1472 *KSME International Journal, Vol. 15 No. 11, pp. 1472~1481, 2001*

Adaptive Compensation Control of Vehicle Automatic Transmissions for Smooth Shift Transients Based on Intelligent Supervisor

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In this paper, an advanced shift controller that supervises the shift transients with adaptive compensation is presented. Modern shift control systems for vehicle automatic transmission are designed to provide smooth transients for passengers' comfort and better component durability. In the conventional methods, lots of testing and calibration works have been done to tune gains of the controller, but it does not assure optimum shift quality at all times owing to system variations often caused by uncertainties in shifting hydraulic systems and external disturbances. In the proposed control scheme, an adaptive compensation controller with intelligent supervisor is implemented to achieve improved shift quality over the system variations. The control input pattern which generates clutch pressure commands in hydraulic actuating systems, is updated through a learning process to adjust for each subsequent shift based on continuous monitoring of shifting performance and environmental changes. The proposed algorithm is implemented and evaluated on the experimental test setup. Results from the experimental studies for several operation modes show both improved performance and adaptability of the proposed shift controller to uncertain changes of the shifting environment in vehicle power transmission systems.

Key Words : Adaptive Compensation, Shift Controller, Intelligent Supervisor, Power Transmission Systems

1. Introduction

Nowadays, many of the passenger cars adopt automatic transmissions for shifting gears, and studies on achieving smooth shift transients under all operating conditions have been extensively carried out by means of both hardware improvement and algorithm development. Modern shift control systems for vehicle automatic transmission are designed to provide smooth transients for passenger comfort and better component durability. In the conventional methods, much testing and calibration works have been done to tune gains for a controller, but it does not assure

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optimum shift quality at all times owing to system variations often caused by uncertainties in shifting hydraulic systems and external disturbances. In recent years, electronically controlled transmissions with direct control of the clutch pressure improved significantly the controllability and contributed progress in driveability and performance of vehicles. The use of direct control of clutch pressures enables more advanced shift control technology, which in turn enables transmissions with reduced mechanical and hydraulic components and complexity.

During the change of gears for shifting, there always exists shift shock, and it degrades shift feeling for passengers. The active pressure control of hydraulic actuators in automatic transmission is essential in improving shift feeling by achieving smooth torque transients during gear shifting. However, the hydraulic system of automatic transmission is one of the most complicated vehicle subsystems in that it includes a lot of uncertain parameters and complexity in modeling. It consists of a large number of power and control elements, for example, a torque converter, clutch actuators, orifices and planetary gear sets. Though several researches on the modeling of hydraulic systems in automatic transmissions were reported (Karmel, 1986), those approaches still have limitations in being used as good alternatives of the actual model, which in turn cannot be used for real-time automatic transmission control.

In addition to the difficulties in the analysis and control of shifting from the viewpoint of the hydraulic systems, the power transmission system has several variations that result in shift variations. System variations in automatic transmission during the shift process include the change in clutch characteristic, change in oil temperature and disturbances due to input torque loss of transmission or external loads. In particular, the shift process has many operating modes and is highly affected by the nonlinear dynamics of the vehicle. Guaranteeing smooth torque transients for all possible operating modes are significant challenges in the shift controller design.

Several applications of modern control theory to vehicle automatic transmissions are reported. Ibamoto et al. (1995) developed smooth shift control system using output torque estimation. In this case, the transmission output torque is estimated using engine or torque converter characteristics and the existing speed sensor. Thus torque fluctuation during shifting is detected and fed back to compare the torque reference, which is generated from the estimated torque itself. However, the inaccuracy of estimated torque caused by degraded performance of the engine and changes in torque converter characteristics deteriorate shift quality. A new automatic transmission control method that ensures high robustness and sufficient control performance has been developed through applications of the sliding mode control and a robust control theory (Furukawa et al., 1994, Zheng et al., 1999). In robust control, we should design a fixed controller to guarantee its robust behavior within realistic plant variation. However, the range of potential modeling error in vehicle power transmission systems is quite large, due to the fluctuating operating environment, wear of components and deterioration of oil. Hence, applying the nonlinear control laws, which define the "error bounds" of models, to the automatic transmission control has some limitations. The vehicle power transmission control system has complex, uncertain and highly nonlinear dynamic processes. Thus, it is difficult to use a model-based control method for smooth power transmission.

