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EMA-CVT Performance for UDDS and HWFET Cycles with Fuzzy Logic Approach

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Abstract

Continuously variable transmission (CVT) is moreeffective in transferring power from the engine to the wheels than gear-based transmission as it able to provide an unlimited number of gear ratios to suit different drivingenvironments. Conventional CVT system that operatesbased on hydraulic actuation mechanism experienced slow acceleration when move from stop, less torque while climbing the mountain and continuously create unpleasant noise. The hydraulic fluid viscosity falls below the optimum value when its temperature is too high due to long run and result in losses of the input power transmitting. An alternative to conventional actuation system, the electromagnetic actuation (EMA) mechanism,is discussed in this paper. The EMA forcewas controlled byvarying the supply current with a fuzzy logic controller (FLC) based on sensor input. A simulation that mimic a Toyota Wish car moves along the UDDS and HWFET driving cycles has been introduced here. The FLC was successfully producing the required current to operate the EMA for the mention driving cycles.For UDDS cycle, the system generated about 2.2-2.6 kN electromagnetic force with about 5.6-6.06 A current supply. On the other hand, for HWFET cycle with current supply of 5.75-6.05 A, the required electromagnetic force of 2.4-2.6 kN was produced. Fuzzy Logic Controller enable the system to fast response in generating the required current. For both driving cycles, the controller took about 2.1-2.2 seconds to regulate the current level from zero value to the targeted current level.

Keywords; *Green Transportation; Electromagnetic Actuator; CVT*

INTRODUCTION

A transmission system is used to adjust the proportion of torque and speed, i.e. the power, which is delivered from the engine to the drive shaft of a car. In a manual transmission, the gearbox provides different ratios between the engine and the wheel by a system of gears. The gearbox requires a friction clutch to disengage the engine crankshaft from the gearbox while changing the gear ratios. An automatic gearbox provides various gear ratios automatically by a special gearing mechanism and the torque converter is the component that make the automatic gear changes possible.

Continuous variable transmission (CVT) is a new type of automatic transmission that uses a pair of cone-shaped pulleys connected by a metal belt in providing the ratio of rotations, or the gear ratio, between the engine and the drive shaft. Different gear ratios are achieved through the change in the diameter of the pulleys with accordance to the car speed and road condition. Thus, cars equipped with the CVT system utilized the fuel more efficiently [1]. The CVT will continue to replace traditional gearing system in the coming years as more car manufacturers turn to CVT such as in the new Saga [2], the new City [3], Teana [4], and Audi A5 2.0 TDI [5] to increase their fuel economy.

A study had been conducted by [6] to compare the performance of the manual transmission, automatic transmission and continuously variable transmission. Simulation result on cars with 1500 kg weight and engine capacity of 3000 cc showed that the time

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taken to accelerate to 100 km/h is 10.20 sec for manual transmission, 10.76 sec for automatic transmission, and 7.85 sec for CVT. Besides, The Torotrak Group [7], a green automotive technology company, claimed about 19% less fuel consumption for their CVT transmission compared to a vehicle with conventional gearbox along with a reduction in harmful emissions.

Current pulley-based CVT utilized the electro-hydro-mechanical (EHM) actuation system to provide sufficient clamping force for the desired CVT ratio [8]. The EHM moves and maintain the pulley sheave at the desired position by hydraulic means. Hydraulics, often called fluid power, is a method of transmitting motion and/or force [9]. The amount and direction of the oil flow are controlled electronically by solenoid valves. In this system, the hydraulic pump draws off the engine power continuously to provide the pressurized oil to the system and thus increase the car fuel consumption. According to Tawi et al. [10] CVT that use the EHM actuation system possesses some major issues that make it less efficient such as high power consumption, power loss and belt misalignment. Besides, the hydraulic fluid viscosity falls below the optimum value when its temperature is too high due to long run and result in losses of the input power transmitting. Thus, the holding force of pulley sheave is not stable and affect the response and the performance of the car.Therefore, for further improvement of CVT performance, this study emphasizes on the development of a fast actuation system, "electromagnetic actuated mechanism for CVT system," which is the core discussion of this study. The study will use Toyota Wish as an object of study including calculation, simulation and experimental.

