

Fine Control System for Multi-plate Lock-up Clutch

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ABSTRACT

Expanding the range of operation of lock-up clutch (LC) control to reconcile the achievement of a drive feel with a directness similar to that available from an MT vehicle and increased fuel efficiency has become a trend in the area of automatic transmissions.

The combination of a multi-plate lock-up clutch torque converter (“multi-plate LC TC” below) and an LC direct control hydraulic circuit that provide LC control in response to driving conditions has enabled the realization of a fine control system for an LC that has enhanced the response, cooling, and control performance of the LC.

The application of this LC control system has enabled the range of LC control to be expanded from the previous low throttle opening range to the high throttle opening, low engine speed range. As a result, the time for acceleration from 0-100 km/h at wide-open throttle has been reduced by 0.2 sec, and fuel efficiency in US06 mode and actual fuel efficiency have been increased by approximately 3%.

1. Introduction

Today, as global attention is focused on measures to combat global warming, demands for the reduction of greenhouse gas emissions are increasing. In the automotive area also, reduction of automotive CO₂ emissions is increasingly demanded, in particular through the use of technologies that enhance fuel efficiency. In tandem with this trend, demands are also increasing for the realization of greater ease of driving, and the rate of use of automatic transmissions is consequently increasing. Among these automatic transmissions, there has been a greater diffusion in the past several years of dual clutch transmissions (DCT), which like manual transmissions do not employ a torque converter (TC). Manufacturers are seeking by this means to respond to consumer demands by offering greater driving pleasure through the realization of a drive feel with a sense of directness similar to that of a manual transmission vehicle.

Demands are also being made on TC – the take-off devices used in AT vehicles - for the achievement of performance enhancements such as enhanced drivability and increased fuel efficiency by means of direct torque transmission.

In order to realize these goals, a multi-plate LC TC^{(1),(2)} and LC direct hydraulic control circuit have been employed in combination to enable the achievement of enhanced LC responsiveness, LC heat resistance, and LC controllability by means of the application of LC control that responds to the operating status of the vehicle⁽³⁾.

2. Establishment of Targets for Fine Control

LC control controls the degree of slip in the LC in response to operating conditions including vehicle speed, engine speed, and degree of throttle opening, and controls the transmission of torque by the torque converter. “Fine control” in this paper refers to control of LC slip in response to operating conditions, i.e., control across the entire range of LC operation (Fig. 1). The following development targets were set, based on the projected benefits in terms of enhanced drivability and increased fuel efficiency to be gained from the realization of fine control:

- (1) Expansion of the range of LC control to the entire operating range
- (2) Application of LC slip control in response to vehicle operating conditions

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The range of application of conventional LC is limited (see Fig. 1, “Current AT LC range”). The reason for this limitation is that LC response takes time during deceleration, when the speed ratio is high, and control is applied to turn the LC OFF due to the fact that LC slip generates a large amount of heat, when high torque is generated.

The following performance enhancements were therefore placed on the agenda for the realization of full-range LC control:

- (1) Increased LC response performance
- (2) Increased LC cooling performance

These enhancements were to be achieved through the use of a multi-plate LC TC and an LC direct control hydraulic circuit.

The realization of sufficiently enhanced drivability and increased fuel efficiency from expanding the range of application of LC control to the entire operating range necessitated fine settings for the target slip ratio during vehicle operation. This development agenda would be implemented by means of LC control that responds to the status of vehicle operation.

