

Study of Upshift Control Method by Estimation of Acceleration Waveform

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ABSTRACT

Control that corrects the torque output deviation of shift clutches is required to suppress the shift-shock produced when automatic transmissions up-shift, and enhance product quality. Control technology was developed that serves this purpose by estimating and evaluating the vehicle acceleration waveform generated when shifting, from the variation in output shaft rotations, and then detecting the output deviation of clutch torque and performing learning correction based on that acceleration waveform.

1. Introduction

Recently, the number of automatic transmission gear stages is increasing, and enhancement of shift-shock during up-shifting is becoming an important issue. As the number of gear stages increases, the number of shift times while accelerating to a certain vehicle speed also increases, and shift-shock gives drivers an unpleasant feeling. Conversely, acceleration that does not give a feeling of shift-shock is exhilarating for drivers, and can help to further enhance product quality. Based on case studies of shift-shock using actual vehicles, the aim was to realize a vehicle acceleration waveform (hereafter, “acceleration waveform”) that does not produce the swaying feeling accompanied with the absorption of inertia torque (hereafter, “inertia shock”) during the period when the input shaft rotations change (inertia phase). However, due to the output deviation of clutch torque originating in dispersion, it is a challenge to maintain stable product quality by using only feed-forward control.

This study developed an up-shift control method that corrects the output deviation of clutch torque without adding new sensors, in order to realize a stable acceleration waveform without inertia shock and enhance product quality during shifting.

2. Study Goals

The torque transmission formulas during up-shift in a parallel axis automatic transmission⁽¹⁾ are shown below.

Equations (1) and (2) show the torque transmission formulas during the period when the torque transmission path

switches from the opening-side clutch to the conclusion-side clutch (torque phase).

$$T_{in} = T_{of} + T_{con} \quad (1)$$

$$T_{out} = (T_{of} \cdot i_{of} + T_{con} \cdot i_{on}) \cdot i_f \quad (2)$$

Nomenclature

T_{in} : Input torque [Nm]

T_{of} : Opening side clutch torque capacity [Nm]

T_{con} : Conclusion side clutch torque [Nm]

T_{out} : Output shaft torque [Nm]

i_{of} : Opening side gear ratio [-]

i_{on} : Conclusion side gear ratio [-]

i_f : Final reduction gear ratio [-]

When the torque of the conclusion-side clutch is increased and the torque of the opening-side clutch is reduced to establish the relationship shown in Eq. (3), the inertia phase starts.

$$T_{con} > (T_{of} + T_{in}) \quad (3)$$

Equations (4) and (5) show the torque transmission formulas in the inertia phase.

$$T_{in} = T_{con} - T_{of} + J_{in} \cdot \dot{\omega}_{in} \quad (4)$$

Nomenclature

T_{of} : Opening side clutch torque [Nm]

J_{in} : Input shaft inertia [kg·m²]

$\dot{\omega}_{in}$: Input shaft angular acceleration [rad/s²]

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$$T_{out} = (T_{con} \cdot i_{on} - T_{cof} \cdot i_{of}) \cdot i_f \quad (5)$$

Assuming the torque of the opening side clutch after the start of the inertia phase to be “0” yields the following Eq. (6).

$$T_{out} = T_{con} \cdot i_{on} \cdot i_f \quad (6)$$

Thus, the output shaft torque during the inertia phase is determined by the torque of the conclusion side clutch.

Control methods based on cooperation between the shift clutch torque and the engine torque, that is to say, the clutch input torque^{(2), (3)}, are generally applied to create an acceleration waveform without inertia shock. Figure 1 shows this concept drawing. In the torque phase (time t_0 to t_1), the torque of the conclusion side clutch is increased so that it becomes the same value as the clutch input torque when the torque phase finishes (time t_1), and the torque of the opening side clutch is reduced correspondingly. Then, the input shaft rotations begin to change in a manner that satisfies the conditions in Eq. (3), by reducing the clutch input torque after clutch torque switching is completed.

In addition, in the inertia phase (time t_1 to t_2), an acceleration waveform without inertia shock is achieved by performing smooth output relative to the clutch input torque after the torque of the conclusion side clutch finishes shifting.

