Integrated Engine-CVT Control Considering Powertrain Response Lag in Acceleration

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In this paper, an engine-CVT integrated control algorithm is suggested by considering the inertia torque and the CVT ratio change response lag in acceleration. In order to compensate for drive torque time delay due to CVT response lag, two algorithms are presented : (1) an optimal engine torque compensation algorithm, and (2) an optimal engine speed compensation algorithm. Simulation results show that the optimal engine speed compensation algorithm gives better engine operation around the optimal operation point compared to the optimal torque compensation while showing nearly the same acceleration response. The performance of the proposed engine-CVT integrated control algorithms are compared with those of conventional CVT control, and It is found that optimal engine operation can be achieved by using integrated control during acceleration, and improved fuel economy can be expected while also satisfying the driver's demands.

Key Words : CVT, Integrated Control, Response Lag

1. Introduction

If engine operation is maintained in the minimum fuel consumption region under all driving conditions, a significant improvement in fuel economy can be expected. For a conventional powertrain which consists of an internal combustion engine and an automatic transmission, power output is determined by the throttle valve opening (TVO), which is operated directly by the accelerator pedal. The automatic transmission controls the speed ratio depending on the TVO and the vehicle velocity. Since the engine operation point is determined by the TVO and the transmission ratio, it is impossible to maintain an optimal engine operation at all times in the minimum fuel consumption region. In order to achieve minimum fuel consumption relative to various levels of desired drive torque, both the engine speed and engine torque should be controlled simultaneously, which requires an integrated engine-transmission control. Since an automatic transmission, which has a stepped gear ratio, cannot provide optimal engine operation independent of the vehicle speed, a continuously variable transmission (CVT) is required for integrated engine-transmission control.

An engine-CVT integrated control algorithm has been suggested by Takiyama (1991). He developed an algorithm to control the vehicle velocity from the difference between the desired and actual velocity, and the CVT ratio from the difference between the desired and actual engine speed. However, he neglected transient characteristics of the powertrain, which resulted in poor performance when the magnitude of the vehicle acceleration changed. Recently, Takiyama (1999) investigated an engine-CVT integrated control algorithm with combined air-fuel ratio control to

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realize better fuel economy. In the engine-CVT integrated control, the target engine torque should be determined by considering the powertrain loss. Sakaguchi (1999) suggested an algorithm from the viewpoint of minimizing powertrain loss. Among the sources of powetrain loss of a CVT equipped vehicle, power loss due to the line pressure is a major contributing factor, since line pressure in the CVT hydraulic system can rise up to 50 bars. Power loss due to line pressure is determined from the engine torque and the CVT ratio. Therefore, the CVT ratio should be known to calculate the exact power loss. However, in order to determine the CVT ratio, the target engine torque should be given which can be calculated only when the power loss is known. Kim et al. (2000) developed an integral control algorithm to calculate the powertrain loss by an iteration procedure and showed that acceleration response is improved by powertrain loss compensation.

In a CVT powertrain, the drive torque is a product of the engine torque and the CVT ratio. In a situation where a large step-like increase in the drive torque is demanded, such as in kickdown maneuvers when accelerating rapidly, the response lag of the engine torque and that of the CVT ratio change translate directly into a drive torque response delay. Yasuoka (1999) developed an algorithm to obtain the demanded drive torque for optimum fuel economy. In his algorithm, he used the engine torque to compensate the drive torque response delay caused by the CVT response lag. Yasuoka calculated the target torque by assuming that the accelerator pedal travel represents the demanded drive torque and used the target gear ratio as the CVT ratio. In previous work by the authors, Kim et al. (1997) suggested a fuzzy logic based control algorithm considering the CVT shift dynamics.

In this paper, an integrated engine-CVT control algorithm is suggested to improve the transient performance of CVT vehicles by considering the inertia torque due to the CVT ratio change and the CVT ratio change response lag. Algorithms to compensate the drive torque response delay due to CVT response lag are presented by introducing the optimal engine torque and optimal engine speed compensation. Using the control algorithm suggested in this study and dynamic models of the CVT powertrain, performance of the integrated engine-CVT control algorithms are investigated during acceleration and are compared with those of conventional CVT control.

