RESEARCH ON THE ADVANCED ACTIVE REAR STEERING CONTROL FOR A THREE-AXLE ELECTRIC BUS

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An active rear steering (ARS) control algorithm is proposed for a three-axle electric bus with four in-wheel motors at the middle and rear axles. The tire wearing is quantified using the side slip angles of the axles and weighted by the axle's vertical loads. And based on equal life design principle, the steering angle of the rear axle is properly controlled to alleviate the tire wearing caused by kinematic interference between the driving axles. Meanwhile, the stability of the AFS control algorithm is proved after linearization. A simulation platform is established in Trucksim software combined with Simulink. A sharp turning test case is particularly designed to show the performance of the proposed algorithm, which is compared with a non-rear-steer solution and a simple ratio-based solution. The advanced test results show that the tire wearing of the driving axles can be improved as desired.

Keywords: Electric Bus, Active Rear Steering, Tire Wearing

1. Introduction

Vehicle system dynamics and integrated control is a new discipline developed in recent years, and it is also a hot research topic in the field of international automotive engineering. Especially for electric vehicle with multi motor drive electric wire chassis, integrated control system is a high order nonlinear system of interdisciplinary and multi objectives and constraints, the high performance and high reliability of the integrated control research is particularly important. At present, this technology is developing along the direction of dynamics system modeling, simulation, analysis and control integration. Among them, the high accuracy of vehicle dynamics modeling, multi-sensor information fusion and state estimation, dynamic fault tolerant integrated control, based on active and passive safety functions of distribution integration technology is still need further research topics at the forefront.

With the increasingly serious shortage of energy and environmental pollution, electric vehicles have become the focus of the development of the current vehicle industry, will also become the inevitable direction of future vehicle development. Electric vehicles have become the comprehensive

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application platform of electric, lightweight and intelligent vehicle technology, and promote the new round of vehicle industry technology revolution. The technical level of different types of electric vehicles depends on their motorized, lightweight and intelligent level. From the aspects of power system layout, distributed drive electric vehicle has good mobility, the advantages of fast response of motor control, drive chain short, compact structure, high mechanical efficiency, vehicle quality is light, has replaced the centralized driving electric vehicle trends. The control mode of each subsystem, benefited from the development of electric bus and network communication technology, a comprehensive technology including wire drive by wire, brake by wire, wire suspension and steering by wire, also has the possibility to replace the traditional mechanical hydraulic control device of the trend. The combination of distributed drive power system configuration and full line by wire technology makes electric vehicles more potential in safety, stability, power, comfort and economy. However, the application of highly integrated distributed drive by wire chassis platform also brings new challenges to chassis integrated control. In order to improve the vehicle performance and reliability, it is very important to study the integrated control system for the electric vehicle with distributed drive on wire chassis platform.

In recent years, electric vehicles are taking an increasingly important role in the modern transportation field. Especially, electric buses in cities are acting as pioneers in application of EVs, as they have more practical advantages than private passenger cars. The advantages include a relatively fixed driving path, more space for battery layout, more financial support from the governments, etc. Many types of distributed driving systems have been researched in the past few years [1-3]. The vehicle safety and stability of motor-driven EVs can be greatly improved when combined with the traditional ABS, ASR, ESP and VSC control [4].

Some researchers have investigated the driving control algorithm for different types of distributed driving system to improve the vehicle performance. To coordinate the driving and steering control, Hirana Y et al. linearized the vehicle model based on the input/output relationships of the vehicle, and a μ-synthesis robust control method was applied to the coordinate the 4WS and 4WD control [5]. Based on the body slip angle and yaw rate estimation, Karbalaei et al. used the fuzzy control method to coordinate the active steering and direct yaw control, where the steering angle of the wheels and the yaw torque were well coordinated for better performances [6]. Junmin W et al. used the sliding-mode control method to obtain the ideal traction force, and the control allocation method was used to distribute the tire forces, by which the active safety and vehicle maneuverability was improved [7]. Using the adaptive fuzzy neural network and PID control algorithms, Hou Y et al. integrated the vehicle dynamics control (VDC) and active-front-steering system (AFS) to improve vehicle maneuverability and safety [8].

In this paper, a novel three-axle bus with independently steerable rear axle and four distributed driving motors is researched. Such a distributed driving and multi-axle steering system has much practical potential. For example, the steerable rear axle can improve the vehicle mobility with smaller minimum turning radius. However, severe tire wearing may happen due to the kinematic interference between the driving axles. This paper attempts to find a way to evaluate the tire wearing and alleviate it by proper active rear steering control.