However, the actual clutch torque has output deviation originating in the initial tolerance and other dispersion. Therefore, even when feed-forward control of clutch torque based on the clutch input torque is used to create an acceleration waveform without inertia shock, inertia shock is still generated due to this output deviation of clutch torque. That is to say, dispersion also occurs in the shift-shock, making it a challenge to secure stable product quality. For example, when the clutch torque is lower than the command value, insufficient clutch torque in

the torque phase results in phenomena such as high-rpm idling. Likewise, when the clutch torque is higher than the command value, inertia shock is generated.

In addition, it is thought that this output deviation of clutch torque can be detected by adding a hydraulic sensor or a torque sensor, but this leads to increased cost and weight. Methods have been devised that use torque converter characteristics formulas to estimate the output shaft torque during the inertia phase from the rate of change in the input shaft rotations, and then use that estimated torque to perform shift control^{(4), (5)}. However, when beginning to change the rotations by reducing the clutch input torque, the transient reduction in the clutch input torque needs to be accurately estimated to detect the output deviation of clutch torque. Therefore, it is desirable to estimate only the clutch torque from the output shaft torque, according to the relationship in Eq. (6).

For these reasons, this study aimed to correct the output deviation of clutch torque without adding new sensors, and realize a stable acceleration waveform without inertia shock by:

- (1) Estimating the acceleration waveform while shifting from the existing rotation sensor signal; and
- (2) Performing clutch torque learning correction so that the acceleration waveform approaches the target waveform, based on evaluation of the inertia shock resulting from the estimated waveform.

3. Clutch Torque Learning Control

3.1. Overview of Control

Equation (7) shows the relationship between the clutch torque and running resistance.

$$T_{out} = T_{rl} + J_v \cdot \dot{\omega}_v \quad (7)$$

Using this output shaft torque as the target value yields the following.

$$\hat{T}_{out} = T_{rl} + J_v \cdot \hat{\dot{\omega}}_v \quad (8)$$

$$T_{out} - \hat{T}_{out} = J_v \cdot (\dot{\omega}_v - \hat{\dot{\omega}}_v) \quad (9)$$

$$T_{con} - \hat{T}_{con} = J_v' \cdot (\dot{\omega}_v - \hat{\dot{\omega}}_v) \quad (10)$$

$$J_v' = J_v / (i_{on} \cdot i_f) \quad (11)$$

$$\Delta T_{con} = J_v' \cdot \Delta \dot{\omega}_v \quad (12)$$

Nomenclature

T_{rl} : Road load torque [Nm]

J_v : Vehicle inertia [kg·m²]

$\dot{\omega}_v$: Output shaft angular acceleration [rad/s²]

$\hat{T}_{out}$: Target output torque [Nm]

$\hat{\dot{\omega}}_v$: Target output angular acceleration [rad/s²]

$\hat{T}_{con}$: Target clutch output torque [Nm]

ΔT_{con} : Output deviation of clutch torque [Nm]

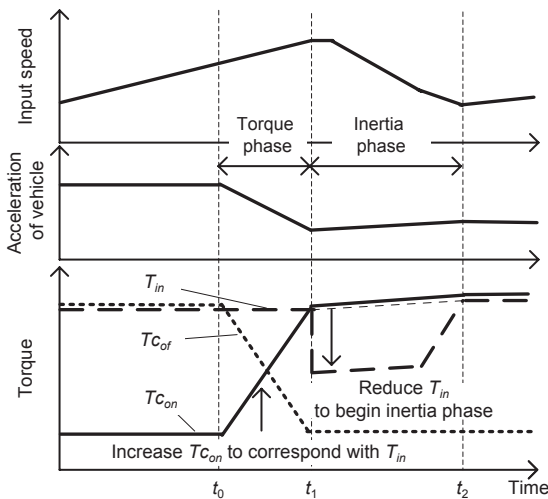


Fig. 1 Concept of reducing fluctuation of longitudinal acceleration during inertia phase

$\Delta\dot{\omega}_v$: Deviation of output angular acceleration [rad/s^2]

Therefore, as shown in Fig. 2, the output deviation of clutch torque can be obtained without the effects of running resistance, from the inertia mass of the vehicle and the angular acceleration of the output shaft; that is to say, the deviation between the target acceleration waveform and the actual acceleration waveform.

The clutch torque learning correction in this study uses this relationship to detect the output deviation of clutch torque from the acceleration waveform output as a result of feed-forward control based in the clutch input torque, as shown in Fig. 3 (a). The feed-forward control output value is then corrected the next time shifting is performed so that the acceleration waveform approaches the target waveform, as shown in Fig. 3 (b).

