Design and Control of Clutch-by-wire System for Automated Manual Transmissions

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Abstract: With the growing traffic density and increasing comfort requirements, the automation of the drive train will gain importance in vehicles. The automatic clutch actuation relieves the drivers especially in urban driving and stop-and-go traffic conditions. In this paper, an electro-mechanical actuator for clutch-by-wire (CBW) system is implemented as the first stage for the development of automated manual transmissions. The prototype of CBW actuator is designed systematically, which is composed of the electric motor, worm & worm wheel and crank mechanism. And the test rig is developed to perform the basic function test for the automatic clutch actuation. The developed prototype is validated by the experimental results on the test rig.

Keywords: Automated Manual Transmission (AMT), Clutch-By-Wire (CBW), Automatic Clutch, Test Rig

1. INTRODUCTION

With the increasing traffic density, drivers are getting tired and uncomfortable, and he/she gets faced with the danger of traffic accidents due to frequent shift. To decrease this discomfort, drivers like automatic transmissions more than manual transmissions but the automatic transmission is a burden to them because of high cost and high fuel consumption. For this reason, the concern about automated manual transmissions (AMT) is highly getting increased, that has the advantages such as high efficiency, low cost and easy manufacturing [1,2].

Already in the 1960s, automotive manufacturers began to offer automated clutch operating systems designed to simply vehicle operation. But the early systems were functionally inadequate, maintenance-intensive and prone to frequent repairs. Recently, these disadvantages could be eliminated with modern vehicle electronics. Most European clutch manufacturers, for example, Fitchel & Sachs, Luk and Valeo, have been intended to develop the electronically controlled clutch. There have been researched into design and control of the clutch automation systems with improvement of shift feeling and cost reduction [3].

The development process of AMT is performed into two steps, clutch automation and shift automation. The clutch automation is to notice the driver's desire of gearshifting and operate the clutch automatically. In the manual transmission vehicle, the clutch plays a role to cut power at shifting and stopping and to transmit power at driving. The torsional vibration of vehicle powertrain sensitively responds to the clutch operation and has influence on ride comfort. Therefore, it is an important part of clutch control at launching and shifting how to minimize the torque fluctuation during engaging and disengaging the clutch [4,5]. To overcome this problem, it is necessary to develop adequate actuators, sensors and control algorithms.

In this paper, an electro-mechanical type CBW prototype is implemented using a DC motor and crank mechanism, which fits in a small vehicle and has the advantages of simple construction and low cost. The parameters of crank mechanism, DC motor and gear ratio are selected systematically and designed by load analysis using the performance simulator. The test rig is developed to perform the basic function test for this automatic clutch. The developed CBW prototype is validated by experimental data employing the test rig.

2. DEVELOPMENT OF CBW SYSTEM

2.1 Conceptual design of CBW system

The conventional hydraulic clutch system consists of master cylinder, slave cylinder, reservoir, release fork and release bearing [6]. In this paper, an electro-mechanical type CBW system is proposed, which replaces a mechanical clutch control mechanism between master cylinder and pedal with an electro-mechanical actuator and an electric control unit [7]. The proposed CBW system is composed of an electric motor, worm gear and crank mechanism, and it is attached to the conventional hydraulic clutch system. The driver's desire to disengage a clutch is converted into the velocity of a DC motor and it changes into the hydraulic oil pressure. The pressurized oil passes through the pipe and is delivered to the slave cylinder. The displacement of slave cylinder induces the stroke of release bearing through the release fork. Due to these operations, a release bearing pulls diaphragm spring and the clutch is finally disengaged. Figure 1 shows the schematic diagram of CBW system considered in this paper.

