Proceedings of the World Congress on Engineering and Computer Science 2007
WCECS 2007, October 24-26, 2007, San Francisco, USA

Enhanced Coasting Lock-Up of Torque Converter Clutch after Power-Off Up-Shift using Modified P-PI Control

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***Abstract*—This paper presents a new coasting lock-up controller for the torque converter clutch in automatic transmissions. It was developed to reduce engagement shock and fuel consumption during coasting lock-up, especially when the engine speed drops after a power-off up-shift. P and PI controllers were sequentially adopted in the torque converter clutch control unit without using torque or pressure sensors. In addition, a function of jump-down of command duty was implemented to compensate a sudden increase of engine speed with a high change rate, due to unstable hydraulic pressure. According to the test results in a real vehicle, the new controller fulfilled coasting lock-up successfully after the power-off up-shift, showing diminished engagement shock and improved fuel saving, in comparison with the conventional controller with bigger duty or engine speed-up control.**

***Index Terms*—coasting lock-up, torque converter clutch, engagement shock, fuel saving, and PID control.**

I. Introduction

Torque converters are widely used in the automobile industry. Most automobiles with automatic transmissions are produced with the torque converters. It is situated between the engine and the transmission so that the torque from the engine is delivered to the transmission, through the fluid flow between the impeller and the turbine (Fig. 1). This fluid coupling allows the engine and the transmission to rotate at different speeds [1] -[2]. In other words, contrary to manual transmissions, they do not necessarily have to be disconnected during gearshift and the vehicle can stop with the engine running. Moreover, the torque from the engine is multiplied by the internal fluid flow of the torque converter, even though energy loss exists. This is why automatic transmissions with torque converters are more powerful than manual transmissions when accelerating an automobile from a complete stop. However, as the speed difference (slip) between the engine and the transmission decreases, less torque multiplication is generated, having better efficiency in energy transfer. Consequently, since higher torque multiplication and better system efficiency cannot be achieved at the same time, it is important to maintain a balance between them. In this regard, hybrid vehicles are not equipped with torque converters [3] -[6].

Automobile manufacturers have adopted torque converter clutches (TCC) to minimize the energy loss of torque converter's fluid flow in a high range of vehicle speeds, while maximizing the torque multiplication effect in low and medium ranges. The TCC locks up the turbine (transmission) and the impeller that is connected to the torque converter case (engine). If it is closed, the engine, transmission, and the vehicle wheel will rotate at the same speed, achieving the best system efficiency with no difference in speed between system elements [7]-[9].

Lock-up of the TCC divides into two control states; power-on

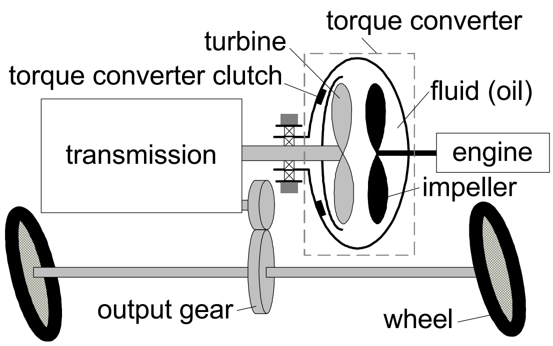

Fig. 1 Schematic diagram of torque converter and its clutch

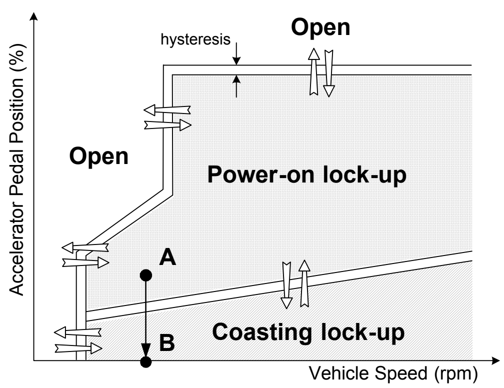

Fig. 2 Driver's intention, vehicle speed, and lock-up states of TCC

Manuscript received July 9, 2007.
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lock-up and coasting lock-up (power-off lock-up), which is determined by the driver's intention (acceleration pedal position) and vehicle speed (Fig. 2). Especially, by coasting lock-up, considerable amounts of fuel can be saved while coasting at medium and high speeds because the vehicle is moving by its own inertia force. Therefore, when coasting, the fuel into the engine can be cut off, as long as the vehicle speed is higher than the idle speed of the engine.