One significant approach in dealing with such complexity and uncertainty in nonlinear dynamical processes is the intelligent control scheme such as fuzzy and neural network control. In this paper, we describe the design of an adaptive learning shift controller that is developed by synthesizing several basic ideas from neuro-fuzzy and conventional adaptive control. For the realization of this shift control, we utilize the adaptive neuro-fuzzy inference system (ANFIS, Jang. 1993) as a supervisor and design the adaptive compensation scheme based on the investigation on shift characteristics.

The outline of this paper is as follows. In Sec. 2, a vehicle power transmission system is presented, along with the equations constituting its dynamic model. We also briefly describe the uncertainties in shift process and present our motivation about adaptive compensation scheme in this section. In Sec. 3, we describe the design of the adaptive compensation scheme to achieve improved shift quality over system variations based on intelligent supervisor using neuro-fuzzy inference system. In Sec. 4, the experimental verification of the proposed algorithms is given. A description of the experimental hardware is included.

2. Power Transmission Control System

Figure 1 shows the power transmission system considered in this study. It consists of an engine, a torque converter, a power transmission system, a driveline, and a hydraulic control system that is a key factor as an actuator for smooth shift control. The power produced by the engine is delivered to the driving wheels through the power transmission system, and the automatic transmission changes gears by engaging and disengaging the hydraulically driven clutches. The transient shock or torque during the change of gear ratio degrades passengers' comfort and the durability of hardware components. Thus, it is important that the modern shift control system for vehicle automatic transmissions should provide smooth transients for passenger comfort and better component longevity.

The dynamic equation for shaft torque is a function of the clutch torque, the turbine torque, and external loads as given in Eqs. (1) ~ (2). It is well recognized that the transient torque during gear shift is physically reflected on the change of turbine speed (Narita, 1991). Thus, turbine shaft acceleration is also represented as the function of the clutch torque, the turbine torque, and external loads.

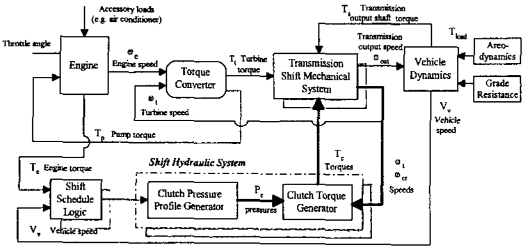


Fig. 1 Block diagram of the vehicle power transmission system

Torque phase

$$T_s = C_1 T_t + C_2 T_c + C_3 T_L \tag{1a}$$

$$\dot{\omega}_t = C_4 T_t + C_5 T_c + C_6 T_L \tag{1b}$$

Inertia phase

$$T_s = C_7 T_t + C_8 T_c + C_9 T_L \tag{2a}$$

$$\dot{\omega}_t = C_{10} T_t + C_{11} T_c + C_{12} T_L \tag{2b}$$

In Eqs. (1) ~ (2), T_s is the output shaft torque, $\dot{\omega}_t$ is the turbine speed, T_t is the turbine shaft torque, T_c is the clutch torque, T_L is the external load and C_i's($i=1\sim12$) are the constant coefficients that are determined by the mathematical model of the power transmission system.

During the inertia phase, the shift characteristics can be manipulated by those variables in Eq. (2), and thus the desirable clutch torque as the control variable is as follows:

$$T_c^{com} = \frac{1}{C_{11}}[\dot{\omega}_t^{ref} - C_{10} T_t - C_{12} T_L] \tag{3}$$

In Eq. (3), T_c^{com} is the desired clutch torque to be controlled, and $\dot{\omega}_t^{ref}$ is the desired turbine speed. If all variables are available without modeling error, the desired clutch torque can be analytically obtained.

However, there are several uncertainties in the power transmission system illustrated in Fig. 2. The uncertainties in clutch torque result from variations in oil properties and friction characteristics of the clutch plates. As shown in Fig. 3, variation related to solenoid valves can cause significant differences in the clutch pressure characteristics. As a result, variation of shift quality can occur by the hydraulic pressure applied to the friction elements.