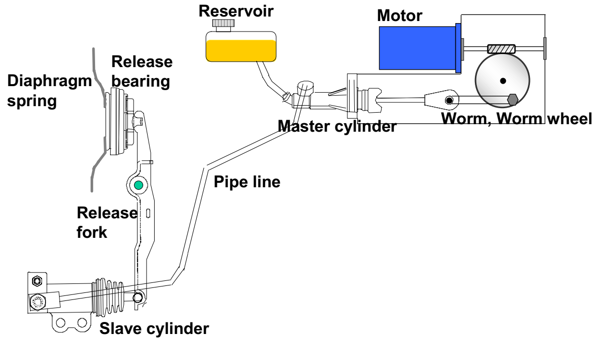


Fig. 1 Schematic diagram of electro-mechanical type CBW system

2.2 Design of crank mechanism

For a design of CBW actuator, the desired maximum force of master cylinder is induced from clamp load of diaphragm spring. The clutch system for a sport utility vehicle is studied in this paper. The clamp load of clutch is initially 5198N and the release load considered cushion spring is 1700N as in Figure 2. However, the clamp load increases to 6669N due to clutch facing abrasion caused by long distance driving, then the release load of 2200N needs to disengage the clutch. The conventional hydraulic clutch system has an efficiency of 70%. Therefore, the force for the disengagement of clutch needs 1026N max.

The mechanism of a clutch actuator is able to be a worm gear type, a lead-screw type or a lever-mechanism type [8]. In this paper, the clutch actuator is constituted by worm gear and offset crank mechanism. Figure 3 shows the schematic diagram of offset crank mechanism. The reaction torque of worm wheel is calculated using crank mechanism equations when the force of master cylinder is given 1026N and the design parameters of clutch actuator is determined considering worm gear ratio and electric motor power.

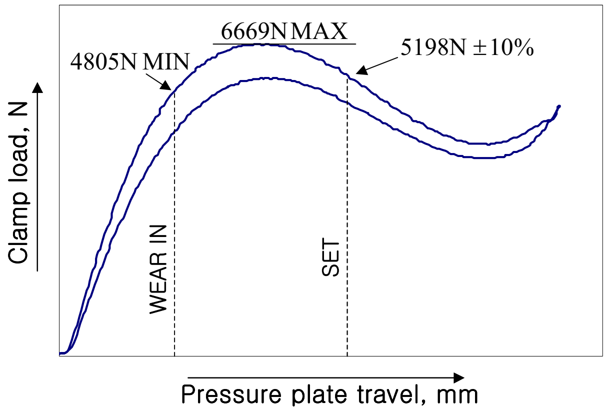


Fig. 2 Load-deflection characteristics of clutch

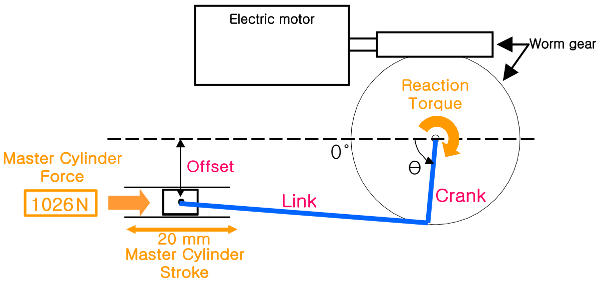


Fig. 3 Schematic diagram of offset crank mechanism

$$S = \sqrt{(r+l)^2 - e^2} - \left(r\cos\theta + \sqrt{l^2 - (r\sin\theta - e)^2} \right) \quad (1)$$

$$T = r\left(\sin\theta + \frac{\cos\theta (r\sin\theta - e)}{\sqrt{l^2 - (r\sin\theta - e)^2}} \right) F_p \quad (2)$$

To determine the design parameters such as crank arm r, link length l, and offset e. The analysis of this mechanism is performed using Equations (1), (2) [9]. It is examined how the reaction torque of worm wheel and the stroke of master cylinder piston change according to the parameter variations. Figure 4 shows the simulation results for reaction force and stroke where the specifications of electro-mechanical type CBW actuator are as shown in Table 1. The length of crank arm that has large influence on reaction torque is determined to consider the piston stroke and rotating angle of worm wheel. On the other hand, the length of link and offset are decided to consider only space condition because they have little effect on the reaction torque. The calculated reaction torque of worm wheel is 15.4Nm and the piston stroke is 20mm. A wiper DC motor is selected as an actuator and its output torque is 0.32Nm. The ratio of worm gear is determined to consider an allowed torque of wiper motor and angular speed of worm wheel. We decide the worm gear ratio of 63:1.