II. Coasting Lock-Up and Power-Off Up-Shift

In general, coasting lock-up is carried out by engaging the TCC, immediately after the driver's lift-foot-up (LFU) from the acceleration pedal (Fig. 3), as in [9]-[10]. For example, as in Fig. 2, if the driving condition of the vehicle changes from *A* (power-on) to *B* (power-off) due to the LFU, the TCC is engaged in order to curb the dropping engine speed so that fuel cut-off can be induced afterwards.

A. Coasting lock-up without power-off up-shift

The most typical coasting lock-up is shown in Fig. 4, which the LFU is not entailed with a gearshift. The engine speed, higher than the turbine speed before the LFU, is synchronized with the turbine speed by the TCC engagement after the LFU. In this case, the lock-up is relatively straightforward because the engine speed change after the LFU is not big.

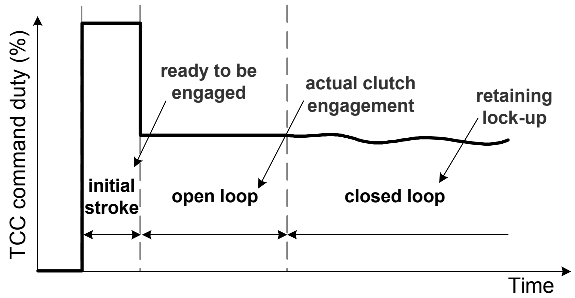

Fig. 3 Command duty (pressure) of lock-up clutch solenoid

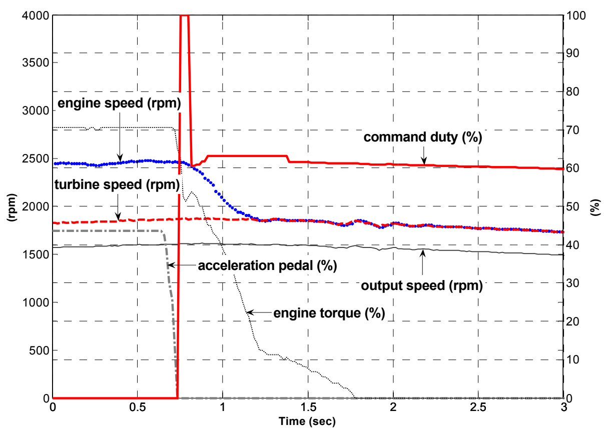

Fig. 4 Normal coasting lock-up without gearshift

B. Conventional coasting lock-up after power-off up-shift

Power-off up-shift following the LFU results in a significant drop of the engine speed, as can be seen in Fig. 5. Likewise, the inertia force of the engine becomes very low after the power-off up-shift, contrary to the big inertia force after the LFU without the gearshift. On one hand, these large differences in the inertia force and the speed can be decreased by applying pressure that is much higher than that of conventional coasting lock-up. On the other hand, slight modification of the conventional control, i.e., merely applying higher duty for longer lengths of time to acquire higher pressure, causes abrupt TCC engagement shock (Fig. 5). This shock is detrimental for the TCC in terms of durability and an unpleasant feeling for the driver.

