Adaptive Anti-Shock Coasting Lock-Up Control of the Torque Converter Clutch

D. Y. Lee, H. H. Ju, J. S. Rhee, S. H. Lee, and H. S. Lee

Abstract**—**Cars with the automatic transmission are fragile to coasting shock caused by the engine torque behavior and the lock-up of the torque converter clutch (TCC). If the driver lifts his foot up from the accelerator pedal, the engine torque will decrease and the car will start to coast. In the coasting, the TCC is almost locked up for better fuel saving, i.e., the engine and turbine rotates almost at the same speed. However, as the engine torque decreases with the synchronized turbine and engine, the coasting shock follows the driver's lift-foot-up (LFU), which is very annoying for the driver. To prevent this shock, it is necessary to construct more intelligent TCC controller allowing lock-up without both the loss of fuel economy and the coasting shock. This paper suggests the adaptive anti-shock coasting lock-up control strategy and investigates its feasibility with the vehicle test by showing that the shock is measurable and predictable. The experimental results show that the newly developed controller successfully decreased the coasting shock without disturbing the normal lock-up of the TCC or the fuel economy.

Keywords**—**Adaptive control, coasting, shock, lift-foot-up, torque converter clutch, and lock-up.

I. INTRODUCTION

IN the automobile industry, automatic transmission (AT) is very popular especially in Asia and the U. S. Over 80 percent of cars in the road have AT and most of them are equipped with the torque converter.

The torque converter is placed between the engine and the automatic transmission and delivers the power from the engine to the transmission unit. It has impeller for actuating fluid by engine, stator for guiding the fluid flow from the impeller, and turbine for receiving the power of inflow from the stator/impeller. These three elements complete fluid coupling that multiplies the torque, which is the most important reason to use the torque converter. The amplified torque results in better acceleration capability of the automatic transmission car especially in low speed. On the other hand, the amplification of torque is proportional to the difference between rotational speeds of the impeller and turbine. As the speed difference increases, the efficiency of this fluid coupling decreases, but torque amplification ratio rises. For better fuel economy, the speed difference must be under control and minimized, even though the fluid coupling of the torque converter that inherently produces slip between the engine and turbine provides a few advantages such as robustness against the torsional vibration from the engine and the realization of gear shift without disengaging of the engine and transmission. However, the slip in the torque converter brings about the increase of its oil temperature, which may cause harmful effect on the torque converter and the transmission as well.

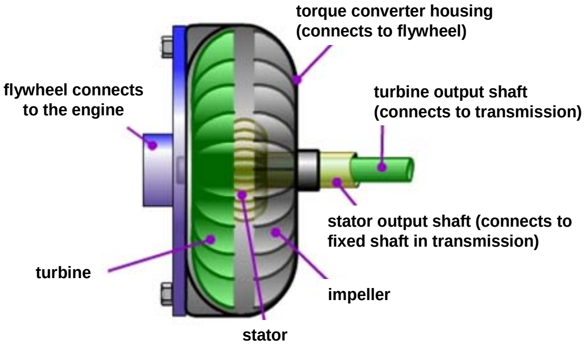

Fig. 1 Schematic diagram of torque converter and its clutch

Thus, the torque converter is implemented with the torque converter clutch (TCC) that enables the synchronization of the engine and turbine. If it is fully locked up, the engine and turbine rotate at the completely same speed; otherwise, they can have speed difference (slip). The more lock-up of the TCC is possible, the better fuel economy is achieved, but the advantages of the torque converter vanish. Therefore, balancing between the advantages and disadvantages of the TCC lock-up becomes important, and somewhat complicated strategy is needed to decide when and how to lock up or release the TCC.

