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Use of Fuzzy Controller for Hybrid Traction Control System in Hybrid Electric Vehicles

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***Abstract* - In the normal condition, the front wheels follow the control trace of the driver and rear wheels follow the direction of the vehicle .The vehicle will spin and lose the control trace of the driver if the traction force is greater than the friction force. Therefore, a vehicle should maintain an adequate slip ratio of the tires and follow the control trace of the driver. This paper described a fuzzy Controller for Hybrid Traction Control System in Hybrid Electric Vehicles (HEVs) that prevented the spinning of the drive wheels during take-off and acceleration through targeted, brief brake impulses in motor torque. The task is to have the fuzzy supervisory controller generate the electric brake torque, for motor of a HEV. The electric brake torque is treated as reference input regenerative braking torque, for lower level control modules. When these lower level motor controller tracks its reference input, the desired slip ratio, can be reduced. Emergency lane change, tire slip ratio change simulations and experimental results were performed to show the effectiveness of the control. The efficiency and easy implementation of the Fuzzy Controller lead to the conclusion that Fuzzy Logic is an adequate and promising framework for Hybrid Traction Control System in Hybrid Electric Vehicles.**

Index Terms* - *Fuzzy Controller, Hybrid Traction Control System, Hybrid Electric Vehicle.

I. INTRODUCTION

The focus of current research towards electric, hybrid electric, and fuel cell vehicles has been on increasing energy efficiency and reducing emissions. Future vehicles will include electric drive-train components that must be capable of performing conventional anti-lock braking, traction control, and active yaw control safety functions. From the viewpoint of electric and control engineering, Hybrid electric vehicles (HEVs) have evident advantages over conventional internal combustion engine vehicles (ICVs). Firstly, Torque generation is very quick and accurate, for both accelerating and decelerating. This should be the essential advantage. In Hybrid electric vehicles, motor and TCS (traction control system)should be integrated into “ Hybrid Traction Control System (HTCS)” , since a motor can both accelerate or decelerate the wheel. Its performance should be advanced one, if we can fully utilize the fast torque response of motor. Secondly, Output torque is easily comprehensible. There exists little uncertainty in driving or braking torque inputted by motor, compared to that of combustion engine or hydraulic brake.

In recent years fuzzy logic control techniques have been applied to a wide range of systems. Many electronic control systems in the automotive industry such as automatic transmissions, engine control and traction control systems are currently being pursued. These electronically controlled automotive systems realize superior characteristics through the use of fuzzy logic based control rather than traditional control algorithms.

Fuzzy Logic Control is a type of control, which is based on Fuzzy set theory and reasoning. David Elting and Mohammed Fennich in their research told that automotive systems realize superior characteristics through the use of fuzzy logic controllers [1] especially in nonlinear cases. The brake system is a challenging control problem because the vehicle-brake dynamics are highly nonlinear with uncertain time-varying parameters [2]. Fuzzy controllers have the benefit of not requiring a mathematical model of the plant [3], while still being highly robust [4]. Also, certain fuzzy control designs can be implemented that have the ability to learn [6] or to adapt [5] themselves to improve its performance. Because of these features, fuzzy controllers have been successfully implemented in the automotive field for controlling both wheel dynamics [6], [4], [3], and vehicle dynamics [7], [8].

Bernd M. Baumann has demonstrated the suitability of fuzzy control techniques for the power-train management of Hybrid electric vehicles [19]. However, his operation strategy represents how the individual components of the drive train will interact with one another, emphasizes the means for controlling the power flow, such as transmissions or clutches, and dependency of the components on each other. Niels J. Schouten optimizes the energy flow between the main components of the HEV and optimizes the energy generation and conversion in the individual components. The driver power command, state of charge of the battery, and electric motor speed are used by a fuzzy logic controller to compute the optimal generator power and a scaling factor for the electric motor. The driver power command, optimal generator power, and scaling factor are used to compute the optimal internal combustion engine and motor power [20]. However, its theory emphasizes the driver inputs (from brake and accelerator pedals) are satisfied consistently, the battery is sufficiently charged at all times, and the fuel economy of the PHV is optimized.