C. Coasting lock-up incorporated with engine speed control

In order to eliminate engagement shock or durability-related problems, engine's low speed can be increased to the same level as the turbine speed by the engine control unit before or in the beginning of coasting lock-up. As can be seen in Fig. 6, there is no engagement shock in the beginning of coasting lock-up, when the coasting lock-up is incorporated with engine speed-up

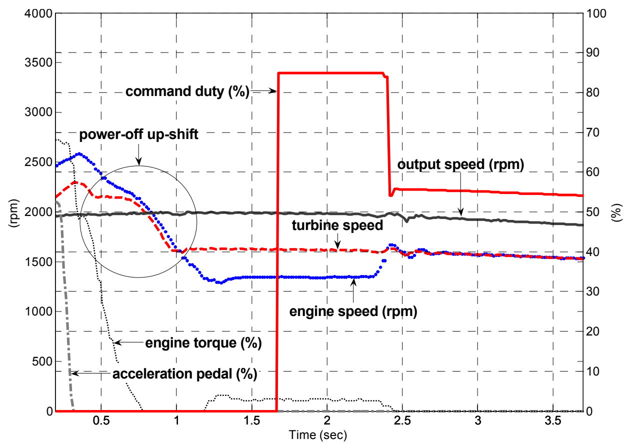

Fig. 5 Modified coasting lock-up after power-off up-shift

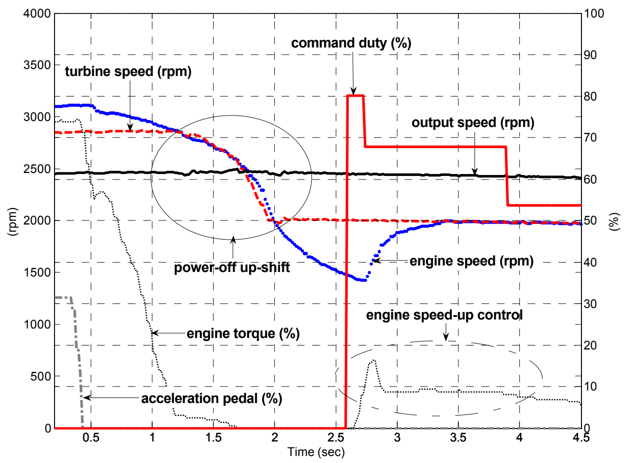

Fig. 6 Coasting lock-up incorporated with engine speed control after power-off up-shift

control. The engine, however, inevitably consumes additional fuel during the engine speed-up control. In other words, the engine torque must be kept high to increase the engine speed intentionally, which requires extra fuel to be burned [11] -[12].

As mentioned above, it is difficult to lock-up the engine and the turbine after power-off up-shift due to the huge difference in speed (inertia force). Moreover, sudden engagement shock is a potential problem when the conventional lock-up control scheme is used. The engine speed-up control could be used as an alternative method. However, even though the lock-up can be successfully conducted without shock, additional fuel must be consumed for increasing engine speed. It is not an ultimately desirable solution, because the primary reason of coasting lock-up is to save fuel consumption. Therefore, the engine speed-up control must be superseded by a more intelligent coasting lock-up controller. In this study, a modified P-PI controller was proposed, which does not bring about the engagement shock and additional fuel consumption.

III. MODIFIED P-PI CONTROLLER

The TCC engagement shock, shown in Fig. 5, is mainly dependent on the first two control phases, such as the initial stroke with maximum command duty and the open loop control with a constant command duty. The former is a preparation process to have the TCC ready to be pushed, and the latter is to wait for the necessary pressure to be stable for the actual engagement. This control scheme works well in the case of normal coasting lock-up. Nonetheless, the presence of power-off up-shift before coasting lock-up results in very difficult initial condition for coasting lock-up, i.e., different control strategy is required after gearshift. The first two control phases of the conventional coasting lock-up were replaced by P and PI controller, respectively.

