

In-Situ Steering Dynamics Analysis of Skid Steering for Articulated Motor-Driven Vehicle

Tao Xu, Yanhua Shen, and Wenming Zhang
University of Science and Technology Beijing

ABSTRACT

The traditional hydraulic steering mode in articulated motor-driven vehicle makes the vehicle structure complex. Further more, the forces between the front and rear part of the articulated vehicle could damage the articulated joint body in the process of vehicle steering. However, skid steering mode could make the vehicle steer with the different speed of each wheel, which is flexible without hydraulic steering system. The purpose of this paper is to introduce the principle of skid steering mode in articulated motor-driven vehicle. In this paper, the theory of traditional wheeled vehicle's skid-steering mode and hydraulic steering mode of articulated vehicle are used to establish the in-situ skid-steering kinematic and dynamic model. Based on the model, the vehicle trajectory and the dynamic relationships among the body structure of the vehicle, longitudinal forces, lateral forces of each wheel are described. With these analyses, the kinematic and dynamic simulations are implemented according to the parameters of an underground mine articulated vehicle, which could provide references for the designing and studying of articulated motor-driven vehicle with skid steering mode.

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1. INTRODUCTION

The articulated vehicle is widely used in engineering machinery technology. It can realize the 2WD or 4WD mode for the articulated vehicle with motorized wheels, which is also called articulated motor-driven vehicle. For the 4WD articulated motor-driven vehicle, each wheel is controlled independently. With the analysis of structure feature of the articulated motor-driven vehicle, it can be simplified to three parts, which include the front part of the vehicle, the rear part of the vehicle and the articulated joint body.

The hydraulic steering mode is mainly used in articulated motor-driven vehicle. It could realize the vehicle steering in different working conditions. However, there still exist several problems considering vehicle structure and response time of hydraulic steering system. Firstly, the tire wears seriously because of the slipping of wheel in the process of vehicle steering. [1] Secondly, the steering of the vehicle mainly relies on the hydraulic cylinders and articulated joint body, which the forces in the joint body could not be ignored. [2] Thirdly, the steering angle of the articulated vehicle is generally about 45 degrees that is limited by the structure of hydraulic cylinder. [3] Finally, there still exist the response problems of vehicle steering due to the delay action of the hydraulic steering system.

Comparing with the hydraulic steering mode, skid steering mode use the different speed of each wheel to change the direction of the vehicle since there is no steering device. [4] The vehicle with skid steering mode could implement in-situ steering mode or zero-radius steering mode, which make the vehicle have better steering

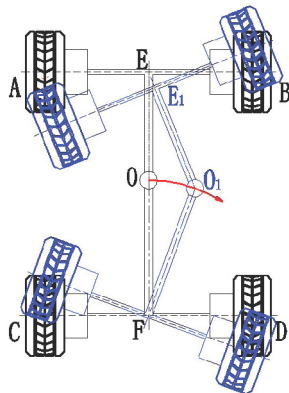
performance and maneuverability. In the process of the vehicle steering, the wheels are in the state of torsional deformation, thus there will be less generation of tire wear. [5] Currently, skid steering mode is mainly used in crawler vehicles, skid steer loaders and some multi-axis vehicles. Yi et al. [4], Maclaurin, [5] Fauroux et al. [6], Ren et al. [7], Michihisa et al. [8] and Fahim et al. [9] used the skid steering mode in different vehicles according to the steering principle. They studied the force characteristics of each wheel in the skid steering process. However, none of these works investigate the skid steering mode in 4WD articulated vehicle that each wheel can be controlled independently.

In this paper, skid steering mode is applied to articulated motor-driven vehicle that the wheels can be controlled independently. The organization of the rest of this paper is as follow. In [section 2](#), the articulated motor-driven vehicle with skid steering mode will be introduced with several assumptions; and a kinematic model of articulated motor-driven vehicle is established to study the motion characteristics of the vehicle. The front part of the vehicle is taken as a research object to discuss the dynamic characteristics of skid steering mode, and investigate the relations among the structure of the vehicle, the force and speed of the wheels in [section 3](#). In [section 4](#), the dynamic and kinematic simulations are implemented according to the structure of an underground mine articulated vehicle with motor-driven wheels to verify the model. The results could provide references for the designing and controlling of skid steering mode in articulated motor-driven vehicle.