In addition, uncertainties in the input torque from engine to automatic transmission, i. e. in the turbine shaft torque are deeply concerned with shift transients and their effect on shift characteristics is required to be compensated for.

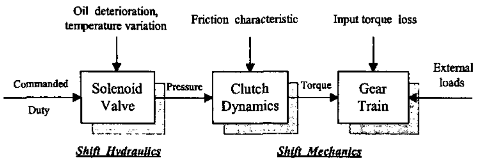


Fig. 2 Uncertainties in power transmission control system

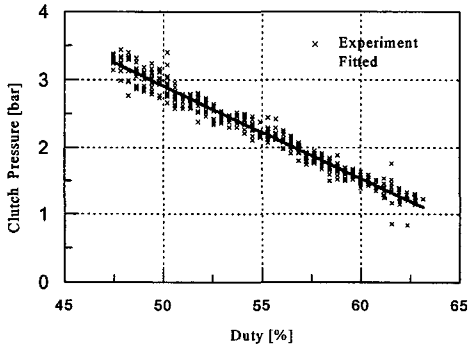
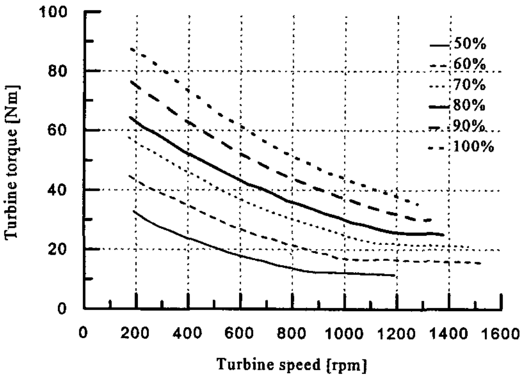


Fig. 3 Variations in shift hydraulics

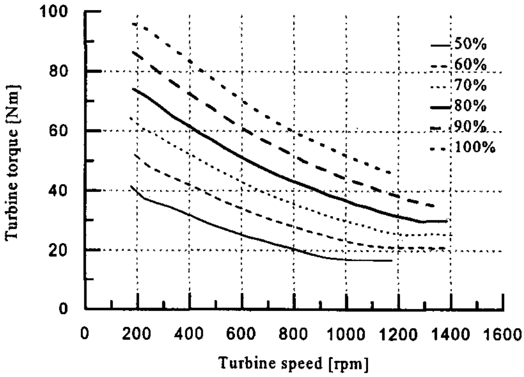
To achieve smooth shifts against such variations in power transmission systems, the commanded clutch torque in Eqs. (3) should be adjusted according to change in the input torque levels.

The input torque to the automatic transmission, which is generated by engine, and amplified by torque converter. Thus, the magnitude of this torque is mainly determined by throttle operation and torque converter characteristics. In particular, turbine torque is transferred to the automatic transmission as a result of the oil-induced flow in the torque converter, and the oil properties depend on the oil temperature.

As can be seen from Fig. 4, the torque converter characteristic is considerably affected by temperature of internally induced oil. Results from experiments indicated that the torque loss caused by the drag torque in torque converter due to variation in oil temperature is quite significant (about 5~25%). Hence, the effect of the solenoid valve characteristics and drag torque can be handled by considering the oil temperature. Thus, throttle angle and oil temperature are selected as the two input variables to construct the supervisor by neuro-fuzzy learning method.



(a) At oil temperature 30℃



(b) At oil temperature 80℃

Fig. 4 Variations in turbine torque affected by throttle position and oil temperature

3. Adaptive Compensation Scheme

In this study, we develop an adaptive learning control method for improving shift transients of vehicle power transmission systems based on an adaptive neuro-fuzzy supervisor. Two variables, i. e., throttle angle and oil temperature can determine the input torque to the automatic transmission, and hence can be considered to mainly influence the shift conditions. The nonlinear relationship between the above described two input variables and the desired outputs, i. e., the control parameters are modeled using the adaptive neuro-fuzzy supervisor. The control input pattern which generates clutch pressure commands in hydraulic actuating systems, is updated through a learning process and the adaptive compensation law to adjust for each subsequent shift based on

