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SELF-ENERGIZING CLUTCH ACTUATOR SYSTEM: BASIC CONCEPT AND DESIGN

Jinsung Kim [*], Seibum B. Choi
Department of Mechanical Engineering, KAIST, Korea

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ABSTRACT - As improving fuel efficiency has become an issue in the field of automotive industry, the developments of advanced transmission technologies such as automated manual transmissions (AMTs) and dual clutch transmissions (DCTs) have led to the incentives of energy efficiency. However, the control performance is not quite satisfactory since the dry clutch systems used in conventional transmissions are generally suitable for manual operation by a driver rather than automated controls. To cope with such problems, this paper suggests a novel design for a clutch actuator system suitable for automatic transmissions. System characteristics composed of self-energizing mechanism and the electromechanical device are presented to analyze self-energizing effect and the stiffness of actuator system. Also, the dynamic model and control system for clutch positioning are developed.

INTRODUCTION

Interest in improving fuel efficiency of vehicles has grown significantly in recent years. There is a consensus that the transmission can give the most fuel efficiency benefit for the same amount of production cost increment.

In the transmission history, there are several types of automotive transmissions (1). Automatic transmissions (AT) have been broadly preferred by many drivers since the first one was developed by Oldsmobile in 1937. However, it has an inevitable drawback of low efficiency due to the use of a torque converter and a planetary gear train. Furthermore, the higher the speeds of transmission are, the more the complexity of the system is. In other words, it is not easy to control the AT system reflecting driver's intention. Lately, with the advances in relevant technology, several types of transmission have been developed as introduced below.

In recent years, automated manual transmissions (AMT) attract the driver's attention particularly in Europe (2), (9), (11). It is mostly the same as manual transmissions (MT) except for some extra features. Compared with manual transmission, the major difference is that the clutch actuator and synchronizers used in a gearbox for a gearshift are servo-actuated hydraulically or electromechanically. The major drawback of AMT is torque interruption while performing gearshift automatically. As a result, shift comfort or drivability is degraded undesirably. It is thus required to develop a sophisticated control method for clutch engagement and synchronizers in order to preserve the passengers comfort.

The dual clutch transmission (DCT) is expected to become very popular in the field of automotive transmission industry since it satisfies the convenience of automatic transmissions while guaranteeing the high fuel efficiency of manual transmissions (3), (4), (10). In addition, the DCTs equipped with electromechanical actuations and dry clutches are one of the most efficient transmission systems (4). Unfortunately, the dry clutch systems used in conventional transmissions are generally suitable for manual operation by a driver rather than automated controls. However, the existing structure of conventional clutch actuators has been adopted