2. Integrated Engine-CVT Control Algorithm

The purpose of the integrated engine-CVT control is to realize optimal engine operation for minimum fuel consumption while also satisfying the driver's demand. For optimal engine operation, the engine should be operated at the optimal operating line(OOL). In Fig. 1, an OOL for minimum fuel consumption is shown on the engine characteristic map with TVO and isopower curves. The OOL for the minimum fuel consumption can be determined from the BSFC (brake specific fuel consumption) contours and iso-power curves. The optimal engine operation point is defined as the point where the optimal engine power curve crosses with the OOL. Minimum fuel consumption can be achieved by operating the engine at the optimal operation point by simultaneous TVO and CVT ratio control, or in other words, an integrated control.

In Fig. 2, a block diagram of the integrated engine-CVT control algorithm suggested in the previous work (1997) is shown. The integrated engine-CVT control consists of calculation of;

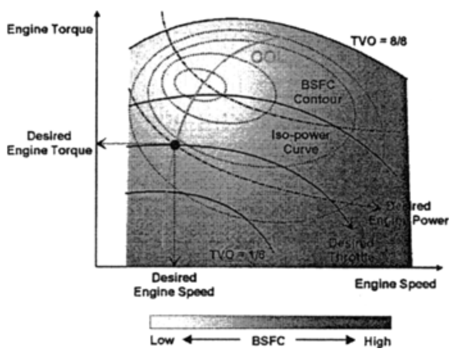

Fig. 1 Engine characteristic curves and OOL

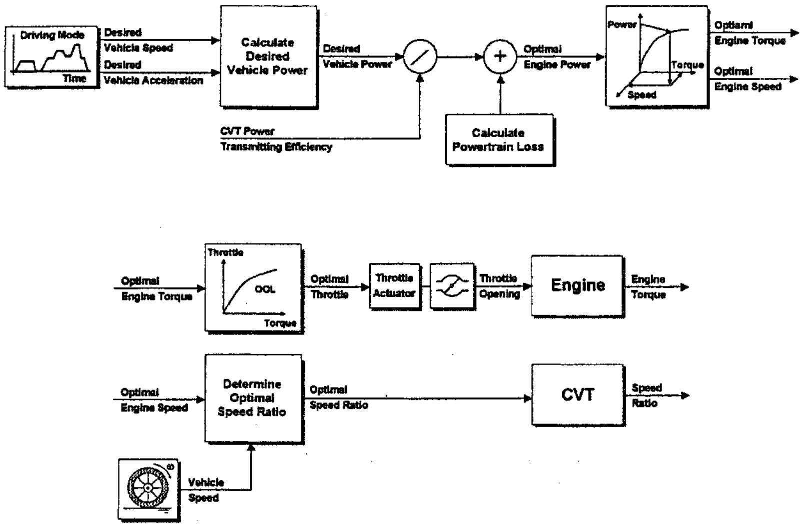

Fig. 2 Block diagram of engine-CVT integrated control algorithm

(1) the optimal engine power, and (2) the optimal TVO and CVT speed ratio. The integrated engine-CVT control is carried out in the following manner. The power required for the vehicle $P_{v,desired}$ is calculated by the following equation

$$P_{v,desired}=(F_L+M\dot{V}_{desired})\,V_{desired} \qquad (1)$$

where F_L is the road load, M is the vehicle mass, $\dot{V}_{desired}$ is the desired vehicle acceleration, and $V_{desired}$ is the desired velocity. In the ideal situation without the powertrain loss, the optimal engine power is obtained as

$$P_{e\ optiaml}=P_{v\ desired} \qquad (2)$$

However, in a CVT vehicle, there exists powertrain loss such as CVT hydraulic loss and auxiliary device loss. In order to obtain this powertrain loss, the optimal engine operation point, or the optimal engine power, should be determined, which can be calculated only when the powertrain loss is known. In a previous study (2000) by the authors, powertrain loss was estimated by an iteration procedure. Including the powertrain loss, the optimal engine power is modified as