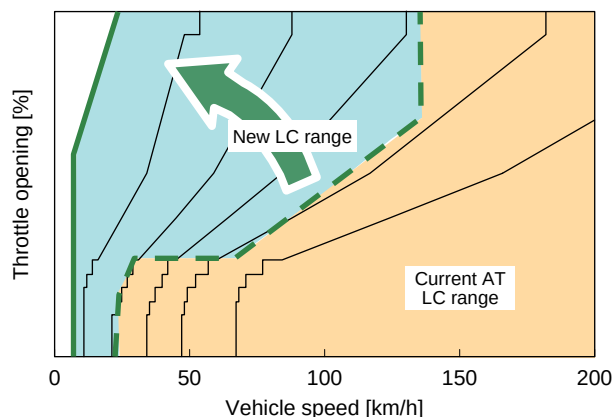


Fig. 1 Lock-up clutch map

3. Multi-Plate LC TC

3.1. Configuration

This section will discuss the features of the multi-plate LC TC (Fig. 2) used in this project. Among the performance parameters demanded from TCs used in FF vehicles are the ability to respond to vehicle hybridization, and their contribution to the reduction of the total length of the AT in order to help ensure collision safety. While the flow channels in standard TCs have a flatness rate of 80%, in 2001 Honda led the world in developing an ultra-flat TC with flow channels with a flatness rate of 60%, and mass-produced the unit as a TC for FF vehicles.

Given that a multi-plate LC is made up of multiple components, including piston chambers, multiple disc plates, and clutch guides, if the conventional flow channel

width was employed, the dimensions of the TC shafts would unavoidably increase. To enable the new TC to be used in FF vehicles, the dimensions of the shafts of the flow channels formed from the blades and torus sections were further reduced, enabling the achievement of a length equivalent to that of a conventional TC.

Another major feature of the TC is that the fact that the piston chamber forms an enclosed space enables the application of torque capacity control equivalent to that applied by the shift clutches.

3.2. LC Response Performance

The achievement of enhanced LC response performance was an important factor in the achievement of full-range LC control. This section will first discuss the operating state of LC control. Figures 3 and 4 respectively show a single-plate and a multi-plate LC. Both types of LC control the operation of the LC pistons by means of the difference between the LC operating pressure and the TC pressure. The achievement of enhanced hydraulic response performance for the LC operating pressure and the TC pressure is therefore a factor in the achievement of enhanced LC response performance. In a single-plate LC, the facts that the flow channels for LC operating pressure and TC pressure are reversed in the transition from LC OFF [Fig. 3(a)] to LC ON [Fig. 3(b)] and that the LC operating pressure and the TC pressure come together in the LC piston section are factors in the delay in the response characteristic of the LC pistons. The response performance of the LC pistons is enhanced in a multi-plate LC, in which the control hydraulic pressure moves in the same direction in LC OFF [Fig. 4(a)] and LC ON [Fig. 4(b)], by maintaining the TC pressure at a constant level and controlling the LC operating pressure, the precision of which has been increased, in relation to the transient state in LC ON.

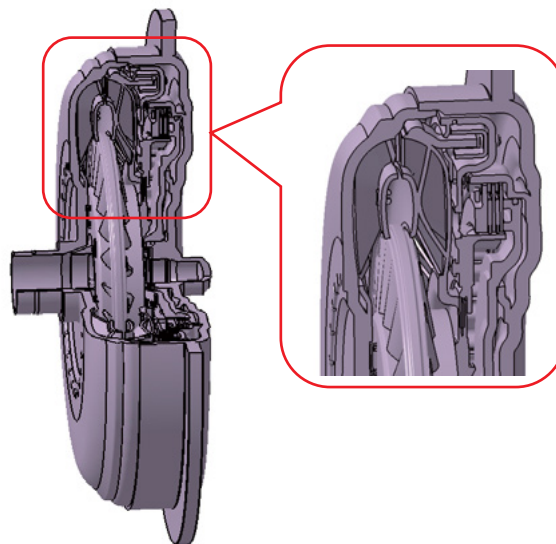


Fig. 2 Side view of developed torque converter

3.3. LC Cooling Performance

The cooling performance of the LC facings is another factor that has a strong effect on full-range LC control. The ATF lubrication is used for the cooling of the LC facings. In a single-plate LC, when the LC is ON, the facings seal the LC operating pressure and the TC pressure [Fig. 3(b)], and it is therefore challenging to achieve an effective flow of the ATF lubrication over the facings. In a multi-plate LC, because the LC pistons form spaces that are always closed, there is no need to seal the TC and LC operating pressure, and lubrication grooves can be employed on the surface of the LC facings [Fig. 4(b)].