METHODOLOGY

An analytical model of the EMA-CVT is formulated based on the vehicle traction force for various road conditions, power requirement to generate the electromagnetic force (Fem) and the simplified CVT mathematical models found in literature. Development of new electromagnetic actuator mechanism is presented in this section. A fuzzy logic based control system is presented in this chapter as a mean to intelligently regulate the power required by the EMA-CVT for various driving scenario.

EMA-CVT Analytical Model

A vehicle needs to generate an enough tractive force to overcome the opposing force due to the combination of gravitational force, rolling resistance at the tire, and aerodynamic drag force. The acceleration of a vehicle is defined by all the forces acted on it and follows the Newton's second law could be represent as,

$$m_c a = F_{TR} - F_{RL} \qquad (1)$$

wherem_c is the total mass of the vehicle, F_TR is the traction force of the vehicle, and F_RL is the total road load. The road load resistive forces are normally the rolling resistance between tires and road surfaceR_roll, aerodynamic dragR_AD, and uphill grading resistanceR_g.The traction torque of the car is computed by using the following equation[11]:

$$T_{t(\theta)} = R_w m_c g \left(\mu_R \frac{{l_{fr} + f_r h}/{L_{wb}}}{{1 + \mu h}/{L_{wb}}} + \sin \theta_r \right) \qquad (2)$$

wherem_c is the mass of the vehicle in kg, g is the gravitational acceleration constant equal to 9.81 m/s^2, R_w the wheel radius, μ_R the adhesion coefficient of the road, l_{fr} distance from the front wheel to CG in m, f_r the coefficient of rolling motion resistance, h is the height of CG in m, L_{wb} the wheel base in m, θ_r the slope angle with respect to the horizon in degree.

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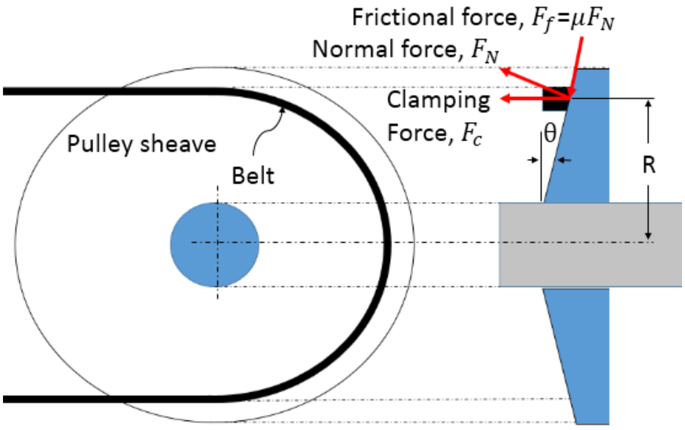

Figure 1: Force analysis on the pulley surface

Normally, the pushing force is higher than the pulling one since it has to move against the rotating belt. Figure 1 shows the basic force acting on the surface of the pulley. The clamping force that need to be supplied to maintain the gear ratio can be calculated using equations below (Mohamed & Albatlan, 2014; Nishizawa et al., 2005; Rahman et al., 2014; Yamaguchi et al., 2005):

$$F_S = \frac{T_{out}\cos(\theta_b)}{2\mu_S R_S} \qquad (3)$$

Where, T_{out} are transmission torque forsecondary pulley in Nm, θ_b is the belt angle, $\mu_S$is belt frictional coefficient of secondary pulley, $R_S$is radius forsecondary pulley in m.In this study, the electromagnetic actuator (EMA) function is to generate an electromagnetic force to push and hold the CVT pulley sheave at desired gear ratio. The electromagnetic force is designed to be equal or higher than the required clamping force. The design is emphasized more on the pushing electromagnetic force since it is crucial to maintain the belt at its exact position to produce the desired gear ratio (GR). The force generated from electromagnetic actuator could be simplified by following equation (Boldea & Nasar, 1997; Clarke, 2017; Leander et al., 1987)

$$F_{em} = \frac{A_g B_g^2}{2\mu_o} \qquad (1)$$

By substituting the magnetic field strength $H = F_m/l_e$ into magnetic flux density equation $B = \mu_0 H$, the equation becomed[16]

$$B = \frac{F_m \mu_0}{g} = \frac{N I \mu_0}{g} \qquad (02)$$

Substituting into equation (1), yield the following equation.