$$P_{e\ optiaml}=\frac{P_{v\ desired}}{\eta_{cvt}}+P_{ptloss} \qquad (3)$$

where η_{cvt} is the CVT efficiency, and P_{ptloss} is the powertrain loss. From the optimal engine power and the OOL, the optimal engine torque $T_{e,optimal}$ and the optimal engine speed $\omega_{e,optimal}$ can be obtained as described earlier. In addition, the optimal TVO to generate $T_{e,optimal}$ is also determined from the optimal operation point. The optimal CVT ratio $i_{optimal}$ can be determined from $\omega_{e,optimal}$ and the actual vehicle velocity V as follows:

$$i_{optimal}=\frac{\omega_{e\ optimal}}{N_{frg}\omega_v} \qquad (4)$$

where N_{frg} is the final reduction gear ratio, and ω_v is the vehicle velocity. The above algorithm can be applied for steady-state driving situation with powertrain loss. However, during the transient state when the CVT ratio changes, the effect of the inertia torque due to the CVT ratio change should be considered. Furthermore, in order to improve the acceleration performance, drive torque compensation is required considering the CVT ratio change response lag during the transient state.

3. CVT Powertrain Dyanmic Model

Figure 3 shows a powetrain model of a CVT vehicle. In this study, a wet type clutch is used as a starting element. The Drive torque T_d at the wheel is obtained as

$$T_d=J_v\dot{\omega}_v=N_{frg}i\,(T_e-T_{eloss}-J_{eq}\dot{\omega}_e)$$

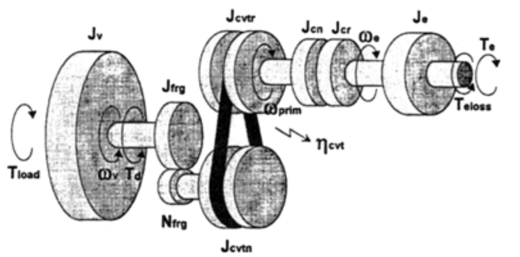

Fig. 3 CVT Powertain model

$$- T_{load} \tag{5}$$

where J_v is the vehicle inertia, i is the actual CVT ratio, T_{eloss} is the engine torque loss, and T_{load} is the road load. J_{eq} is the equivalent inertia viewed from the engine side and is expressed as

$$J_{eq} = J_e + J_{cr} + J_{cn} + J_{cvtr} + \frac{J_{cvtn}}{i^2} + \frac{J_{frg}}{(iN_{frg})^2} \tag{6}$$

where J represents the inertia of the powertrain element such as the engine (J_e), clutch (J_{cr}, J_{cn}), CVT drive pulley (J_{cvtr}), driven pulley (J_{cvtn}), and the final reduction gear (J_{frg}).

Differentiating Eq. (4) relating the engine speed ω_e and the vehicle speed ω_v by replacing $i_{optimal}$ with the actual CVT ratio i gives the following equation:

$$\dot{\omega}_e = N_{frg}\left(\frac{di}{dt}\omega_v + i\dot{\omega}_v\right) \tag{7}$$

From Eqs. (6) and (7), the vehicle acceleration can be obtained as

$$\dot{\omega}_v = \frac{N_{frg} i (T_e - T_{eloss}) - T_{load} - N_{frg} i \frac{di}{dt} J_{eq}\omega_v}{J_v + J_{eq} N_{frg}^2 i^2} \tag{8}$$

In the above equation, di/dt is the CVT ratio change rate which is determined from the CVT shift dynamics. In this study, the following CVT shift dynamics by Ide (1995) is used:

$$\frac{di}{dt} = \alpha(i)\,\omega_p (P_p - P_p^*) \tag{9}$$

where α is the constant depending on the speed ratio, ω_p is the primary pulley speed, P_p is the primary actuator pressure, and $P_p{}^*$ is the primary pressure at a steady state.

