this control.

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In DI engines, the specific fuel consumption is influenced by the air-fuel ratio and Exhaust gas recirculation (EGR) rate as well as engine torque and engine speed. Therefore target values for these variables must also be calculated to minimize fuel consumption, and the engine is controlled so as to achieve target values.

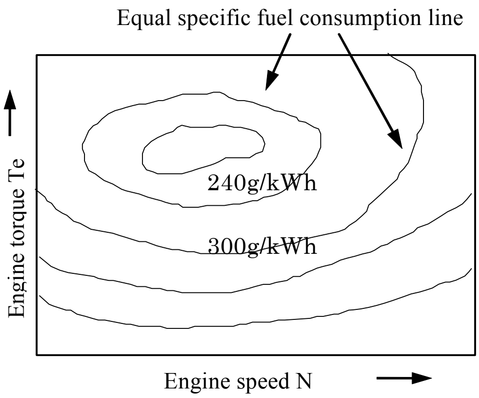

Fig. 1 An example of fuel consumption

2.2 Concept System

Figure 2 shows the cooperative control system for DI engine and CVT. The drive by wire structure includes a sensor for measuring the degree the accelerator is depressed and an electronic throttle control device. An EGR system is used to purify the NOx component of exhaust emissions.

2.3 Concept Scheme

Figure 3 shows the block diagram of the drive torque demand controller based on DI engine and CVT that can minimize fuel consumption. The controller consists of a target driving torque calculation block, a fuel consumption optimization block, and a dynamic control block.

2.3.1 Target driving torque calculation block

The target static driving torque Tdo is obtained from a two-dimensional table showing accelerator depression degree and vehicle speed. The desired driving torque data are stored in the two-dimensional table. The target transient deriving torque Td is calculated by passing the target static driving torque Tdo through a dynamic lag filter, such as

$$Td(i) = \frac{\Delta t}{T} \cdot Td0(i) + \left(1 - \frac{\Delta t}{T}\right) \cdot Td(i-1) \qquad (1)$$

$$T = \frac{120 \cdot Vm}{N \cdot \eta \cdot Vd}, \qquad (2)$$

where, Vm is the volume of the intake manifold, Vd is total engine displacement, N is engine speed (rpm), ηis volumetric efficiency, Δt is time interval, and i is time.

This procedure simulates torque response delay in the current engine control systems caused by air flow delay in the intake manifold.

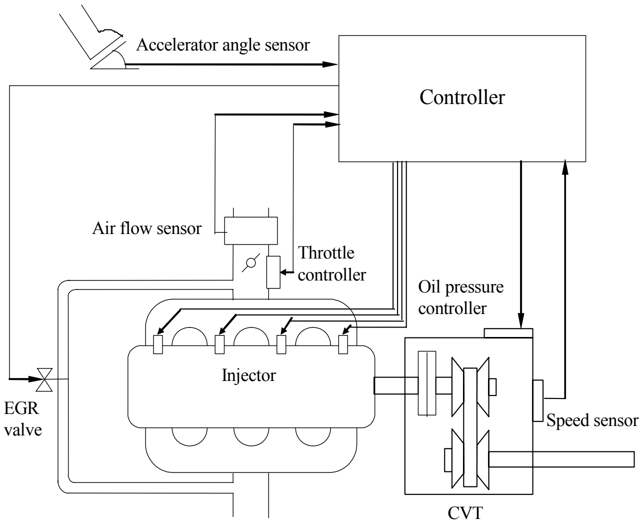

Fig. 2 Cooperative control system for the DI engine and CVT

2.3.2 Target driving torque calculation block

This block calculates target values for an engine and transmission such as the target air-fuel ratio, target engine torque, and target gear ratio which minimize fuel consumption.

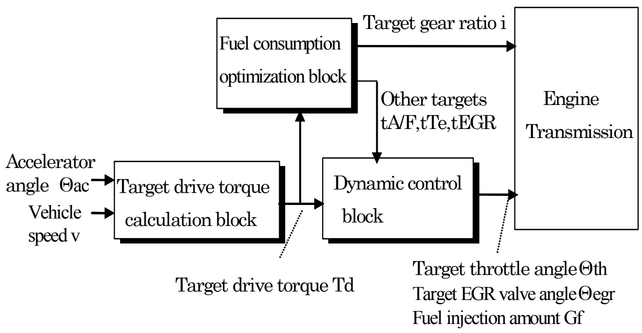

Fig.3 Block diagram of DI and CVT cooperative control scheme

The specific fuel consumption used, Cf (g/kWh), can be expressed as

$$Cf = \frac{10^3 \times Gf}{P} \quad , \tag{3}$$

where Cf is specific fuel consumption per unit of time (g/kWh), Gf is fuel injection amount (kg/h), and P is engine power (kW).