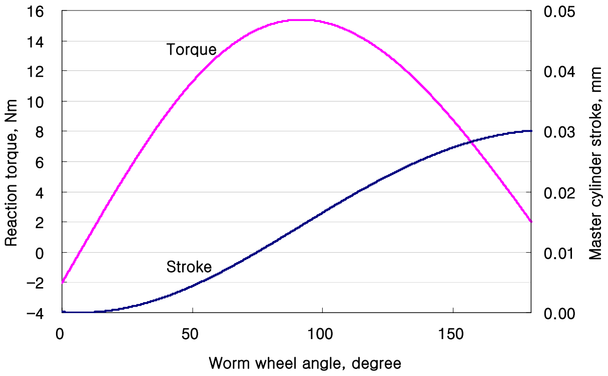


Fig. 4 Simulation results for reaction force and stroke with crank=15mm, link=150mm, offset=13mm

Table 1 Specifications of electro-mechanical type actuator

Crank	15mm
Link	150mm
Offset	13mm
Worm wheel reaction torque	15.4Nm (at 89.2°)
Piston stroke	20mm (5mm ~ 25mm)
Worm wheel angle	83.66° (50.76° ~ 134.42°)
Gear ratio	63 : 1
Worm wheel torque	20.2Nm (margin 1.3)
Disengagement time	0.46sec (83.66°/0.46sec)

2.3 Implementation of CBW system

The CBW actuator is composed of a DC motor, worm gear, master cylinder and sensor, and its prototype is as shown Figure 5. The TPS (Throttle Position Sensor) is used for a feedback sensor and installed to worm wheel. The linear potentiometer is alternatively installed to the master cylinder in order to measure the master cylinder position. The prototype of CBW actuator is somewhat large because was made to adjust the length of crank and change the motor for some kinds of test. But it will be able to make compactly with regard for vehicle test at last.

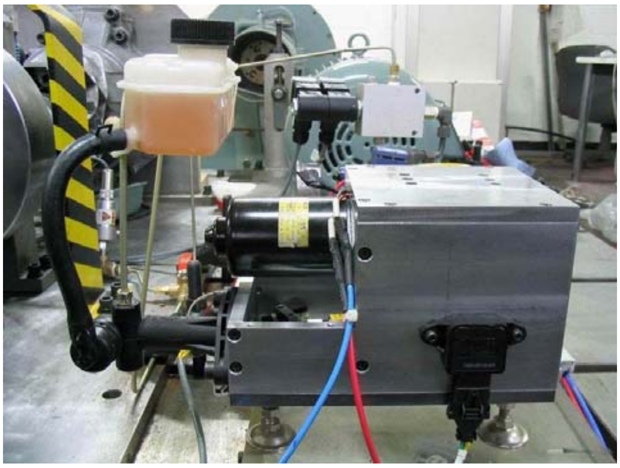
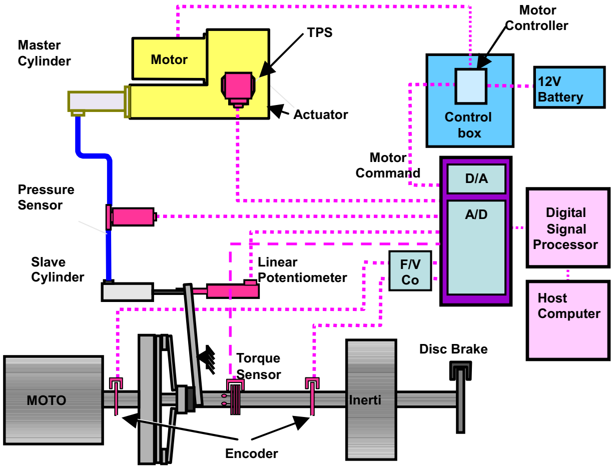


Fig. 5 Prototype of electro-mechanical type actuator

3. TEST RIG

The CBW test rig is developed for the purpose of motion test of electro-mechanical actuator, and is as shown Figure 6. An induction motor and inverter controller simulate an automotive engine at various driving conditions. The rotating velocity and torque are controlled by the inverter controller in test rig. The controller for a test rig contains on/off switches for supplying power and a fuse for protecting over current. It also consists of signal amplifiers, F/V converters, AD/DA boards, digital signal processor and PC for acquiring data and signal processing.