$$F_{em} = \frac{(N I)^2 \mu_o A_g}{2 g^2} \qquad (3)$$

Where N is number of turns, I is the supplied current, μ_0 is the permeability of free space (has a fixed value of $4\pi \times 10^{-7}$), g is the airgap or in this case it is the actuator stroke length (L_{stroke}) separating between the two ferromagnetic bodies, and A_g is the airgap face area. From the above equation, the electromagnetic force depends on the number of coil turns, supplied current, effective area of the core, and the gap between the electromagnet and the pulling object. The only controlled parameter is the supplied current. The electromagnetic force produced is directly proportional to the supplied current, which means that the force shall be increased greatly by increasing the current supply. However, over flow of the current may create over heating which will damage the solenoid. In practical, for better performance and safety, a cooling system is needed to cool the solenoid.A new-version of electromagnetic actuator is presented in this paper. The bobbin where the copper wire is wound on it, as shown in **Error! Reference source not found.**, is made from iron to increase the stored magnetic energy to produce stronger electromagnetic force. A stopper or mover, made of iron, is attached on the non-magnetic (aluminium) plunger to act as an object of the actuator force.

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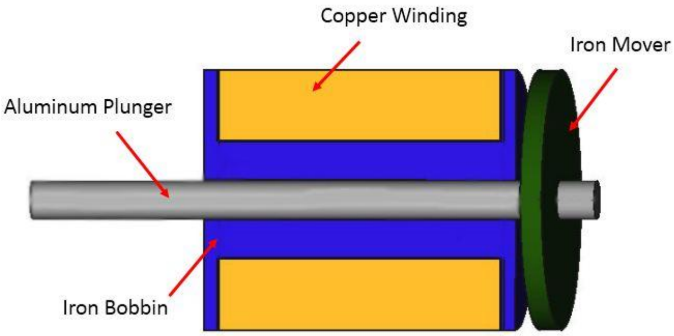

Figure 2: Cut view of new electromagnetic actuator

2.2 EMA-CVT Performance based on UDDS and HWFET Cycles

Simulation Performance of electromagnetic force and electrical current requirement for operation of EMA-CVT of a Toyota Wish passenger car with the EPA Urban Dynamometer Driving Schedule (UDDS) and the EPA Highway Fuel Economy Test Cycle (HWFET) cycles is presented in this section. The car with the mass of 1700 kg, maximum speed of 120 km/h or 33 m/s, the road friction coefficient equal to 0.5, the wheel radius of 0.295 m, the drag area of 0.633, and rolling motion resistance coefficient of 0.02 was considered. The traction torque associated with the clamping force that required to operate the EMA-CVT system are modeled in Matlab simulation as described in Figure 3 where the input parameters of the system are vehicle speed and road grades. The traction force of the car model block was built based on the equation (2) where the car weight, air density, rolling coefficient and drag coefficient was considered. From the traction force, the traction torque at propeller shaft (or the output shaft of the CVT) was found by multiplying with the wheel radius size and the gear ratio of the final gear. The required current estimator model block was built based on equation (3) and (6) where it calculate the corresponding current based on the traction torque at the propeller shaft, CVT pulley's size, and the size of EMA.