II. TCC CONTROL

SIEMENS Automotive Systems Corp. has constructed its own TCC control strategy for years. Overall control scheme can be classified into four states such as open, full lock-up, lock-up during shifting, and coasting lock-up. TCC controller of the Transmission Control Unit (TCU) selects one state out of those four based on the control strategy map (Fig. 2) and various real-time driving conditions including transmission oil temperature, uphill or downhill detection, selected gear, fuel

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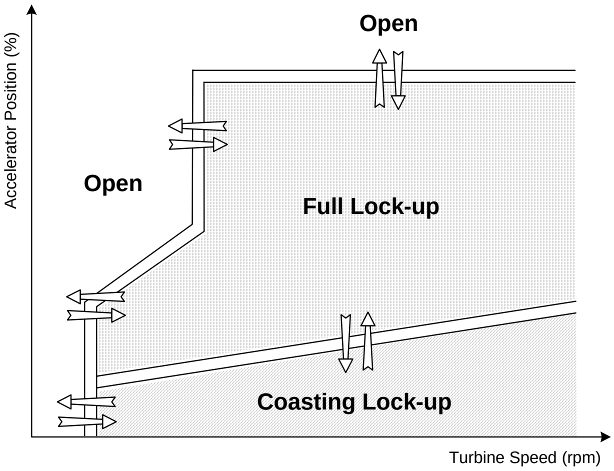
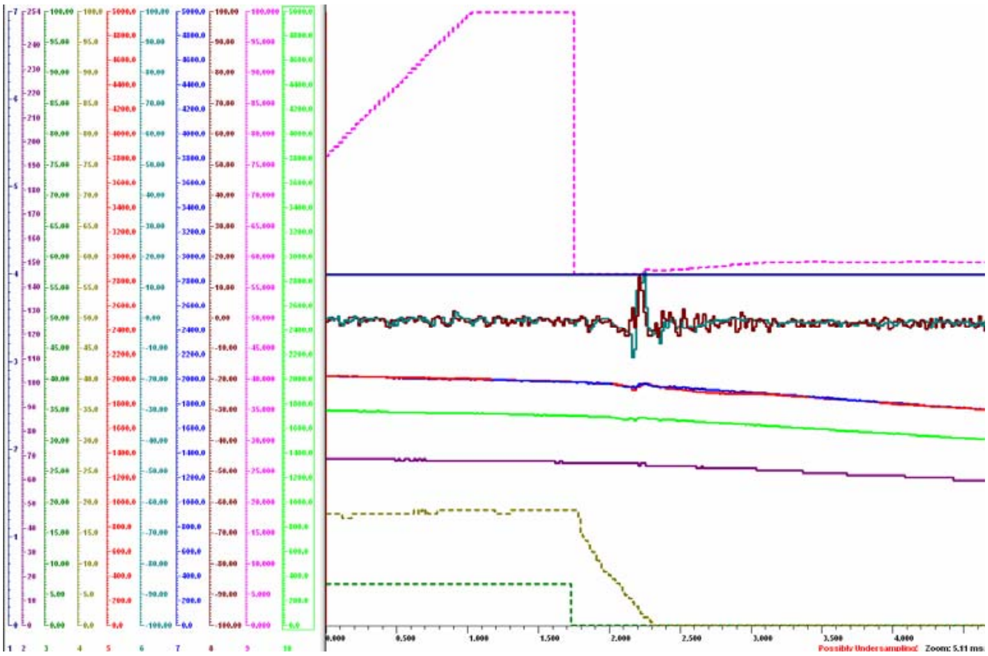


Fig. 2 TCC control strategy map

cut-in/off, etc.

