Adaptive Fuzzy Controller for Hybrid Traction Control System based on Automatic Road Identification

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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 describes a fuzzy Controller for Hybrid Traction Control System in 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. 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 and tire slip ratio change simulations are 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.

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]. This paper describes a fuzzy Controller for Hybrid Traction Control System in 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.

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).

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:

\[ T_e = \left[\left(g \cdot s \cdot R \cdot G - (2 \cdot BF \cdot P) - (2 \cdot BF \cdot P)\right)\frac{G}{G_{axle}}\right] (1) \]

\[ g_{gear} = \frac{G_{axle}}{G_{trans}} (2) \]

\[ G_{axle} = \frac{G_{trans}}{G_{motor}} (3) \]

Where \( T_e \) is the electric brake torque, \( s \) represents the vehicle acceleration (deceleration). \( G \) is the gear ratio, \( R \) is the wheel radius, \( BF \) is the brake factor respectively, \( P \) are the front, rear brake pressure respectively, \( g_{gear} \) is the gear ratio, \( G_{motor} \) is the gear on the transaxle, \( G_{trans} \) is the transaxle gear ratio, \( G_{trans} \) is the gear on the differential, \( G_{motor} \) is the gear on the motor clutch, \( G_{axle} \) is the transaxle gear on the motor clutch, and \( G_{motor} \) 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:

\[ P_f = P = P_{mc} \text{ for } P_{mc} \leq X \]

\[ P = X + \delta \left(P_{mc} - X\right) \text{ for } P_{mc} > X \]

Where \( P_{mc} \) is the master cylinder pressure. \( X \) is the master cylinder pressure at which brake proportioning changes. \( \delta \) is the brake proportioning.

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

\[ F_{rear} = 2 \cdot BF \cdot P \cdot R \]

\[ F_{front} = 2 \cdot BF \cdot P \cdot R \]

Where \( F_{front} \) and \( F_{rear} \) represent the front, rear brake forces respectively. Vehicle deceleration, in \( g \) 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:

\[ a = \frac{F}{m} \]

Where \( g \) is the acceleration due to gravity, \( a \) is the vehicle acceleration.

C. Vehicle Model
The eight-dimensional vehicle model is introduced and is shown in more detail in Fig. 2.2.

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, \( W_z \), in the z direction.

\[
\begin{align*}
\frac{dx}{dt} &= u \cos\theta + v \sin\theta + W_z \sin\theta, \\
\frac{dy}{dt} &= u \sin\theta - v \cos\theta, \\
\frac{dz}{dt} &= W_z \cos\theta.
\end{align*}
\]

\( \theta \) is the vehicle yaw angle, and \( \mathbf{u} = [u, v, W_z] \) is the vehicle velocity vector in the vehicle-fixed axis system. The total velocity of the vehicle is

\[
\mathbf{v}_t = \left[ \begin{array}{c} v_1 \\ v_2 \end{array} \right] = \frac{1}{2} \begin{bmatrix} 1 & 1 \end{bmatrix} \mathbf{v} = \frac{1}{2} \mathbf{v}.
\]

This is the velocity equivalent value of wheel velocity, \( v_w \), where \( v \) is the vehicle chassis velocity. \( v_w \) is the velocity equivalent value of wheel velocity, \( v_w = r \cdot w \), where \( r \) and \( w \) 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, \( \Delta e \). The controller receives the signals \( e \) and \( \Delta e \) as inputs and generates, as output, the motor torque, \( T_m \), to drive the motor.

Define a slip ratio error, \( e \), as:

\[
e = \frac{e - \lambda}{\lambda},
\]

where \( \lambda \) is the vehicle slip ratio, and \( \lambda_0 \) is the designed 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 \((e, \Delta e)\) 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.

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, \(\lambda_o=0.10\). The surface index used, \(\mu=0.20\), is consistent throughout the lane change. Fig. 3.1 ~ Fig. 3.3 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>
<thead>
<tr>
<th>Parameters in the Simulations.</th>
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<tbody>
<tr>
<td>Vehicle weight</td>
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<td>Wheel inertia</td>
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<tr>
<td>Gear Ratio</td>
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<tr>
<td>Max. of Hydraulic Braking torque</td>
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<tr>
<td>Max. of Engine torque</td>
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<tr>
<td>Max. of Regenerative Braking torque</td>
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<tr>
<td>Battery Nominal Capacity</td>
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<td>Battery Total Voltage</td>
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<td>1st order Delay in Motor torque response</td>
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![Membership function plots](image1)

![Membership function plots](image2)

<table>
<thead>
<tr>
<th>Table 2.1 Fuzzy Controller Rule Table</th>
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<tbody>
<tr>
<td>MOTOR_TORQUE</td>
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<td>NB</td>
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![Fig. 3.1 The left wheel slip ratio. Note: the slip ratio oscillation can be suppressed with proposed Fuzzy controller.](image3)
Fig 3.2 The right wheel slip ratio. Note: the slip ratio oscillation can be suppressed with proposed Fuzzy controller.

Fig 3.3 Lost control of the skidding vehicle without Fuzzy controller for Hybrid Traction Control System (FHTCS)

Fig 3.4 The motor negative torque

Fig 3.5 The Energy storage system state-of-charge (SOC)

Fig 3.6 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 3.7 The motor torque

IV. 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, $\lambda_{dr}$, 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.

REFERENCES