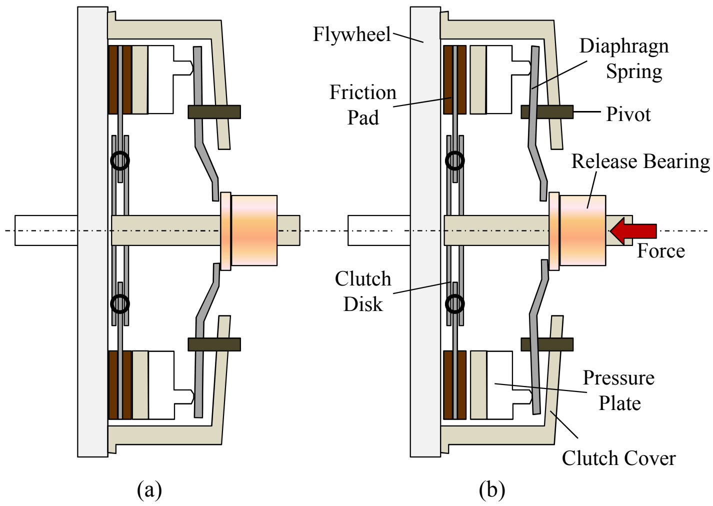

Figure 1: Conventional clutch actuator system for manual transmissions

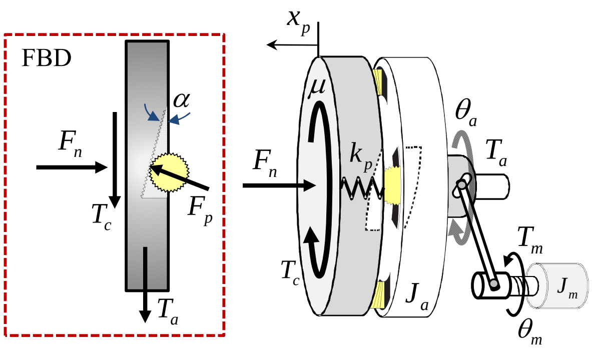

Figure 2: Schematic of the new clutch actuator system

without any improvement in terms of system design by almost all manufacturers. This implies that the control aspect is in conflict with the mechanical aspect. Thus, integrated system design approach is needed to achieve the ultimate goal in this problem.

In this paper, a newly developed automotive clutch actuator using novel drive principle is developed in terms of a control aspect as well as a mechanical design aspect. The proposed actuation system utilizing self-energizing effect is proposed to solve the known issues of excessive energy consumption for actuation.

DESIGN CONCEPT AND OPERATION PRINCIPLE

Background

Automotive clutch actuator systems are classified into two parts with respect to a clutch type. One is a torque converter which is a kind of fluid coupling and used in automatic transmissions. Although a torque converter gives the significant amount of torque amplification and seamless actuation during gearshift operation, there is some energy loss due to the slippage and stirring of fluid. The other is the clutch assembly for manual transmissions which are equipped with a dry friction clutch shown in Figure 1. It has a diaphragm in order to assist driver's foot operations throughout a clutch pedal. However, due to the preload on a diaphragm spring, excessive actuation force should be needed (5). Thus, it may deteriorate control performance in automatics.

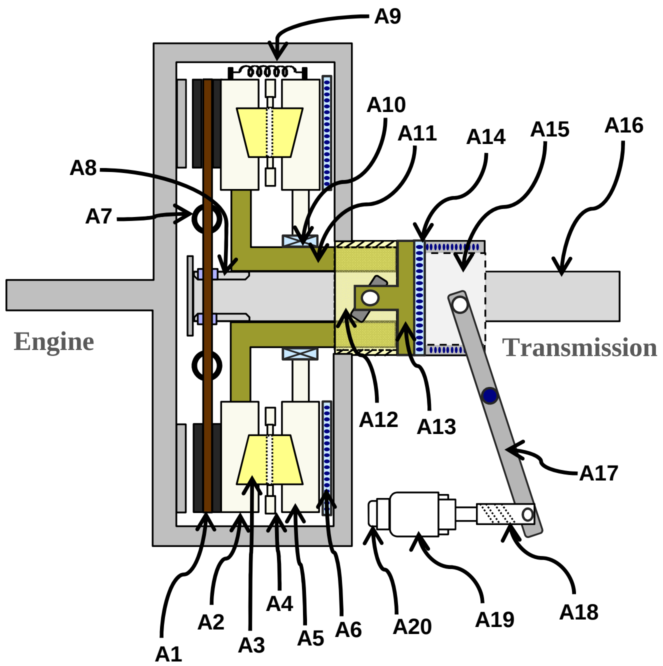

Figure 3: Clutch actuator mechanism

No. Nam	e	No.	Name
A1 Frictio	n disk	A11	Actuation neck
A2	Actuation plate (Rack1)	A12	Worm shaft
A3 Pin	ion gear	A13	Slot joint
A4	Pinion guide	A14	Thrust bearing 2
A5	Fixed plate (Rack2)	A15	Release bearing
A6	Thrust bearing	A16	Transmission Input shaft
A7 Dam	per Spring	A17	Lever
A8 Sp	line	A18	Ball screw
A9 Return	spring	A19	Electric motor
A10 Ball	bearing	A20	Encoder

Table. 1. Description of clutch actuator parts

Some of these problems motivated us to develop a new design concept for a clutch actuator system without torque converter or diaphragm spring. Note that the new actuator system is driven by an electromechanical device with a dry clutch in order to maximize energy efficiency.

Design Concept and Self-energizing Effect

The proposed clutch actuator system has self-energizing mechanism to amplify the engagement force. Exploiting the rack and pinion structure in the clutch actuator makes wedge mechanism to be implemented in the rotating apparatus. Since the engagement force is amplified, it is enough to use standard 12V electricity without resort to the use of large size motors. Consequently, the proposed system reduces energy cost of a drivetrain system, significantly. This is the key advantage of the self-energizing clutch actuator system.