2. Vehicle Configuration and Problem Description

Vehicle configuration of the three-axle electric bus. The overall platform for the researched three-axle electric bus is shown as Figure 1. In Figure 1, l_i are the distances between the axles and the vehicle mass center, it has minus value when the corresponding axle is on the backward of the mass center. B_i are the track widths of the three axles, v_x, v_y, γ are the longitudinal speed, lateral speed and yaw rate of the bus, $\delta_{f,i}$, $\delta_{r,i}$ are the steering angles of the front and rear wheels.

As shown in Figure 1, the four wheels at the middle and rear axles are independently driven by four motors. Meanwhile, to alleviate severe tire wearing caused by kinematic interference between the axles and improve mobility, the electric bus is designed with steerable front and rear axles. The steering of the front axle is directly controlled by the driver's steering wheel input. The steering of the real axle can be independently controlled by the rear steering motor. The steering trapezoid mechanisms of the steering axles are well-designed, which ensures that the geometric steering center locates in the extension line of the middle shaft. The main parameters of the bus paltform is listed in Table 1.

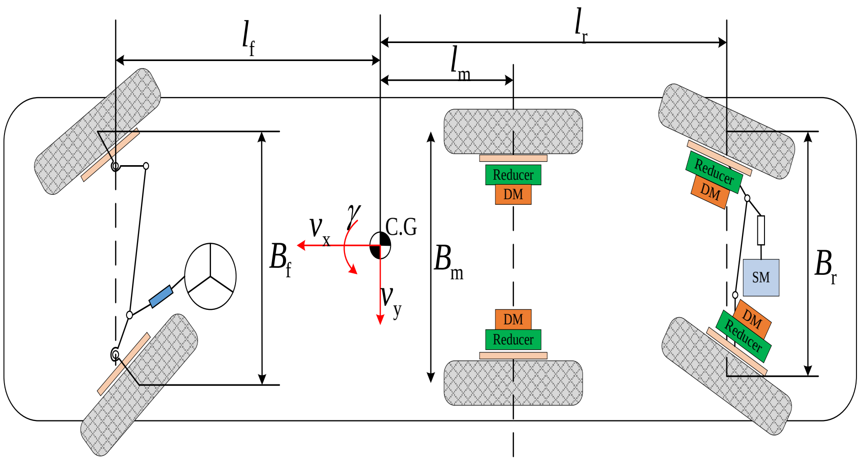

Fig. 1. The overall platform for the researched electric bus

Table 1

Basic parameter of the electric bus

Name	Symbol	Value
Rated loaded mass	m	13000kg
Yaw moment of inertial	I_z	108000kg·m^2
C.G. position parameters	(l_f, l_m, l_r, h_g)	(3.4,-1,-2.1,1.2)m
The track widths	(B_f, B_m, B_r)	(2.15,2.1,2.1)m
Wheel rolling radius	R_w	0.35m

The tire wearing problem of the driving axles. When the multi-axle bus is steering, there may exist inherent kinematic interference, which may cause severe tire wearing. Severe tire wearing is detrimental to the service life and safety of the vehicle, especially for the large loaded buses. Although small side slip angle are needed to provide lateral tire force when steering, large side slip angles caused by inter-axle kinematic interference cause severe tire wearing for multi-axle driving vehicles. For a three-axle electric bus, the problem can be alleviated by designing independently steerable rear axle. As the middle axle are not steerable, the might still be kinematic interference between the middle and rear driving axles. In this paper, the task of the active rear steering controller is to generate proper rear steering angle to coordinate the tire wearing between the middle and rear driving axles.

3.Active rear steering control algorithm

Establishment of the control algorithm. As the geometric steering center locates in the extension line of the middle shaft, the most simple and reliable rear steering strategy is to determine the real steering angle in proportion to the front steering angle according to the static geometrical relationship, shown as equation (1).

$$\delta_r = \arctan\left(\frac{l_r - l_m}{l_f - l_m}\tan\delta_f\right) \tag{1}$$

Obviously, the above control strategy is open-loop, and the dynamic side slip effects of the tires are not considered. The strategy can alleviate the tire wearing to a certain extent, but the tire wearing condition between the two driving axles maybe inharmonious. In this paper, a new strategy based on the estimated side slip angles of the axles is proposed, by which the rear wheel steering angle is controlled dynamically to coordinate the tire wearing of the middle and rear driving axles.

