Development of Automatic Clutch Manual Transmission for Automotive Applications

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***Abstract*—The automotive electronics have made a great progress nowadays. In order to improve the convenience of driving and the efficiency of energy usage, many vehicle manufacturers have paid attention on electric motor controlled systems to improve the system efficiency and control accuracy. The replacement of traditional brush electric motors or mechanical motors by using brushless motors has become an important on vehicle subsystems. Specifically, Field Oriented Control (FOC) of brushless motors have become a promising solution for high-performance drive systems.**

This paper proposes an Automatic Clutch Manual Transmission (ACMT) system based on a brushless motor and FOC drive. In order to implement a manual shifted automatic clutch system, a systematic clutch control logic is designed by organizing control rules under various driving conditions. In addition, a clutch friction model is used to increase the degree of perfection. Finally, an ACMT system test bench is built to evaluate the automatic clutch control under different vehicle test conditions.

***Index terms*—Automatic clutch manual transmission, clutch logic and clutch model**

I. INTRODUCTION

Nowadays, Automatic Transmission (AT) is the most common type of vehicles worldwide due to the simple and convenient drive system [1]. However, the fuel efficiency is still the issue for AT vehicles comparing traditional Manual Transmission (MT) vehicles. Considering the normal operation, MT can usually achieve a more efficient vehicle transmission system [2]. Under this effect, it is desired to improve the driving requirement for MT vehicles by adding the automatic clutch system [3]. This transmission system is referred as ACMT for MT vehicles [4].

Fig. 1 illustrates the overall signal flowchart of ACMT [5]. The overall system can be categorized by three control layers. They are driver operation layer, control strategy layer and actuators layer. Driver operation layer, generally refers to the driver's intention, or the control unit's intention, such as autonomous vehicles. The control strategy layer includes the control method of all vehicle subsystems, such as brake, steering, and the clutch. The clutch system will be the primary focus in this paper. [6] develops a clutch model to analyze the transmission torque during the clutch engagement. [7] propose a cost function to evaluate the transient behavior of the engagement. Actuators layer includes the power source of the system such as motors and mechanisms. By comparing several types of motors, brushless permanent magnet (PM) motors are able to achieve the best drive efficiency. In addition, the disturbance observer can also be implemented to increase the drive response [8, 9]. Furthermore, the acceleration estimate can also be implemented to increase the overall controller bandwidth [10]. Among these advantages, a brushless PM motor is selected the actuator level to implement the ACTM system.

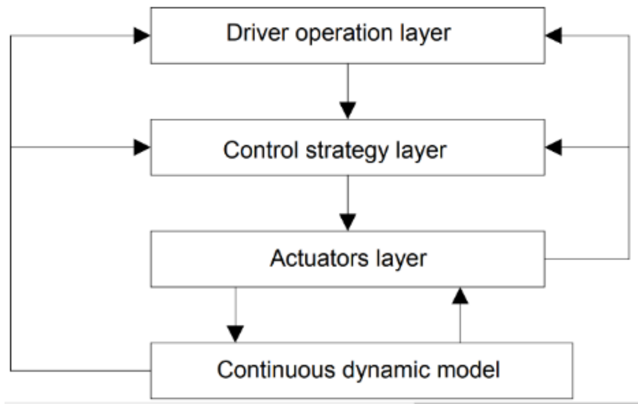

Fig. 1 The controller signal flowchart of ACMT

The main purposes of this paper are listed as follows:

(1) Develop an ACMT system based on a brushless PM motor and FOC drive in order to improve accuracy and efficiency of clutch control.

(2) Realized the clutch control logic based on various driving conditions.

(3) Build an ACMT laboratory test bench to experimentally evaluate the clutch control performance.

II. CLUTCH CONTROL LOGIC

In order to develop an ACMT system among various driving conditions, the control logic and flowchart for clutch engagement and disengagement are developed. The clutch movement is enable under three key driving scenarios.

1. The clutch is disengaged when engine speed is less than 800 rpm or the gear is shifted.

2. Speed limit of each gear: starting in 1st, 2nd or Reverse gear. In the 3th, 4th, and 5th gears, there is a minimum speed limit.

3. Engine brake

Based on these scenarios, the ACMT control logic can be developed by Fig. 2.