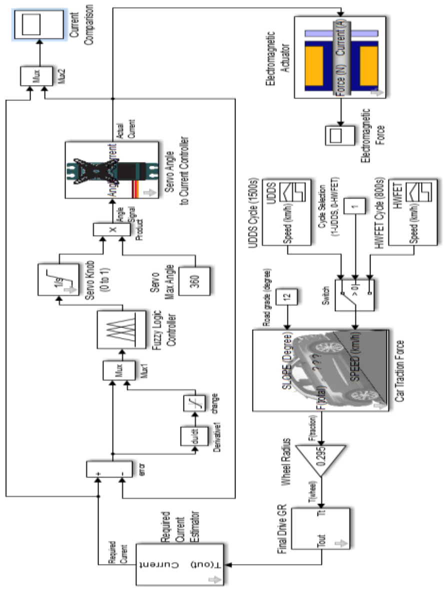

Figure 3: EMA-CVT simulation block diagram in Matlab

The required traction was designed according to the predefined driving dynamics known as EPA Urban Dynamometer Driving Schedule (UDDS) and EPA Highway Fuel Economy Test Cycle (HWFET) [19]. The UDDS cycle simulates an urban route of 12.07 km with frequent stops. The maximum speed is 91.25 km/h and the average speed is 31.5 km/h. The cycle consists of two phases: the first phase begins with a cold start and run for 505 s (about 5.78 km at 41.2 km/h average speed) and the second phase run for 867 s as shown in Figure 4. Furthermore, the HWFET cycles as shown in Figure 5 is a chassis dynamometer driving schedule developed by the US EPA for the determination of fuel economy of light duty vehicles. It simulates a highway route of 16.45 km with average speed of 77.7 km/h at 765 seconds.

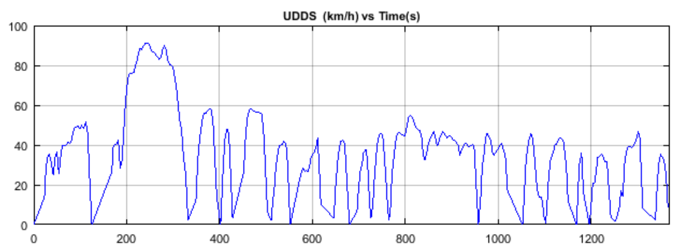

Figure 4: Urban dynamometer driving schedule (UDDS)

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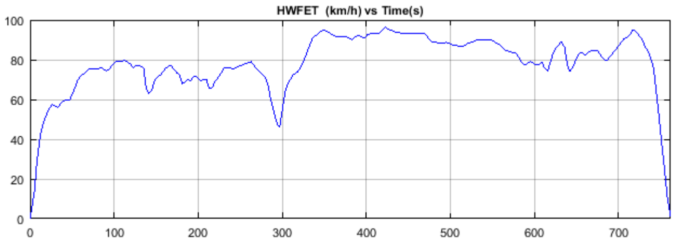

Figure5: Highway Fuel Economy Test Cycle (HWFET)

RESULT AND DISCUSSION

The Fuzzy logic controller simulation block in Figure 3 has two inputs: current error and rate of current error, respectively, and one output: current flow.Figure 6 and Figure 9 compared the required clamping force and generated electromagnetic force for the UDDS and HWFET driving cycle respectively. The generated electromagnetic forces are equal or higher than the required clamping force and this ensure the CVT pulley sheave can maintain its position. Based on the electromagnetic force above, the system regulate the current supply accordingly as shown in Figure 7 and Figure 10 respectively for UDDS and HWFET cycles. In order to generate the electromagnetic force of 2.6 kN, the electromagnetic actuator draw about 2.6 ampere current from the power supply. The current requirement is directly proportional to the electromagnetic force and agreed with the equation (6). Figure 8 and Figure 11 shows the current level error, i.e. the different between the targeted current and the produced current level. If it is zoomed, the controller took about 2.1 and 2.2 seconds to regulate the current level from zero value to the targeted current level.

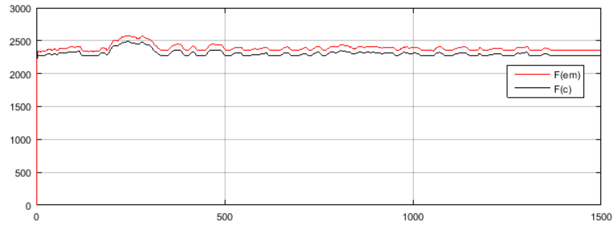

Figure 6: Simulation result for required clamping force and generated electromagnetic force for UDDS cycle