(a) Schematic diagram of test rig

(b) Experimental apparatus

Fig. 6 CBW test rig

4. EXPERIMENTAL RESULTS

4.1 Control characteristics of CBW prototype

The step responses for master/slave cylinder piston are shown in Figure 7. The displacement of master cylinder piston follows to reference input by using PID controller and its maximum stroke is 20mm. From the figure, the disengagement time is measured up to 350msec and engagement time 240msec under the condition of battery voltage, 13.5V. The step response for slave cylinder has a time delay of 46msec, time difference between the command signal and actuating signal, because of an ineffective stroke of master cylinder. However, the disengagement time of slave cylinder equals to a master cylinder and the engagement time is faster than a master cylinder as 220msec

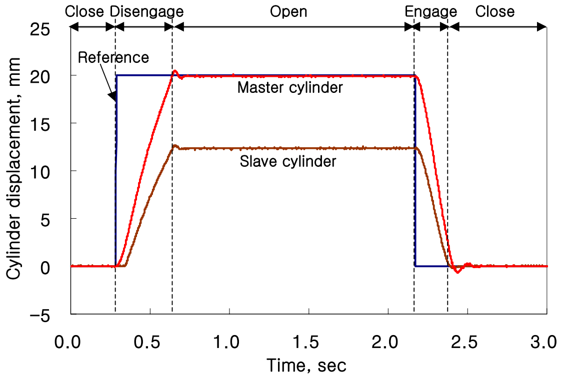


Fig. 7 Step response of CBW actuator

Figure 8 shows the measured pressure of hydraulic line. The hydraulic pressure increases to maximum 29bar and is appeared somewhat overshoot that is the release load characteristics of diaphragm spring. The pressure converges to 23.5bar at steady state and the master/slave cylinder forces are calculated to 784N and 1117N.

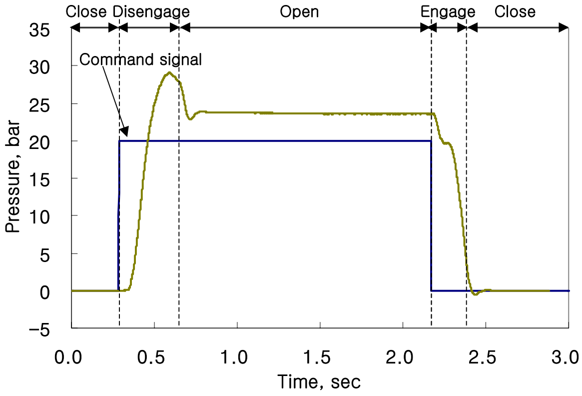
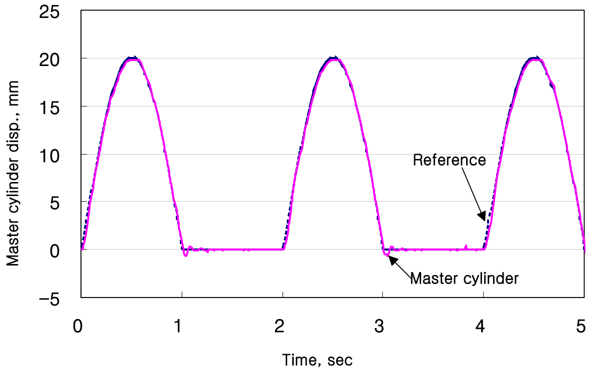
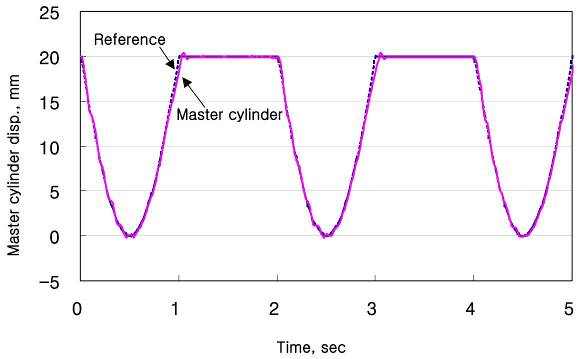


Fig. 8 Experimental results for hydraulic line pressure

Figure 9 illustrates the time response of master cylinder with a half sinusoidal input of 0.5Hz. The frequency response is as shown Figure 10, bode plot. The bandwidth of disengagement and engagement are 1.6Hz and 2.4Hz, the frequency when the magnitude reaches 3dB. And the maximum resonance value is observed 0.4dB in case of clutch engagement.