The side slip angles of the driving axles is estimated as:

$$\begin{cases} \hat{\alpha}_{\rm m} = \arctan\left(\dfrac{\hat{v}_{\rm y} + l_{\rm m}\cdot\hat{\gamma}}{\hat{v}_{\rm x}}\right) \\ \hat{\alpha}_{\rm r} = \arctan\left(\dfrac{\hat{v}_{\rm y} + l_{\rm r}\cdot\hat{\gamma}}{\hat{v}_{\rm x}}\right) - \delta_{\rm r} \end{cases} \tag{2}$$

where $\hat{\alpha}_{\rm m}, \hat{\alpha}_{\rm r}$ are the estimated side slip angles of the middle and rear axles respectively.

In this paper, the tire wearing of the driving axles are quantified using the side slip angles of the axles, and weighted by the axle's vertical loads. Meanwhile, the quantified tire wearing of the driving axles are controlled to be equal, according to the equal life design principles. The description is as follow:

$$\left(\hat{F}_{\rm z,m,1} + \hat{F}_{\rm z,m,2}\right)\hat{\alpha}_{\rm m} = \left(\hat{F}_{\rm z,r,1} + \hat{F}_{\rm z,r,2}\right)\hat{\alpha}_{\rm r} \tag{3}$$

where $\hat{F}_{{\rm z},i,j}$ are the estimated vertical loads of the wheels.

Combining equations (2)-(3), the rear wheel steering control strategy is given as:

$$\delta_{\rm r} = \arctan\left(\frac{\hat{v}_{\rm y} + l_{\rm r}\cdot\hat{\gamma}}{\hat{v}_{\rm x}}\right) - \frac{\left(\hat{F}_{\rm z,m,1} + \hat{F}_{\rm z,m,2}\right)}{\left(\hat{F}_{\rm z,r,1} + \hat{F}_{\rm z,r,2}\right)}\arctan\left(\frac{\hat{v}_{\rm y} + l_{\rm m}\cdot\hat{\gamma}}{\hat{v}_{\rm x}}\right) \tag{4}$$

Stability analysis. The rear steering control algorithm in (4) does not directly rely on the front steering angles, but relies on the estimated feedback yaw and lateral motion. It forms a closed-loop control system. Therefore, it is essential to prove the stability of the closed-loop active rear steering algorithm before application. As the tire slip angle and body slip angle are small, the above equation can be linearized as:

$$\delta_{\rm r} = (1-w)\beta + (l_{\rm r} - wl_m)\gamma/v_x \tag{5}$$

where w is the ratio between the vertical loads of the middle and rear axles, β is the vehicle body slip angle.

As the rear steering angle does not rely on the front steering angle, to demonstrate the stability of the rear steering control algorithm, we assume $\delta_{\rm f}$=0. A linear 2DOF single track model is used to descript the dynamic response of the lateral and yaw motion under input of $\delta_{\rm r}$ as follow:

$$\begin{cases} \dot{\beta} = \dfrac{\beta}{mv_{\rm x}}\sum_{i}^{\rm f,m,r} C_i + \left(\dfrac{1}{mv_x^2}\sum_{i}^{\rm f,m,r} C_i l_i - 1\right)\gamma - \dfrac{C_r\delta_r}{mv_{\rm x}} \\ \dot{\gamma} = \dfrac{\beta}{I_z}\sum_{i}^{\rm f,m,r} C_i l_i + \dfrac{\gamma}{I_z v_x}\sum_{i}^{\rm f,m,r} C_i l_i^2 - \dfrac{C_r\delta_r l_r}{I_z} \end{cases} \tag{6}$$

where C_i are the lateral stiffness of the tires at the three axle.

Substitute the control law (5) into (6), the system matrix of the closed-loop control system is:

$$A_{\rm c} = A_0 + BK_{\rm con} \tag{7}$$

where

$$A_0 = \begin{bmatrix} \frac{1}{mv_x}\sum_{i}^{f,m,r} C_i & \frac{1}{mv_x^2}\sum_{i}^{f,m,r} C_i l_i - 1 \\ \frac{1}{I_z}\sum_{i}^{f,m,r} C_i l_i & \frac{1}{I_z v_x}\sum_{i}^{f,m,r} C_i l_i^2 \end{bmatrix}, B = \begin{bmatrix} -\frac{C_r}{mv_x} \\ -\frac{C_r l_r}{I_z} \end{bmatrix}, K_{con} = \begin{bmatrix} 1-w & \frac{(l_r - w l_m)}{v_x} \end{bmatrix} \quad (8)$$

Numerical calculation results show that the eigenvalues of A_c always have negative real part within the whole possible range of v_x and w, which ensures the stability of the closed loop control system. To sum up, equation (4) gives stable active rear steering control law to coordinate the tire wearing between the middle and rear driving wheels.