There are some clutch systems with self-energizing effect that ball ramp mechanism is employed (6), (7). However, they are unsuitable for a proportional torque control since an excessive stick-slip phenomenon can occur. In the proposed system, self-energizing effect is generated on the surface of a clutch disk. Figure 2 shows the free body diagram of the

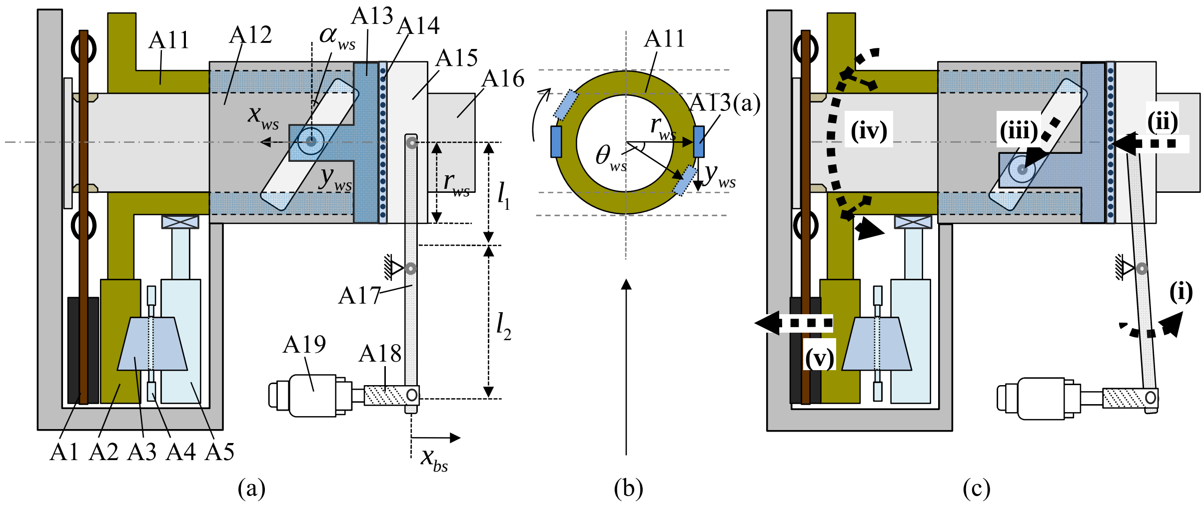

Figure 4: Operation principle of the clutch actuator system (a) Disengaged phase. (b) Cross section of the worm shaft. (c) Engaged phase.

relationship between the driving torque and the resulting clutch frictional torque. Unless there are the inclined surfaces engraved in two supporting plates (see A2 and A5 in Figure 3), the reaction force F_p is eliminated, and the system is not able to have self-energizing effect.

Furthermore, it is possible to provide self de-energizing effect originated from a one-way clutch characteristic during disengagement. Since the state that both clutches are engaged simultaneously is not allowed in DCT systems, it is particularly advantageous to be used in the dual clutch structure.

Operation Principle

Referring to Figure 3 and Figure 4, operation process for the clutch engagement is described in order. Once the electric motor (A19 in Figure 4) is operated by a certain amount of current, (i) the ball screw (A18) and the lever (A17) transmit the torque to the release bearing (A15) whose rotation is constrained. (ii) The force is applied on the thrust bearing (A14). (iii) The slot joint (A13) can axially move and rotate while connected to the transmission input shaft. Also, it is connected with the actuation neck (A11) inside the worm shaft (A12). On the other hand, the worm shaft (A12) can neither axially move nor rotate since it is rigidly connected with the clutch cover. Due to the relative motion between the slot joint and the worm shaft, the actuation plate (A2) coupled with the actuation neck is rotated along with inclined slots of the worm shaft. The fixed plate (A5) can be rotated but cannot move toward the friction disk to allow the actuation plate to be rotated, relatively. (iv) Rotational motion of the actuation plates coincides with axial motion since the pinions are formed on the circumference of the fixed plate having a certain radius from the shaft center line. Accordingly, by the actuation plate, (v) the friction disk, which is spline-connected in the transmission input shaft (A16), is forced toward the engagement position at which it contacts the opposite surface in the flywheel. In addition, it should be noted that the connection of the return springs (A9) between the fixed plate and the actuation plate should be needed to make the actuation plate return to a default position when the clutch operation is in the open phase where the clutch is disengaged.