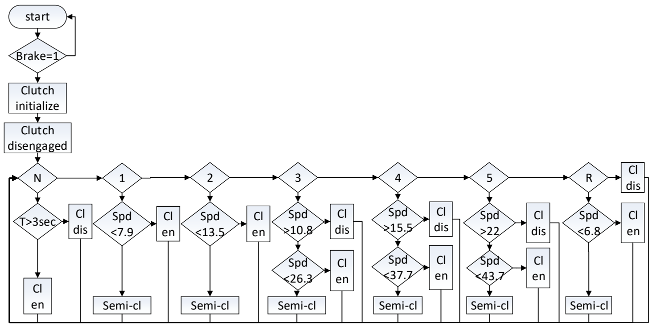

Fig. 2. ACMT control logic flow

where cl en represents the clutch engaged, semi-cl is semi-clutch, cl dis are clutch disengagement, and Spd is the engine speed.

In Fig. 2, three main clutch logic parts are included. They are engine idle, gear position determination, and speed classification. For the engine idle, the driver must step on the braking pedal to enable the ACMT system. After the ACMT system is enable, the clutch position control is initialized, as illustrated in Fig. 3. It is noted that the full actuating stroke of the clutch is determined by the relationship of the motor torque output.

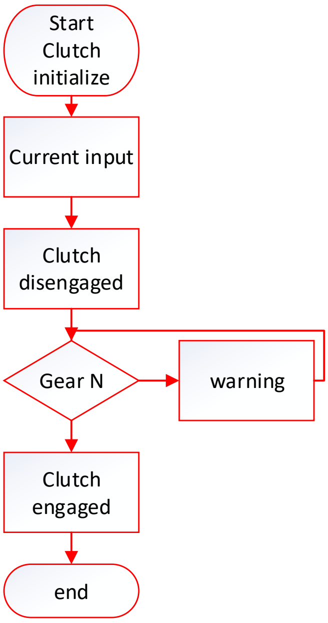

Fig. 3 The initialization of the clutch position control

During the second part of gear position determination, a horizontal and vertical direction sensor is used to detect the position of the gear shift lever. By mapping the 2-D position of the lever, we can obtain the gear.

Finally, the third part of ACMT logic is to classify the vehicle speed. Based on different speed conditions, the clutch combination status is divided into three categories: fully engaged, semi-clutch and completely disengaged. Fig. 4 illustrates the relationship among these three categories.

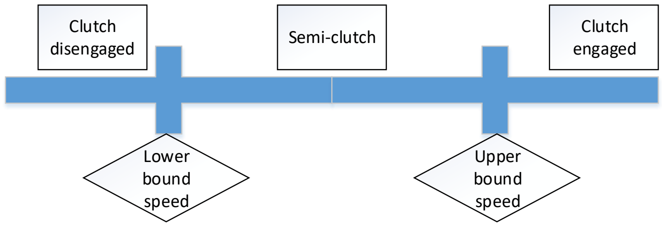

Fig. 4 Three categories of the clutch position: fully engaged, semi-clutch and disengaged according to different speeds

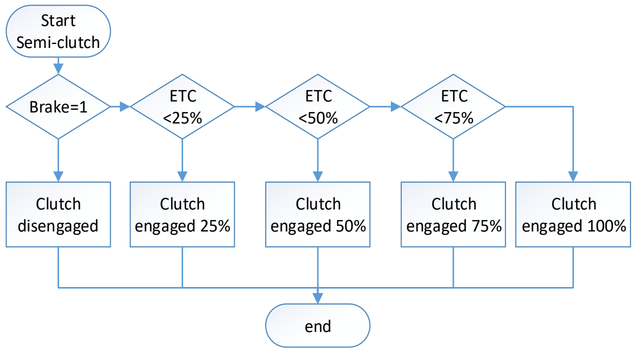

Fig. 5 Semi-clutch logic flow chart

When the speed is sufficiently fast, the clutch needs to remain engagement to transfer the torque into the transmission. Similar clutch engagement should be controlled when the brake is commanded. When the vehicle is sufficiently slow, it is necessary to separate the clutch and reduce the engine load to increase the speed. The purpose is to avoid the engine stall. In addition, between the full engagement and the complete separation, there is still a transition process, defined by semi-clutch. Because the vehicle dynamic is strongly affected by the semi-clutch control, this control logic is discussed separately.