4. Simulation Results

The simulation platform. To verify the effectiveness of the proposed ARS control algorithm, a simulation platform is established for the three-axle electric bus with four distributed driving wheels and steerable front and rear axles, shown as Figure 3. The rear-axle steering system, the distributed powertrain system, the battery model, the driver model and the controller algorithm model are all established in Simulink, and the bus platform is established in Trucksim software.

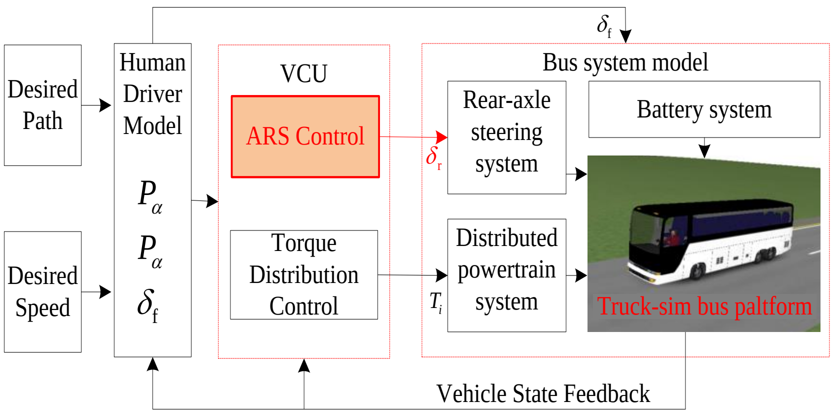

Fig. 2. The simulation platform for ARS control algorithm.

In the vehicle control unit (VCU), a torque distribution controller and an ARS controller are included. As our main task is to test the ARS control algorithms, the driving/braking torque are distributed evenly between the motors for simplicity in our simulation.

Simulation results analysis. A sharp turning test case is particularly designed as shown in Figure 4. Two half-circle road with radius of 10m is connected in opposite direction, and a straight road of length 20m is connected in both ends. The whole road has good adhesion condition and the targeted and initial vehicle velocity is set as 20km/h. The active steering control algorithm in this paper is proposed for coordinating the tire wear between the driving wheels, severe tire wear only happens during sharp turning at low speed on circular road with small radius. The turning radius is very small, the maximum speed for driving through such a road is limited, when the velocity is much higher than 20km/h, the bus will rather rollover or sideslip when turning. When the turning speed is higher, the average sideslip angle of the wheels will be greater. After the lateral tire forces are saturated, the bus tends to rollover (on high adhesion road) or sideslip (on low adhesion road) because of overspeed. In the simulation test, three ASR control methods are compared, including firstly the "No rear steer control", where the rear steering axle is locked, secondly the "Even algorithm", where the rear steering angle is given as equation (1), and lastly the "Proposed algorithm", where the rear steering is controlled as equation (4).