In the state of open, the TCC is completely open because the application duty for its solenoid valve is zero; oil flow is zero; applied pressure to the clutch is zero. However, it is impossible to get any advantages of the TCC with open state. It is desirable to lock it up as much time as possible to achieve the greatest benefits of TCC in terms of fuel economy. Full lock-up is conducted by increasing the application duty up to 100 % so that the turbine is completely locked up and synchronized with the engine. Even though it minimizes the energy loss in the torque converter, it may be an obstruction in some cases. For instance, gear-shift brings about sudden change of turbine speed, and it leads to forced change of engine speed and bad shift feeling for the driver unless moderate slip exists in the TCC. During gear-shift, fully locked-up TCC is slightly open to make slip between the engine and turbine, which allows smooth shift feeling without surrendering better fuel economy. Not only for the gear-shift is slip intended, but also for the coasting is the slip allowed even if its target slip magnitude is very small. If the driver removes his foot from the accelerator pedal in a relatively high vehicle speed, the engine torque will fall to zero and the car will start to move by its inertia. The engine torque fall and the synchronization between the turbine and engine trigger the coasting lock-up shock, which is uncomfortable for the driver. As in an example shown in Fig. 3, the application duty to TCC is immediately changes for the state transition from full lock-up to coasting lock-up as the driver lifts his foot up. The engine is no longer required to provide the power or torque to the vehicle, and then its torque fades away. Around 500 (msec) after the start of coasting lock-up control, the turbine and output speed fluctuates in short time because of the engine's vibration. The big change rate (gradient) of the turbine speed causes uncomfortable drive feeling of judder.

Even though many studies on the torque converter and its clutch have been carried out, a large number of researches have been focused on the modeling, dynamic analysis, and lock-up/slip controller design. Only few studies have been concerned about the prevention of the coasting shock. Choi *et al.* proposed the control of the engine torque itself to reduce the acceleration/deceleration shock of the TCC [1]. Togai *et al.* constructed an active control method to make their power-train robust against annoying vibration [2]. As their studies showed, it is valuable to achieve the robustness against engine torque vibration or acceleration/deceleration shock by modifying engine control unit (ECU). On the other hand, it is also feasible to get stable and smooth coasting lock-up by modifying coasting lock-up controller itself. It would be more efficient rather than modifying the engine input that would affect the



X-axis: time (sec)

Y-axes:
1. gear position
2. vehicle speed (km/h)
3. accelerator pedal position (%)
4. engine torque (%)
5. engine speed (rpm)
6. engine speed gradient (rpm/sec)
7. turbine speed (rpm)
8. turbine speed gradient (rpm/sec)
9. TCC application duty (%)
10. output speed (rpm)

Fig. 3 Shock during coasting lock-up

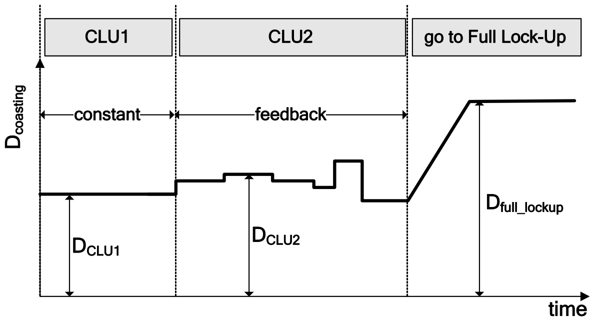


Fig. 4 Coasting lock-up control phases

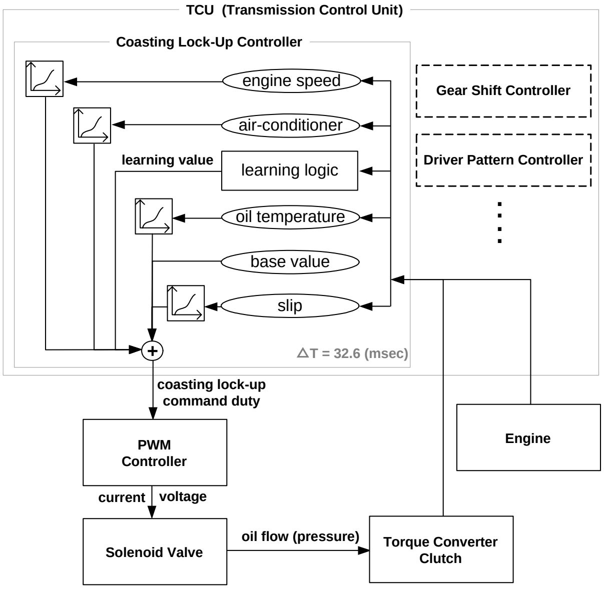


Fig. 5 Control flow of CLU

whole power-train system. Thus, instead of sophisticated change of other elements of the power-train, more intelligent coasting lock-up controller was proposed in this paper to prevent the coasting lock-up shock.