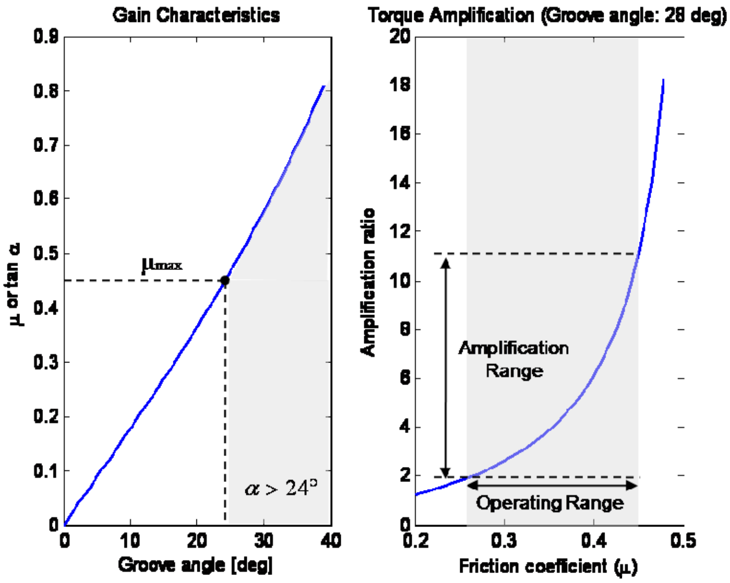

Figure 5: Torque amplification characteristics

<u>Inclined Surface Angle Design</u>

Since the uniqueness of the proposed system is the existence of self-energizing mechanism, it should be noted the way how to determine the degree of the torque amplification. The operating phase is assumed in a steady state in which the clutch is engaged and the motion of the actuator remains thereafter. The torque amplification ratio Υ is given by

$$\Upsilon \triangleq \frac{T_c}{T_a} = \frac{\mu R_c}{r_p \tan\alpha - \mu R_c} \approx \frac{\mu}{\tan\alpha - \mu} \quad (1.1)$$

where, T_c is the resulting clutch torque and T_a the actuator driving torque, respectively. It is clear that the torque amplification ratio Υ depends on the inclined surface angle α and the friction coefficient μ. In a certain range of μ, this ratio is too large. On the other hand, when the friction coefficient μ is greater than $\tan\alpha$, the larger clutch torque is required to ensure the engagement. Therefore, the condition of $\mu < \tan\alpha$ is determined to guarantee appropriate torque reinforcement. In the developed system, the resulting inclined surface angle is chosen to be 28 deg under the nominal range of dry friction coefficient. This characteristic is described in Figure 5.

DYNAMIC MODEL

The dynamic model of the proposed system consists of the electric motor and the mechanical actuator. The developed model is based on the schematic of the system in Figure 2.

<u>DC Motor</u>

For electromechanical actuation, a brushed DC motor is used. The electric and mechanical dynamics of the DC motor system are represented as:

$$L_m \frac{di_m}{dt} + R_m i_m + V_{emf} = u \quad (1.2)$$

$$J_m \dot{\omega}_m = T_m - T_{fm} - T_L \quad (1.3)$$

where, L_m is the inductance, i_m the current, R_m the resistance, V_{emf} the back-emf voltage, u the applied voltage, ω_m the motor speed, T_m the motor torque, T_{fm} the friction torque, and T_L the load torque.