The details of the semi-clutch position is shown in Fig. 5 When the speed is not fast or slow enough, the clutch open and close judgment would be controlled by the semi-clutch sub-function. In Fig. 5, it is assumed that the driving intention can be roughly divided into two situations: acceleration and deceleration. When the driver is intended to accelerate and the throttle depth is large, the clutch is closed more in order to transmit more torque. On the other hand, if the driver wants to decelerate and step on the brake, the clutch is disengaged in advance to prevent the engine from turning off because of the low engine speed.

It is noteworthy that the semi-clutch sub-function process is determined based on the upper and the lower boundary speed illustrated in Fig. 4. In this paper, these two boundary speeds are determined based on the relationship of the engine and vehicle speed.

First, the engine speed can be represented by

$$\omega_e = \text{gearbox output shaft speed} \times \tau_g \qquad (1)$$

where ω_e is the rotating speed of the engine and τ_g is the gear ratio. In addition, the vehicle speed is shown by

$$\text{vehicle speed} = (\omega_g/\text{final ratio})\times 2\pi\times r_w\times\tau_g \qquad (2)$$

where ω_g is the gearbox output shaft speed and r_w is the radius of the wheel. By combining (1) and (2), the relationship between the vehicle speed and ω_e is

$$\omega_e = (\text{vehicle speed}\times\text{final ratio}\times\tau_g)/(2\pi\times r_w) \qquad (3)$$

In (3), the ratio of each gear can be summarized as listed in Table I.

Table.1 Gear Ratios with respect to Boundary Speeds

gear ratio of each gear		final ratio	upper speed (km/h)	lower speed (km/h)
gear	2WD		engine 800rpm	engine 1500rpm
1	3.992	4.875	3.9†	7.9
2	2.150		7.2†	13.5
3	1.432		10.8	26.3
4	1.000		15.5	37.7
5	0.862		17.9	43.7
R	4.220		3.7†	6.8

† The lower boundary speed of 1, 2 and R gears can be ignored due to the extremely low speed, so it is suitable for starting.

Table. 1 organizes the different gear ratios of each gear, and defines the values of the upper and lower speeds. It is assumed that the engine is separated at 800 rpm, which is the same to the speed of the engine stall. Under ideal conditions, the low bound speed can be calculated, as shown in the penultimate column in Table I. In addition, the low bound speeds of the 1, 2 and R gears are extremely low. Under this effect, it is suited as a starting gear, and also echoes the aforementioned clutch logic rule 2, which can only be started in 1, 2 and R gears. On the other hand, the upper bound speed is defined as the half of the ideal shift engine speed 3000 rpm. When the engine speed is beyond 1500rpm, the corresponding upper bound speed of each gear is also given in the last column of Table. 1.

III. Clutch Control Instant Experiment Results

The section demonstrates the feasibility of clutch logic based on the laboratory experimental verification. On the basis, a 32-bit microcontroller TI-TMS320F28069 is used to implement the clutch logic mentioned in section II. By integrating all the clutch logics in this microcontroller, the ACMT system can be tested by observing the resulting gear shift output signals. The structure of the experimental platform is shown in Fig. 6.

In this test, the signals of the X sensor and Y sensor are two signals to determine the gear location. Besides, ETC is the throttle, and the brake signal is simplified by only 0 (disable) and 1(enable). It is noted that all these relevant parameters are available in commercial vehicles. In the following tests, the experiment are separated by two parts: acceleration and deceleration.