III. COASTING LOCK-UP CONTROL

Once the vehicle starts to coast and the coasting lock-up control (CLU) is begun, CLU1 comes first and CLU2 follows and is sustained until the end of CLU, as shown in Fig. 4. While the constant duty is being applied to the clutch for CLU1, the TCC controller decides to surrender or continue the CLU based on the activation of the fuel cut-off, slip magnitude, etc. The engine torque fades away during CLU1 because the driver left his foot from the accelerator. The turbine and engine speeds go through slight fluctuation and then stabilized as in Fig. 3. CLU2 keeps carrying out CLU after CLU1, if certain conditions are satisfied, for example, the fuel cut-off is activated and slip magnitude between the engine and turbine is small. CLU2 performs a feedback control to make the slip smaller than target slip. The bigger slip happens, the higher duty of CLU2 is applied to the TCC, and vice versa.

In phase CLU1, the TCC control duty is determined by following equation:

$$D_{CLU1} = D_{CLU\_base} + D_{CLU\_learning} + D_{CLU\_temp} + D_{CLU\_slip} + D_{CLU\_engine} + D_{CLU\_ac}. \tag{1}$$

D_{CLU_base} : Base application duty
$D_{CLU\_learning}$: Learning value
D_{CLU_temp} : Compensation of oil temperature
D_{CLU_slip} : Compensation of slip magnitude
D_{CLU_engine} : Compensation of engine speed
D_{CLU_ac} : Compensation of air conditioner

As in (1), the application duty is calculated with base, learning, and compensation values. Base value is calibration data for deciding the level of application duty, which does not change once it is set. In addition to base value, other figures assist for more delicate control. Even if the duty level would be determined by the base value validated in a certain vehicle, it would not be enough to lock the TCC up for the coasting for other vehicles. In this case, the application duty level must be increased and learning value fulfills that modulation. Other compensation factors are for more detailed correction with respect to various driving conditions such as air conditioner on/off, engine speed change, slip, and AT oil temperature.

In contrast to CLU1 that cannot be maintained over a previously defined time, CLU2 sustains CLU as long as conditions for the transition to other states (open or full lock-up) are not met. CLU2 is implemented with PD controller whose role is to keep the slip within a reference value because better fuel economy can be achieved with stable coasting lock-up with smaller slip. On the other hand, controlling the slip under few revolutions per minute to save more fuel would make the TCC fragile for the coasting shock. For the almost locked-up turbine and engine, they have no room to move independently and are prone to disturbance resulting in

TABLE I
SPECIFICATION OF TEST VEHICLE

Test Transmission		HMC/KMC A5GF1
Engine		HMC/KMC Theta (2400 cm^3)
Maximum Power		1.627 (kW)
Maximum Torque		225.4 (N·m)
Vehicle Weight		16.37 (kN)
Wheel Radius		0.31 (m)
Test Driving Speed		60-80 (km/h)
Test Gear		4th
Test Road		plane road
Gear Ratio	1st	4.250
	2nd	2.316
	3rd	1.594
	4th	1.161
	5th	0.817
	R	4.272
	Final	2.950

annoying shock for the driver, i.e., one of them must fluctuate unavoidably if the other suddenly vibrates with some reasons. However, it would be possible to reduce the shock in Fig. 3 by inducing moderate slip during its occurrence if their sudden fluctuation is measurable and predictable.

IV. PREDICTABILITY TEST

Shock itself is difficult to define quantitatively, but its existence can be inferred from some physical values. For automobile, the driver would feel uncomfortable when the vehicle speed changes abruptly. Vehicle speed is the outcome of the multiplication of the turbine speed by gear ratio in vehicles with AT. In other words, sudden change of vehicle speed causing uncomfortable feeling can be monitored by the turbine speed gradient. Provided that the turbine and engine is almost locked up, their speed gradients can be used to measure and predict the interference between the engine and turbine under the coasting lock-up.

