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Relaxed static stability based on tyre cornering stiffness estimation for all-wheel-drive electric vehicle

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ABSTRACT

A novel dynamics control approach for all-wheel-drive electric vehicle (EV), relaxed static stability (RSS) approach is proposed with two advantages. Firstly, it allows vehicle lateral dynamics system to be inherent unstable to improve configuration flexibility. Secondly, handling performance could be improved based on closed-looped pole assignment with additional yaw moment. In this paper, basic control framework of RSS is proposed, including 'Desired Pole Location', 'Pole Assignment' and 'Tyre Cornering Stiffness Estimation' modules. The tyre cornering stiffness is estimated online to improve the robustness of the controller. The experiments based on an EV testbed show the performance and efficiency of RSS.

1. Introduction

All-wheel-drive (AWD) electric vehicle (EV), which applies independent motor to drive each wheel, is becoming widely focused with unique features. It employs independent motors to directly drive the wheels without any mechanical link. The torque acting on each wheel can be controlled independently, which provides great convenience to conduct vehicle dynamics control, such as Traction Control (TC), Direct Yaw Control (DYC) or integrated control (Wong et al., 2016; Chan, 2008; Zhang, Zhang & Wang, 2016; Wang, Zhang & Wang, 2014; Ivanov, Savitski, & Shyrokau, 2015; Jalali et al., 2016; Ni & Hu, 2017). Moreover, since the acting torque information on each wheel is available, it also boosts the research of tyre-road adhesion condition and vehicle behavior parameter observation (Wang, Fujimoto, & Hara, 2016; Hu, Yin, & Hori, 2011; Doumiati, Victorino, & Charara, 2011; Nam, Fujimoto, & Hori 2012)

DYC is one of the most popular topics among the dynamics control technologies of AWD EV (Shuai, Zhang & Wang, 2014a, 2014b; Shibahata, Shimada, & Tomari, 1993). The main principle is to generate additional yaw moment to control the vehicle to track the desired behavior to improve the handling performance. M. Nagai proposes a model matching controller to control the vehicle to follow the desired 2DOF lateral dynamic model (Nagai et al., 1997). Y. Hori claims that it's necessary to calculate the desired behavior based on 2DOF lateral dynamic model because of the safety concern (Sakai & Hori, 1998). Goodarzi discusses the performance of optimal controller on yaw moment generating (Goodarzi & Mohammadi, 2014). Xiong proposes an optimal controller with real-time online estimation of the tyre cornering stiffness to improve the control accuracy against tyre uncertainties (Xiong, Yu, & Wang, 2012). Hedrick uses sliding mode control during the process of yaw moment generating, and the driver behavior is also taken into consideration (Chen, Hedrick, & Guo, 2012). To deal with DYC control problem in high nonlinear maneuver condition, Hori proposes a controller based on body slip angle fuzzy observer (Geng, Mostefai, & Hori, 2009), and he further proposes a slip angle estimation block using the lateral tire force sensors (Nam, Fujimoto, & Hori, 2012, 2014). Shuai investigates the time-varying delay of CAN network in DYC and Active Front Steer (AFS) systems, and he proposes an H_∞ based delay-tolerant controller (Shuai et al., 2014a; 2014b). H. Zhang proposes a generalized Proportional-integral (PI) controller to deal with uncertainties of longitudinal velocity in AFS and DYC combined control systems (Zhang & Wang, 2016)

Above researchers' work have made great contributions. However, DYC still have apparent deficiency, which will be discussed in details later. In this paper, a novel lateral dynamics control approach-relaxed static stability (RSS) will be proposed based on our previous work (Ni & Hu, 2016a; 2016b; Ni et al., 2015; Ni & Hu, 2016a; 2016b). The major novelty and contribution of RSS lies on: 1) RSS's basic principle is totally different from that of DYC. It can be considered as novel overall theory of ground

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vehicle. The main idea is that the vehicle's lateral dynamics system can be designed as unstable (inherent oversteer), which is significant for improving structure configuration flexibility. 2) RSS utilizes pole assignment approach to improve the closed-looped handling performance. The desired pole locations of closed-looped lateral dynamics system could be easily adjusted to meet different handling demand of different type vehicles, such as safety demand for passenger car, or agility demand for combat vehicle.

In this paper, following sections are organized. In Section 2, the necessity to use RSS in ground vehicle field is claimed compared to the history of flight control. In Section 3, the control framework of RSS is described, including ‘Desired Pole Location’, ‘Pole Assignment Controller’ and ‘Tyre Cornering Stiffness Estimation’ modules. In Section 4, the experiments based on an EV testbed show the efficiency of RSS.

