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The optimal direct yaw-moment control of the four-wheel steering tractor-semitrailer

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ABSTRACT

Considering the Gim tire model, the nonlinear four-wheel steering tractor-semitrailer dynamic model was set up to analyse the lateral stability of the tractor-semitrailer. An optimal direct yaw-moment controller of the four-wheel steering tractor-semitrailer was developed based on model following technique and the optimal control theory. Simulation on the nonlinear four-wheel steering tractor-semitrailer dynamic model in Matlab/Simulink software environment was described. The Simulation results show that the four-wheel steering direct yaw-moment control tractor-semitrailer have the most appropriate handling stability compared with the front wheel steering tractor-semitrailer, the front wheel steering direct yaw-moment control tractor-semitrailer, and the four-wheel steering tractor-semitrailer.

KEYWORDS

Four-wheel steering; Handling stability; Direct yaw-moment control; Gim tire model; Optimal control.

INTRODUCTION

Tractor-semitrailer, has become one of the most important road transport, because of high transport efficiency, low fuel consumption, and door-to-door transportation. Tractor-semitrailer which includes a tractor and a semitrailer has different handling and stability properties compared with the passenger cars. The lateral instability (trailer swing, jack-knifing, rollover) of the tractor-semitrailer has caused more and more accidents. For the passenger car, DYC and 4WS can effectively improve handling and stability performances[1-4]. In recent years, more and more researchers focus on DYC and 4WS of the tractor-semitrailer, and have considerable achievements[5-8]. In the future, DYC and 4WS will be widely used in the tractor-semitrailer, because DYC and 4WS can make a driver handle the tractor-semitrailer more stable. However, for the tractor-semitrailer, most studies independently verified the validity of four-wheel steering or direct yaw moment control based on the linear model, and the study of four-wheel steering direct yaw moment control based on the nonlinear model is little.

In this paper, a nonlinear tractor-semitrailer dynamic model was built based on Gim tire model, and four-wheel steering direct yaw moment controller was designed.

NONLINEA 4WS TRACTOR-SEMITRAILER DYNAMIC MODEL

Vehicle model

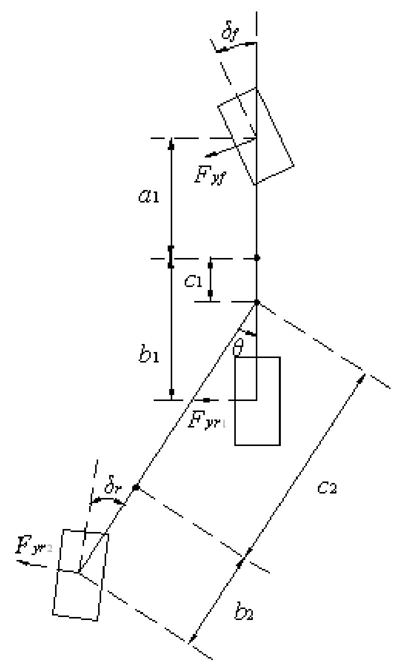


Figure 1 : Schematic diagram of 4WS tractor-semitrailer

The single-body 4WS tractor-semitrailer model is shown in Figure 1. The motions can be described respectively as follow:

$$m_1 u(\dot{\beta}_1 + r_1) = F_{yf} + F_{yr1} + F_y \quad (1)$$

$$I_{Z1}\dot{r}_1 = a_1 F_{yf} - b_1 F_{yr1} - c_1 F_y \quad (2)$$

$$m_2 u(\dot{\beta}_2 + r_2) = F_{yr2} - F_y \quad (3)$$

$$I_{Z2}\dot{r}_2 = -b_2 F_{yr2} - c_2 F_y \quad (4)$$

Where, m_1 and m_2 stand for the mass of tractor and semitrailer respectively; r_1 and r_2 stand for the yaw rate of tractor and semitrailer respectively; β_1 and β_2 stand for the slip angle of tractor and semitrailer respectively; I_{z1} and I_{z2} are the moments of inertia of tractor and the semitrailer, respectively; F_{yf} , F_{yr1} and F_{yr2} are the lateral forces produced by each of the front and rear tires, respectively; For the tractor, a_1 and b_1 and c_1 are the distances from the center of gravity to the front and rear axle and hinge point, respectively; For the semitrailer, b_2 and c_2 are the distances from the center of gravity to the rear axle and hinge point.