3.2. Configuration of Clutch Torque Learning Control System

Figure 4 shows the configuration of the clutch torque learning control system.

The control system comprises a feed-forward control unit based on estimation of the clutch input torque, an acceleration waveform evaluation unit, and a learning

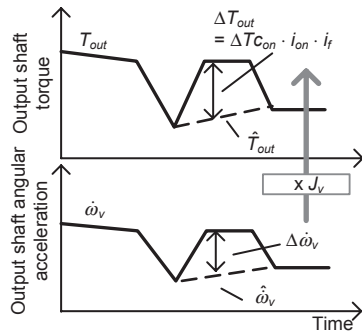


Fig. 2 Relation between output shaft torque and output angular acceleration deviation

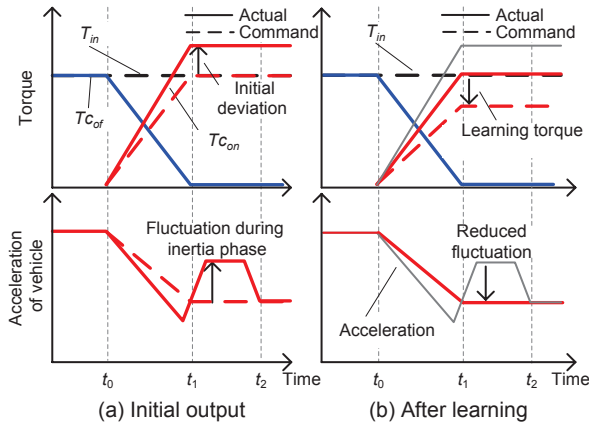


Fig. 3 Concept of learning control for reducing fluctuation of longitudinal acceleration during inertia phase

correction clutch torque calculation unit.

3.2.1. Feed-forward control unit

The feed-forward control unit uses the control concept shown in Fig. 1 to calculate the clutch torques required for both the opening and conclusion sides in order to realize the target acceleration waveforms for the torque and inertia phases, based on the estimated clutch input torque values.

3.2.2. Acceleration waveform evaluation unit

The acceleration waveform evaluation unit estimates the acceleration waveform and calculates the evaluation value of the output deviation of clutch torque based on the estimated waveform.

The acceleration waveform is estimated based on the pulse signal from the existing counter-shaft rotation pickup. The rotations are calculated from the cycle of the pulse signal from the rotation pickup, and differential processing is performed to calculate the angular acceleration. However, due to noise generated by the vibration of the transmission gear used for pulse detection and other factors, simply performing differential processing is insufficient for evaluating the fluctuation in the output shaft torque. This study set a low-pass filter that is suitable for detecting the torque fluctuation during shifting, based on the output shaft torque waveform during shifting measured using an actual vehicle, and the frequency characteristics of the acceleration waveform. The estimated acceleration waveform value is then obtained by passing the angular acceleration obtained

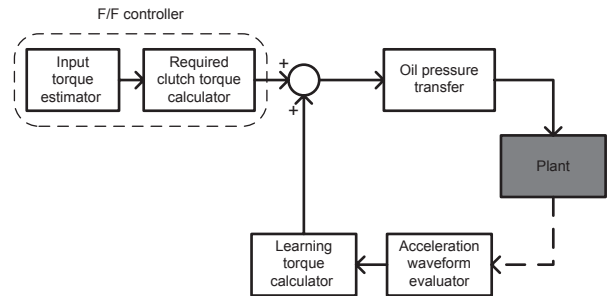


Fig. 4 System diagram of clutch torque learning control for experiment

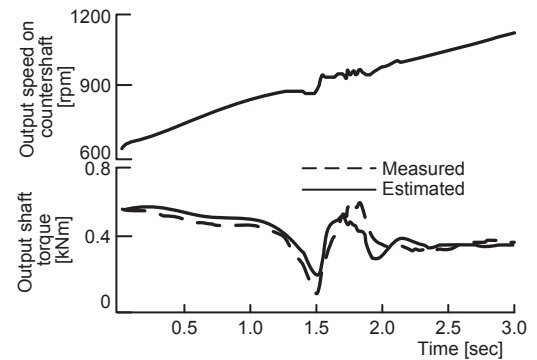


Fig. 5 Comparison of measured and estimated output shaft torque

by differential processing through the set low-pass filter.

Figure 5 compares the results of converting the estimated acceleration waveform value into the output shaft torque based on the relationship in Eq. (7), with the measured output shaft torque waveform. The estimated waveform exhibits the same tendencies as the measured torque waveform, so it is thought that inertia shock can be adequately evaluated using the estimated waveform.