In this paper, it is different from those and describes a fuzzy Controller for Hybrid Traction Control System in

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Hybrid Electric Vehicles (HEVs) that prevents the spinning of the drive wheels during take-off and acceleration through targeted, brief brake impulses in motor torque. It emphasizes the vehicle stable control based on the direct torque control of motor.

II. Hybrid Traction Control System (HTCS) Modeling

A hybrid vehicle operates using two or more different immediate power sources. The typical hybrid electric vehicle uses an electric motor and an internal combustion engine to propel the vehicle. Hydraulic motors and energy storage systems are under development, but are not commercially favored at present. The use of two different power sources allows the vehicle to be designed to exploit the advantages of each power source. A hybrid vehicle increases efficiency through improved energy management and the recovery of energy during braking. Downsizing of the conventional engine is possible with energy management strategies, while regenerative braking allows for the capture of energy which otherwise would be converted to heat by the service brakes. The secondary benefits of hybridization include traction control system (HTCS) and improved performance.

The following section describes the structure of HTCS including the HTCS algorithm and sub-component models.

A. Motor Model

Modern electric drive motors are sophisticated systems with microprocessor based controllers, advanced power electronics, and sophisticated control algorithms. The controllers regulate performance based on many factors including component temperature, bus voltage, and pre-programmed torque ramp rates. However, AC induction motors generally follow a simple torque versus speed rule. Maximum output torque is available from stall to the speed where maximum power. Maximum motor output power is determined by the lowest of either the controller limit at speed or by the power the vehicle can supply. Fig. 2.1 shows Numerical modeling of the traction electric motor. Motor efficiency curves were included in the model to determine the extra vehicle power required due to efficiency losses.

Most HEVs employ both a conventional braking system and a Regenerative Braking System. The conventional braking system typically includes frictional drum or disc braking assemblies selectively actuated by a hydraulic system. The Regenerative Braking System utilizes the electric motor, providing negative torque to the driven wheels and converting kinetic energy to electrical energy for recharging the battery or power supply. The dissipation of kinetic energy during braking, by an electric or hybrid vehicle can be recovered advantageously by controlling power electronics such that the electric traction motor behaves as a generator. The energy recovered during this process can be returned to the energy storage device for future use.

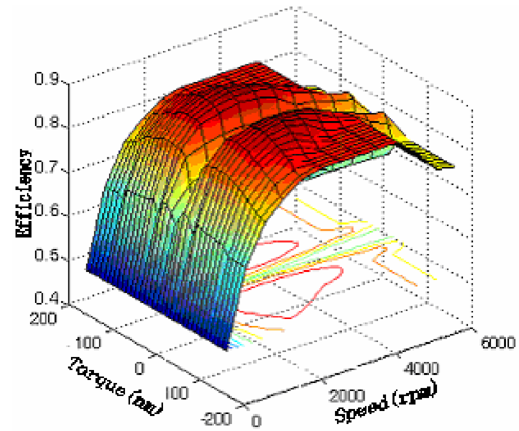

Fig. 2. 1 Numerical modeling of the traction electric motor.

B. Hydraulic Braking System Model [9]

A parallel braking system applies regenerative braking torque, to the driven wheels, in addition to hydraulic braking torque provided by the foundation braking system. Compression braking, determined in the motor controller based on Parallel HEV CC commands, is electric motor braking without application of hydraulics and gives the driver the feeling of engine drag present in an internal combustion engine vehicle while advantageously recovering kinetic energy, and is used in addition to a parallel braking system. Hydraulic brake torque is commanded by application of the brake pedal from the driver. Regenerative brake commands are predetermined as a function of master cylinder pressure in the traction motor controller and are based on PHEV CC commands. The electric brake torque added to the hydraulic brake torque in the parallel braking system is determined as a function of the Master Cylinder Pressure (MCP). [10,11,12,13]