Gim tire model

The Gim tire model was used here. The tire forces can be formulated as follow[9]:

$$\begin{cases} F_x = C_s s_s l_n^{\ 2} + \mu_x F_z (1 - 3l_n^{\ 2} + 2l_n^{\ 3}) & s_s < s_{sc} \\ F_x = \mu_x F_z & s_s \geq s_{sc} \end{cases} \tag{5}$$

$$\begin{cases} F_y = C_\alpha s_\alpha l_n^{\ 2} + \mu_y F_z (1 - 3l_n^{\ 2} + 2l_n^{\ 3}) & s_\alpha < s_{\alpha c} \\ F_y = \mu_y F_z & s_\alpha \geq s_{\alpha c} \end{cases} \tag{6}$$

Where, μ_x and μ_y are the longitudinal and transverse adhesion coefficients respectively; l_n is the dimensionless value of the tire ground wire length; C_s and C_α are the tire longitudinal and transverse stiffness respectively; s_s and s_α are the vertical and lateral slip rate respectively; s_{sc} and $s_{\alpha c}$ are the tire lateral and longitudinal critical slip ratio respectively; F_z is wheel normal load.

4WS Design

To achieve zero slip angle of steady steering, front wheel and rear wheel angle of the tractor can be defined as follow[3]:

$$\xi = \frac{\delta_{r1}}{\delta_f} = \frac{-b_1 + [\dfrac{ma_1}{c_{r1}(a_1 + b_1)}]u^2}{a_1 + [\dfrac{mb_1}{c_f(a_1 + b_1)}]u^2} \tag{7}$$

REFERENCE MODEL

Considering the linear tire and taking the front steering angle δ_f and corrective yaw moment M as the inputs, the tractor slip angle β_1, tractor yaw rate r_1, semitrailer yaw rate r_2 and tractor and semitrailer center line angle θ as the state variables, combining the equations (1)-(4), the state response can be written as:

$$A_{ac}\dot{X}_{ac} = B_{ac}X_{ac} + C_{ac1}U_1 + C_{ac2}U_2 \tag{8}$$

Where,

$$X_{ac} = \begin{bmatrix}\beta_1 & r_1 & r_2 & \theta\end{bmatrix}^T, \quad U_1 = \begin{bmatrix}\delta_f\end{bmatrix}, \quad U_2 = \begin{bmatrix}M\end{bmatrix}, \quad C_{ac1} = \begin{bmatrix}-C_f & -C_f a_1 & 0 & 0\end{bmatrix}^T, \quad C_{ac2} = \begin{bmatrix}0 & 1 & I_{z2}/I_{z1} & 0\end{bmatrix}^T$$

$$A_{ac} = \begin{bmatrix} (m_1+m_2)u & -m_2c_1 & -m_2c_2 & 0 \\ -m_2uc_1 & Iz_1 + m_2c_1^{\ 2} & m_2c_1c_2 & 0 \\ -m_2uc_2 & m_2c_1c_2 & Iz_2 + m_2c_2^{\ 2} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad B_{ac} = \begin{bmatrix} b_{11} & b_{12} & b_{13} & C_{r2} \\ b_{21} & b_{22} & b_{23} & -C_{r2}c_1 \\ b_{31} & b_{32} & b_{33} & -C_{r2}(b_2 + c_2) \\ 0 & 1 & -1 & 0 \end{bmatrix}$$

$$b_{11} = C_f + C_{r1} + C_{r2},$$

$$b_{12} = \frac{C_f a_1 - C_{r1}b_1 - C_{r2}c_1}{u} - m_1 u$$

$b_{13} = \dfrac{-C_{r2}(b_2 + c_2)}{u} - m_2 u$, $b_{21} = C_f a_1 - C_{r1} b_1 - C_{r2} c_1$

$b_{22} = \dfrac{C_f a_1^2 + C_{r1} b_1^2 + C_{r2} c_1^2}{u} + m_2 u c_1$, $b_{23} = \dfrac{C_{r2}(b_2 + c_2) c_1}{u}$

$b_{31} = -C_{r2} b_2 - C_{r2} c_2$, $b_{32} = \dfrac{C_{r2} c_1 b_2 + C_{r2} c_1 c_2}{u} + m_2 u c_2$, $b_{33} = \dfrac{C_{r2}(b_2 + c_2)^2}{u}$

In the above equations, C_f and C_{r1} are the front and rear tire cornering stiffness of tractor respectively; C_{r2} is the tire cornering stiffness of semitrailer; α_f and α_{r1} is the front and rear tire slip angle of tractor respectively; α_{r2} is the tire slip angle of semitrailer; θ is the tractor and semitrailer center line angle.