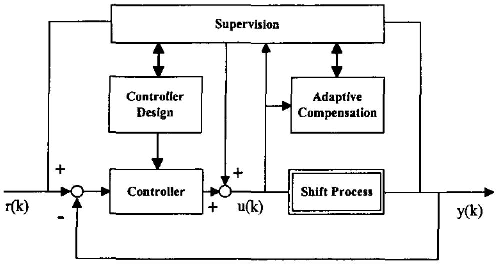


Fig. 5 Supervision and control of shift process

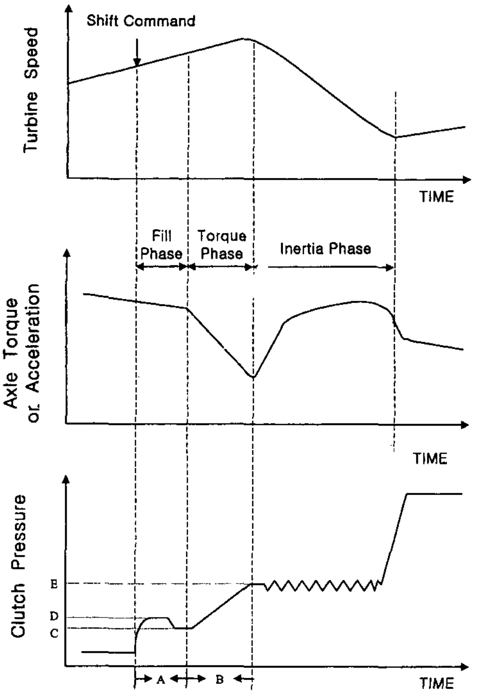


Fig. 6 Shift control process

continuous monitoring of shifting performance and environmental changes. The overall control scheme with the supervisor is shown in Fig. 5.

3.1 Parameterization of shift control

The shift process and control parameters are illustrated in Fig. 6. The desired clutch pressure for shift control is adjusted by shift control parameters such as fill time (A), fill pressure (D), and the entry pressure to each phase and its duration (B), (C), and (E). The desired clutch pressure is continuously updated by the updated control parameters. In particular, the entry pressure to inertia phase is the key control parameter for smooth shift transients. It is well recognized that the shift transient torque in output shaft is dominant in the inertia phase and can be reduced by controlling the clutch torque.

In this study, we focus on supervision and adaptation for the inertia phase during shifting. This control method can be also generalized for both fill phase and torque phase algorithm development.

3.2 Intelligent supervisor

To maintain acceptable shift quality against variety of system characteristics such as input torque and oil temperature, it is necessary to manipulate the controller parameters. Introduction of supervisory control to the shifting point control has been tried so far, but the supervisory control of shifting process itself has not been extensively studied yet.

In this study, we developed a neuro-fuzzy model that supervises the shift process based on the information of throttle position and oil temperature. The neuro-fuzzy system used in this study for modeling the nonlinear relationship between the input variables and the corresponding inertia phase control is a fuzzy inference system built on the framework of a neural network, and the models for the nonlinear systems can be effectively established with this fuzzy system. It consists of 5 layers as shown in Fig. 7. The first layer performs fuzzification operation for the input variables, and the firing strengths are calculated in the second layer. The firing strengths are normalized in the third layer, and then the fourth layer performs the fuzzy inference operation. Finally, the defuzzification operation is carried out and the overall output of the fuzzy inference is provided in the fifth layer. The adaptive neuro-fuzzy inference system for supervising shift control was constructed and then trained using the selected experimental data. The architecture of the intelligent supervisor is shown in Fig. 7. The ANFIS used here contains 9 rules, with three membership functions being assigned to each input variables. It has two inputs, i. e., throttle position and oil temperature, and Sugeno-type fuzzy inference scheme is used to generate output, i. e. control parametric surface.