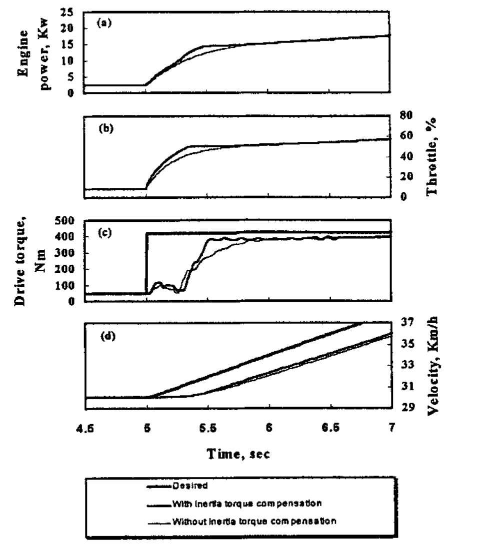

Fig. 4 Response for inertia torque compenstaion

4. Inertia Torque Compensation

The effect of the inertia torque during the transient state is investigated in this section. The last term on the right side of Eq. (8) is the inertia torque due to the CVT ratio change, di/dt. di/dt has a positive value during downshifts when the speed ratio increases and has a negative value during upshifts (Kim et al. 1998). Therefore, the inertia torque when the speed ratio increases contributes to reducing the acceleration torque, which results in hesitation of the vehicle response. In this study, the power due to the inertia torque is defined as

$$P_{inertia} = N_{frg} i \frac{di}{dt} J_{eq}\omega_v\omega_e \tag{10}$$

Compensating the power due to the inertia torque, the optimal engine power is modified as

$$P_{e\ optiaml} = \frac{P_{v\ desired}}{\eta_{cvt}} + P_{aux} + P_{hyd} + P_{inetia} \tag{11}$$

Figure 4 shows simulation results for the engine-CVT integrated control with inertia torque compensation. The performance of the CVT vehicle with inertia torque compensation is compared with the results without compensation. In the simulation, a 1300 cc engine is used and powertrain loss is included. It is seen from Fig. 4 that the engine torque (a) with the inertia torque compensation shows a larger value than the engine torque without compensation. The drive torque(c) also increased corresponding to the increased engine torque. Consequently, the vehicle velocity with the inertia torque compensation follows the desired velocity more closely than the vehicle velocity without compensation.

5. CVT Ratio Change Response Lag Compensation

As shown in Eq. (5), vehicle drive torque is a product of the engine torque and the CVT ratio. In general, 90% of the engine torque response is obtained within several hundred milliseconds whereas that of a belt drive CVT takes around one second. Therefore, the CVT ratio change response lag has a large effect on the response delay of the drive torque during acceleration such as a kickdown maneuver. As shown in Fig. 4(c), when accelerating, the drive torque shows a response lag compared with the desired torque. This response lag is due to the CVT ratio change response lag, which results in response lag in the vehicle velocity. Therefore, in order to improve the acceleration performance, a remedy to reduce the effect of the CVT response lag on the drive torque should be provided.

5.1 Optimal engine torque compensation

In order to compensate for the drive torque response lag due to the CVT ratio change response lag, the following algorithm is suggested:

$$T_{e,compensated} = T_{e,optimal}\frac{i_{optimal}}{i} \tag{12}$$

where $T_{e,compensated}$ is the compensated engine torque, and $T_{e\ optimal}$ is the optimal engine torque which is determined from Fig. 2. During acceleration such as in a kickdown maneuver, i follows $i_{optimal}$ with a smaller value than $i_{optimal}$ (Fig. 4), which results in a larger $T_{e,compensated}$ than $T_{e,optimal}$ from Eq. (12).