OPTIMAL CONTROLLER

Figure 2 Represents the principle of the optimal controller.

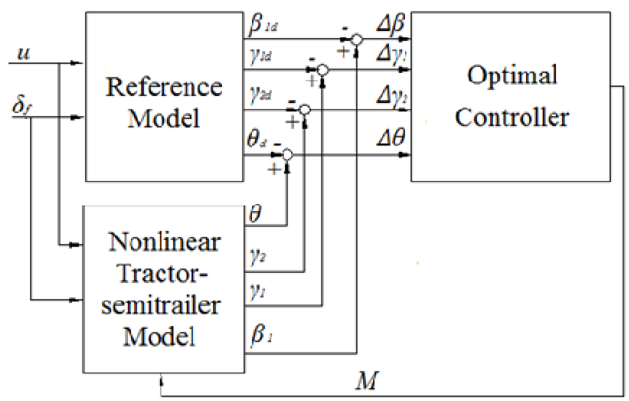


Figure 2 : Schematic diagram of the optimal controller principle

Taking the reference state variables, the reference vehicle model state response can be written as:

$$A_d \dot{X}_d = B_d X_d + C_d U_1 \tag{9}$$

where, $A_d = A_{ac}$; $B_d = B_{ac}$; $C_d = \begin{bmatrix} -C_f & -C_f a_1 & 0 & 0 \end{bmatrix}^T$ 。

To track the reference vehicle model, let $X = \begin{bmatrix} \Delta\beta & \Delta\gamma_1 & \Delta\gamma_2 & \Delta\theta \end{bmatrix}^T = X_{ac} - X_d$, we can get:

$$A_{ac} \dot{X} = B_{ac} X + C_{ac2} U_2 \tag{10}$$

The quadratic cost function associated with system (17) can be defined as:

$$J = \int_0^\infty \left(X^T Q X + u^T R u \right) dt \tag{11}$$

By solving the riccati equation, we can get the optimal control law is:

$$u = -KX = -R^{-1} A_{ac}^{-1} B_{ac}^{\ T} P X \tag{12}$$

Where, $Q \rangle 0$, $R \rangle 0$, P is definite constant matrix.

RESULT AND DISSCUSS

The major parameters are as follows:

m_1=6870 Kg ; m_2=6181 Kg ; I_{Z1}=20441 $Kg \cdot m^2$; I_{Z2}=81912 $Kg \cdot m^2$; a_1=1.96 m ;

$c_{\alpha r1}$=143.33 kN/rad ; $c_{\alpha r2}$=80.312 kN/rad ; $c_{\alpha f}$=143.33 kN/rad ; b_1=2.35 m ; b_2= 3.30 m ; c_1= 2.05 m ; c_2=5.23 m .

The tractor-semitrailer speed is 30 m/s. The maximum amplitudes of the sinusoidal input in Figure 3 are 0.058rad. The simulation time is 10s.