The amount of command duty and the duration of time are the critical elements in the first control phase of initial stroke. During the predefined time, P controller was adopted to determine the necessary amount of command duty (u_{k_P}) at every control period (T) with respect to the slip (e_k , speed difference) between the engine and the turbine, as in (1). For the synchronization of the engine and the turbine, the target speed of the engine speed is the current turbine speed, and the application duty is varied in proportion to the difference between the current engine speed (N_E) and the target speed (N_T). This enables the coasting lock-up to be adaptable in various driving conditions.

$$u_{k_P} = K_{P_P} \cdot e_k \ . \tag{1}$$

$$e_k = N_{T_k} - N_{E_k} . \tag{2}$$

Once the initial filling in the oil path is completed, the TCC is subject to abrupt engagement by sudden increase or fluctuation of pressure. On the other hand, the coasting lock-up will fail, if

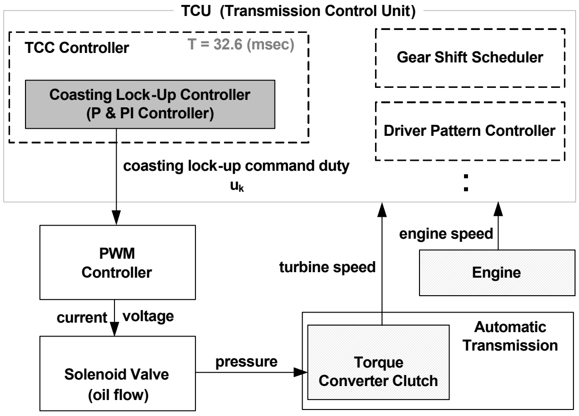

Fig. 7 Schematic diagram of overall structure of transmission controller and coasting lock-up controller

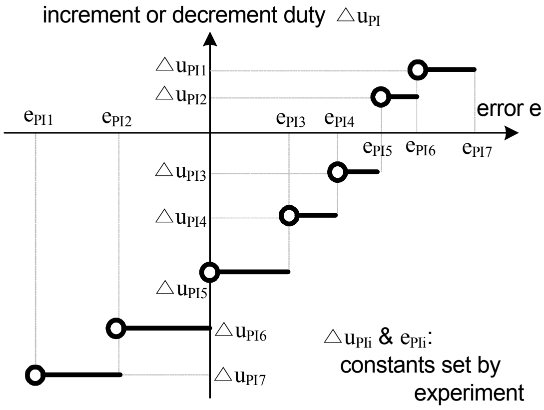

Fig. 8 The increment or decrement of command duty for the proposed I controller

the pressure is insufficient. PI controller was implemented in order to prevent both the fail of lock-up and engagement shock. P factor is necessary against the sudden engagement, decreasing pressure as the engine speed goes up to the target speed. I factor is used to guarantee the success of lock-up by acquiring gradual pressure change with the continuity from the previous P control phase. Discrete form of PI controller (3) can be represented by (4), and it was implemented on the TCC controller as in Fig. 7.

$$u(t) = K_P \cdot e(t) + K_I \cdot \int_0^T e(t)dt \ . \tag{3}$$

$$u_{k_{PI}} = u_{k-1_{PI}} + K_{P_{PI}} \cdot (e_k - e_{k-1}) + K_{I_{PI}} \cdot T \cdot e_{k-1} . \tag{4}$$

$$K_{P_{PI}} \cdot (e_k - e_{k-1}) \approx \Delta u_{P_{PI}} (\Delta e). \tag{5}$$

$$K_{I_{PI}} \cdot T \cdot e_{k-1} \approx \Delta u_{I_{PI}} (e). \tag{6}$$

The approximated increment or decrement values ($\Delta u_{P_{PI}}$

and $\Delta u_{I_{PI}}$) of (5) and (6) are determined in a step-wise manner (Fig. 8). No pressure or torque sensors are used here: the exact relationship between command duty (oil flow) and actual hydraulic pressure or torque in the TCC is unknown. Moreover, time delay exists between the duty application and the hydraulic pressure generation. After all, it is more important to focus on the overall behavior and tendency of the engine speed rather than on the precise estimation of the generated pressure and command duty. Then the increment or decrement of the command duty according to the slip magnitude is necessarily approximated as in Fig. 8.

IV. Implementation and Experiment Set-Up

The proposed controller was implemented on a commercial vehicle, Magentis (Fig. 9), 4-door sedan of Hyundai-Kia Motors Co. It is equipped with a 5-step automatic transmission and a 2.4-liter displacement gasoline engine. No elements in the vehicle were modified except for the coasting lock-up controller. To avoid the deviation due to different slopes and surface conditions of a road, the experiment was carried out on a plane road and repeated at the same place.