In Fig. 5, simulation results for the integrated engine-CVT control with CVT response lag compensation by Eq. (12) are compared with the results without compensation. In the simulation, the powertrain loss and the inertia torque compensation are included for both cases. As shown in Fig. 5, the engine torque(a) with the CVT response lag compensation increases during acceleration by Eq. (12). This is because the actual CVT ratio(b) shows a smaller value than the optimal ratio as expected. The increased engine torque results in an increased drive torque(c). Therefore, the vehicle velocity with compensation follows the reference velocity more closely than the vehicle velocity without compensation. In Fig. 5(e), the engine operation trajectory for the integrated engine-CVT control with the CVT response lag is plotted during acceleration with the OOL. It is observed from Fig. 5(e) that engine operation is carried out above the OOL since the engine speed cannot change rapidly compared with the engine torque change due to the CVT ratio response lag. The purpose of the integrated

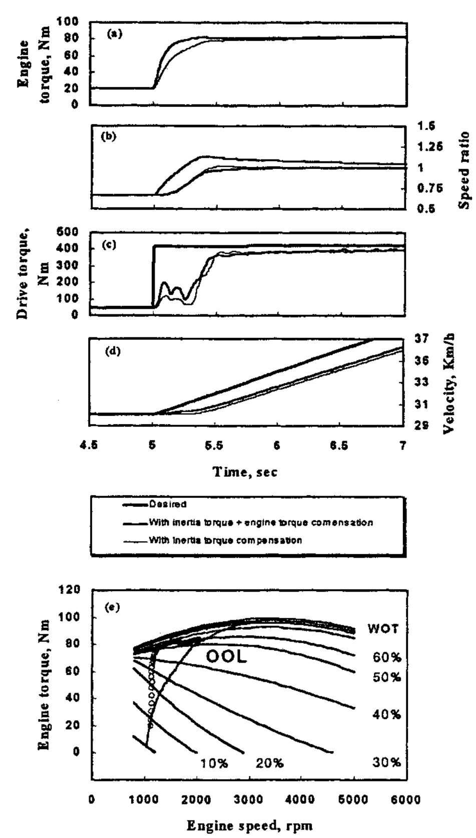

Fig. 5 Response for engine torque compensation for CVT response lag

engine-CVT control is to achieve optimal engine operation while also satisfying the driver's demand. From Fig. 5, we can see that even if the acceleration performance is improved by optimal engine torque compensation, the engine operation is performed outside the OOL during acceleration.

5.2 Optimal engine speed compensation

Another way to increase the drive torque during the acceleration is to increase the CVT ratio. If the optimal CVT ratio $i_{optimal}$, which is larger than the optimal ratio, is created, the larger actual ratio i will be generated. Since drive torque is a product of the engine torque and the actual speed ratio, an increased drive torque can be obtained. One way to obtain a larger $i_{optimal}$ is to increase the optimal engine speed, $\omega_{e,optimal}$ since the speed ratio i is determined from the ratio between the optimal engine speed and the actual vehicle speed. Therefore, in this study, an algorithm to increase $\omega_{e,optimal}$ is presented by using $i_{optimal}$ and i:

$$\omega_{e,compensated} = \omega_{e,optimal} \frac{i_{optimal}}{i} \tag{13}$$

where $\omega_{e,compensated}$ is the compensated engine speed. $\omega_{e,optimal}$ is determined from the integrated control algorithm in Fig. 2.

In Fig. 6, simulation results for the engine-CVT integrated control with the CVT response lag compensation by Eq. (13) are compared with the results without compensation. As shown in Fig. 6, the engine torque (a) with compensation does not change from the torque without compensation since the optimal engine speed is only increased for the CVT ratio response lag compensation. The optimal CVT ratio (b) changes showing an increased value compared with the CVT ratio by engine torque compensation (Fig. 5 (b)). The actual CVT ratio with compensation is larger than the ratio without compensation. Therefore, the drive torque (c) with compensation is increased owing to the increased CVT ratio, which results in improved response of the vehicle velocity (d). The engine operation trajectory (e) during acceleration is plotted with the OOL. Compared