The electric brake torque added to the hydraulic brake torque in the parallel braking system is determined as a function of the MCP. The following equation is used to determine the relationship between electric brake torque and hydraulic brake pressure:

$$T_e = \left[\left(g's\cdot R_w\cdot G\right)-\left(2\cdot BF_f\cdot P_f\right)-\left(2\cdot BF_r\cdot P_r\right)\right]/\left(g_{gear}\cdot g_{axle}\right) \quad (1)$$

$$g_{gear} = G_{diff}/G_{cmt} \quad (2)$$

$$g_{axle} = G_{axle\_cm}/G_{axle\_m} \quad (3)$$

Where T_e is the electric brake torque, $g's$ represents the vehicle acceleration (deceleration) /acceleration due to gravity, R_w is the wheel radius, G is the vehicle weight, BF_f and BF_r are the front, rear brake factor respectively, P_f and P_r are the front, rear brake pressure respectively, g_{gear} is the gear ratio, g_{axle} is the transaxle gear ratio, G_{diff} is the gear on the differential, G_{cmt} is the gear on the motor clutch, G_{axle_cm} is the transaxle gear on the motor clutch, and G_{axle_m} is the transaxle gear on the motor.

The front and rear brake pressure is a function of the sensed master cylinder pressure and is determined as follows:

$$P_f = P_r = P_{mc} \text{ for } P_{mc} \le X \quad (4)$$

$$P_r = X + \delta(P_{mc} - X) \text{ for } P_{mc} > X \quad (5)$$

In which P_{mc} is the master cylinder pressure. X is the master cylinder pressure at which brake proportioning changes. δ is the brake proportioning.

The front and rear brake forces are related to the brake pressure, as shown in the following relationships:

$$F_{rear} = 2 \cdot BF_r \cdot P_r / R_w \quad (6)$$

$$F_{front} = 2 \cdot BF_f \cdot P_f / R_w \quad (7)$$

Where F_{front} and F_{rear} represent the front, rear brakes force respectively. Vehicle deceleration, in $g's$, is plotted as a function of the total brake force, which is the sum of front and rear brake forces divided by the vehicle weight:

$$F_t = F_{front} + F_{rear} = G \cdot a_x / g \quad (8)$$

Where g is the acceleration due to gravity, a_x is the vehicle acceleration.

C. Vehicle Model

The eight-dimensional vehicle model is introduced and is shown in more detail in Fig. 2. 2.

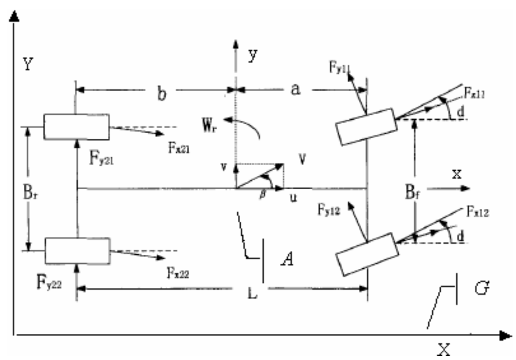

Fig. 2. 2 The ground-fixed and vehicle-fixed reference frames, G and A

In order to develop the equations of motion for the basic model, a suitable reference frame must be defined. In the vehicle-fixed axis system, A, (see Fig. 2. 2) the vehicle has the following velocity components [18]:

- Forward speed, u, in the x direction,
- Lateral velocity, v, in the y direction,
- Yaw velocity, W_r, in the z direction.

$$(du/dt - v \cdot W_r) G/g = (F_{x11} + F_{x12})\cos d - (F_{y11} + F_{y12})\sin d - F_f - F_w \quad (9)$$

$$(dv/dt + u \cdot W_r) G/g = (F_{y11} + F_{y12})\cos d + (F_{x11} + F_{x12})\sin d + F_{y21} + F_{y22} \quad (10)$$

$$I_z \cdot dW_r/dt = (F_{y11} + F_{y12}) * \cos d * a + (F_{x11} + F_{x12}) * \sin d * a - (F_{y21} + F_{y22}) * b$$
$$-(F_{x11} - F_{x12}) * \cos d * B_f / 2 + (F_{y11} - F_{y12}) * \sin d * B_f / 2 \quad (11)$$