2. CCV to improve configuration flexibility

2.1. Inspiration of airplane design and flight control

Control Configured Vehicle (CCV) concept has been widely used in flight control area. The control methods of CCV concept include relaxed static stability, envelope limit control, maneuver load control and active structural mode control (Anderson & Mason). For the traditional design process of airplane. The airplane configuration only depends on the propulsion system design, aerodynamic system design and other mechanical systems design. The flight control system design process is on the outside of the primary configuration and optimization loop. The control system has no influence on the structure configuration. In other words, the control system will not be designed until after the final airplane configuration has been selected. The airplane design process under CCV concept is totally different (Anderson & Mason). It includes the control system design in parallel with other subsystems for final configuration. The control system directly affects configuration selection. The combination of mechanical and control systems leads to the maximization of the overall performance. Take RSS control method as example. For traditional airplane, the aerodynamic center must be in the back of C.G to achieve enough longitudinal static stability. By using CCV concept, if a feedback active control system is utilized to provide artificial stability, the airplane's longitudinal stability can be relaxed. Therefore, the C.G location can be placed in the back of aerodynamic center, which significantly improves the configuration flexibility. The down tail loads can even result in an up-loaded tail so that the wing loads are reduced. The size and weight of horizontal tail can be reduced to achieve reduced fuel consumption, reduced drag, and better maneuvering capability.

Previous ground vehicle overall design process is same to traditional process of airplane. The configuration selection of the ground vehicle only takes mechanical systems into consideration. The control system design process is separated from the mechanical systems. After the overall configuration is determined, various control systems will be added, such as TC, ABS or DYC systems. The history of airplane overall configuration principle could provide significant guidance. With more control systems involved, it's necessary to utilize CCV concept in ground vehicle to improve the overall performance.

2.2. Pole location discussion-configuration flexibility improvement

According to vehicle dynamics theory (Milliken & Milliken, 1994), the vehicle should be understeer to achieve stable handling response. It is usually described by Static Margin (S.M.): (Milliken & Milliken, 1994).

$$\text{S.M.} = \frac{C_r}{C_f + C_r} - \frac{l_f}{L} \tag{1}$$

Where C_f and C_r is front and rear tyre cornering stiffness. l_f is the distance from front axle to C.G. L is the wheelbase.

When S.M. is higher than 0, the vehicle will be inherent understeer. The higher the S.M. value is, the more understeer the vehicle will be. The value of S.M. depends on the configuration of the vehicle. Understeer is a basic principle to configure the vehicle's structure.

Traditional vehicles easy to achieve inherent understeer according to Eq. (1). The engine and transmission systems are usually located at the front of the vehicle, which decreases the value of l_f, and consequently enhances the understeer characteristics. However, for some new type vehicles, such as AWD EVs, it is hard to configure them to be inherent understeer. Heavy battery pack is usually located at the middle of the vehicle, and the independent motors are separated near the wheels, which leads to a back C.G. location. As mentioned in (Esmailzadeh, Goodarzi, & Vossoughi , 2003), the configuration problem is a common problem for EVs, which leads to inherent handling instability. CCV concept and RSS control provides great idea to solve this problem. Like how it works in airplane field, it allows the vehicle lateral dynamics system to be inherent unstable to improve the configuration flexibility, and to be closed-looped stable based on the yaw moment feedback.

How much RSS can improve the configuration flexibility should be discussed. The pole location of the lateral dynamics system will be discussed to give a clearer observation. The state-space of 2DOF lateral dynamic model is described as (Milliken & Milliken, 1994):

$$\dot{x} = Ax + B\delta \tag{2}$$

Where:

$$x = \begin{bmatrix} \beta \\ r \end{bmatrix}, \quad B = \begin{bmatrix} -\dfrac{C_f}{mu} \\ -\dfrac{l_f C_f}{I_z} \end{bmatrix} \tag{3}$$

$$A = \begin{bmatrix} \dfrac{C_f + C_r}{mu} & \dfrac{l_f C_f - l_r C_r}{mu^2} - 1 \\ \dfrac{l_f C_f - l_r C_r}{I_z} & \dfrac{l_f^2 C_f + l_r^2 C_r}{I_z u} \end{bmatrix} \tag{4}$$

Where l_r is the distance from rear axle to C.G. r is the yaw velocity. β is the side slip angle. m is the vehicle mass. I_z is the yaw inertia. u is the vehicle speed. The pole locations can be described as:

$$p_{1,2} = \frac{I_z\left(C_f + C_r\right) + m\left(l_f^2 C_f + l_r^2 C_r\right) \pm \sqrt{\Delta}}{2 I_z m u} \tag{5}$$

Where:

$$\Delta = \left[I_z\left(C_f + C_r\right) - m\left(l_f^2 C_f + l_r^2 C_r\right)\right]^2 - 4 I_z m\left[mu^2 - \left(l_f C_f - l_r C_r\right)\right]\left(l_f C_f - l_r C_r\right) \tag{6}$$

To show the pole distributions of inherent understeer vehicle, a front-drive passenger car's specifications will be used as Table 1 shows.

In order to discuss how CCV and RSS improves the configuration flexibility, the variation of poles location when configuration changes should be discussed.

Fig. 1(a) shows the case when C.G location changes. The original C.