For the experiment under coasting, the vehicle was accelerated up to approximately 80 (km/h) with the acceleration pedal pressed and the gear below the 5th. Then the pressed acceleration pedal was released to induce power-off up-shift. The gear changed automatically from the 4th to the 5th by gear-shift scheduler of TCU, and the proposed P-PI controller ensued for coasting lock-up. However, in addition to the automatic power-off up-shift, manual power-off up-shift is also probable in a real vehicle. Thus, the experiment was conducted with a gear lever in both D (automatic mode) and M (manual mode).

Once the P-PI controller was implemented in the real vehicle, the command duty was adjusted so that the engine and turbine could be successfully locked-up without the support of the engine control unit. However, the engagement shock might still happen, when the TCC is locked-up. Further modification of command duty was carried out under various driving conditions for the sake of shock diminution. Nonetheless, the P-PI controller could not always perform shock-free lock-up because the hydraulic pressure sometimes became unstable (suddenly high) for some reason, causing engagement shock. Since this problem is beyond the calibration of P-PI control duty, another function that is widely used in clutch control was added. As illustrated in Fig. 10, the command duty jumps down, when the engine speed increases with a very big change rate as the TCC pressure suddenly increases. The dropped duty dampens the effect (sudden engagement) of surged pressure in the TCC, and it eventually inhibits the shock.

Along with the shock, another important interest in this experiment is fuel saving, that is, whether the newly suggested controller is still advantageous in terms of fuel consumption, in comparison with the engine speed-up control. Both the P-PI controller and engine speed-up controller were applied, and the amount of fuel consumption was measured, respectively, for further comparison.

Fig. 9 The test vehicle: Magentis of Hyundai-Kia Motors Co.

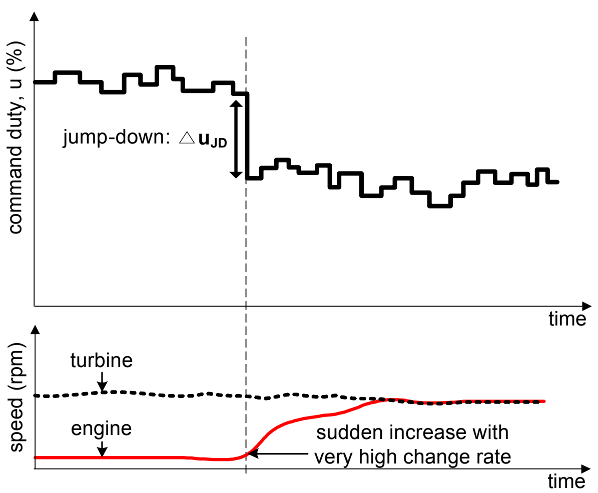

Fig. 10 Jump-down of command duty in case of sudden increase of engine speed due to unstable surge of TCC pressure

V. Experimental Result

Various experiments were conducted to evaluate the designed controller after calibrating the new parameters related to the P-PI controller on the real vehicle. First, it was