$$F_w = C_d * A * v^2 / 21.15 \quad (12)$$

$$F_f = G * f = G * f_0 (1 + v^2 / 19440) \quad (13)$$

$$I_w * dW(1,1)/dt = T_d(1) - F_{x11} * R_w - M_f(1,1) - T_b(1,1) - T_e/2 \quad (14)$$

$$I_w * dW(1,2)/dt = T_d(2) - F_{x12} * R_w - M_f(1,2) - T_b(1,2) - T_e/2 \quad (15)$$

$$I_w * dW(2,1)/dt = -F_{x21} * R_w - M_f(2,1) - T_b(2,1) \quad (16)$$

$$I_w * dW(2,2)/dt = -F_{x22} * R_w - M_f(2,2) - T_b(2,2) \quad (17)$$

In which F_x is tyre forward force. Tyre lateral force, F_y, depends on vertical load and slip angle. F_f represents the rotating resistance. B_f is the distance between two front tires. F_w denotes the windward resistance. I_z denotes its yaw inertia about the mass center. I_w is the tyre moment of inertia. A is the windward area. a is the distance between the center of mass and the front axis. b is the distance between the center of mass and the rear axis. g is the acceleration due to gravity. d is the front steer angle. $M_f(1,1) \sim M_f(2,2)$ are the wheel rotating resistance torques. $W(1,1) \sim W(2,2)$ are the wheel yaw velocities. T_d is the engine torque. T_e is the electric brake torque. T_b is the frictional brake torque. C_d is the windward damping coefficient. f is the coefficient of friction.

D. Fuzzy Controller

This paper investigates the use of a fuzzy control to assign the electric brake torque, T_e. The electric brake torque is used as reference input for another control system. This setup is a two-layered control architecture with multiple slave controllers (whole vehicle controllers) as lower level modules, and a fuzzy controller (HTCS controller) acting as a higher level, supervisory module.

The idea is for the fuzzy controller to supervise the lower layer controllers to maintain good overall operation of the controlled system over changing environment [14], [15]. Since conventional control theories are not intelligent enough to tackle complicate tasks [16], by designing the overall control system in this manner, the supervisory controller handles the intelligence. This allows the lower level controllers to be designed simply as tracking controllers using the reference signals generated by the supervisory controller. This, in turn, enables the vehicle dynamics to track desired vehicle dynamics [17].

The slip ratio, λ, is one of the output parameters in the whole vehicle model. Ordinary, slip ratio λ is used to evaluate the "slip". For accelerating wheel, slip ratio λ is defined as, $\lambda = (v_w - v)/v_w$, where v is the vehicle chassis velocity. v_w is the velocity equivalent value of wheel velocity, $v_w = r \cdot w$, where r, w are the wheel radius and wheel rotating velocity, respectively. In this paper, the fuzzy logic control, a two-dimensional rule table is created based on the error, e, between the desired slip ratio and actual signals, and on the change in the error, Δe. The controller receives the signals e and Δe as inputs and generates, as output, the motor torque, T_e, to drive the motor.

Define a slip ratio error, e, as: $e = |\lambda| - |\lambda_d|$. Where λ is the vehicle slip ratio, and λ_d is the desired vehicle slip ratio.

To drive the vehicle along the desired track while the slip ratios cater to the desired vehicle slip ratio, the control action must impose the behaviour of the motor as a function of its actual state quantified by SLIP_RATIO_ERROR and ERROR_CHANGE.

The universe of discourse and the linguistic terms of the input variable SLIP_RATIO_ERROR represented in Fig. 2. 3 are defined to distinguish the situations when the vehicle is accelerating (linguistic term PS, PM, PB), decelerating (linguistic term NS, NM, NB), and purely rolling (linguistic term Z).

The input variable ERROR_CHANGE has an universe of discourse and a set of three linguistic variables (PB, PM, PS, ZO, NS, NM, NB) containing the information on the degree of the accelerating or decelerating (see Fig. 2. 4)

The defuzzification method of the output variable MOTOR_TORQUE is centre-of-area.

The linguistic variable SLIP_RATIO_ERROR has seven linguistic terms while ERROR_CHANGE has seven linguistic terms leading to a maximum number of 49 terms that can be achieved. The rules designed to control the vehicle have the general format

If (SLIP_RATIO_ERROR, ERROR_CHANGE) then (MOTOR_TORQUE).