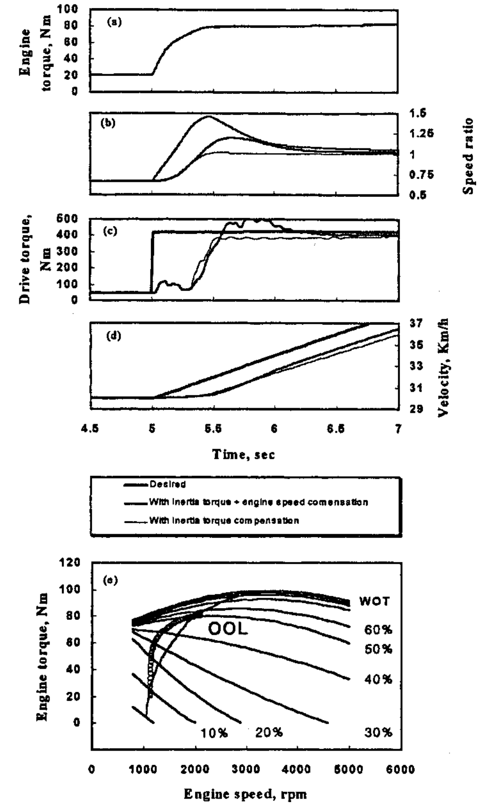

Fig. 6 Response for engine speed compensation for CVT response lag

with the engine operation trajectory with optimal engine torque compensation (Fig. 5 (e)), it is seen that improved engine operation can be achieved by engine speed compensation. Therefore, we can say that for the CVT ratio response lag compensation, the optimal engine speed compensation algorithm gives better engine operation around the OOL than engine torque compensation while showing almost the same vehicle velocity response.

In Fig. 7, a block diagram of the modified integrated engine-CVT control algorithm is shown. The modified integrated control algorithm consists of (1) the optimal engine power calculation, and (2) the optimal TVO and CVT ratio determination. The optimal engine power is calculated from the desired vehicle power by considering powertrain loss and the inertia torque due to the CVT ratio change. From the optimal engine power and the OOL, the optimal engine

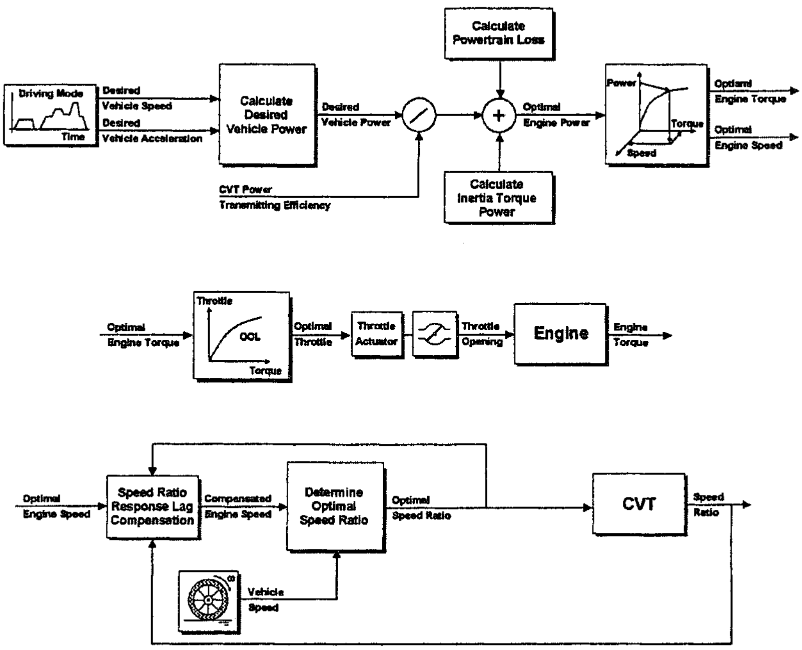

Fig. 7 Block diagram of modified engine-CVT integrated control algorithm

operation point is determined where the optimal engine torque, speed can be obtained. The optimal TVO is determined from the optimal operation point. The optimal CVT ratio is determined by the engine speed compensation algorithm suggested in this study considering the CVT ratio response lag.

6. Comparison of Engine-CVT Integrated Control Algorithm with Conventional CVT Control

In order to evaluate the engine-CVT integrated control algorithm developed in this study, vehicle performance using the integrated control is compared with those of the conventional CVT control.