In addition, to realize an acceleration waveform without inertia shock, it is important to match the torque of the conclusion side clutch with the clutch input torque at the end of the torque phase, i.e., in the early stage of the inertia phase. When the torque of the conclusion side clutch exceeds the clutch input torque in the early stage of the inertia phase, the pull-in torque in the torque phase increases due to the relationship shown in Eq. (2) and Eq. (3). In addition, inertia absorption torque is generated due to the relationship shown in Eq. (4). This increase in the pull-in torque and the generation of inertia absorption torque lead to increased inertia shock. Therefore, the subject of learning control is the output deviation of clutch torque in the early stage of the inertia phase, and the control system evaluates the variation in the estimated acceleration waveform value that occurs as a result of this output deviation.

Figure 6 shows the method of calculating the evaluation value in the early stage of the inertia phase. The waveform that linearly connects the minimum estimated acceleration waveform value in the torque phase with the estimated acceleration waveform value after shifting ends is set as the target waveform. The period until the rate of change in the gear ratio reaches a certain level is set as the initial inertia phase interval, and the average value of the deviation between the estimated acceleration waveform value and the target waveform during this initial interval is used as the evaluation value in the early stage of the inertia phase.

3.2.3. Learning correction clutch torque calculation unit

The learning correction clutch torque is calculated as

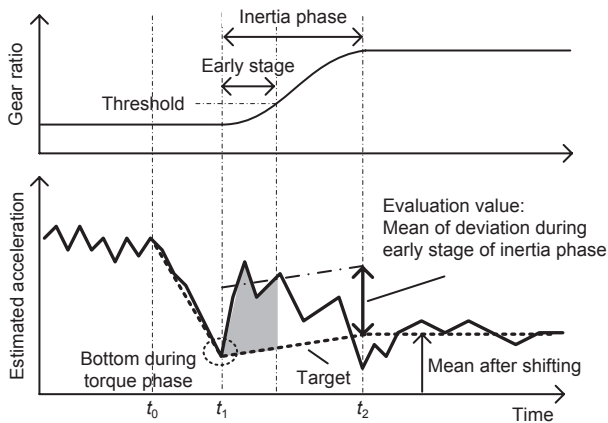


Fig. 6 Evaluation of deviation during early stage of inertia phase

an integral amount by comparing the relative sizes of the evaluation value in the early stage of the inertia phase and the convergence target value, and adding to or subtracting from the previous learning correction clutch torque. The addition/subtraction amount per learning time is fixed, and the set value is obtained by dividing the maximum value of the output deviation of clutch torque by the target convergence times.

4. Confirmation in an Actual Vehicle

4.1. Test Conditions

Running tests were performed using an actual vehicle, and the test conditions were set as follows:

- The shift mode was 1-2 up-shift, which has a large difference in driving power before and after the shift, making shift-shock quality an issue.
- A constant accelerator pedal opening value was used to limit the clutch input torque conditions, and learning was repeated at the same shift point according to a preset shift map.

4.2. Validity of Evaluation by Estimation of Acceleration Waveform

Figure 7 shows the results of calculating the waveform evaluation values in the early stage of the inertia phase from the vehicle acceleration measured using an acceleration sensor and the above-mentioned estimated acceleration waveform values.

The respective waveform evaluation values in the early stage of the inertia phase exhibit a correlation, which confirmed that the estimated acceleration waveform values can adequately function as a substitute for the acceleration sensor.

4.3. Progression of Clutch Torque Learning and Convergence

Figure 8 shows the learning results when initial output deviation of clutch torque of +40 Nm is applied relative to the feed-forward control value.

The addition/subtraction amount per learning time was

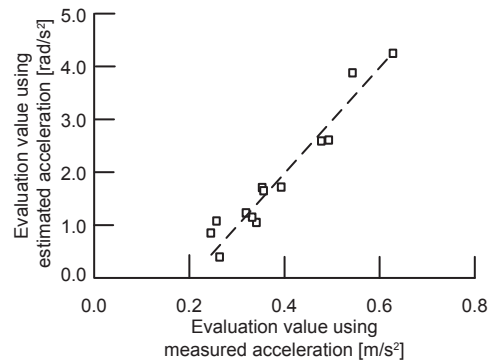


Fig. 7 Comparison of evaluation value using measured and estimated acceleration

set using a number of convergence target learning times of 20 times. In addition, the value corresponding to an output deviation of clutch torque of +10 Nm was set as the convergence target value.