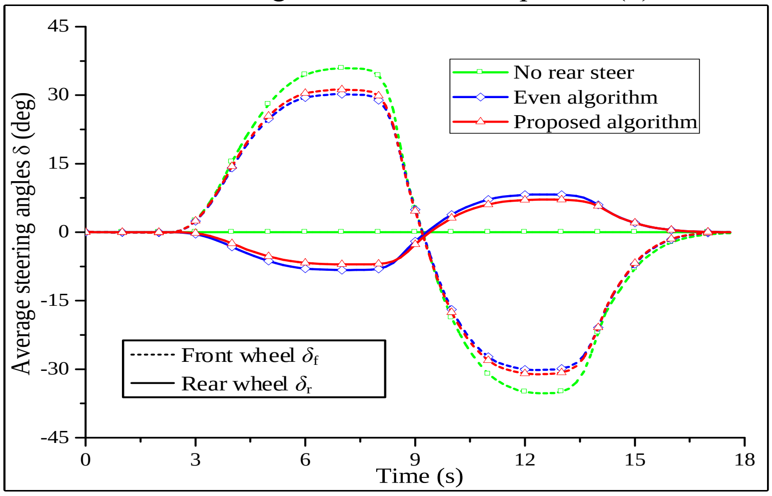

Fig .3. Path tracking results

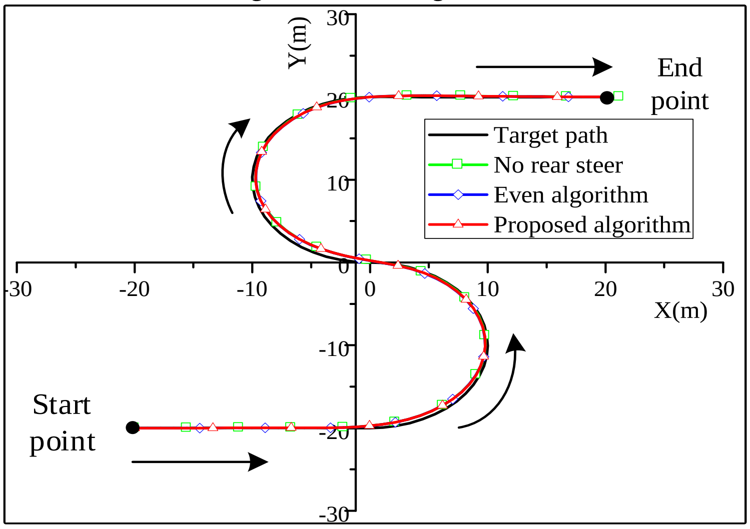

Fig.4. Average steering angles

As shown in Figure 3, the targeted driving path can be well tracked under all these three control methods, which reflects that the electric bus has a minimum steering radius less than 10m under different control method. From Figure 4, we see that the bus need a bigger average front wheel steering angle to follow the targeted path when the “No rear steer” method is used, which is easy to understand as the method amplifies the under-steer trend. The average rear steering angle under the proposed algorithm is relatively bigger than the even algorithm, and the average front steering angle is relatively smaller consequently. The control performance is shown in Figure 5, the solid lines (regardless of color) represent the rear tire, and the dashed lines (regardless of color) represent the middle tire. Different line colors represent the results under three different kind of control methods. It’s shown that when no rear steer is given, although the side slip of the middle tires is not big, the average slip angle of the rear tires is quite large, with a peak value of more than 7deg, which will cause unacceptable tire wearing for the rear tires. When the even algorithm is used, the slip angles of the driving tires are reduced, tire wearing is greatly alleviated, but there are still obvious gap between the slip angles of middle tire and rear tire. The gap is unreasonable and contrary to the equal life design principle, as the vertical load ratio between the middle and rear axles are close to 1 during the driving test. According to the equal tire wearing principle given as equation (4), the average slip angles of the middle and rear tires should be close as their vertical loads do. When the proposed algorithm is used, as shown in Figure 6, the average slip angles of the middle tires and rear tires are controlled to be close, the middle tires and the rear tires has close wearing extent during the whole test. Meanwhile, the great reduction of the tire slip angles achieved by the “Even algorithm” remains.

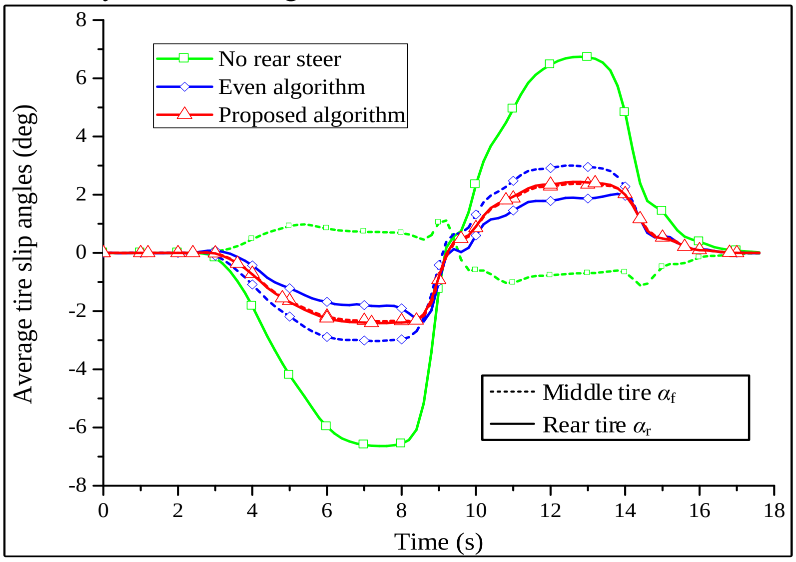

Fig.5. Average tire slip angles

5. Conclusion

Aiming at alleviating the tire wearing between the driving axles, an AFS control algorithm for a novel three-axle electric bus with distributed driving and multi-axle steering system is carried out. The proposed AFS algorithm is proved to have good stability. And the sharp turning test cases shows that the rear wheel steering controller manages to alleviate and coordinate the tire wearing between the middle and rear driving wheels.

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