Engine power P can be written as

$$P = \frac{2\pi \cdot N \cdot Te \cdot g_0}{60 \times 1000} \quad , \tag{4}$$

where Te is engine torque (kgfm), N is engine speed (rpm), and g0 is gravity acceleration.

There is also the following approximate relation between engine torque Te and fuel injection amount Gf:

$$\begin{aligned} Te &= Tc - Tpl - Tfr - Tfp \\ &= k \cdot \frac{Gf}{N} \cdot f(A/F, uniform \cdot stratiform, \mathrm{Re}gr) \cdot g(k\frac{Gf}{N}) \quad (5) \\ &\quad - Tpl(Pm) - Tfr(N) - Tfp(N, Pf) \end{aligned}$$

where Tc is combustion torque (kgfm), Tpl is pump loss torque (kgfm), Tfr is friction torque (kgfm), Tfp is fuel pump drive torque (kgfm), A/F is air-fuel ratio, Regr is EGR rate, Pm is intake manifold pressure, Pf is fuel pressure (atm), f is combustion efficiency correction coefficient, g is operating point correction coefficient, and k is constant.

The specific fuel consumption Cf can be written as follows by eliminating a variable Gf from expressions (3) through (5).

$$Cf = \frac{ko}{Te} \cdot G^{-1}\left[\frac{Te + Tpl(Pm) + Tfr(N) + Tfp(N, Pf)}{f(A/F, uniform \cdot stratiform, \mathrm{Re}gr)}\right] \tag{6}$$

$$G(x) = x \cdot g(x)$$

Here, ko is constant.

Now, the specific fuel consumption function Cf is minimized under various restrictions concluding target driving torque achievement. The restrictions include engine speed, torque, gear ratio, pulley input rotation speed, air-fuel ratio, EGR rate, ensuring a manifold pressure for the brake, achieving target drive torque, and vehicle speed. The relation between drive torque Td and engine torque Te in the table is static. On the other hand, the relation is in transition as follow,

$$Te = \ell 1 \cdot \frac{Td}{i} + \ell 2 \cdot \frac{1}{i} \cdot \frac{dv}{dt} + \ell 3 \cdot \frac{dN}{dt} \, , \tag{7}$$

where, li (i=1, 2, 3) is constant determined by inertia moment of rotators, final gear ratio, torque transmission efficiency, and so forth. We use expression (7) to optimize transient fuel consumption.

Restrictions mentioned above are needed for driving an engine stably ensuring that emissions and driving performance are satisfactory.

We analyzed the specific fuel consumption function of expression (6) under the restrictions. The problem of optimizing fuel consumption is equal to the problem of determining air-fuel ratio A/F, shift gear ratio i, and EGR rate Regr to minimize a specific fuel consumption function Cf under the restrictions and given a target driving torque Td and vehicle speed v. At the same time, engine torque Te, engine speed N, air flow rate at cylinder port Qap, fuel injection amount Gf are also determined, and become target values for engine and transmission control.

To minimize a nonlinear fuel consumption function Cf, we used a simplex method which does not require a partial differential of a function. Engine control is usually digital control. Characteristics such as expression (6) are generally stored in some tables. Because the calculation of partial differential is impossible at some operating points, we used a simplex method that does not require calculating differential values. For minimization of fuel consumption function Cf under various restrictions, we also introduce penalty functions, which increase value of fuel consumption Cf , when the restrictions are not satisfied.

2.3.3 Dynamic control block

The dynamic control block calculates the degree to which the throttle is open, Θth; the fuel injection amount, Gf; and the degree to which the EGR valve is open which achieve targets for engine control, that is, target engine torque Te, target air flow rate Qap, and target EGR rate Regr. There is transport delay for the air flow and EGR flow. A dynamic model is needed for controlling the air flow rate and EGR rate. The following expressions are used to derive the control scheme for achieving the target air flow rate.