However, as can be seen in Fig. 3, it is normally the engine with nonzero torque that causes uncomfortable feeling with the turbine speed fluctuation during CLU. Thus, it is more desirable to see the engine speed gradient rather than the turbine speed gradient. Moreover, it is noteworthy that the shock during CLU can be felt within one second at most after starting CLU because the engine torque fades away during that time. This phenomenon needs to be investigated in detail and the occurrence time of the shock is necessary to be measured to see any possible tendency.

Test driving has been carried out with a vehicle made by HMC/KMC and its test condition is listed in Table I. The shock is considered to be occurred when the engine speed gradient becomes bigger than a reference value of 13.8 (rpm/sec) that was determined by experience, which means the CLU shock is measurable to some extent. Coasting lock-up was conducted under the constant vehicle speed between 60 and 80 (km/h), and then the engine speed gradient was measured and the lapse time after starting CLU was saved when the engine gradient fluctuates over 13.8 (rpm/sec) because the engine speed change will result in the CLU shock after all. The selected gear for the predictability test is 4th gear because it is known by experience that CLU shock tends to occur in the lock-up with lower gear.

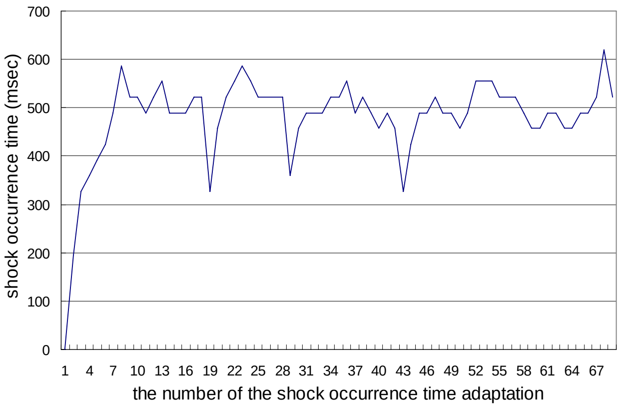


Fig. 6 Experiment of shock occurrence time tendency (predictability)

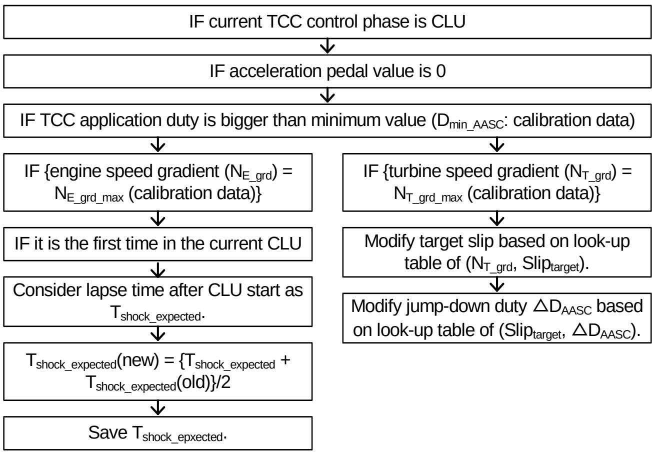


Fig. 7 Adaptation of the expected shock occurrence time, target slip, and jump-down duty in the beginning of AASC

Regarding the investigation of the CLU shock occurrence time, it is more important to figure out the tendency than to find the exact occurrence time because the transmission is a hydraulic system that is inherently impossible to take very fast action. Even though the control duty is applied, its real effect (hydraulic pressure) is achieved after 30 (msec) at least. Since it is more practical to focus on overall tendency, the average of the occurrence time was considered as a base data for CLU shock detection in this study. The experimentally found tendency of the occurrence time is shown in Fig. 6 and it can be said that the shock will appear between 450 and 550 (msec). Consequently, it is proved that the interference between the engine and turbine is predictable, but the turbine speed fluctuation following engine speed behavior remains as a problem to be solved.

