

Integrated Longitudinal Vehicle Dynamics Control with Tire/Road Friction Estimation

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ABSTRACT

The longitudinal dynamics control is an essential task of vehicle dynamics control. In present, it is usually applied by adjusting the slip ratio of driving wheels to achieve satisfactory performances both in stability and accelerating ability. In order to improve its performances, the coordination of different subsystems such as engine, transmission and braking system has to be considered. In addition, the proposed algorithms usually adopt the threshold methods based on less road condition information for simpleness and quick response, which cannot achieve optimal performance on various road conditions.

In this paper, an integrated longitudinal vehicle dynamics control algorithm with tire/road friction estimation was proposed. First, a road identification algorithm was designed to estimate tire forces of driving wheels and the friction coefficient by the method of Kalman Filter and Recursive Least Squares (RLS). Then, a rule based integrated control algorithm which coordinate the engine torque control, brake pressure control and transmission shifting control was built to improve the vehicle driving performance.

During the longitudinal dynamics control procedure, the transmission shifting control algorithm firstly decided whether the vehicle starting up at the 1st or the 2nd gear based on the road condition. Then, the engine torque control algorithm was applied to adjust the slip ratio of driving wheels. Its process was divided into three phases. In each phase, different control rules with integration of engine torque and brake torque were set by the combined feed forward and feedback methods to meet with requirements of accuracy, rapidity and stability. The brake pressure was determined by method of sliding mode control (SMC) for its rapid adjustment characteristic, in the meanwhile, it was also an important component to be considered in engine torque feedback control.

Finally, the algorithm was verified by using Matlab/Simulink and CarSim co-simulation, the results show that the proposed control algorithm could regulate slip ratios of driving wheels fast and accurately, and the vehicle driving performance could be improved effectively.

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INTRODUCTION

The longitudinal dynamic control system is designed to improve vehicle handling, stability, deceleration or acceleration performance during braking or accelerating by maxing out the potential road-tire adhesion [1]. In consequence of the vital role that longitudinal dynamic control system plays in vehicle system, plenty of researches on the longitudinal dynamic control have been focused [2,3,4].

There are two important issues in longitudinal dynamic control, the adhesion information and integrated control logic. The adhesion information between road and tire is very important for longitudinal dynamic control. In order to utilize the available tire forces as much as possible on various roads, identification of peak tire-road friction coefficient and its optimal slip ratio is a critical link for guaranteeing the performance of longitudinal dynamic control system [5]. Furthermore, compared with the braking longitudinal control, the driving longitudinal control is more advanced and complicated because of its integration requirement with different subsystems such

as braking system, engine, transmission and differential. The coordination control logic should be designed to integrate the subsystems and exclude their interventions from each other. For example, the growth torque of both driving and braking in the same time during an accelerating slip control would generates meaningless energy loss [6]. Therefore, if the tire-road friction information could be identified and a preferable integrated control logic could be established, the maximum tire-road forces could be utilized and the performance of longitudinal control system will be improved.

Unlike normal vehicle dynamic information, the tire-road friction coefficient is hard to measure directly. A cutting-edge approach is to equip with intelligent tire which monitor the tire adhesion information in real time by the sensors such as ultrasonic approach, optical position detection and piezoelectric film sensor mounted inside of tires [7,8,9]. However, these research is still in their early stage and unsuitable for

wide application due to the newly equipped sensors and the increased cost. Therefore, more research is focused on the methods and algorithms for tire-road adhesion information estimation.

The longitudinal dynamic control system usually utilizes the braking system to adjust the slip ratio of driving wheels because of its rapid response, simplicity of operation and availability in most vehicles. But adopting the braking control would cause troubles such as energy loss, brakes overheating and the vibration of vehicle [10]. The engine control is an optimal control option of longitudinal dynamic control system, because it takes into account both accelerating performance and fuel economy. But as its response speed is relatively slowly, the engine torque control is usually utilized in combination with other control methods [11]. The transmission control could improve the effectiveness of starting step and the condition of engine works. However, conflicts might exist if the subsystems were controlled independently, in which way the control performance might be worse. Furthermore, feedback control methodologies were widely used in the longitudinal control systems [12]. It has the advantage of stability and accuracy, but its weakness of slowing adjustment rate is also obvious. A feed forward control methodology could be an effective compensation. In addition, the estimation of road condition is usually simple in current methods, and the control parameters are set conservatively because the tire safe margin cannot be identified explicitly. It has to sacrifice the performance of acceleration to guarantee the performance of stability.