$$Qap = \frac{N \cdot Vd \cdot \eta \cdot Pair \cdot Mair}{120 \cdot R \cdot Tm} \, , \tag{8}$$

$$\frac{dPair}{dt} = \frac{R \cdot Tm}{Vm \cdot Mair} \cdot (Qat - Qap) \, , \tag{9}$$

$$Qat = Cd \cdot \frac{Aair \cdot Pa}{\sqrt{Ta}} \cdot \sqrt{\frac{2 \cdot k \cdot Mair}{(k-1) \cdot R}} \cdot f\left(\frac{Pm}{Pa}\right), \text{and} \tag{10}$$

$$Aair = BYPATH + \frac{\pi \cdot rth^2}{4} \cdot (1 - \frac{\cos(6 + \theta th)}{\cos 6}) \, . \tag{11}$$

$$\text{When } x > \left(\frac{2.0}{k + 1.0}\right)^{\frac{k}{k-1}}, \; f(x) = \sqrt{x^{\frac{2}{k}} - x^{\frac{k+1}{k}}} \, . \tag{12}$$

When $x \le \left(\frac{2.0}{k+1.0}\right)^{\frac{k}{k-1}}$,

$$f(x) = \sqrt{\left(\frac{2.0}{k+1.0}\right)^{\frac{2}{k-1}} - \left(\frac{2.0}{k+1.0}\right)^{\frac{k+1}{k-1}}} \quad . \qquad (13)$$

Here, Qat is air mass flow rate at throttle (kg/s), Qap is air flow rate at cylinder port (kg/s), Pm is intake manifold pressure (Pa), Pair is partial pressure of air in the intake manifold (Pa), N is enigne speed (rpm), ηis volumetric efficiency, Tm is temperature in the intake manifold (K), Vd is the displacement (m3), Vm is intake manifold volume (m3), R is gas constant (J/mol K), Mair is average mass of air molecular, Pa is atmospheric pressure, Ta is intake air temperature (K), Cd is the discharge coefficient, k is ratio of specific heats, BYPATH is the leak flow area (m2), rth is throttle bore radius (m2), Θth is throttle opening degree (deg), and t is time (s).

We obtain the following expression by differentiating expression (8).

$$\Delta Pair = \frac{120 \cdot R \cdot Tm \cdot \Delta Qap - Vd \cdot \eta \cdot Pair \cdot Mair \cdot \Delta N}{N \cdot Vd \cdot \eta \cdot Mair} \qquad (14)$$

The following expression is derived from expression (9)

$$Qat(i) = Qap(i) + \frac{Vm \cdot Mair}{\Delta t \cdot R \cdot Tm} \cdot \Delta Pair \ , \qquad (15)$$

where, i is time (one time corresponds toΔt), and Δt is time interval.

When the target air flow rate at cylinder port tQap is given, the partial air pressure deviation ΔPair is calculated based on the target air flow deviationΔQap and expression (14). Furthermore, the target air flow rate at throttle tQat is calculated from expression (15). If the target air flow rate at throttle is obtained, the target throttle opening degree tΘth which achieves the target air flow rate is determined. This target signal is transmitted to the throttle control module to control the throttle.

3 Simulation

3.1 Acceleration Test

An acceleration test was conducted to confirm the generation of the target value for the optimization block and the torque control performance for the dynamic control block. Figure 4 shows the simulation results. Smooth orbits for the target air-fuel ratio, and engine torque were achieved by the calculation of the optimization. The actual values match the target values very well.

The simulation confirmed the effectiveness of the optimization block and the dynamic control block.

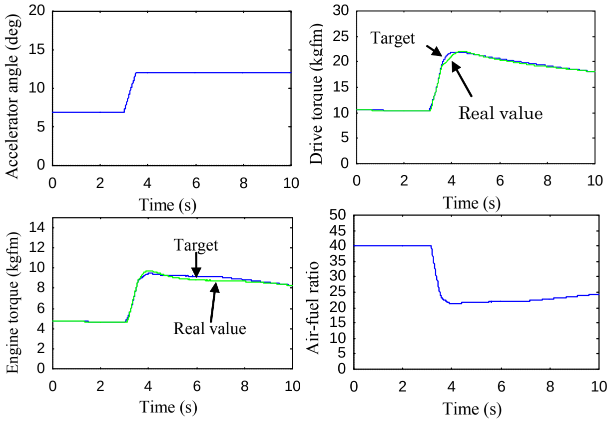

Fig. 4 Simulation results of acceleration test

3.2 10-15mode test

A simulation of the 10-15 mode tests in Japan to evaluate exhaust emissions was performed. Two schemes were evaluated for comparison. The scheme (b) is the one proposed in this paper.