The supply of ATF lubrication to the grooves using TC pressure and the use of TC pressure flow channels extending from the inner to the outer diameter of the pistons has enabled the achievement of a smooth flow of

ATF lubrication by means of centrifugal hydraulic pressure. In addition, the use of lubrication holes in the gear hubs in the inner sections of the pistons has also increased cooling performance by enabling an efficient flow of ATF lubrication.

4. LC Direct Hydraulic Control Circuit

4.1. LC Response Performance

In order to enhance LC response performance, the newly developed hydraulic circuit has been provided with a dedicated control valve, the purpose of which is to increase the accuracy of the LC operating pressure to the same level as that of the shift clutches. Figure 5 shows the new hydraulic circuit.

A conventional hydraulic circuit is shown in Fig. 6. LC operating pressure and TC pressure are initially

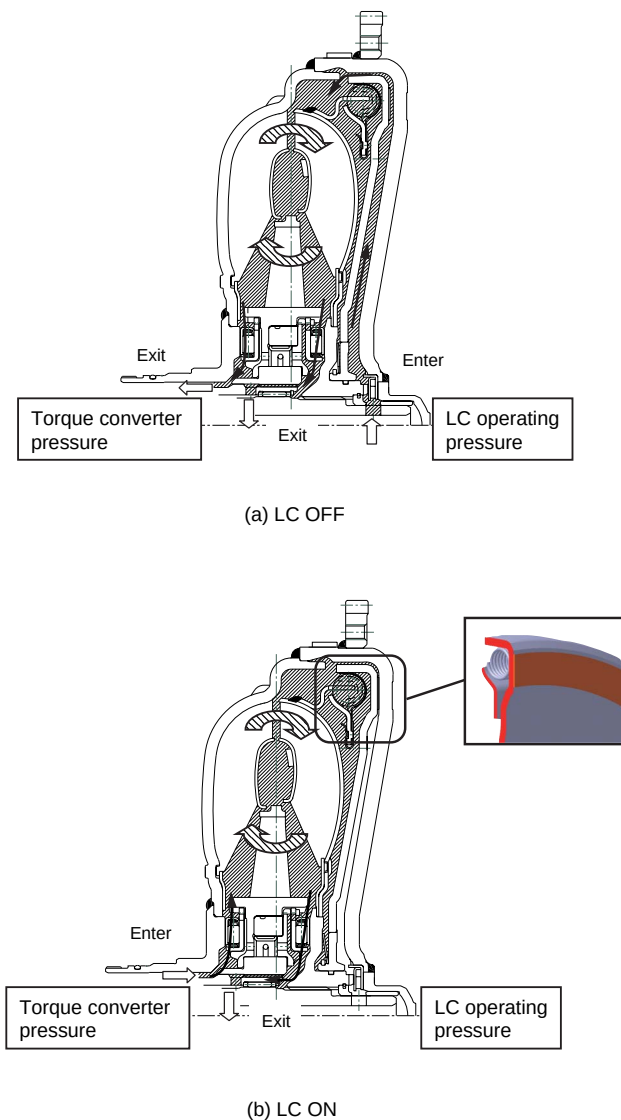


Fig. 3 Oil flow of torque converter with single plate LC (previous)