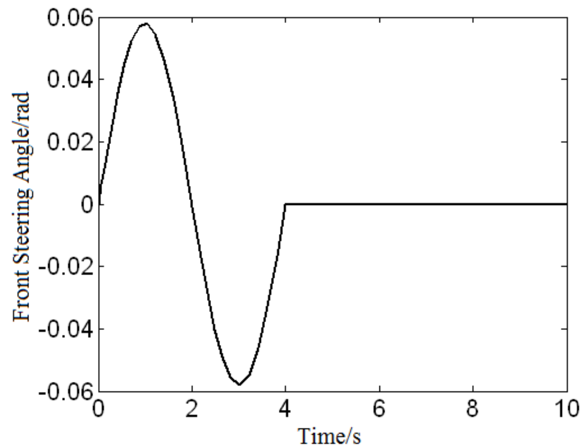
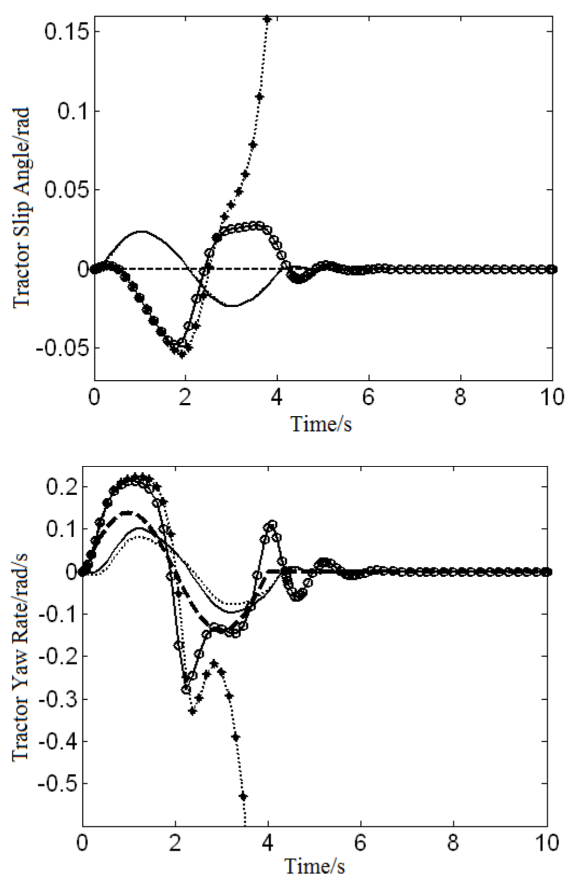


Figure 3 : The input of front steering angle



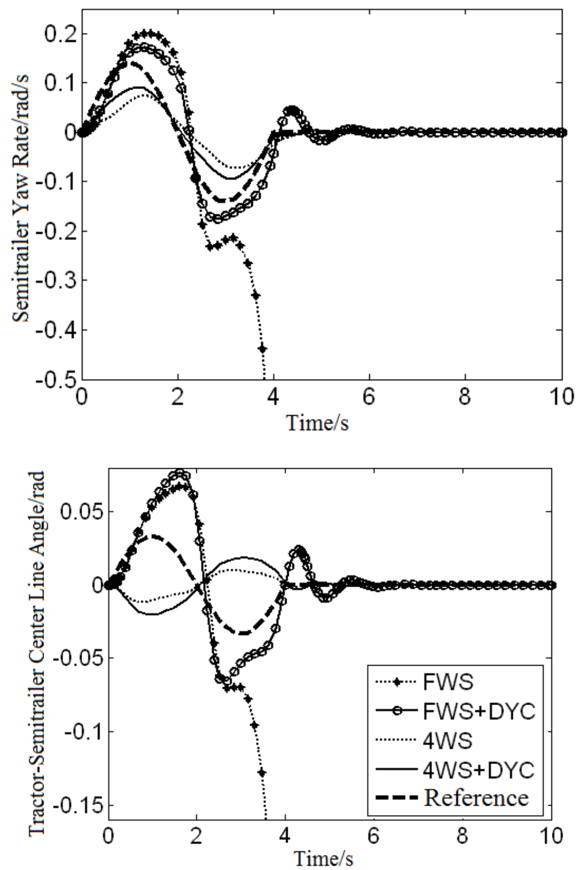


Figure 4 : Responses of the tractor slip angle, tractor yaw rate, semitrailer yaw rate and tractor and semitrailer center line angle

The simulation results show that when the maximum amplitudes of the sinusoidal input is 0.058rad, uncontrolled vehicle loses stability about 3s, at this time the tractor slip angle, tractor yaw rate, semitrailer yaw rate and tractor and semitrailer center line angle increase sharply. The other three are able to maintain stable. For direct yaw moment control vehicle, the tractor slip angle is bigger than the other two, and the direction of the tractor slip angle is opposite to the traveling direction, at the same time, the amplitude of tractor yaw rate, semitrailer yaw rate and tractor and semitrailer center line angle changes bigger than the other two. For 4WS and 4WS direct yaw moment control vehicle, the direction of the tractor slip angle is the same as the traveling direction, and the responses of 4WS direct yaw moment control vehicle are bigger than 4WS, which can improve the handling stability effectively.

CONCLUSIONS

In this paper, Gim tire model was adopted to set up the nonlinear four-wheel steering dynamic model of tractor-semitrailer, then a four-wheel steering with direct yaw-moment control scheme was proposed. Based on the established dynamic model, simulations in Matlab/Simulink software environment were described. The simulation results suggest the four-wheel steering direct yaw-moment control tractor-semitrailer can improve handling and stability performance effectively, which makes the driver drive the vehicle normally.

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