CVT Ratio Control for Improvement of Fuel Economy by Considering Powertrain Response Lag

Heera Lee
Senior Research Engineer, Hyundai Motor Company
Hyunsoo Kim*
Professor, School of Mechanical Engineering, Sungkyunkwan University, 300 Chunchun-dong, Suwon, 440-746, Korea

A high level CVT ratio control algorithm is proposed to improve the engine performance by considering the powertrain response lag. In this algorithm, the desired CVT speed ratio is modified from the vehicle velocity, which is estimated after the time delay due to the powertrain response lag. In addition, the acceleration map is constructed to estimate the vehicle acceleration from the throttle pedal position and the CVT ratio. Using the CVT ratio control algorithm and the acceleration map, vehicle performance simulations are performed to evaluate the engine performance and fuel economy. It is found that the fuel economy can be improved about 3.6% for FUDS by the ratio control algorithm for the target vehicle. In selecting the appropriate time delay, compromise between the fuel economy and the acceleration performance is required.

Key Words : CVT(Continuously Variable Transmission), Speed Ratio, Powertrain, Response Lag

1. Introduction

Global concerns on energy limitation and CO_2 gas reduction enforce the automotive engineers to produce more energy-efficient and environmentally friendly vehicles. It is reported that the 50% improvement of fuel efficiency contributes to 33% reduction of CO_2 gas. Therefore, in conventional passenger cars, improvement of the fuel efficiency can be considered to be of vital importance to meet the requirement for the emission reduction as well as the fuel economy.

In the powertrain level, the fuel economy of the passenger cars can be improved in various ways. One possibility is to improve the propulsion system, i.e., the powertrain. Increasing the efficiency of the different powertrain components, such as the engine and the transmission, is one way to do so. Another approach is to operate the powertrain as a whole in a more fuel-optimal way. Especially the operating point in which the engine delivers the required energy is an integral element to the fuel consumption. It is well known that metal belt continuously variable transmission (CVT) is able to achieve more efficient operating levels with respect to drive performance and fuel consumption than conventional multi-ratio gearbox transmission.

In the CVT speed ratio control, the desired CVT ratio is determined from the engine optimal operation point and the present vehicle velocity. For an ideal driving situation, this desired speed ratio is able to move the engine operation point on the optimal operation line for the minimum fuel consumption. However, in reality, there exists a powertrain response lag from the driver's accelerator pedal input to the wheel torque. This powertrain response lag causes a deviation from the optimal engine operation point. Figure 1

* Corresponding Author,
E-mail : hskim@me.skku.ac.kr
TEL : +82-31-290-7438; **FAX** : +82-31-290-5849
Professor, School of Mechanical Engineering, Sungkyunkwan University, 300 Chunchun-dong, Suwon, 440-746, Korea. (Manuscript **Received** April 18, 2003; **Revised** August 12, 2003)

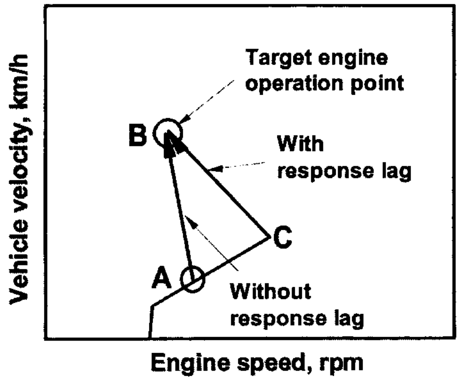

Fig. 1 Effect of response lag on engine performance

shows the effect of powertrain response lag on the engine operation. Without the response lag, the engine moves at almost constant speed for a given throttle angle as the vehicle speed increases. However, if there exists a powertrain response lag, the desired speed ratio is calculated from the vehicle speed which lags by the amount of the powertrain response lag. This results in the larger speed ratio than expected. This larger speed ratio causes the increased engine speed at the same vehicle velocity. Therefore, the engine moves following the path A-C-B, which shows a deviation from the ideal path A-B for the given throttle valve opening. This deviation causes the extra fuel consumption.