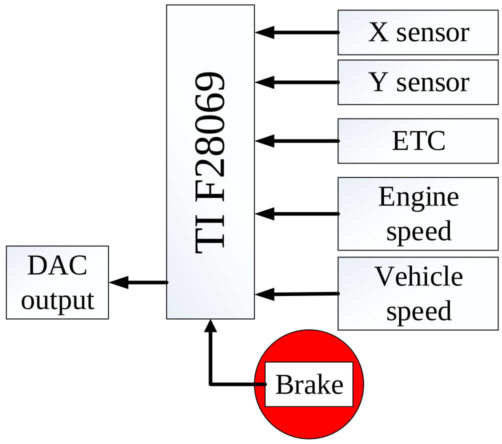

Fig. 6 The structure of clutch control experiment

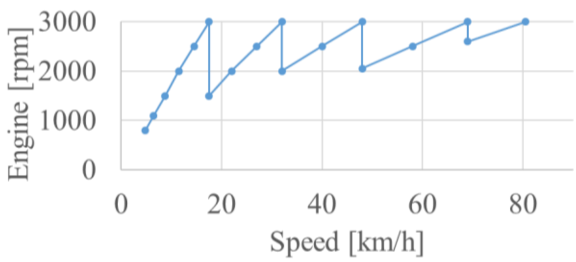

Fig. 7 Definition of upshift engine speed

A. Acceleration:

During the acceleration experiment, the upshift engine is defined by Fig. 7, which is used as the input for gear shift. Fig. 8 shows the clutch position control result when the vehicle speed is increased. The orange color is transmission gear. It is shown that the gear is different according to the actual speed and the engine speed. During the switch from 1st to 5th gear, we can get the result of the clutch position in blue color, where 0 means disengaged, 1 means engaged. In this test, when the engine speed is nearly 3000 rpm, the gear shifts so that the engine speed suddenly drops and then continue to re-accelerate. Repeat this process from 1 to 5 gears. According to the logic diagram in Fig. 2, the clutch position becomes 1 when the gear is engaged. By contrast, the position is 0 when the gear reaches Neutral. Based on this experiment, it is concluded that the proposed ACMT control logic shifts the gearbox smoothly during the vehicle acceleration.

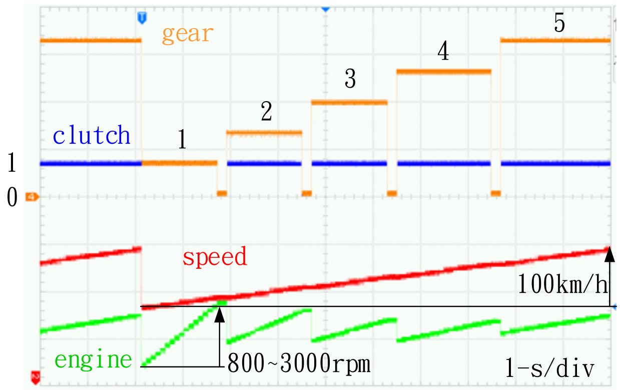

Fig. 2 Upshift speed clutch position result

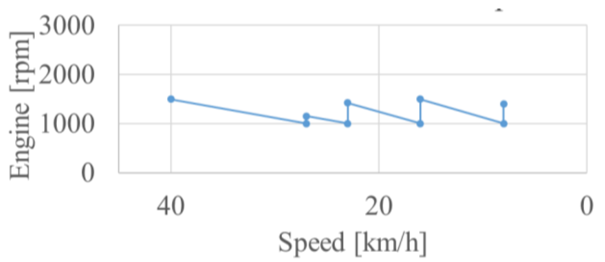

Fig. 9 Definition of downshift engine speed

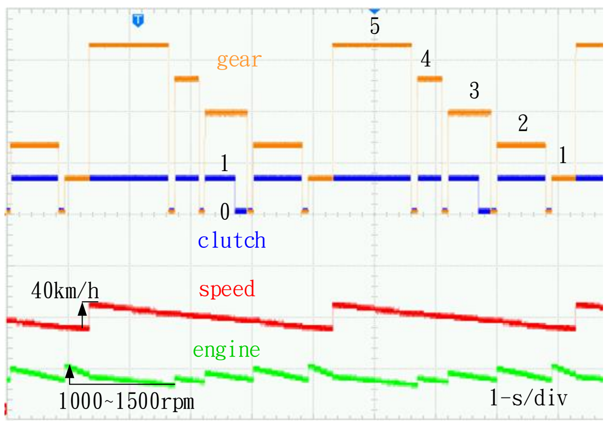

Fig. 10 Downshift speed clutch position result

B. Deceleration:

During the deceleration experiment, the downshift engine is also defined by Fig. 9. Fig. 10 shows the clutch position control result when the vehicle speed is decreased. It is seen that the 5th gear is shifted sequentially down to 1st gear. The speed gradually decreases from 40 km/h to 0. Because the vehicle speed is too slow when the ACMT system is under the 3rd gear. According to the flowchart in Fig. 2, the control logic enters the clutch disengagement function, leading to the clutch position at zero. Based on this test, the proposed ACMT control logic also shifts the gearbox smoothly during the vehicle deceleration.