At the learning initial point A (Fig. 9), the rotations

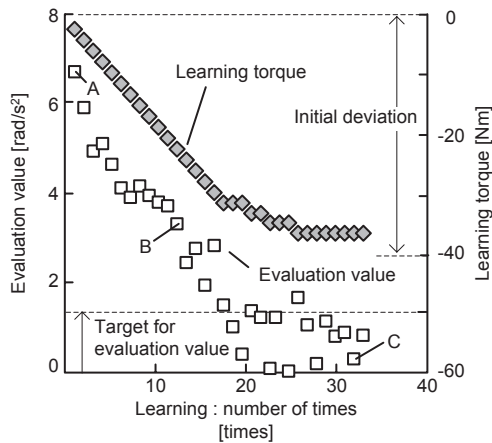


Fig. 8 Results of clutch torque learning control

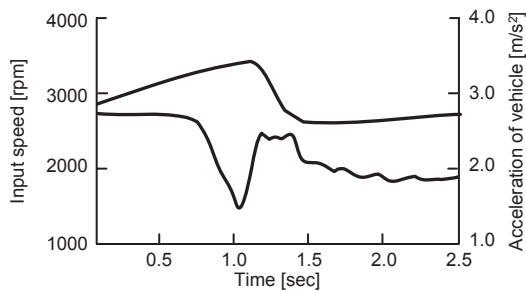


Fig. 9 Input speed and acceleration at A

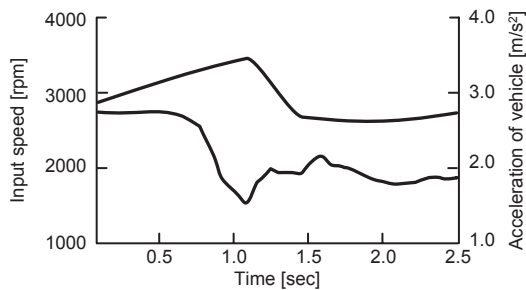


Fig. 10 Input speed and acceleration at B

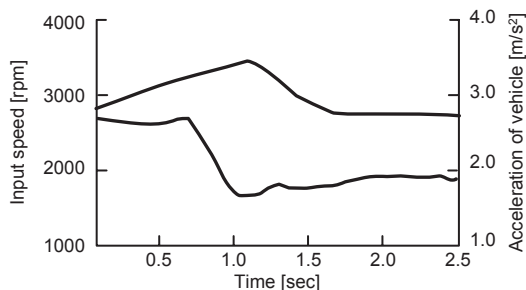


Fig. 11 Input speed and acceleration at C

began to change and inertia shock was generated when the inertia torque was absorbed by the clutch torque due to output deviation of clutch torque. At the learning transient point B (Fig. 10), clutch torque learning was performed relative to point A, and a decrease in the inertia shock was confirmed. At point C after learning had converged (Fig. 11), inertia was not absorbed by the clutch torque, inertia shock was not generated, and the acceleration waveform was confirmed to have converged to the target waveform. These results show that output deviation of clutch torque could be converged to a range of approximately 10 Nm, which indicates that clutch torque learning control using estimation of the acceleration waveform can realize a stable shift-shock waveform without inertia shock.

In addition, the input shaft rotations in Figs. 9 through 11 show that the inertia phase time lengthened by 0.2 sec as learning converged. This is because only clutch torque learning was performed, so the amount of decrease in the clutch input torque remained at the initial setting, and the input shaft rotations changed more slowly due to the relationship in Eq. (4). There are concerns that a longer inertia phase time may produce a slow feeling that lowers product quality, or that heat generation may affect clutch durability. In response, convergence of the inertia phase time to a target time is also thought to be possible by having the control system simultaneously learn the amount of decrease in the clutch input torque corresponding to the clutch torque learning correction.

5. Conclusion

The following developments were performed to enhance product quality during up-shift without adding new sensors.

- (1) Estimated acceleration waveform values during shifting were obtained by performing differential processing and appropriate filter processing on the counter-shaft rotation sensor signal.
- (2) A method was established for evaluating the output deviation of clutch torque during the initial inertia phase interval based on the estimated waveform.
- (3) A learning control method was developed that corrects output deviation of clutch torque based on the evaluation results, and realizes a stable acceleration waveform without inertia shock.

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