To overcome these response lags, several researches have been carried out such as adopting the additional flywheel (Vroemen et al., 2000; Serrarens et al., 2000) and the engine-CVT consolidated control (Yasuoka et al., 1999; Kim et al., 2000; Osamura et al., 2001). But these attempts require additional hardware such as a flywheel, electronic throttle control device, which require extra cost.

In this paper, the CVT speed ratio control algorithm to improve the engine performance is proposed by considering the powertrain response lag. In this algorithm, the desired speed ratio is calculated from the vehicle velocity, which is after the time delay $\Delta\tau$ by considering the powertrain response lag. Using the algorithm, vehicle performance simulations are carried out to evaluate the engine performance and fuel economy.

2. Powertrain Response Lag

In the CVT powertrain, the response lag consists of the engine torque response lag, CVT response lag, drive torque response lag, etc. Generally, the characteristics of the engine torque response can be classified into a steady state and dynamic response. In a dynamic response, there exists a response lag, which results from the engine mechanism. Thus, to evaluate the performance and fuel economy for the CVT equipped vehicle, this response lag must be considered.

The internal combustion engine considered in this study is a four cylinder, 1.6 Liter, DOHC type. For the four cylinder internal combustion engine, an instantaneously demanded engine torque T_e is realized within about two crank shaft revolutions. So, after two revolutions the combustion of the new air/fuel mixture in each cylinder has contributed to the newly induced torque level. For engine speeds between 1000 and 5500 rpm, this makes a response lag, which is about 120 msec at 1000 rpm and 22 msec at 5500 rpm, (Vroemen et al., 2001). Considering this response lag, the engine torque response is modeled as

$$T_e = \frac{e^{-T_{d\,engine}s}}{1+\tau_e s} T_{es} \tag{1}$$

where $T_{d\,engine}$ is the response lag time of the engine torque as a function of the engine speed, τ_e is the time constant.

For the air throttle angle, there exists a response lag about 140 msec, which is caused by the response characteristics of the physical limitation, etc (Vroemen et al., 2001). Thus, the air throttle angle response can be modeled as

$$\theta_{th} = \frac{e^{-T_{d\,throttle}s}}{1+\tau_{th} s} \theta_{th\,d} \tag{2}$$

where $T_{d\,throttle}$ is the response lag time of the air throttle, $\theta_{th\,d}$ is the desired throttle angle and τ_{th} is the time constant.

In the metal belt CVT system used in this study, when the upshift begins with the lowest speed ratio, the oil is supplied from the line pressure control valve to the primary actuator. Since the

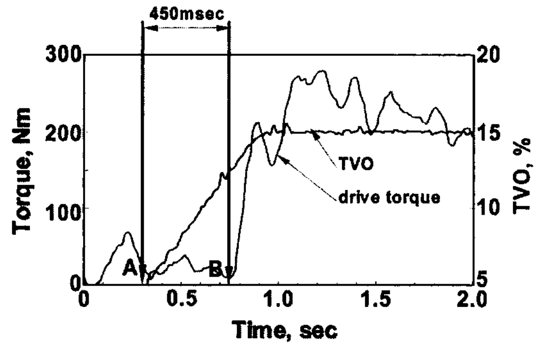

Fig. 2 Powertrain response lag of bench tester

primary actuator is empty at the lowest gear ratio, there exists a filling time to fill up the empty volume of the primary actuator. Experiments show that the filling time is at about 200 milliseconds depending on the line pressure. Besides, the response characteristics of the electronic control system, the solenoid valve dynamics, pulley and belt elasticity cause a response lag about 110 milliseconds (Vroemen, 2001). Figure 2 shows the experimental result of the driving torque by the CVT bench tester, which consists of 1.6 *l* DOHC engine, CVT and flywheel. The driving torque was measured at the CVT output shaft for a stepwise engine TVO input from 5% to 15%. From the experimental results, it is found that the response lag of the drive torque is 450 msec. The response lag was measured from the TVO input (point A) to the point B where the driving torque begins to increase, which is due to the response of the engine torque, the air throttle, CVT, etc. By considering the additional response lag from the driving shaft to the wheel, the powertrain response lag may exceed 500 msec.

3. τ Algorithm

The CVT speed ratio control consists of the high level and the low level control. In conventional electronic controlled CVT vehicle, the high level control determines the desired CVT speed ratio, $i_{desired}$ as

$$i_{desired}=\frac{\omega_{e\,optimal}}{N_f\omega_v} \tag{3}$$

where N_f is the final reduction gear ratio and ω_v is the present vehicle velocity. $\omega_{e\,optimal}$ is the optimal engine operation point, which is determined as the point where the throttle valve opening (TVO) curve crosses with the OOL. Once the desired speed ratio is determined, the low level controller realizes the actual speed ratio, i, to follow the reference input, $i_{desired}$. The actual speed ratio i is defined as

$$i=\frac{\omega_p}{\omega_s}=\frac{\omega_p}{N_f\omega_v} \tag{4}$$

where ω_p and ω_s are the primary and the secondary pulley speed, respectively.

If the response lag in the powertrain does not exist, the optimal engine operation point can be achieved by the desired speed ratio from Eq. (3) even if some deviation exists due to the CVT dynamics. However, in reality, the powertrain response lag exists, which causes an extra deviation in realizing $\omega_{e\,optimal}$. Therefore, if the vehicle velocity after the time delay τ is used in the calculation of the desired speed ratio, an improved engine performance is expected.

The next step is how to determine the vehicle velocity after the time delay. Assuming that the vehicle acceleration α is constant for a short period, the velocity ω_v^* after the powertrain response lag τ, can be estimated as

$$\omega_v^*=\omega_v+\alpha\tau \tag{5}$$

Substituting ω_v^* into Eq. (3), the desired speed ratio by considering the powertrain response lag τ is modified as

$$i_{desired}^*=\frac{\omega_{e\,optimal}}{N_f\omega_v^*} \tag{6}$$

where $i_{desired}^*$ is the modified desired CVT speed ratio. In order to implement the above equation, α needs to be determined. The easiest way is to measure α by the acceleration sensor. In this study, another way to estimate α is proposed by assuming that α is proportional to the TVO. The procedure for obtaining α is shown in Fig. 3. As for the given TVO, the engine torque is calculated with respect to the engine speed from the engine map. Next step is to perform a launching simulation with a fixed CVT ratio i, which gives an

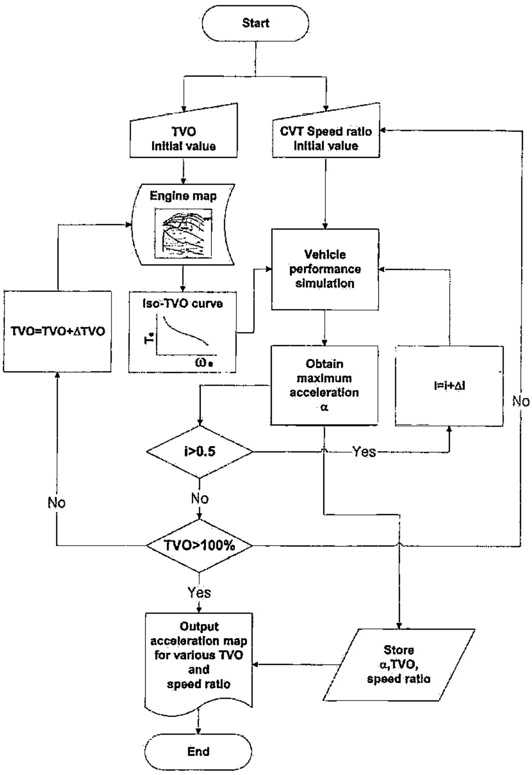

Fig. 3 Flow chart to obtain α map

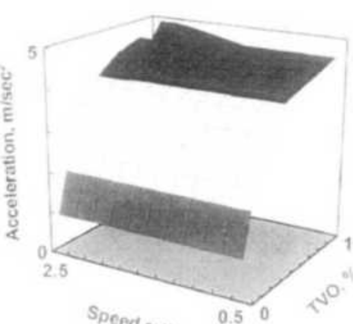

Fig. 4 α map

acceleration profile with respect to the time. From the acceleration profile, the maximum acceleration is selected as α for the given TVO and i. This procedure is repeated by changing the speed ratio and the TVO, and we can obtain a 3-D acceleration-TVO-speed ratio map, which shall be called "α map". in Fig. 4, the α map for the vehicle used in this study is shown and the vehicle parameter is shown on Table 1. From the α map and Eq.

Table 1 Vehicle parameters

Engine Type	DOHC
Engine Stroke Volume	1600 cc
Engine Maximum Torque	143 Nm
CVT Gear Ratio	i=0.49~2.48
Starting Device	Wet Type Multi-Disc Clutch
Vehicle Mass	1206 kg
Final Reduction Gear Ratio	5.763
Wheel Radius	0.281 m

(6), ω_v^* can be estimated. The high level speed ratio control algorithm considering the powertrain response lag shall be called, "τ algorithm".

As shown in Eq. (6), the modified desired speed ratio $i^*_{desired}$ will be varied faster to the high speed ratio (the highest speed ratio=0.49) than the desired speed ratio of Eq. (3), which causes a fast upshift. In the case when a fast acceleration is required such as a kickdown maneuver, the speed ratio is sufficiently downshifted and upshifted to obtain the fast acceleration. But, since the speed ratio control by the τ algorithm performs a fast upshift, the downshift does not be carried out sufficiently, which causes a worse driveability.

To evaluate the driveability, a simulation for a kickdown from 20% throttle opening to WOT is performed and the simulation results are shown in Fig. 5. As shown on the simulation results, since the speed ratio is modified by the τ algorithm in the acceleration, the speed ratio varies faster than that of the conventional control, which results in the worse driveability than that of conventional control. To guarantee the driveability in the acceleration as in a kickdown, the following conditions are added and

$$0\%/\text{sec} < \frac{d\theta_{th}}{dt} < 25\%/\text{sec} \text{ and } 0\% < \theta_{th} < 60\% \quad (7)$$

where $\frac{d\theta_{th}}{dt}$ is the response speed of TVO. In the case when the condition (7) is met, the τ algorithm is applied. Otherwise, the τ algorithm is not applied and the desired speed ratio is computed

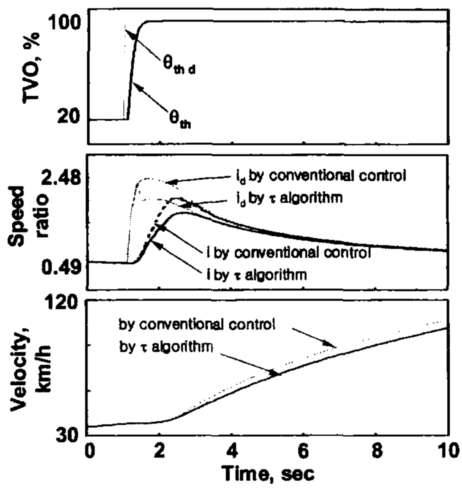

Fig. 5 Comparison of simulation results for a kick-down maneuver

by (3), which is the same as in the conventional speed ratio control.

4. Simulation Results and Discussion

To evaluate the τ algorithm, simulations are performed for federal urban driving schedule (FUDS). Simulation results using the τ algorithm are shown on the Fig. 6, which shows the response of the first 400 seconds for FUDS. In the simulation, the delay time $\tau=500$ msec is used to estimate the vehicle velocity. Fig. 6(a) shows the vehicle velocity and (b) shows the response of the CVT speed ratio. The desired speed ratio i_d is modified by the τ algorithm when the condition (7) is met.

In Fig. 7, closer view of the CVT speed ratio and the engine operational point are compared with those of the conventional electronic control CVT for 20～30 seconds of FUDS. As shown on Fig. 7(a), the desired speed ratio i_d with τ algorithm (I) is changed faster than that of the conventional electronic control (II). The engine is operated on the area where the torque is higher and the speed is lower than those by the conventional CVT (Fig 7(b)).

The engine operation trajectories for the full FUDS are compared in Fig. 8. Fig. 8(I) is by the conventional electronic control and (II) is by the τ algorithm with $\tau=500$ msec. As shown on Fig. 8, the engine operation of (II) is carried out more closely on the OOL than those of (I), which is shifted to higher torque and lower speed.

Figure 9 shows the comparison of the fuel economy for the τ algorithm with $\tau=500$ msec

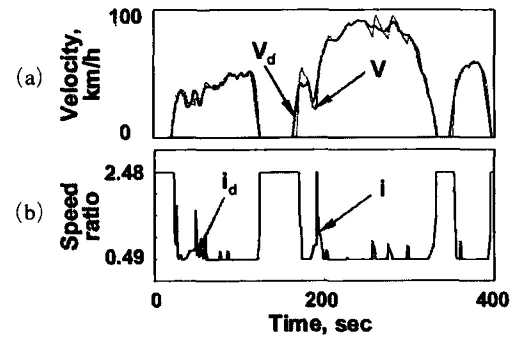

Fig. 6 Simulation results for τ algorithm with $\tau=$ 500 msec

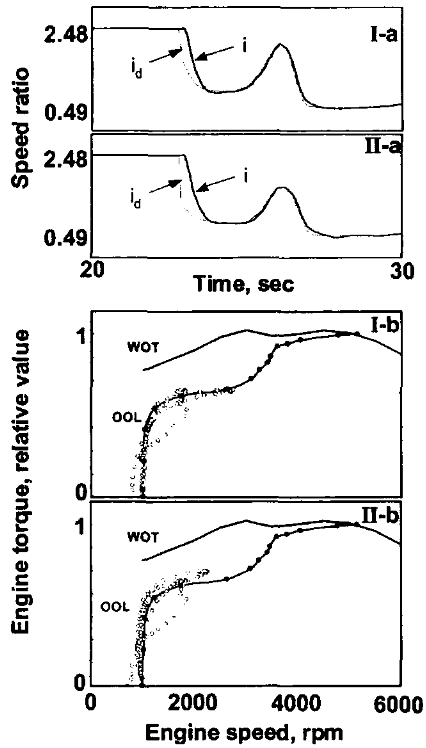

Fig. 7 Comparison of speed ratio and engine operation point for conventional electronic control (I) and for τ algorithm (II)

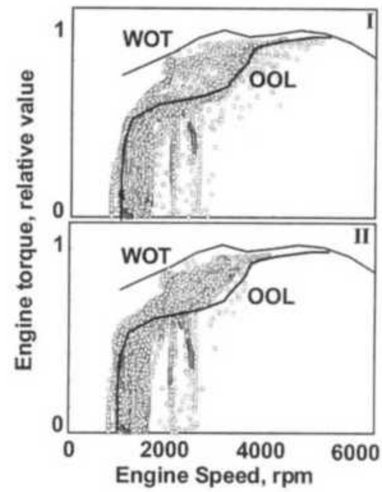

Fig. 8 Comparison of engine operation trajectory of federal urban driving schedule for conventional electronic control (I) and for τ algorithm (II)