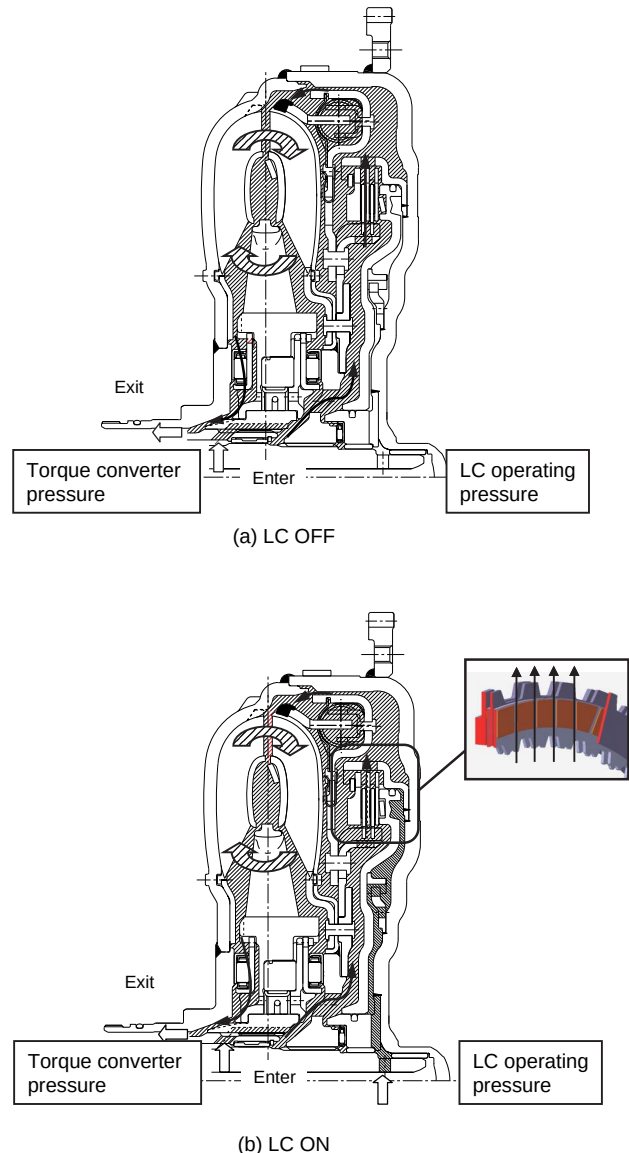


Fig. 4 Oil flow of torque converter with multi plate LC

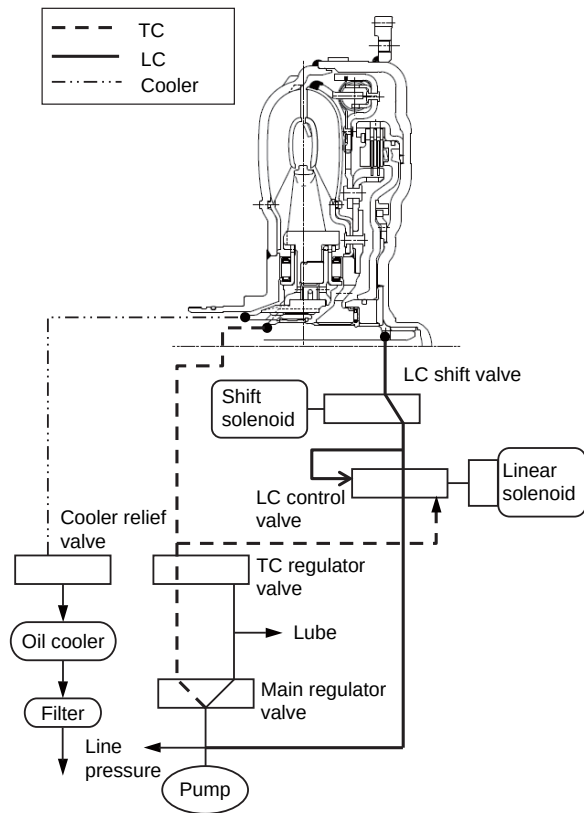


Fig. 5 Multi-plate type hydraulic circuit

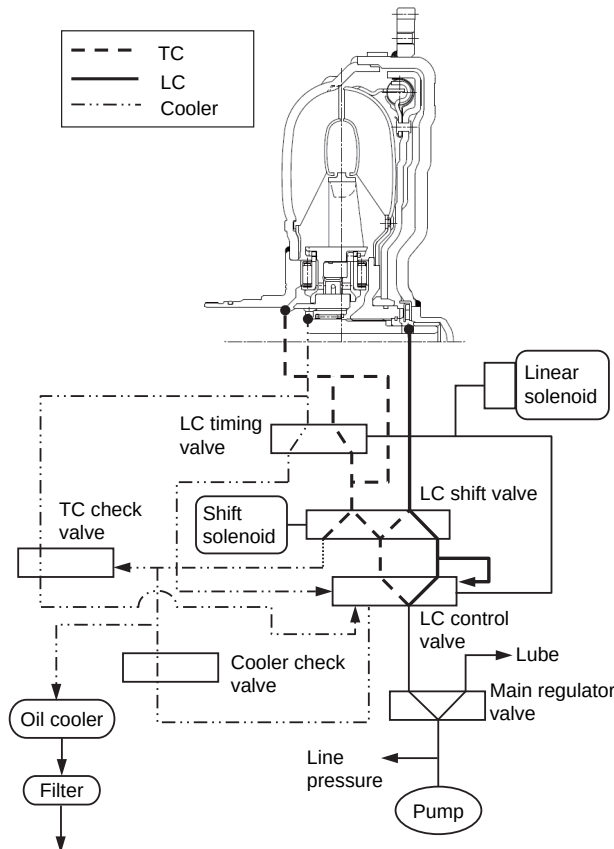


Fig. 6 Single-plate type hydraulic circuit (previous)

identical, but LC operating pressure control generates a pressure differential by means of an LC control valve. Because of this, when the LC pistons are in operation, the TC pressure fluctuates simultaneously with fluctuation in the LC operating pressure, and this is a factor in the delay in the response of the LC pistons. The LC direct hydraulic control circuit uses the LC valve exclusively for control of the LC operating pressure, enabling the LC pistons to be controlled by the LC operating pressure alone, thus increasing controllability to the level of that of the shift clutch pressure.

Because LC control functions by means of a balance between LC operating pressure and TC pressure, it is important to enable LC operating pressure to be compensated by TC pressure. Conventionally, system settings have attempted to create conditions in which changes in the TC pressure affect the LC operating pressure, using the TC pressure on the outlet side to operate the LC control valve. However, the use of TC pressure made LC control more challenging due to the fact that TC pressure is affected by the operation of the LC pistons, and that TC pressure is also changed by vehicle operating conditions, because it is hydraulic pressure that has first passed through the TC. The LC direct hydraulic control circuit helps avoid these LC control issues by means of the fact that the TC pressure is constant in multi-plate lock-up clutches, and by using the inlet-side TC pressure as the pressure acting on the LC control valve. This results in enhanced controllability of LC pressure, with no change to the compensation of LC operating pressure using TC pressure.

4.2. LC Cooling Performance

The internal pressure of the TC has also been increased in the new hydraulic circuit in order to enhance the cooling performance of the LC facings.

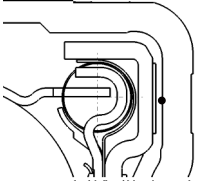
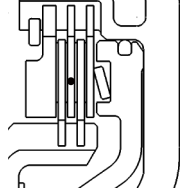
A dedicated TC regulator valve has been employed to maintain the hydraulic pressure in the TC at 570 kPa and to help ensure a TC flow rate of 6 L/min, thus enhancing cooling performance by constantly cooling the LC facings.