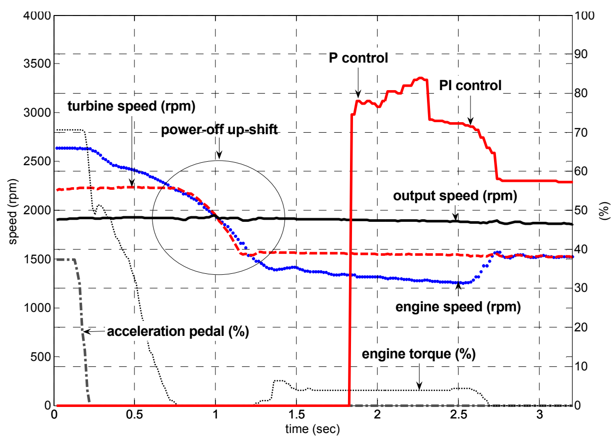

Fig. 11 Coasting lock-up with P-PI controller

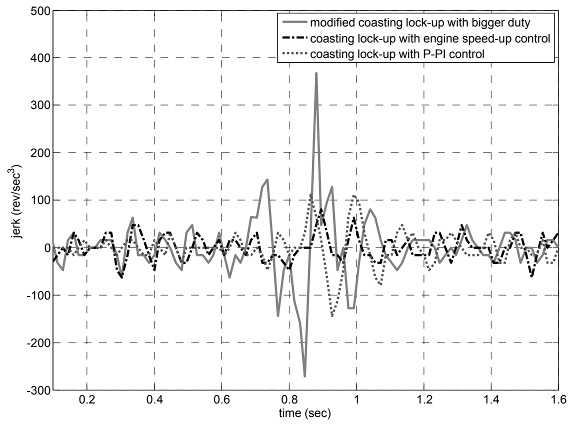

Fig. 12 Comparison of jerk between three coasting lock-up methods: with bigger duty, incorporated with engine speed-up control, and P-PI control

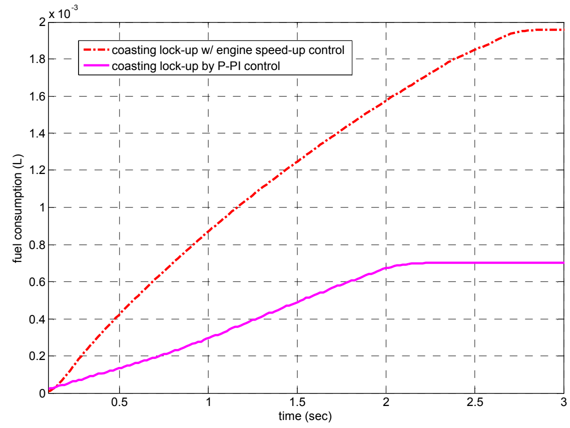

Fig. 15 Comparison of fuel consumption between two coasting lock-up methods: incorporated with engine speed-up control and P-PI control

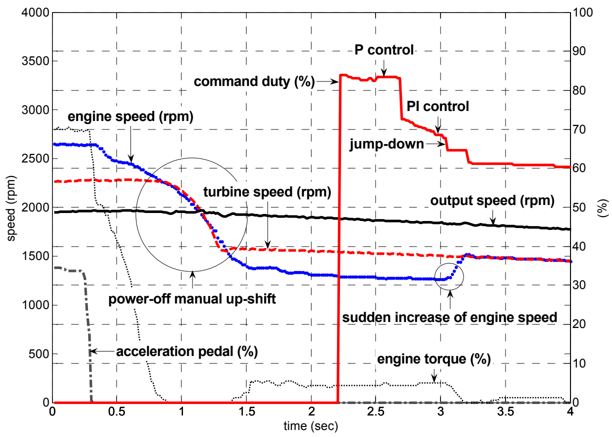

Fig. 13 Coasting lock-up with jump-down function

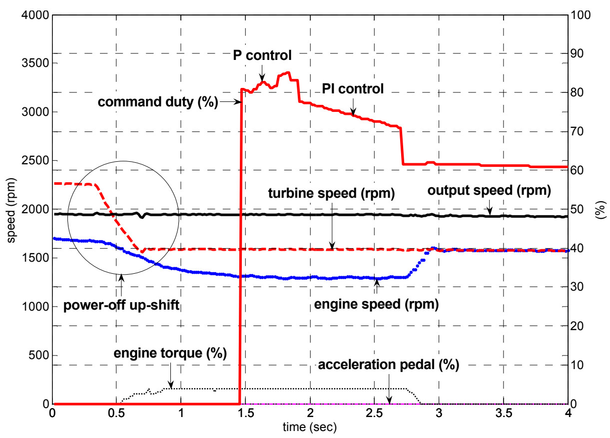

Fig. 14 Coasting lock-up after manual power-off up-shift

investigated whether the P-PI control scheme could fulfill the fundamental role of coasting lock-up, keeping the engine speed high for the sake of subsequent fuel cut-off in the engine. The result is shown in Fig. 11, which represents that the engine is locked-up successfully with the turbine, guaranteeing the fuel cut-off afterwards.