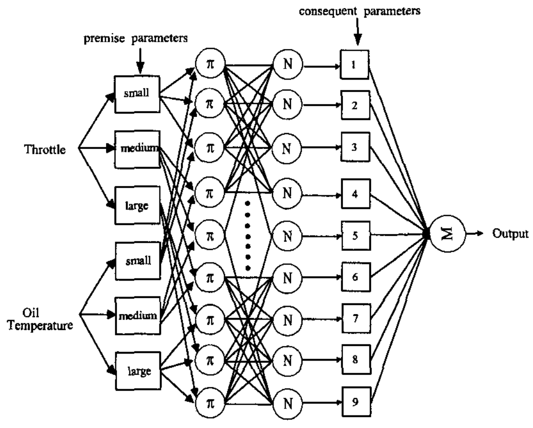
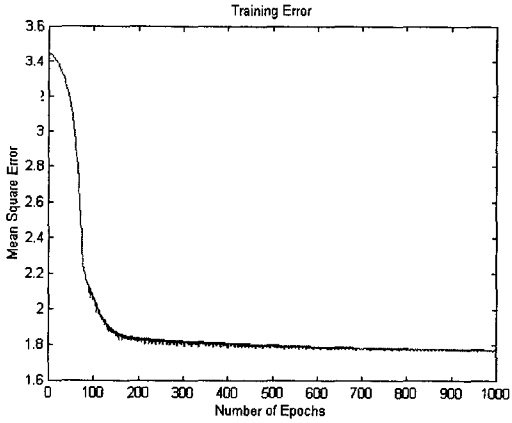
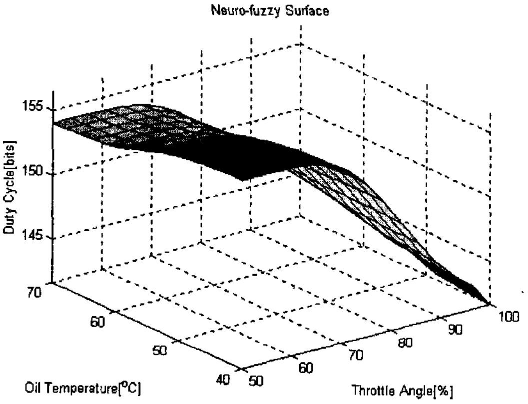


Fig. 7 ANFIS architecture for supervising the intertia phase control during shifts



(a) Learning curve



(b) Control surface

Fig. 8 Training results of the intelligent supervisor

Figure 8 shows training results of the proposed intelligent supervisor. Figure 8(a) shows the MSE (mean squared error) curves for ANFIS used here which indicated most of learning was done in the first 150 epochs. Figure 8(b) shows control parametric surface depending on throttle position and oil temperature and demonstrates how the proposed ANFIS architecture can effectively model a highly nonlinear surface of the control input to inertia phase during shifts.

3.3 Adaptive compensation control

In the presence of uncertain changes in power transmission systems, abnormal or undesired shift transients may be brought out. If turbine angular acceleration is always regulated in certain desirable range, the smooth shift transients can be obtained even under the system variations.

Figure 9 shows a typical pattern for up-shift characteristics. It can be found from the observation of the shift characteristics that there is correlation between shift shock and inertia phase duration. If an attempt is made to minimize shift shock, the time required to complete a gear shift usually becomes excessively long. Conversely, trying to shorten the shift time results in greater shift shock, which in turn degrades the shift feeling.

Based on the analysis of shift characteristics, the inertia phase duration is obviously dependent on the turbine shaft acceleration. Thus, variations in shift quality due to uncertain changes in power transmission systems can be recognized by monitoring the deviation of the shifting duration from the desirable range of shifting duration. In order to keep the shift duration within the

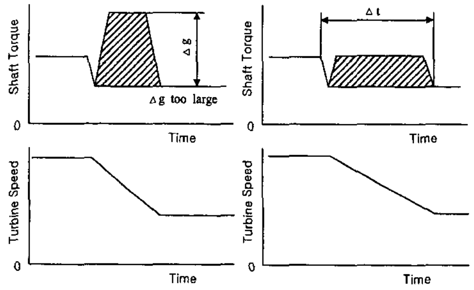


Fig. 9 Typical up-shift characteristics

allowable range in the presence of system variations, the desired clutch torque is adjusted by updating the shift control parameters. In particular, the feed-forward duty cycle, which commands the entry pressure to inertia phase, is updated by applying the adaptive compensation law. The shift performance is continuously monitored in relation to a given desirable shift condition.