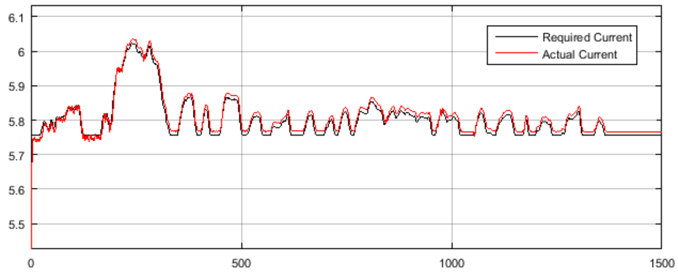

Figure 7: Simulation result for the required and actual current for UDDS cycle

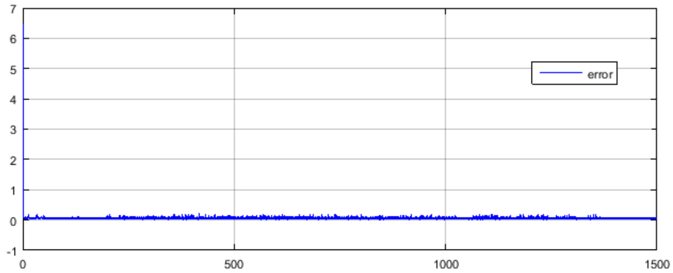

Figure 8: Simulation result for controller error for UDDS cycle

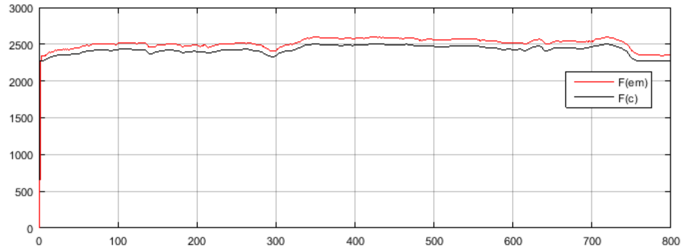

Figure 9: Simulation result for required clamping force and generated electromagnetic force for HWFET cycle

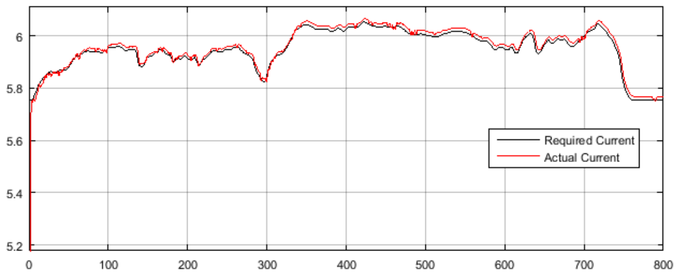

Figure 10: Simulation result for the required and actual current for HWFET cycle

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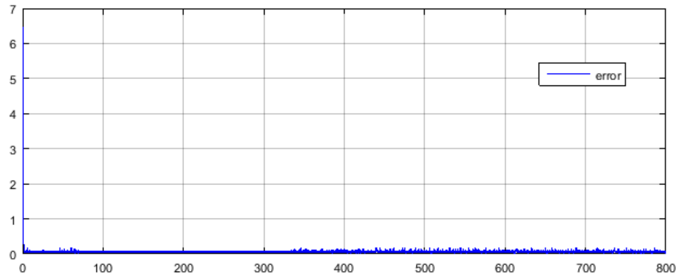

Figure 11: Simulation result for controller error for HWFET cycle

CONCLUSION

This paper present analytical model of the electromagnetic actuated CVT based on Toyota wish size car. Simulation by Matlab Simulink on relation between clamping force, electromagnetic force and current supply was done based on the standard UDDS and HWFET driving cycles. The following conclusions are achieved based on the contents of this paper:

The intelligent system can develop the electromagnetic for as according to the required clamping force. The current was regulated to meet the traction force due to the vehicle speed pattern of UDDS and HWFET.

For UDDS cycle, the system generated about 2.2-2.6 kN electromagnetic force with about 5.6-6.06 A current supply. On the other hand, for HWFET cycle with current supply of 5.75-6.05 A, the required electromagnetic force of 2.4-2.6 kN was produced.

Fuzzy Logic Controller enable the system to fast response in generating the required current. For both driving cycles, the controller took about 2.1-2.2 seconds to regulate the current level from zero value to the targeted current level.

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