5. LC Control in Response to Vehicle Operating Status

5.1. Commercial Appeal of LC

The new control circuit has enhanced the cooling performance of the LC facings (Fig. 7) and expanded the degree of freedom of slip ratio control against that of a single-plate LC. Table 1 shows the conditions employed in temperature measurements of the LC. The enhanced cooling performance has enabled the achievement of a direct response to operation of the accelerator pedal ("AP" below), and the realization of powerful acceleration as a result of increased transmission efficiency. This has reduced the time for acceleration from 0-100 km/h at wide-open throttle by 0.2 sec, and increased fuel

Table 1 Test conditions

Measurement point : ● Single-plate type (previous) 	
Multi-plate type 	
ATF temperature (°C)	100
LC transmitted power (W)	3100
Cooling flow rate (L/min)	4

efficiency in US06 mode and actual fuel efficiency by approximately 3%.

In addition, the selection of an appropriate slip ratio for hill climbing and other driving conditions has helped to ensure torque linearity at the same time that the optimization of the slip ratio has balanced enhanced acceleration performance with enhanced ATF lubrication cooling performance.

5.1.1. Setting of target slip ratios

The following three conditions were established for target values for the slip ratios (Fig. 8) in order to balance fuel efficiency, drive feel, cooling performance, and responsiveness to the intentions of the driver:

- (1) Shift position: In order to respond to the driver's intentions, the slip ratio changes when D range, S range, or manual range are selected. The slip ratio settings for S range and manual range are tighter than for D range, in order to respond to the driver's desire for a sporty drive feel. Here, a tighter setting refers to a setting in which the slip ratio is lower.
- (2) Hill climbing: Hill climbing involves a continuous high degree of throttle opening and low vehicle speed, and a slip ratio, which would prevent the temperature of the LC facings from increasing, was therefore selected for

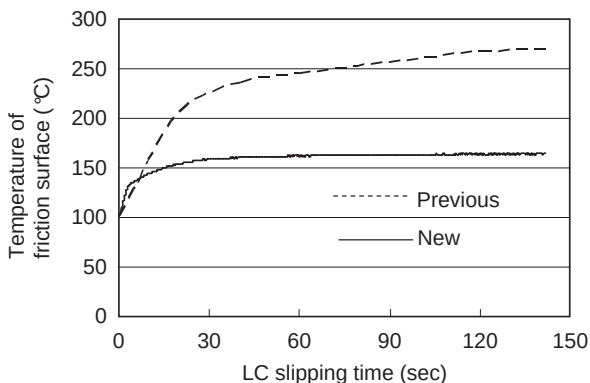


Fig. 7 Test results for facing temperature

this mode. In addition, down-shifting in cooperation with shift control enables the engine speed to be increased and a tighter slip ratio setting to be employed, thus reconciling cooling performance with a satisfactory drive feel.

- (3) Slip control prior to kick-down: Increasing the engine speed before the commencement of down-shifting when the driver intends to accelerate has done away with a sense of sluggishness, while at the same time reducing shift shock.

5.1.2. Control during deceleration

The employment of a configuration in the new multi-plate LC TC that limits the effect of the flow in the TC on the operation of the LC pistons has reduced the time for which the LC is in operation, and enabled the realization of a stable LC response in relation to the speed ratio (Fig. 9).

The reduction of LC response time in the operating range in which the speed ratio is high (Fig. 8) has enabled engagement of the LC during deceleration, thus expanding the area for operation of the engine brake against a conventional AT vehicle. Exploiting this feature, the