Define the performance index as the quadratic function of deviation of the shifting duration from the desirable range of shifting duration:

$$J=\frac{1}{2}e^2 \tag{4}$$

Then, minimize the performance index to drive the error to zero using the gradient descent method.

$$\frac{du}{dt}=-\lambda\left(\frac{de}{dt}\right) \tag{5}$$

For digital implementation, the adaptive updating law is modified by

$$u(k+1)=u(k)-\lambda\left(\frac{de}{du}\bigg|_k\right)e \tag{6}$$

In Eqs. (4) ~ (6), is the deviation from the desirable inertia phase duration, is the commanded clutch torque for k-th shift, and λ is the adaptive gain.

The variations of shift quality can be compensated for by adaptively adjusting control parameters, which in turn make it possible to regulate the turbine shaft acceleration within allowable range.

4. Experimental Studies

4.1 Experimental set-up

Experimental studies have been conducted to test the proposed control method. Fig. 10 shows the schematic diagram of the experimental setup. A photograph of the experimental test setup is shown in Fig. 11. A torque-controlled AC motor is used for an engine, and an inertia load is installed as an external driving load. In addition, the direct clutch pressure control system using the proportional solenoid valve (Shin et al., 2000) has been installed to improve the controllability of the vehicle automatic transmission. By pulse-width-modulating the voltage command to the solenoid valve, the real-time pressure control for each individual clutch can be achieved.

Table 1 Experimental test conditions

Item	Condition
ATF temperature	60±5℃
Line pressure	6.5±0.5 bar
Sampling frequency	100 Hz
Filtering	3-pole LPF, 10Hz cutoff

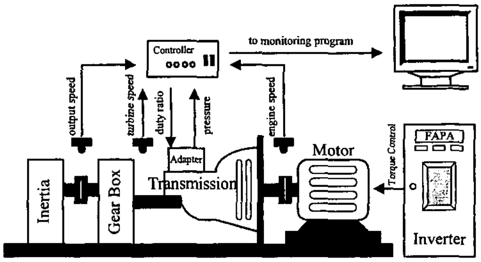


Fig. 10 Schematic diagram of the experimental setup in the dynamometer test

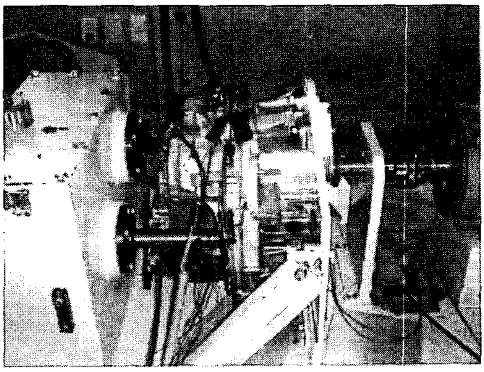


Fig. 11 A picture of experimental test setup

4.2 Experimental results

Bench pressure tests on the solenoid valve were performed. The pressure characteristics were measured for various pressure commands (i. e., duty cycle). The results are depicted in Fig. 12. The pressure varies fairly linearly with the commanded duty cycle from 20% to 80%. The test condition is also shown in Table 1. The sampling time for the control loop is 10msec and oil temperature is around the nominal condition (about

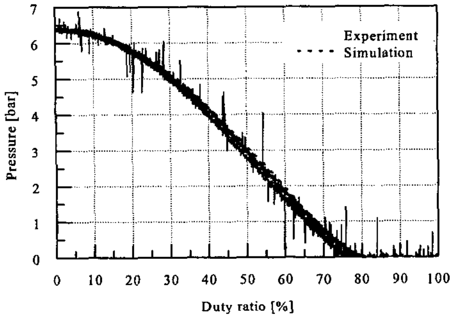
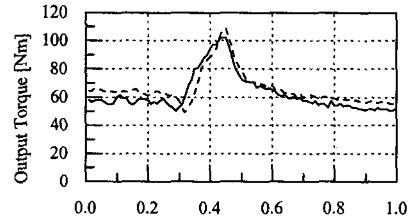
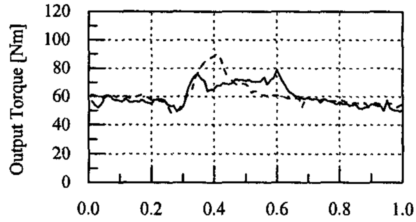