In this paper, a tire-road friction estimation algorithm was proposed with the combination of Kalman Filter and Recursive Least Squares method. The tire forces were observed by the Kalman filter method based on longitudinal vehicle model with the available vehicle signals. And then, the tire-road friction coefficient, which is a parameter of brush tire model, was estimated by Recursive Least Squares method. Based on the estimated road friction coefficient, an integrated longitudinal dynamic control algorithm was proposed with the combination of braking system, engine and transmission. The gear of transmission at starting up phase was firstly decided. Then, the engine torque and braking torque were controlled to adjust the slip ratio of driving wheels. A rule based strategy with the combination of feed forward and feedback methods was designed. Finally, the proposed algorithm was verified by Matlab/Simulink and CarSim co-simulation.

THE TIRE-ROAD FRICTION ESTIMATION ALGORITHM

The Tire Force Observation Based on Kalman Filter

The schematic diagram of longitudinal vehicle model used for tire force estimation is shown in Figure 1, whose aerodynamic resistance and tire rolling resistance are neglected and only the tire-road adhesion forces are considered. In this model, only the longitudinal direction is concerned and the vehicle is driven by front wheels.

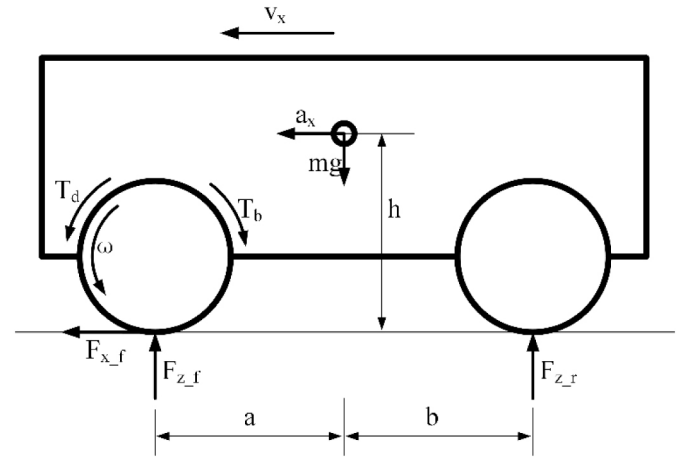


Figure 1. Longitudinal vehicle model during acceleration

The dynamic equations of the longitudinal vehicle model showed in Figure 1 is:

$$\begin{cases} \dot{x}(t) = A(t)x(t) + B(t) + w(t) \\ z(t) = H(t)x(t) + v(t) \end{cases} \quad (1)$$

Where

$$x(t) = [F_{x_{fl}} \quad F_{x_{fr}} \quad \omega_{fl} \quad \omega_{fr}]^T$$

$$z(t) = [a_x \quad \omega_{fl} \quad \omega_{fr}]^T$$

$$A(t) = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -\frac{r}{I_w} & 0 & 0 & 0 \\ 0 & -\frac{r}{I_w} & 0 & 0 \end{bmatrix}$$

$$B(t) = \begin{bmatrix} 0 & 0 & \frac{T_d - T_{b_{fl}}}{I_w} & \frac{T_d - T_{b_{fr}}}{I_w} \end{bmatrix}^T$$

$$H(t) = \begin{bmatrix} \frac{1}{m} & \frac{1}{m} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$F_{x_{fl}}$ and $F_{x_{fr}}$ are the longitudinal tire forces of front left and front right wheel respectively. ω_{fl} and ω_{fr} are the rotation speed of front left and front right wheel respectively. a_x is the longitudinal acceleration of vehicle. r is the effective rolling radius of wheels. I_w is the inertia moment of the wheels, T_d is the driving torque of wheels, $T_{b_{fl}}$ and $T_{b_{fr}}$ are the braking torques of front left and front right wheel respectively. m is the mass of vehicle. The system process noise $w(t)$

is an 4-dimensional zero-mean white noise vector, the measurement noise $v(t)$ is a 3-dimensional zero-mean white noise vector, and $w(t)$ and $v(t)$ are mutually unrelated.