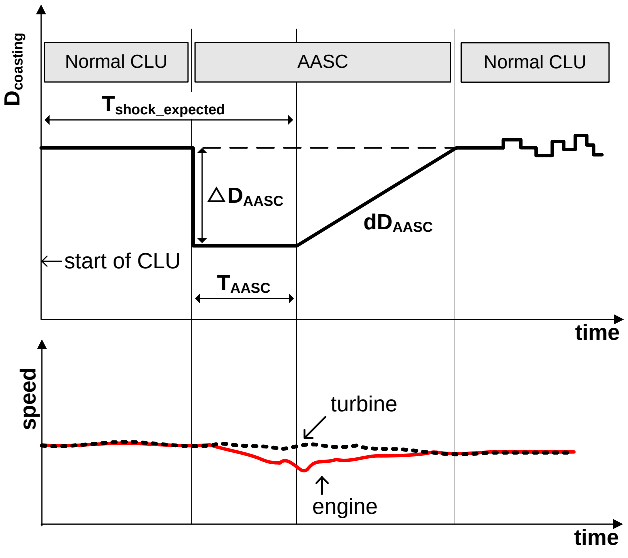


Fig. 8 Adpative anti-shock control strategy and expected engine and turbine speed behavior

V. ADAPTIVE ANTI-SHOCK CONTROL

Since CLU shock is measurable and predictable as mentioned above, it can be decreased or prevented by inducing moderate slip between the engine and turbine somehow before and after its expected occurrence time. Slip between the engine and turbine can be produced by applying lower duty to TCC, but simply lowering the application duty level might cause early fail or abandonment of CLU. Thus, only short modification method is essential to keep normal CLU application duty level.

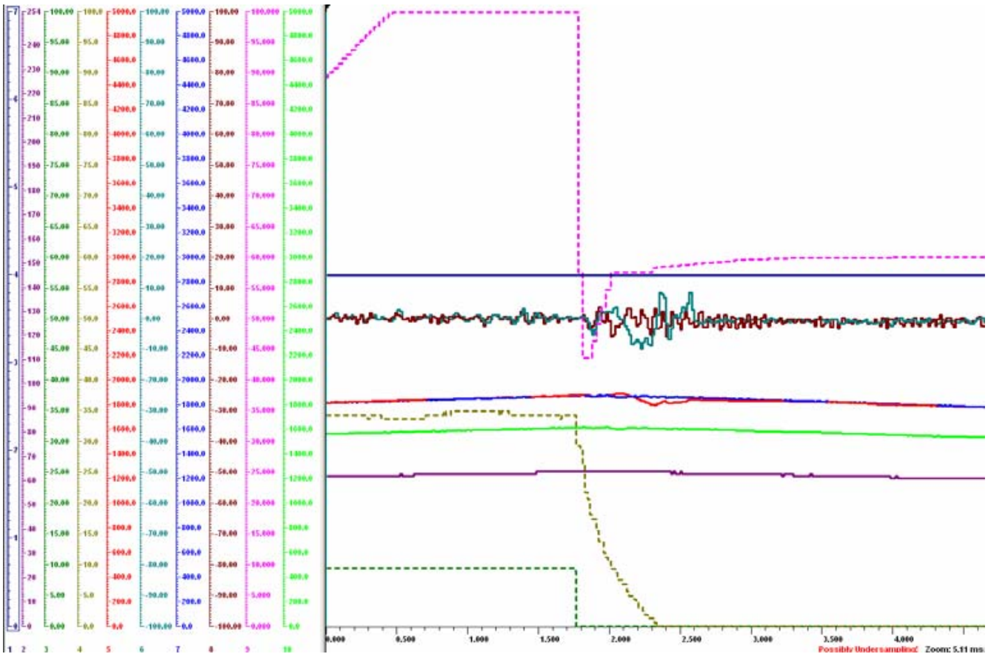
Immediate decrease ($\triangle D_{AASC}$) of the application duty (jump-down) was adopted for anti-shock slip control in this work. Once it is jumped-down, it is increased again up to the original duty with predefined slope (dD_{AASC}) after holding the constant application duty for a certain time (T_{AASC}), as shown in Fig. 8. Normal CLU control of Fig. 4 is interrupted before the activation the adaptive anti-shock control (AASC), but it continues after the end of AASC. On the other hand, for more successful anti-shock performance, it is important that the expected time of shock occurrence ($T_{shock\_expected}$) must be adapted to different driving conditions and vehicles because the shock may appear in different time according to different vehicle, road, and driver. Thus, the lapse time is measured always newly when the shock is detected and its new value is considered to calculate new $T_{shock\_expected}$ that will be used for the AASC in the next CLU (see Fig. 7). The shock detection, however, is permitted only once during one CLU to avoid the wrong repetition of shock detection.