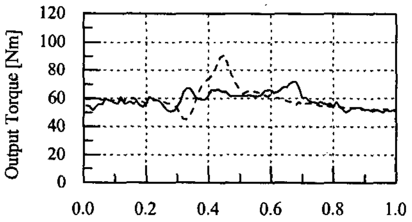
Fig. 12 Solenoid valve characteristics



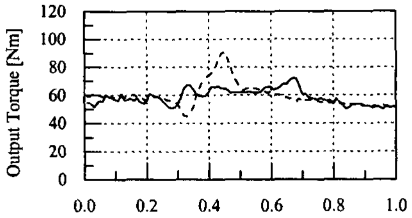
(a) 1st shift



(b) 3rd shift



(c) 5nd shift



(d) 7nd shift Time[Sec.]

Fig. 13 Subsequent shift transients with adaptive compensation (solid line) and without adaptive compensation (dashed line)

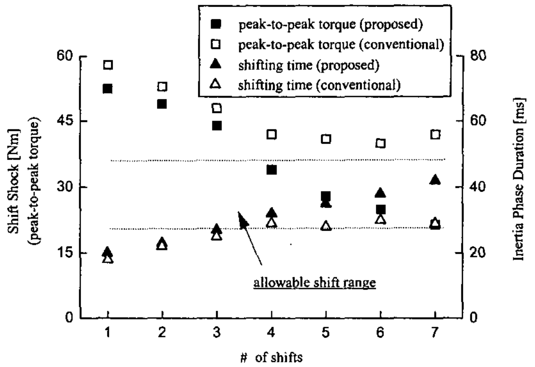


Fig. 14 Shift results : shift shock [Nm] vs inertia phase duration [ms]

70℃).

Experiments are performed for uncertain changes in the power transmission system, which result in degraded shift performance. The subsequent shift results by adaptively adjusting the entry command of duty cycle to inertia phase are shown in Fig. 13. Figure 13 shows a test result comparing the subsequent shift results with adaptive compensation and without adaptive compensation (i. e., applying the fixed entry pressure to inertia phase). As can be seen, actual output torque during inertia phase is subsequently reduced into the allowable shift range when the proposed shift controller is applied, while the conventional controller cannot improve the undesirable shift performance.

In terms of the shift shock and inertia phase duration, the shift performances are evaluated as shown in Fig. 14. It shows that stable shift quality can be obtained by keeping the duration of inertia phase within certain desirable range. It can be seen from the experimental results that the peak-to-peak values of the shift shocks in the inertia phase are subsequently reduced when an adaptive compensation is applied in the shift control.

Experimental results indicate that the proposed shift controller generates clutch pressure commands through the learning process by the intelligent supervisor and adjusts the control parameters for each subsequent shift based on continuous monitoring of the shift performance. In addition, the application of the adaptive compensation law for the inertia phase control makes it possible to obtain better adaptability to several uncertain changes in shift process, for example, variations in external load torque and power produced by the engine and delivered by the torque converter.

5. Conclusions

In this paper, an adaptive compensation controller with an intelligent supervisor is implemented to achieve smooth transients under all possible operating modes in vehicle automatic transmission. An adaptive neuro-fuzzy inference system has been constructed as the intelligent supervisor. In addition, the adaptive compensation law to cope with the variations in shift process has been introduced. The control input pattern which generates clutch pressure commands in the hydraulic actuating system, is updated through a learning process and the adaptive compensation law to adjust for each subsequent shift based on continuous monitoring of shifting performance and environmental changes.

The effectiveness of the proposed control method has been evaluated through the experimental studies. The results for several chosen conditions prove both improved performance and adaptability to uncertain changes in vehicle power transmission systems. Future work will require the generalization of the proposed control scheme to overall shift phase, i. e., fill phase and torque phase algorithm development.

Acknowledgement

This study was supported in part by the Korea Science and Engineering Foundation (KOSEF) through the Turbo and Power Machinery Research Center at Seoul National University.

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