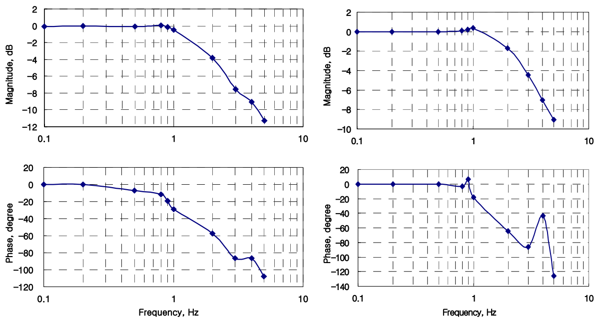


(a) From disengagement to engagement



(b) From engagement to disengagement

Fig. 9 Dynamic responses for 0.9Hz half sinusoidal input

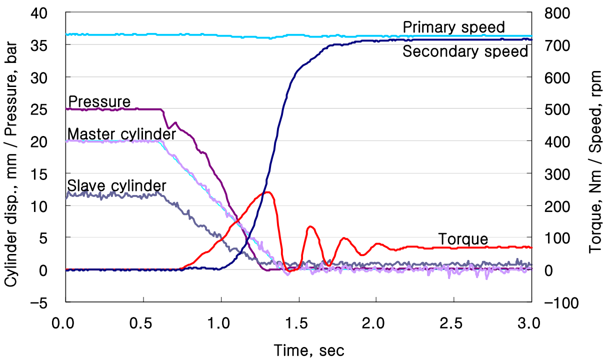


(a) Disengagement (b) Engagement

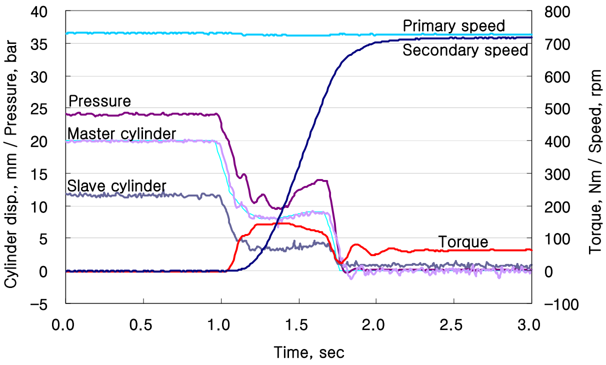
Fig. 10 Frequency responses of clutch actuator

4.2 Launching test

The experimental results at launching condition are as shown Figure 11. Figure 11 (a) shows test results when engaging during 0.8sec without clutch control. The transmitted torque increases as engaging clutch due to inertia and load corresponding to rolling resistance of a vehicle. After that the speed of friction disc is synchronized with a flywheel when the transmitted torque is greater than rolling resistance. The transmitted torque leads to a large fluctuation but the speed of flywheel generates a small oscillation under the influence of inverter controller. The fluctuations of torque and speed are able to be reduced by controlling the displacement of master cylinder as shown in Figure 11 (b).This result implies that the CBW prototype proposed in this paper is able to control the clutch automatically with less torque fluctuation and faster engaging time.



(a) Experimental results without control



(b) Experimental results with control

Fig. 11 Launching test

5. CONCLUSIONS

This paper describes the development of vehicle performance simulator and the implementation of clutch actuator for CBW system. Listed below are the conclusions that are made from the research conducted in this paper.

- The clutch actuator for CBW system is designed systematically and its prototype is implemented. The performance of developed prototype is evaluated through launching and shifting test using test rig. From the test results, it has the response time with 350msec for disengagement and 240msec for engagement, which is considered to be suitable as a CBW actuator.
- There will be carried out further researches on an engagement algorithm considering the transmitted torque and experiments at worn clutch condition. And the research on more compact design must be performed to practically implement the proposed CBW actuator to real vehicle.

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