The discrete Kalman filter method based on linear discrete system is widely used in engineering because of its advantages in computer aid calculation and the less requirements of data storage [13]. The discretization of the continuous vehicle system is necessary for the discrete Kalman filter approach. In this paper, the zero-order hold (ZOH) method is utilized to discretize the continuous vehicle model. And the discrete system state space equation is:

$$\begin{cases} x_{k+1} = A_k x_k + B_k + w_k \\ z_k = H_k x_k + v_k \end{cases} \quad (2)$$

Based on equation (2), the discrete Kalman filter estimation processes, including the prediction, state estimation, filter gain matrix calculation, step prediction error variance matrix calculation and the estimation error variance matrix calculation process, are processed. As long as the initial system condition was been set, according to the measured values z , the state estimation x could be recursive calculated, and the tire force F_{x_fl} and F_{x_fr} which included in vector x could be achieved [5].

The Other Vehicle Information Calculation

Only the longitudinal direction is concerned. Assuming that the vertical forces of both left and right sides are same, the vertical tire force F_z of each front wheels can be calculated by the mass and acceleration of vehicle as follow:

$$F_{z_fl} = F_{z_fr} = \frac{mg \cdot b - ma_x \cdot h}{2(a+b)} \quad (3)$$

Where F_{z_fl} and F_{z_fr} are the vertical tire forces of front left and front right wheel respectively, g is the acceleration of gravity, a and b are the distances from the center of vehicle mass to front and rear axle respectively, h is the height of center of vehicle mass.

Concerning that the slip rates of the driven wheels are very small, the longitudinal velocity of vehicle can be estimated by rotating speeds of driven wheels as follow [14]:

$$v_{x_ref} = \frac{(\omega_{rl} + \omega_{rr})r}{2} \quad (4)$$

Where v_{x_ref} is the reference longitudinal velocity of vehicle, ω_{rl} and ω_{rr} are the rotating speeds of rear left and rear right wheel respectively.

The 'practical' slip ratios κ and the 'calculative' slip ratio s of front wheels could be calculated as follows [15]:

$$\kappa_{fl} = \frac{\omega_{fl} \cdot r - v_{x_ref}}{v_{x_ref}} \quad (5)$$

$$\kappa_{fr} = \frac{\omega_{fr} \cdot r - v_{x_ref}}{v_{x_ref}} \quad (6)$$

$$s_{fl} = \frac{\omega_{fl} \cdot r - v_{x_ref}}{\omega_{fl} \cdot r} = \frac{\kappa_{fl}}{\kappa_{fl} + 1} \quad (7)$$

$$s_{fr} = \frac{\omega_{fr} \cdot r - v_{x_ref}}{\omega_{fr} \cdot r} = \frac{\kappa_{fr}}{\kappa_{fr} + 1} \quad (8)$$

Where κ_{fl} and κ_{fr} are the 'practical' slip ratios of front left and front right wheels respectively, used as a parameter of brush tire model. s_{fl} and s_{fr} are the 'calculative' slip ratios of front left and front right wheels respectively, used as a control variable in longitudinal dynamic control.

The Longitudinal Brush Tire Model

The brush tire model is widely used for estimation or control purposes because of its simplicity and its characteristic is correspondence with the experimental tire behaviors such as the friction ellipse influence and tire nonlinear characteristics, e.g. tire force saturation [16]. If only the longitudinal direction is concerned, expression could be simplified as follow:

$$F_x = \begin{cases} \text{sign}(\kappa) \cdot F & , f \leq 3\mu F_z \\ \mu F_z & \text{else} \end{cases} \quad (9)$$

Where

$$F = f - \frac{1}{3\mu F_z} f^2 + \frac{1}{27\mu^2 F_z^2} f^3$$

$$f = \left| C_x \cdot \left(\frac{\kappa}{\kappa + 1} \right) \right|$$

$$\text{sign}(x) = \begin{cases} 1 & x > 0 \\ 0 & x = 0 \\ -1 & x < 0 \end{cases}$$

μ is the road friction coefficient, or rather, the peak adhesion coefficient of road. Usually the peak adhesion coefficient is larger than sliding adhesion coefficient, but in the brush tire model, they are assumed to be same. C_x is the longitudinal stiffness of tire, depend on tire properties such as tire size, tread width, tread stiffness, inflation pressure, load, and so on, which tend to be static for a short period [5]. Therefore, it could be assigned as a fixed value in a short time.

Estimation μ by Recursive Least Squares Method

As mentioned above, the parameters of F_z and κ can be calculated online by equations (3), (5) and (6), and C_x is looked as a constant. The parameter μ in equation (9) can be estimated. In this paper, the value of tire-road friction coefficient μ is estimated by the usage of