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Estimation of tire-road friction coefficient based on frequency domain data fusion

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A B S T R A C T

Due to the noise of sensing equipment, the tire states, such as the sideslip angle and the slip ratio, cannot be accurately observed under the conditions with small acceleration, which results in the inapplicability of the time domain data based tire-road friction coefficient (TRFC) estimation method. In order to overcome this shortcoming, frequency domain data fusion is proposed to estimate the TRFC based on the natural frequencies of the steering system and the in-wheel motor driving system. Firstly, a relationship between TRFC and the steering system natural frequency is deduced by investigating its frequency response function (FRF). Then the lateral TRFC is determined by the steering natural frequency which is only identified using the information of the assist motor current and the steering speed of the column. With spectral comparison between the steering and driving systems, the data fusion is carried out to get a comprehensive TRFC result, using the different frequency information of the longitudinal and lateral value. Finally, simulations and experiments on different road surfaces validated the correctness of the steering system FRF and the effectiveness of the proposed approach.

1. Introduction

The active front steering (AFS), as a kind of steering-based vehicle stability control (VSC) systems, can generate the driver's desired lateral force and yaw moment more quickly with no intervention of braking, compared to the direct yaw moment (DYC)-based VSC [1]. In addition, the application of the motor has various merits in the control and functional aspects, such as high motor response, and precise torque generation [2]. Besides, it can also be treated as an accurate feedback sensor. In recent years, the motor-based vehicle state estimation has become a hot spot of research [3].

For longitudinal control, some researchers have investigated the advantages of the in-wheel motor on longitudinal velocity estimation [4,5]. For VSC, the most important vehicle state is the sideslip angle. By combining a linear vehicle model with the steering system model, a simple observer can be used to estimate sideslip when yaw rate and steering angle are measured, if the steering torque can easily be determined from the current applied to the steering assist motor. In addition to the sideslip angle, the information of the tire -road friction coefficient is indispensable for accurate stability control [6], as the tire forces primarily determine the states of the steering wheel motion.

The TRFC $\mu_{\max}$ in this paper can be defined as Equation (1) [7].

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$$\mu_{max} = \left. \frac{\sqrt{F_x^2 + F_y^2}}{F_z} \right|_{max} \tag{1}$$

where F_x, F_y and F_z are respectively the longitudinal, lateral and vertical tire forces.

This definition shows that μ_{max} can be estimated from longitudinal or lateral dynamics response.

Different approaches have been proposed about the estimation of the tire-road friction coefficient [8–10]. The well-known method is the slope based one. Hedrick [9] and Gustafssonp [10] deemed that the TRFC can be considered as a function of the slope between the slip ratio or sideslip angle and friction coefficient curve. The longitudinal dynamics-based TRFC estimation methods requires large longitudinal tire slip ratios, so the vehicle should accelerate or brake sufficiently in order to provide reliable TRFC estimates [6]. Such a requirement may constitute limitation as the longitudinal tire slip is typically small for normal driving conditions. Bartram [11] found that the tire/road contact interface can influence the driveline vibrations. Following this research and the study of [12], Chen [13] deduced a relation between the TRFC and the high in-wheel motor (IWM) drive system natural frequency using coupling analysis [14]. Based on this relationship, a method is proposed to detect the difference of road condition with the merit that the motor can capture the high frequency information of the driving torque [13].

Compared to the vehicle longitudinal dynamics-based TRFC estimation methods, the vehicle lateral dynamics-based methods do not require excessive longitudinal motion excitations but can be used only when the vehicle is turning [8] The driver needs to keep on turning the steering wheel so that the persistence of excitation condition, which ensures convergence of TRFC, can be satisfied. Hong [15] tried to estimate TRFC using the measured lateral force from sensors installed in the tire. Wang [16] and Wang [17] proposed a sequential tire cornering stiffness coefficient and tire–road friction coefficient estimation method for the four-wheel independently-actuated electric vehicles. This method can estimate TRFC without affecting the vehicle desired motion control and trajectory tracking objectives. But the sideslip angle is still relative large, which means that this approach can't overcome the limitation of steering maneuver. As the tire self-aligning torque (SAT) exhibits high sensitivity to road friction at low slip angles and can be calculated with the electric power steering torque, Matsuda [18] applied a method to estimate front tire road friction accurately at low lateral acceleration. But, when the vehicle is moving straightforward, the sensor noise and error influence the estimation accuracy of the sideslip angle. Meanwhile, the active front steering system which consists of the assist motor, the steering column and the tire, is highly electromechanical. However, only simplified rigid tire models are used in most of the published papers regarding the steering control. The dynamic tire properties cannot be sufficiently captured, which are caused by different wheel and tire parameters. Briefly, these all result in the low accuracy of the friction estimation the slope-based methods if only the time-domain information is used.

Modern advanced driver assistant system(ADAS) such as adaptive cruise control and lane keeping system, try to ensure the safety of the vehicle, under the case that the tire and the vehicle are operating within the stable and/or safe conditions. This means that there is a small slip ratio and sideslip angle. The TRFC estimation is indispensable to calculate the safety distance to surrounding objects. Chen's approach [13] is proposed for this case using longitudinal dynamics. If Chen's is also suitable for the lateral situation, a similar frequency relation should exist in the active front steering system, and can be used to estimate TRFC. With the development of data fusion theory, Li [19] and Chen [20] tried to implement it in TRFC estimation to reach a more accurate performance under complex maneuver. As AFS and IWM are two key technologies which will be implemented in the future electric vehicles, the assist steering motor and the driving motor can act as different road condition sensors. So the data fusion of these information resources should be also investigated to improve the robustness of the estimation.

A TRFC estimation method based on frequency domain data fusion under the conditions with small acceleration is presented in this paper. For implementing the method, firstly, the impact of the lateral road friction on the natural frequency of the steering system should be found. A simplified motor model and a first-order delay-based dynamic tire model are considered to establish the column-assist-type steering system. As a result of analysis of the steering dynamics in the frequency domains using its frequency response function (FRF), the equation of the natural frequency is obtained. It infers that the squared natural frequency changes linearly along with the road friction. Then, with the identification method in [13], the lateral TRFC is determined using only the signal of the assist motor current and the steering column rotation speed. Spectral comparison hereafter is conducted between AFS and IWM, to propose the data fusion approach. It combines the lateral and longitudinal TRFC to get a comprehensive and accurate value. The correctness of the equation of the natural frequency and advantages of the total estimation scheme is validated by the simulation and the experimental results under small sideslip angle conditions.

2. System modeling

2.1. Active front steering system

The active front steering system in this article is a column-assist-type, whose assist motor steers the front wheel through the worm gear structure by rotation of the steering column, shown as Fig. 1 [21].