The rules are listed in Table 2. 1.

The layout of the entire control system is shown in Fig. 2. 5. The Fuzzy Controller structure is represented in Fig. 2. 6. The role of each block is the following:

- the *Fuzzification Interface* converts the input values (e, Δe) into linguistic terms of the input fuzzy variables (SLIP_RATIO_ERROR, ERROR_CHANGE), with a correspondent certainty value,
- the *Knowledge Base* stores the data that defines the input and the output fuzzy sets, as well as the fuzzy rules that describe the control strategy,
- the *Decision Logic* block applies the fuzzy rules to the input fuzzy variables to obtain the output values (MOTOR_TORQUE),
- the *Defuzzification Interface* achieves output signals (T_e) based on the output fuzzy sets obtained as the result of fuzzy reasoning.

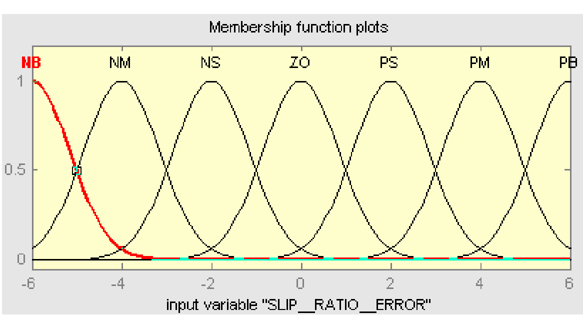

Fig. 2. 3 Linguistic terms of the slip ratio error

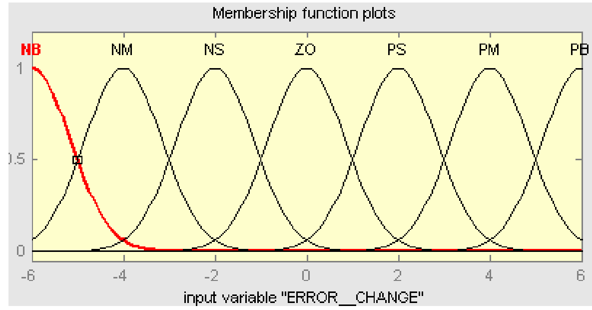

Fig. 2. 4 Linguistic terms of the change in the error

Table 2. 1
Fuzzy Controller Rule Table

MOTOR_TORQUE		SLIP_RATIO_ERROR						
		NB	NM	NS	ZO	PS	PM	PB
ERROR_CHANGE	NB	PB	PB	PM	PS	PM	PM	PM
	NM	PB	PB	PM	PM	PM	PS	PS
	NS	PM	PM	PS	PS	PS	ZO	ZO
	ZO	PM	PS	PS	ZO	NS	NM	NB
	PS	PS	PS	ZO	NS	NM	NM	NB
	PM	PS	ZO	NS	NS	NM	NM	NB
	PB	PB	NS	NM	NM	NB	NB	NB