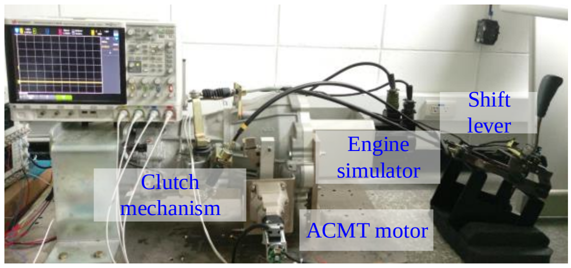

Fig. 11 Photograph of ACMT test platform

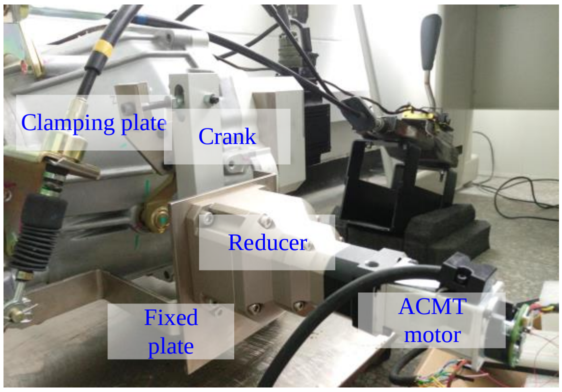

Fig. 12 Illustration of ACMT actuator

TABLE II. ACMT Motor Characteristics

Characteristics	**Values**
Rotor poles	8-pole
Rated torque	0.16Nm
Rated current	1A
Rated speed	3000rpm (200Hz elec frequency)
Resistance	4.7Ω
Inductance	4.7mH
DC bus voltage	12V

IV. ACMT EXPERIMETNAL TEST BENCH

In order to develop an ACMT system, a test platform with actuator mechanism, brushless motor and controller is built. The photograph of test platform is shown in Fig. 11. The proposed ACMT actuator system is also demonstrated in Fig. 12. Key motor characteristics are listed in Table II.

The clutch control performance under 1200 rpm engine speed is given in Fig. 13. In this test, the brushless motor is controlled to rotate 8 mechanical revolutions to adjust the clutch position from fully close to open. It is observed that the proposed ACMT control logic performs well in the actual test bench. More results will be shown in the final paper.

IV. CONCLUSIONS

Key conclusions are summarized as follows:

1. Instead of brush motors, a high-performance brushless motor and FOC drive is realized on the proposed ACMT system to improve the overall system efficiency.
2. The proposed ACMT control logic in section II can control the clutch position under different driving conditions based on the experimental verification.

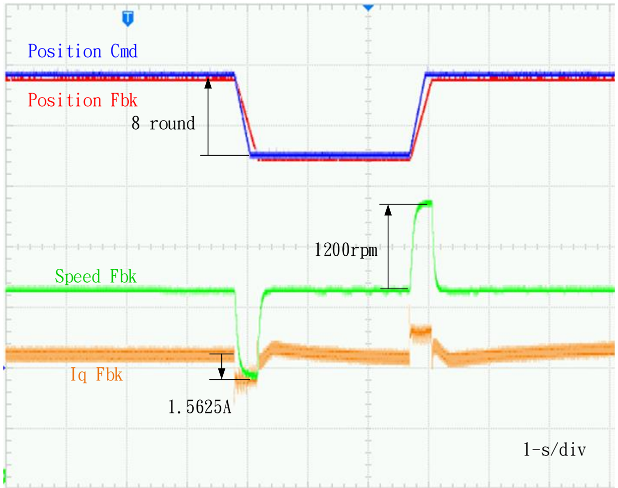

Fig. 3 ACMT clutch control performance

3. An actual ACMT test bench is built to verify the actual vehicle control based on the manual transmission.

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