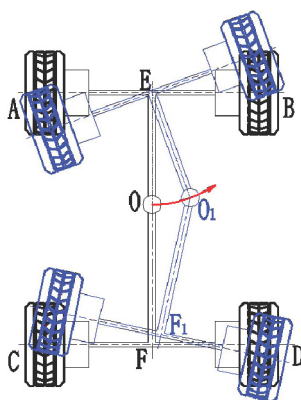
2. IN-SITU STEERING KINEMATIC ANALYSIS OF SKID STEERING FOR ARTICULATED MOTOR-DRIVEN VEHICLE

Skid steering mode is used in the articulated motor-driven vehicle with the purpose of taking the minimum force of articulated joint body. Some rules should be set with several assumptions.

1. The load of the rear part is heavier than the front part of the articulated motor-driven vehicle. The turning center of the vehicle could be made at the center of the rear axle by actively controlling of the rear wheels' speed. (Articulated vehicle with motorized wheels has a virtual axle that is the equivalent of the vehicle axle.) Then, the front wheels speed is controlled based on the motion of articulated joint body, which could make the front part turning with that of the rear part of the vehicle. The steering process is shown in Figure 1(a). This assumption will be an example in the following analysis of the paper
2. The load of the front part is heavier than the rear part of the articulated motor-driven vehicle. The steering process is contrary to the first assumption. The front wheels speed could be actively controlled to make the turning center of the vehicle being at the front axle. The rear wheels speed is passively controlled based on the motion of articulated joint body, which is shown in Figure 1(b).



a. The heavier load is at rear part



b. The heavier load is at front part

Figure 1. In-situ steering process of articulated motor-driven vehicle

The speed of rear wheels is actively controlled when the heavier load is at rear part of the vehicle. The front wheels speed is controlled based on the particular motion trajectory of joint part with the purpose of minimum forces of the articulated joint body. With the analysis above, a kinematic model of articulated vehicle at time t is established in Figure 2.

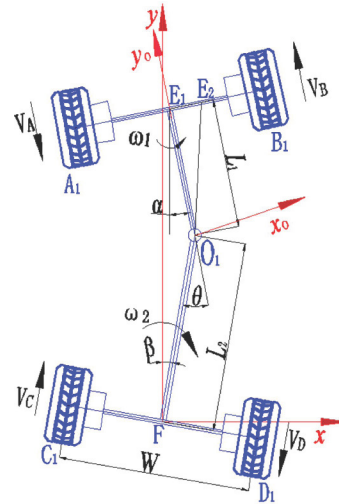


Figure 2. In-situ steering kinematic model of articulated motor-driven vehicle

In Figure 2, a global coordinate system x - F - y is established at the center of rear axle F where the x coordinate is parallel to the rear axle of the vehicle. The y coordinate is perpendicular to the rear axle. A local coordinate system x_0 - O_1 - y_0 is assigned to the front part at the center of articulated joint body O_1 . The positive direction of x_0 is the right direction of the articulated joint body vertical to the front part of the vehicle, and the positive direction of y_0 is the forth direction of the articulated joint body parallel to the front part of the vehicle. In the kinematic mode, A_1 , B_1 , C_1 , D_1 represent left front wheel, right front wheel, rear wheel of right side and left side at time t , respectively. E_2 is the instantaneous steering center of front axle. The speed of the i th wheel (i represent A , B , C or D , which is the same with the following analysis) is V_i . α and β represent steering angle of the front and rear part of the vehicle, respectively. θ is the steering angle of the articulated vehicle. ω_1 and ω_2 are the steering angular velocity of the front and rear part of the vehicle. W is the wheel track. L_1 and L_2 represent the distances from the front axle center and the rear axle center to the articulated joint body, respectively.

2.1. Kinematic Analysis of In-Situ Skid Steering for Rear Part of the Articulated Motor-Driven Vehicle

According to the in-situ skid steering analysis of articulated motor-driven vehicle above, this paper make the speed of rear wheels being v and $-v$ in the in-situ skid steering process, which is shown in equation (1). Thus the turning center of the articulated vehicle could be at the rear axle center F .

$$V_C = -V_D = v$$

(1)

where v is the speed of rear wheels, which is actively controlled related to the steering angular velocity.