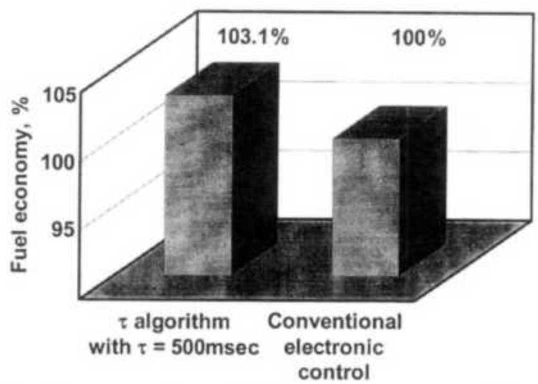

Fig. 9 Comparison of fuel economy for τ algorithm and conventional electronic control

and the conventional electronic control CVT. From the simulation results, the fuel economy by the τ algorithm is better than that of the conventional speed ratio control, which results from the lower engine power consumption due to the higher torque and lower speed of engine operation compared with the conventional speed ratio control for the given TVO and the vehicle velocity.

Fuel economies for various τ are compared in Fig. 10. As shown on Fig. 10, it seems that the fuel economy is improved as τ increases. However, too large τ may cause a sluggish acceleration performance. Therefore, in choosing τ, compromise between the fuel economy and the acceleration performance is required.

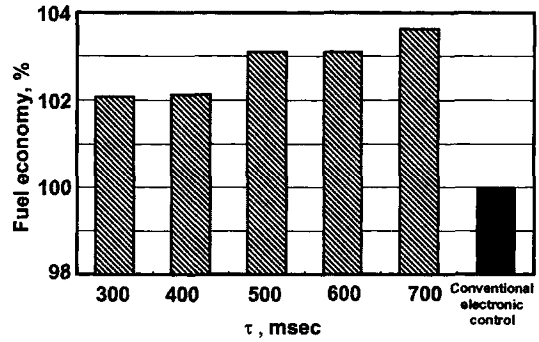

Fig. 10 Comparison of fuel economy for various τ

5. Conclusion

A high level CVT ratio control algorithm is proposed to improve the engine performance by considering the powertrain response lag. In this algorithm, the desired CVT speed ratio is modified from the vehicle velocity, which is estimated after the time delay τ due to the powertrain response lag. In addition, the acceleration map is constructed to estimate the vehicle acceleration from the throttle pedal position and the CVT ratio. Using the CVT ratio control algorithm and the acceleration map, vehicle performance simulations are performed to evaluate the engine performance and fuel economy. It is found that the fuel economy can be improved about 3.6% for FUDS by the ratio control algorithm for the target vehicle. In selecting the appropriate time delay, compromise between the fuel economy and the acceleration performance is required.

References

Kim, T. and Kim, H., 2000, "Integrated Engine-CVT Control Considering Powertrain Response Lag in Acceleration," *KSME International Journal*, Vol. 14, No. 7, pp. 764~772.

Osamura, K., Itoyama, H. and Iwano, H., 2001, "Improvement of Drive Torque Response by

Applying an Integrated Control Algorithm for a Diesel Engine and CVT," *JSAE Review*, pp. 293~298.

Serrarens, A. F. A. and Veldpaus, F. E., 2000, "New Concept for Control of Power Transients in Flywheel Assited Drivelines with a CVT," FISITA Congress, F2000A129.

Vroemen, B. G. and Veldpaus, F. E., 2000, "Control of a CVT in a Flywheel Assited Driveline," FISITA Congress, F2000A133.

Vroemen, B. G., Serrarens, A. F. A. and Veldpaus, F. E., 2001, "Hierarchical Control of the Zero Inertia Powertrain," *JSAE Review*, pp. 519~526.

Yasuoka, M., Uchida, M., Katakura, S. and Yoshino, T., 1999, "An Integrated Control Algorithm for an SI Engine and a CVT," *SAE Technical Paper Series*, No. 1999-01-0752.