Figure 8 shows the simulation results for a kickdown maneuver. The TVO(a) by integrated control increases showing lower values than TVO by conventional CVT control to achieve optimal engine operation. However, the engine torque(b) shows almost the same change in spite of the difference in TVO. This is because the engine torque variation is not much above the TVO region which is larger than 60% for the engine

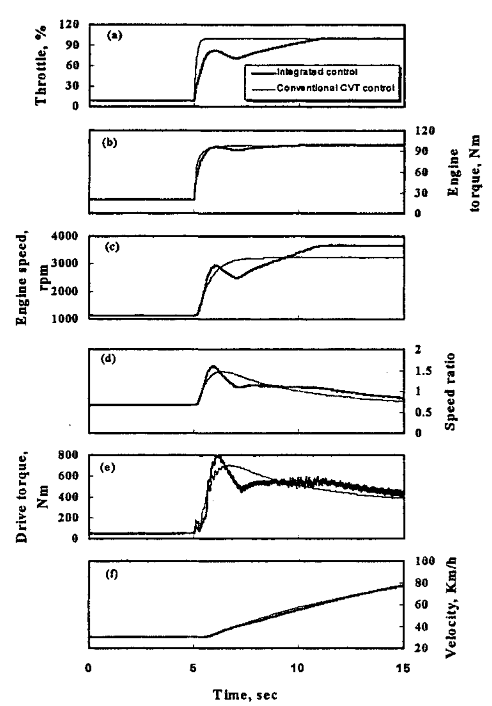

Fig. 8 Comparison of integrated control with conventional CVT control in acceleration

used in this study. The engine speed(c) changes depending on the CVT ratio change(d). The

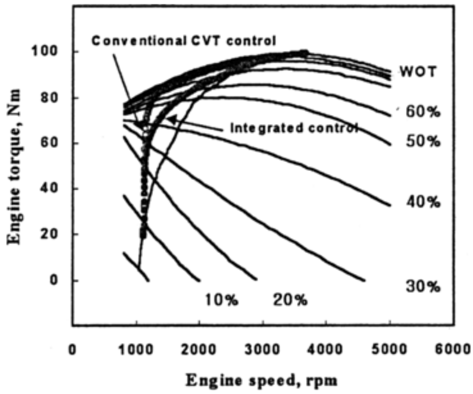

Fig. 9 Comparison of engine operation

CVT ratio(d) by integrated control shows a larger downshift in the beginning stage of the kickdown than the ratio by conventional CVT control according to the engine speed compensation algorithm. The drive torque(e) increases following the CVT ratio response(c). The drive torque by the integrated control shows a larger value than that of the conventional CVT control except some region where the CVT ratio decreases after showing the largest underdrive ratio. It is seen from Fig. 8(f) that the vehicle velocity shows almost the same response for both the integrated control and the conventional CVT control.

In Fig. 9, the engine operation trajectory is compared with the OOL. For the conventional CVT control, the engine operation point increases rapidly according to the TVO change and remains around the WOT line outside the OOL. For the integrated control, the engine operation is carried out near the OOL during the acceleration period compared with that of the conventional CVT control.

It is seen from the simulation results in Fig. 8 ~Fig. 9 that the engine-CVT integrated control algorithm suggested in this study makes it possible to achieve engine operation near the OOL during acceleration while also satisfying the driver's demand. It is expected that improved engine operation on the OOL for minimum fuel consumption is able to provide an improvement in fuel economy.

7. Conclusion

An integrated engine-CVT control algorithm is suggested by considering the inertia torque and the CVT ratio change response lag in acceleration. In order to compensate for the drive torque time delay due to the CVT response lag, two algorithms are presented : (1) an optimal engine torque

compensation and (2) the optimal engine speed compensation. Simulation results show that optimal engine speed compensation gives better engine operation around the optimal operation line compared with optimal torque compensation while showing almost the same acceleration response. In addition, performance of the integrated engine-CVT control is compared with those of the conventional CVT control. It is found from simulation results that the integrated engine-CVT control algorithm suggested in this study makes it possible to achieve engine operation near the OOL during acceleration while also satisfying the drivers demand. It is expected that improved engine operation on the OOL for minimum fuel consumption by the integrated control is able to provide an improvement in fuel economy.

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