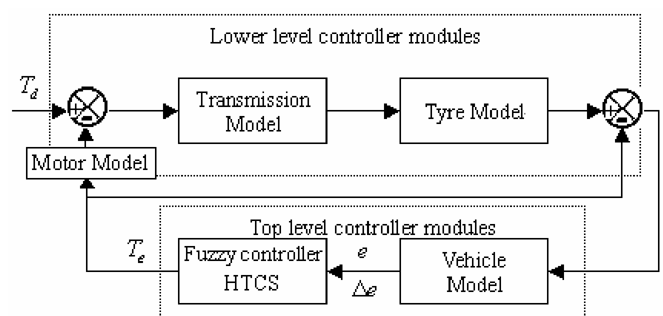

Fig. 2. 5 Block diagrams of control systems

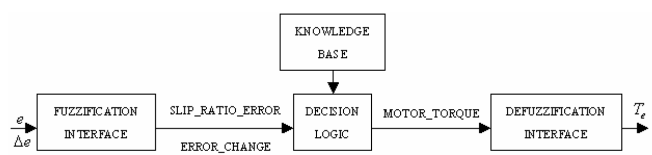

Fig. 2. 6 Fuzzy Controller

III. SIMULATIONS RESULTS

Simulations are carried out to confirm the effectiveness of proposed controller. Tab. 3. 1 shows the parameters. The simulation involves an emergency lane change maneuver. This simulation tracks a desired slip ratio, λ_d =0.10. The surface index used, μ =0.20, is consistent throughout the lane change. Fig. 3. 1 — Fig. 3. 2 show a comparative study between the vehicle with Fuzzy controller for Hybrid Traction Control System (FHTCS) and without. These figures show that the slip ratio oscillation can be suppressed with proposed Fuzzy controller.

Table 3. 1
Parameters in the Simulations.

Vehicle weight	1080[kg]
Wheel inertia	51.6[kgm^2]
Gear Ratio	13.5
Max. of Hydraulic Braking torque	4050[N]
Max. of Engine torque	110[Nm]
Max. of Regenerative Braking torque	2500[N]
Battery Nominal Capacity	8Ah
Battery Total Voltage	288V
1st order Delay in Motor torque response	1[ms]

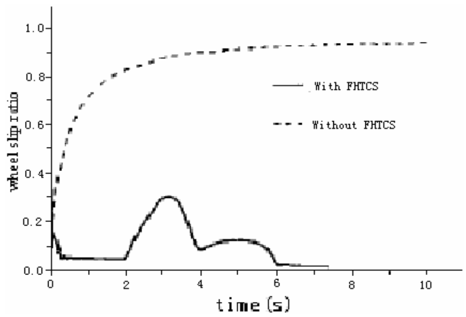

Fig 3. 1 The wheel slip ratio. Note: the slip ratio oscillation can be suppressed with proposed Fuzzy controller.

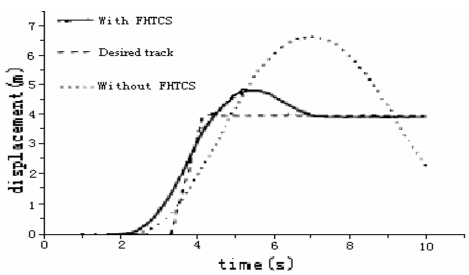

Fig 3. 2 Lost control of the skidding vehicle without Fuzzy controller for Hybrid Traction Control System (FHTCS)

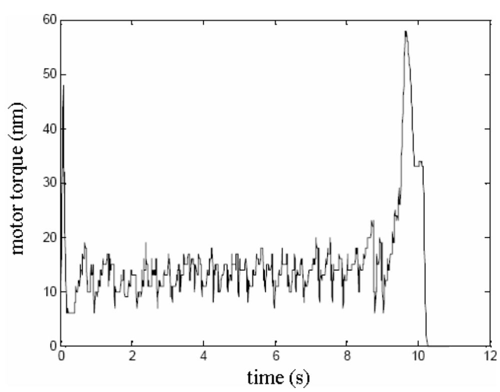

Fig 3. 3 Simulation results of the fuzzy control strategy

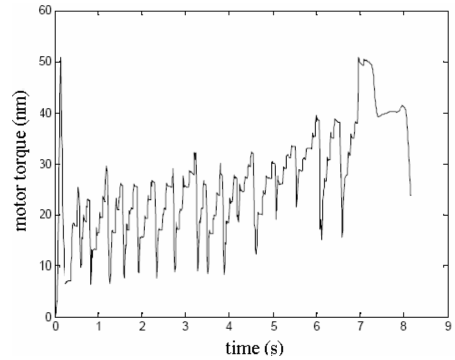

Fig. 3. 4 Simulation results of the logic threshold control strategy

Fig. 3. 3 and Fig. 3. 4 show the difference in amplitude between the fuzzy control strategy and the logic threshold control strategy. Note: the former torque fluctuation is smaller than the latter that is in practice in some commercial cars. Another simulation is carried out to confirm the effectiveness of proposed controller based on automatic road identification. This simulation involves an emergency tire slip ratio change maneuver. The simulation tracks a desired slip ratio, λ_{d1}=0.17 and λ_{d2} =0.08. These figures show that the slip ratio oscillation can also be suppressed with proposed Fuzzy controller (See Fig. 3. 5 and Fig. 3. 6).