Mechanical Actuator

The dynamic model for the mechanical actuator part in contact with a clutch surface is given by

$$J_a \dot{\omega}_a = T_a + T_c - F_p r_p \sin\alpha - T_{fa} \quad (1.4)$$

where, J_a is the moment of inertia of the mechanical actuator, T_a the actuator driving torque, T_c the clutch torque, F_p the reaction force on the clutch surface, r_p the radius of the pinion gear position, and T_{fa} the friction torque. Since the axial motion of the actuator coincides with the rotation of it, the actuator stroke can be defined by

$$x_p = r_p \theta_a \tan\alpha. \quad (1.5)$$

And, the normal force on the clutch surface is assumed to be proportional to the actuator stroke, i.e. $F_n = k_p x_p$. Accordingly, equation (1.4) is rewritten as:

$$J_a \dot{\omega}_a = T_a + k_p x_p \left(\mu R_c - r_p \tan\alpha\right) - T_{fa}. \quad (1.6)$$

NORMAL FORCE CONTROL

Controller Design

To ensure the clutch engagement, a feedback control is designed using a simple proportional-integral-derivative (PID) controller. The error signal is defined as a stroke error, i.e. $e = x_p - x_{pd}$. The desired actuator stroke trajectory can be generated to be differentiable twice. It is assume that the normal force is linearly proportional to the actuator stroke, approximately.

Simulation Result

The result of the feedback control is shown in Figure 6. Although there is some transient error due to the unmodeled dynamics, the normal force tracks the desired profile, which is sufficiently smoothed, very well. As discussed earlier, the inclined surface angle α is set to be 28 degrees for this test.

On the other hand, Figure 7 shows the simulation result of the control with the same feedback gains, but the inclined surface angle α is set to be 16 degrees. The tracking performance is degraded at a steady state. Since self-energizing effect plays role in mechanical force/torque feedback, the large torque amplification may lead to the instability of the control system which is similar to a high gain feedback control. Therefore, the degree of self-energizing effect should be decided very carefully.

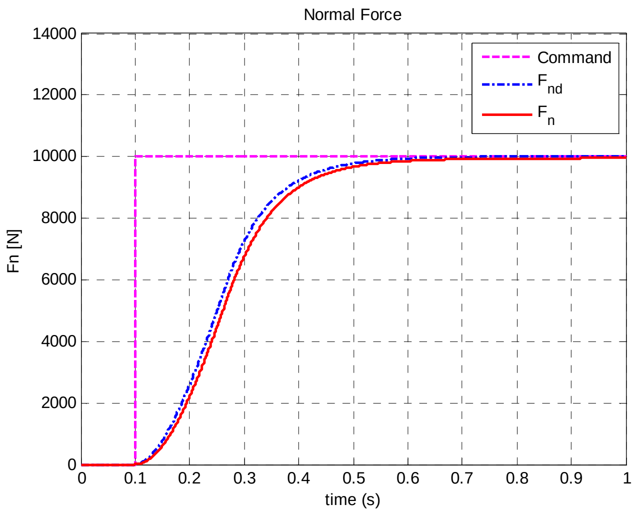

Figure 6: Simulation result: feedback control (alpha=28 deg)

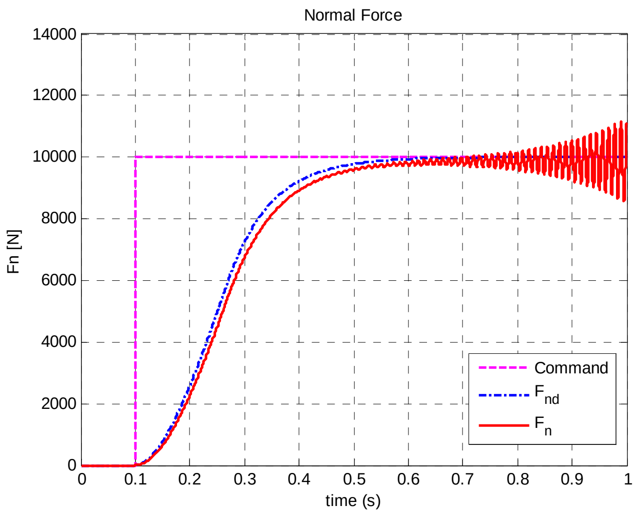

Figure 7: Simulation result: feedback control (alpha=16 deg) with the same control gain of Figure 6.

CONCLUSION

A newly designed clutch actuator system for an automotive drivetrain is introduced with self-energizing mechanism. In order to apply wedge mechanism on a rotating disk for amplifying actuation force, traditional bevel gears are employed between two supporting plates. Some components are fabricated to solve the difficulties of implementing the new idea. For selecting the inclined surface angle, the torque amplification factor is studied which is related to the friction coefficient of the clutch surfaces. A simple feedback controller is designed based on the dynamic model of the proposed system.

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