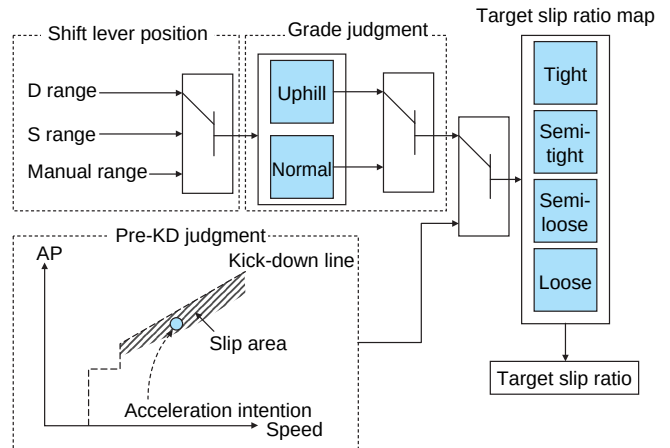


Fig. 8 System diagram of LC target slip ratio

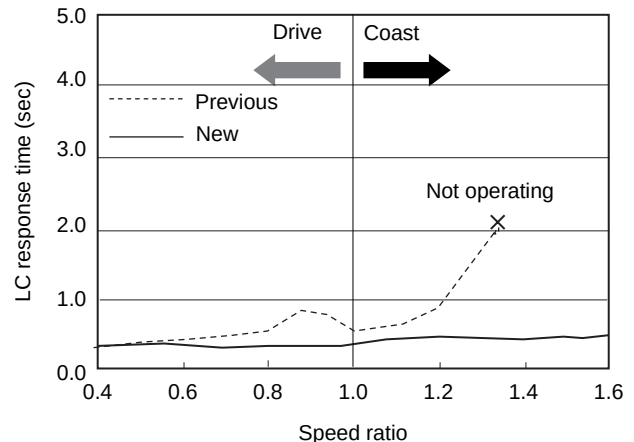


Fig. 9 Test results for LC response time

application of LC ON control in 2nd gear when the system judges that the vehicle is descending a hill enables sufficient braking performance to be realized, enabling the low-hold (L/H) function to be done away with. The conditions set for the application of LC ON control in 2nd gear are the driver's selection of 2nd gear in manual mode and the detection of hill descent. After the system detects that the LC is ON, cooperative control cuts the fuel, enabling the realization of stable engine brake performance (Fig. 10).

Doing away with the L/H function has enabled the achievement of a weight saving of approximately 1 kg and resulted in reduced friction, thereby contributing to increased fuel efficiency.

5.1.3. Control when shifting

Shift shock is an issue when attempting to realize full-range LC control. Conventionally, the transmission of torque fluctuations to the vehicle has been eased by turning the LC OFF during shift, but in the new system, shift shock has been reduced by the application of control to optimize the slip ratio in response to the operating status of the vehicle (Fig. 11).

- (1) Power on, up-shift: The timing of the commencement of the inertia phase (a) and the engagement of the shift clutch (b) is detected, and shift shock is reduced by slightly changing the LC ratio in order to control the LC capacity. In addition, the feeling of directness has been enhanced and fuel consumption has been reduced by maintaining the engagement of the LC after shift.
- (2) Power on, downshift: Reducing the capacity of the LC at the commencement of shift (c) enhances response performance by generating an appropriate level of slip and accelerating the increase in engine speed. In addition, controlling the capacity of the LC by turning the LC ON when clutch engagement (d) is detected in order to help prevent the engine speed from increasing at the conclusion of shift has reconciled the achievement of a smooth shift feel, a direct feel of acceleration, and a

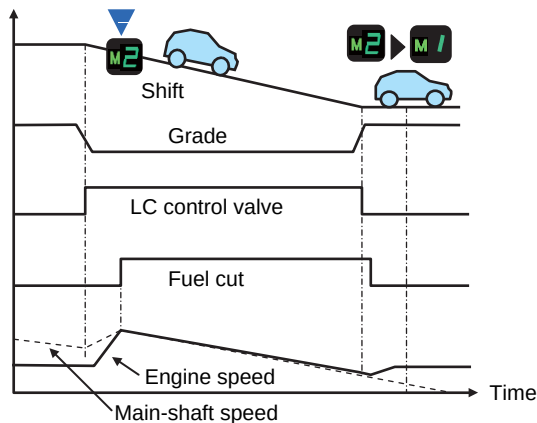
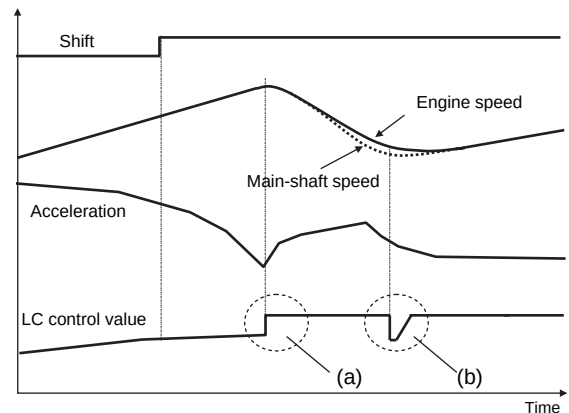