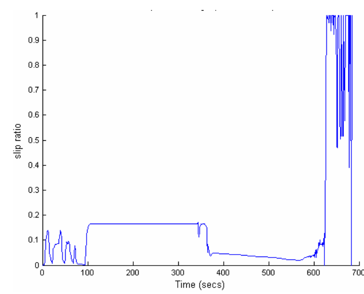

Fig 3. 5 Tire slip ratio change (from 0.17 to 0.08) Note: the slip ratio oscillation can be suppressed with proposed Fuzzy controller based on automatic road identification.

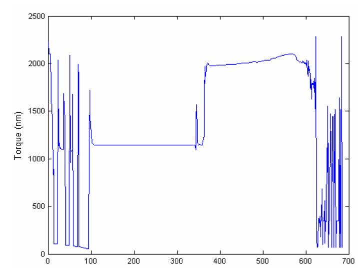

Fig 3. 6 The motor torque

IV. EXPERIMENTAL RESULTS

Then this proposed Hybrid Traction Control System was examined experimentally with one HEV (type A). This slip experiment was carried out on slippery road with experimental low μ road.

Fig. 4.1 shows the slip experimental results with this controller. The velocity equivalent value of wheel velocity and vehicle chassis velocity change as shown in Fig. 4.1(a). This causes the Motor torque to change as Fig. 4.1(b). In result, the slip ratio oscillation can be suppressed. With another vehicle (type B), the initial SOC is 0.7 and the lower level controller modules keep the SOC in the work band (Fig. 4.2). It shows that the top-level controller modules make sure motor provides most of brake torque.

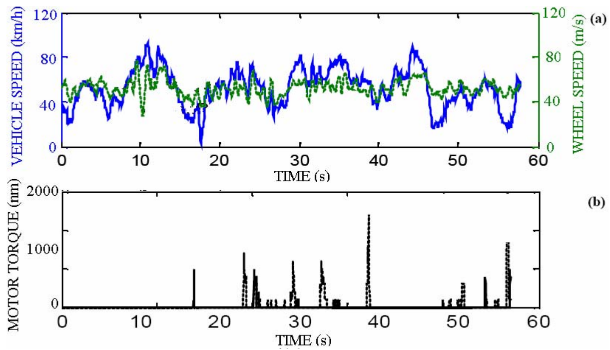

Fig. 4. 1 Experimental results of Hybrid Traction Control (type A)

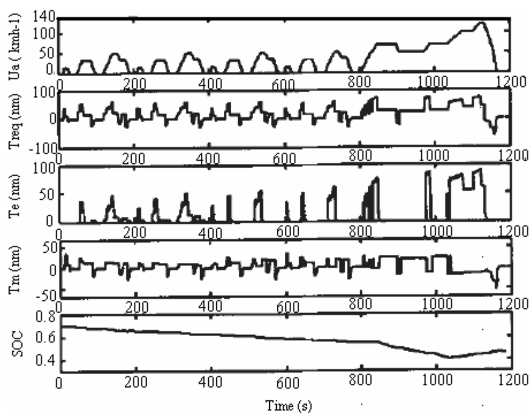

Fig. 4. 2 Initial SOC of 0.7 (type B)

Where

U_a: vehicle chassis velocity T_m: motor torque

T_e : engine torque T_{req} : torque requisite for driving

V. CONCLUSION

This paper investigates the design of a double-input single-output fuzzy supervisory controller [17]. The task is to have the fuzzy supervisory controller generate the electric brake torque, T_e , on motor of a HEV. The electric brake torque is treated as reference input regenerative braking torque, for lower level control modules. When these lower level motor controller tracks its reference input, the desired slip ratio, λ_d , can be reduced. Simulations for emergency lane change and tire slip ratio change are also performed. The results show that the slip ratio oscillation can be suppressed with proposed Fuzzy controller, the motor generates the commanded regenerative braking torque, which is required by lower layer controller, the battery SOC is changed, and the Fuzzy Controller for HTCS is effective, fast, and compact.

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