This can also be seen in Fig. 11, thanks to the P-PI controller, the shock was diminished, compared with the lock-up without the P-PI controller in Fig 5. Normally, the driver feels the shock if the vehicle's acceleration value suddenly fluctuates in a very short time when coasting. Therefore, the shock can be quantitatively evaluated based on the change rate of the acceleration value (jerk), as in Fig. 12. As a result, it is obvious that the P-PI controller reduced the shock in the coasting lock-up following the power-off up-shift, even though the shock is slightly bigger than that of the engine speed-up control.

If the hydraulic pressure in the TCC unexpectedly fluctuates as the P-PI controller fulfills the lock-up, the TCC will suddenly be closed, resulting in the shock. To predict and detect the pressure fluctuation in the TCC, the engine speed change was monitored. When the engine speed surged unintentionally, it was assumed that the pressure in the TCC will be unstable and may fluctuate. In this case, the TCC command duty was reduced immediately, and then the TCC was closed more gradually without the shock. As can be found in Fig. 13, in the middle of PI control, it was estimated that the engine speed was about to surge, so the command duty was jumped-down. Consequently, the abrupt engagement of the TCC was prevented.

As mentioned earlier, the power-off up-shift is conducted with a gear lever positioned not only in 'D', but also in 'M'. In the latter case, the power-off up-shift is not automatically carried out in spite of the driver's LFU. Only if the driver moves the lever, the gearshift is allowed. To consider this situation, the power-off up-shift was carried out with the gear lever in 'M', and the result is shown in Fig. 14. Even for the manual power-off up-shift, the coasting lock-up was achieved by the P-PI controller, having no shock and no additional fuel consumption.

Contrary to the coasting lock-up, incorporated with the engine speed-up control, the newly proposed P-PI controller has also advantage in terms of fuel saving. The amount of fuel consumption was measured, while the coasting lock-up was being conducted, for both the engine speed-up control and the

P-PI control. As shown in Fig. 15, the coasting lock-up with the P-PI controller consumes less fuel in the beginning of the lock-up. The fuel cut-off starts after 2 seconds and no more fuel is supplied. In the case of the lock-up with the engine speed-up control, the fuel cut-off starts later than that of the P-PI control. Moreover, the P-PI shows superiority, regarding the overall amount of fuel consumption.

VI. Summary and Conclusion

A new controller has been developed for the coasting lock-up of the torque converter clutch after the power-off up-shift when the initial engine speed is very low compared to the high turbine speed. The modified P-PI controller was adopted to increase the engine speed to the same level as the turbine speed, with no engagement shock and better fuel saving. It was verified on a commercial vehicle to see its performance and feasibility. The coasting lock-up was successfully fulfilled by the new controller, without the engagement shock. However, it was very difficult to prevent the shock when the pressure in the TCC fluctuates, due to the lack of the torque or pressure sensors. Thus, the P-PI controller was added by the jump-down function to prevent unexpected surge of the pressure. After all, very good engagement performance was achieved with the P-PI controller. Moreover, in comparison with the engine speed-up control, the newly suggested controller showed better performance in terms of the fuel saving, especially in the beginning of the coasting lock-up.

This paper is focused on the lock-up of the TCC after the power-off up-shift. However, it would be more beneficial to synchronize the engine and the turbine before the gear-shift. If they were locked-up before the gear-shift, the engine speed would not drop too much even after the gear-shift. Then a continuous coasting lock-up could be accomplished, with better fuel saving in the end. On the other hand, the coasting lock-up during the power-off up-shift will cause conflict with the gear-shift, providing uncomfortable feeling to the driver during the gear-shift. Therefore, provided no conflict between the power-off up-shift and the coasting lock-up, the coasting lock-up during the power-off up-shift would be suitable for further research works in the future.

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