Fig. 10 Engine brake system with use of LC downhill detection

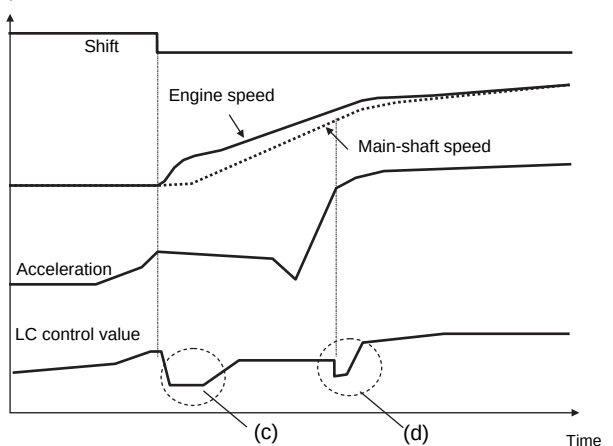
reduction in fuel consumption.

- (3) Power off, downshift: When cooperative control with DBW is engaged (e), the induction of slip in the LC reduces shift shock and noise. Switching the LC ON when the shift clutch engages (f) enables the realization of engine braking like an MT vehicle when AP is OFF, and the achievement of a smooth acceleration feel when AP is ON by means of reducing the increase in engine speed.

(1) Power on up-shift



(2) Power on downshift



(3) Power off downshift

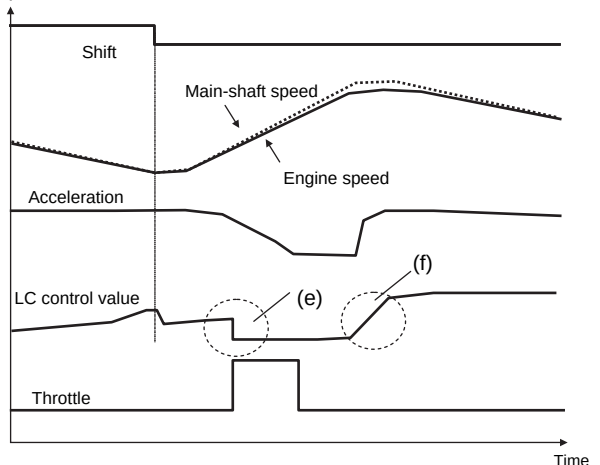


Fig. 11 Test results for LC response time

6. Conclusion

The development of a system of fine control for a lock-up clutch has enhanced drivability and increased fuel efficiency.

- (1) LC responsiveness has been enhanced through the use of a multi-plate LC TC and an LC direct control hydraulic circuit.
- (2) The use of the multi-plate LC TC and LC direct control hydraulic circuit have also enabled the achievement of enhanced LC cooling performance.
- (3) Expanding the range of operation of LC control has enabled the setting of target LC slip ratios in response to vehicle operating conditions.

The use of these technologies has reduced the time for acceleration from 0-100 km/h at wide-open throttle by 0.2 sec, and increased fuel efficiency in US06 mode and actual fuel efficiency by approximately 3%.

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