(a) DI-CVT cooperative control scheme (stoichiometric setting of air-fuel ratio)

The air-fuel ratio is usually set to being stoichiometric. A value for the gear ratio which achieves minimum fuel consumption is determined and an MPI type engine and a transmission are controlled cooperatively.

(b) DI-CVT cooperative control scheme (total and dynamic optimization)

A target air-fuel ratio and target gear ratio which minimize fuel consumption are simultaneously determined by the optimization scheme discussed in Section 2.

The simulation results for the each scheme are shown in Figures 5,6. Fuel consumption is 12.13 km/l under scheme (a), 16.53 km/l under scheme (b). (b) is reduced by 26.0 % compared with scheme (a). The fuel consumption under scheme (a) is bad because the engine is not operated under lean burn conditions. The air-fuel ratio of (b) is stoichiometric in driving points in which the comparatively high engine torque is needed.

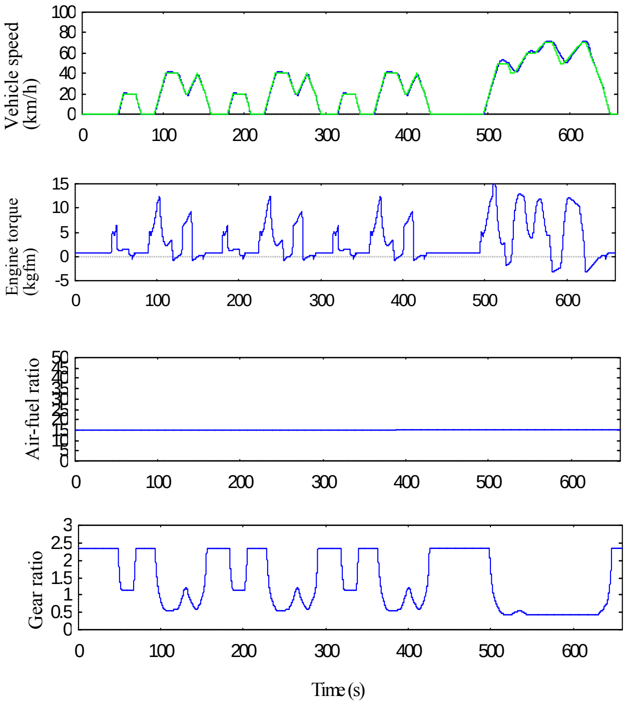

Fig. 5 Simulation results of 10-15mode test (DI-CVT stoichiometoric setting of air-fuel ratio)

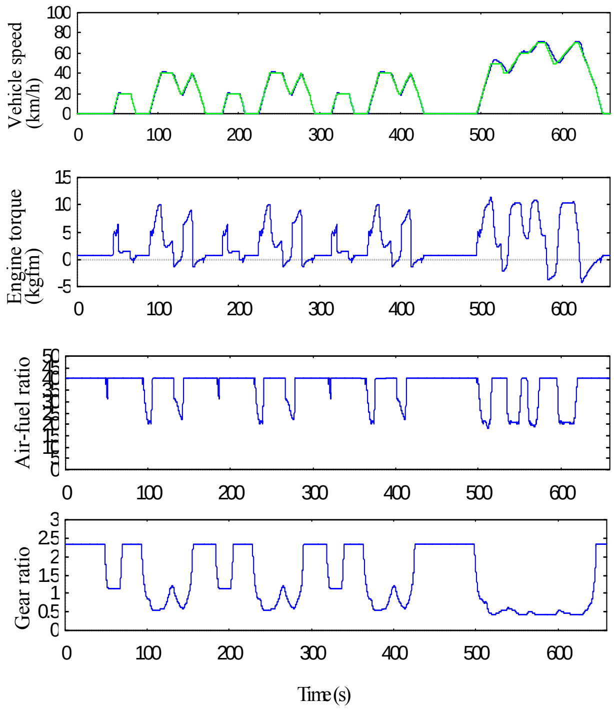

Fig.6 Simulation results of 10-15mode test (DI-CVT total and dynamic optimization)

4 Conclusion

(1)The proposed DI engine and CVT cooperative control scheme calculates the target values for the engine and the transmission which minimize specific fuel consumption. It ensures target drive torque and controls the engine and the transmission cooperatively. The calculation of targets is based on the nonlinear optimizationmethod.

(2)Control performance and fuel consumption performance are confirmed by simulations of the acceleration test and the 10-15 mode tests.

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