Knowing when the shock will appear, the CLU application duty is jumped down with appropriate value for the induction of slip, provided that it will not cause any harmful effects for continuing the CLU. The jump-down duty is chosen from the calibration look-up table in consideration of the target slip. In other words, the bigger turbine speed gradient fluctuation is detected, the bigger target slip and jump-down duty is selected. These variables' modification is conducted in every CLU, so AASC becomes adaptive to various environments such as different engines, transmissions, drivers, etc. Unlike them, holding time and ramp-up slope of AASC do not vary once it is calibrated because they are not critical for slip induction.

VI. EXPERIMENTAL RESULTS

As can be seen in Fig. 9, the vehicle test was carried out with the TCC control state transition from full lock-up to CLU. TCC controller completed full lock-up by increasing the application duty up to 100 (%), and its duty was dropped to 57.6 (%) for CLU control as the accelerator pedal is depressed in a stepwise manner. Test vehicle speed was 64 (km/h), its engine and turbine speeds were 1878 (rpm). After 32 (msec) from the initial point of CLU, CLU control duty was jumped down to 43.6 (%) and held constant for 65 (msec). It is raise again to its initial value of 57.6 (%) with the slope of 0.0875 (%/msec). Then TCC controller continues the normal CLU after this interruption for AASC.

AASC was started in the beginning of CLU because the TCC is a hydraulic system having delay time between the application control duty and real hydraulic pressure as discussed before. Thus, the enough slip could be induced around the expected shock occurrence time by finishing AASC within 230 (msec) after the CLU start. The induced slip enabled the turbine independent of the engine whose torque decreased slowly and completely disappeared around 580 (msec) after the beginning of CLU. Due to AASC, turbine and output speed fluctuation did not occur while the engine speed was being fluctuated with



X-axis: time (sec)

Y-axes:
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3. accelerator pedal position (%)
4. engine torque (%)
5. engine speed (rpm)
6. engine speed gradient (rpm/sec)
7. turbine speed (rpm)
8. turbine speed gradient (rpm/sec)
9. TCC application duty (%)
10. output speed (rpm)

Fig. 9 Experimental result of AASC

the maximum gradient of 8.7 (rpm/sec). Small turbine speed gradient change can be seen, but it is bearable. Consequently, the result shows that the proposed AASC successfully reduces the CLU shock.

VII. Discussion and Conclusion

A new control strategy was proposed in this study for the prevention of vibration or uncomfortable fluctuation of the vehicle speed in the beginning of CLU. It has been shown that the shock is measurable and predictable by experiment, and the anti-shock CLU controller has been designed. Then it has been improved to adapt to various driving conditions for more successful CLU. Its experimental validation has been carried out to show its feasibility. As a result, it has successfully reduced the interference between the engine and turbine by inducing moderate slip. Even if the engine speed fluctuated, the turbine was not affected because of the slip by AASC. In addition, it is obvious that the introduction of AASC is not expected to cause any bad influences on the fuel efficiency because it does not give up the lock-up of the TCC and then the engine speed is kept high enough for fuel cut-off during CLU. Normally the engine speed must not decrease under the some limit for fuel cut-off. It means that AASC would be more profitable in terms of fuel-economy than complete disengagement. It can be concluded, therefore, that the AASC is the effective and practical method for coasting lock-up without both the initial shock and the loss of fuel economy.

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