The trajectory of the rear wheels and articulated joint body will be a circle which the circle center is at point F in the global coordinate system x - F - y . These trajectories could be obtained by [equation \(2\)](#).

$$\begin{cases} x_1^2 + y_1^2 = (W/2)^2 \\ x_2^2 + y_2^2 = L_2^2 \end{cases} \quad (2)$$

where (x_1, y_1) represent the coordinate of rear wheels C and D , (x_2, y_2) represent the coordinate of articulated joint body O .

The steering angular velocity of rear part of the vehicle ω_2 is as follow:

$$\omega_2 = \frac{d\beta}{dt} = \frac{V_C - V_D}{W} = \frac{2v}{W} \quad (3)$$

Based on [equation \(3\)](#) and structural parameters of the articulated motor-driven vehicle, speed of the articulated joint body at rear part of the vehicle could be given by [equation \(4\)](#).

$$\begin{cases} V_{oxr} = \omega_2 \cdot L_2 \times \cos\theta = \frac{2v}{W} L_2 \cos\theta \\ V_{oyr} = \omega_2 \cdot L_2 \times \sin\theta = \frac{2v}{W} L_2 \sin\theta \end{cases} \quad (4)$$

where V_{oxr} and V_{oyr} are the speed of articulated joint body at rear part of the vehicle in x_0 and y_0 direction of the local coordinate system, respectively.

2.2. Kinematic Analysis of In-Situ Skid Steering for Front Part of the Articulated Motor-Driven Vehicle

For the front part of articulated motor-driven vehicle, the center of the front axle $E(x_3, y_3)$ can be modeled by [equation \(5\)](#) with the coordinate of the point $O(x_2, y_2)$.

$$\begin{cases} x_3 = x_2 - L_1 \sin\alpha \\ y_3 = y_2 + L_1 \cos\alpha \end{cases} \quad (5)$$

Combining the point E and point O , the motion trajectory of point E can be expressed by [equation \(6\)](#).

$$x_3^2 + y_3^2 + 2L_1(x_3 \sin\alpha - y_3 \cos\alpha) = L_2^2 - L_1^2 \quad (6)$$

The speed of the articulated joint body at front part of the vehicle could be given by [equation \(7\)](#) with the speed of front wheels.

$$\begin{cases} V_{oxf} = \frac{V_A - V_B}{W} L_1 \\ V_{oyf} = \frac{V_A + V_B}{2} \end{cases} \quad (7)$$

where V_{oxf} and V_{oyf} are the speed of articulated joint body at front part of the vehicle along x_0 and y_0 direction in the local coordinate system, respectively.

The movements of both the front and rear part of the vehicle should be reasonable to minimize the force of articulated joint body, which means that, the articulated joint body of front and rear part of the vehicle should have the same motion relationships. Thus the speed of the front wheels could be expressed by [equation \(8\)](#) with the analysis of [equation \(7\)](#).

$$\begin{cases} V_A = \frac{2v}{W} L_2 \sin\theta + \frac{vL_2}{L_1} \cos\theta \\ V_B = \frac{2v}{W} L_2 \sin\theta - \frac{vL_2}{L_1} \cos\theta \end{cases} \quad (8)$$

Therefore, the steering angular velocity ω_1 can be given by [equation \(9\)](#).

$$\omega_1 = \frac{d\alpha}{dt} = \frac{V_A - V_B}{W} = \frac{2vL_2}{WL_1} \cos\theta \quad (9)$$

2.3. In-Situ Skid Steering Angle θ of the Articulated Motor-Driven Vehicle

According to the [equations \(3\)](#), (9) and the relations among angle θ , α and β , the steering angle of the articulated motor-driven vehicle is determined as:

$$\theta = \int_0^t (\omega_1 + \omega_2) dt = \int_0^t \left(\frac{2vL_2}{WL_1} \cos\theta + \frac{2v}{W} \right) dt \quad (10)$$

Integrating the [equation \(10\)](#), the steering angle θ could be simplified to [equation \(11\)](#).

$$\theta = 2 \cdot \arctan\left(\frac{C-1}{C+1} \cdot B\right) \quad (11)$$

where C and B are constant and their value are: