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Study on the influence of the arrangement of battery pack on the steering characteristics of electric vehicles

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1. Introduction

With the development of automobile industry in China, people pay more attention to electric vehicles. The safe operation of the vehicle is related with the stability. The lateral stability of the electric vehicles is relevant with the steering characteristic. Though influenced by four tires' cornering stiffness and the suspension characteristics, the steering characteristic mainly depends on the longitudinal position of the center of gravity. The steering characteristic of electric vehicles has a great effect on steering control. The steering characteristic of electric vehicles has great influence on the ride comfort and the service life of the tire [1] as well. The study of steering characteristics mainly focused on the influence of the wheels [2-3], suspension structure [4], suspension system [5] and the control system and steering characteristics of four-wheel steering vehicles [6]. Because the battery pack is very heavy, the position of the battery pack directly influence the location of the center of gravity of the vehicle [7], and then affecting its steering characteristic greatly. Therefore, electric vehicles' steering characteristic depends on the position of battery pack so much.

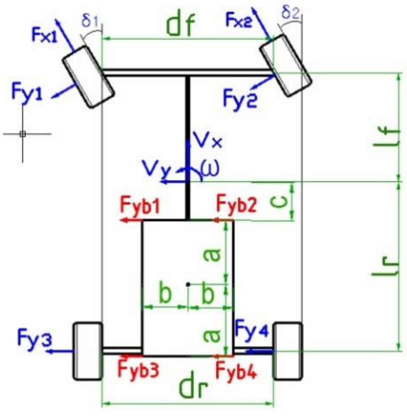

Fig. 1 Dynamics model-top view

2. Vehicle dynamics model

2.1. Force and parameter definition

The simulation is a main way to study the steering characteristic of vehicles, to begin with, establishing the dynamics model to meet the study requirements [8]. The top view is shown in Fig. 1. Isometric diagram is shown in Fig. 2. And isometric diagram of battery pack model is shown in Fig. 3.

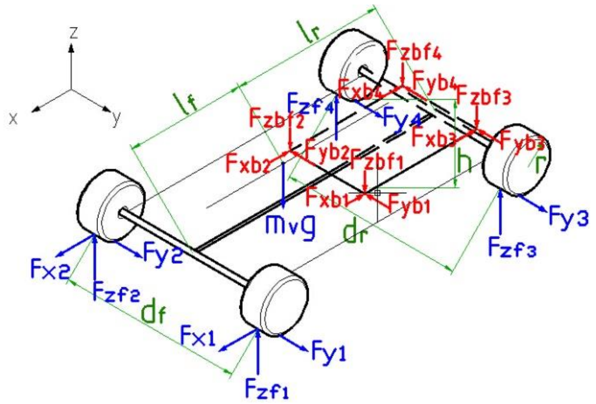

Fig. 2 Dynamics model (without battery pack)-isometric diagram

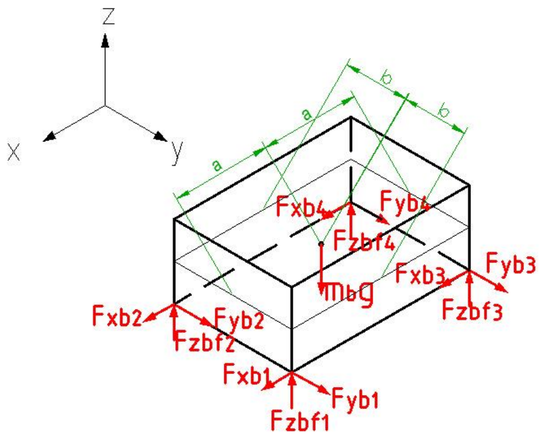

Fig. 3 Battery pack model-isometric diagram

2.2. Establish dynamics differential equation

According to D'Alembert principle, analyzing the forces of dynamics model, and then we can get the dynamics differential equation of the electric vehicle:

$$m_v\left(\dot{v}_x - v_y\omega\right) = F_{x1}\cos\delta_1 + F_{x2}\cos\delta_2 - F_{y1}\sin\delta_1 - \\ -F_{y2}\sin\delta_2 - F_{xb1} - F_{xb2} - F_{xb3} - F_{xb4}. \quad (1)$$

The equation of lateral motion of the vehicle:

$$m_v\left(\dot{v}_y - v_x\omega\right) = F_{y3} + F_{y4} + F_{x1}\sin\delta_1 + F_{x2}\sin\delta_2 + \\ +F_{y1}\cos\delta_1 + F_{y2}\cos\delta_2 - F_{yb1} - F_{yb2} - F_{yb3} - F_{yb4}. \quad (2)$$

Table 1

Symbols in dynamics equation of the electric vehicle dynamics model

Physical quantities	Symbol	Units	Physical quantities	Symbol	Units
Longitudinal force of the left front wheel	F_{x1}	N	Width of the battery pack	$2b$	m
Longitudinal force of the right front wheel	F_{x2}	N	Distance between the front edge of the battery pack and the center of gravity	c	m
Lateral force of the left front wheel	F_{y1}	N	Mass of the battery pack	m_b	kg
Lateral force of the right front wheel	F_{y2}	N	The battery pack's moment of inertia of the Z axis	I_{zb}	kg·m2
Lateral force of the left rear wheel	F_{y3}	N	Longitudinal velocity component of the left front wheel in the body coordinate	v_{x1}	m/s
Lateral force of the right rear wheel	F_{y4}	N	Longitudinal velocity component of the right front wheel in the body coordinate	v_{x2}	m/s
Inside front-wheel side-slip angle	δ_1	rad	Longitudinal velocity component of the left rear wheel in the body coordinate	v_{x3}	m/s
Outside front-wheel side-slip angle	δ_2	rad	Longitudinal velocity component of the right rear wheel in the body coordinate	v_{x4}	m/s
Distance between front axle and the center of gravity	l_f		Lateral velocity component of the left front wheel in the body coordinate	v_{y1}	m/s
Distance between rear axle and the center of gravity	l_r	m	Lateral velocity component of the right front wheel in the body coordinate	v_{y2}	m/s
Vehicle speed	V	m/s	Lateral velocity component of the left rear wheel in the body coordinate	v_{y3}	m/s
Longitudinal speed	v_x	m/s	Lateral velocity component of the right rear wheel in the body coordinate	v_{y4}	m/s
Lateral speed	v_y	m/s	The side slip angle of left front tire	α_{f1}	rad
Moment of inertia of the Z axis	I_z	kg·m^2	The side slip angle of right front tire	α_{f2}	rad
Front tread	d_f	m	The side slip angle of left rear tire	α_{f3}	rad
Rear tread	d_r	m	The side slip angle of right rear tire	α_{f4}	rad
Longitudinal force 1 of the battery pack on the frame(counterforce)	F_{xb1}	N	Vertical load of left front wheel	F_{zf1}	N
Longitudinal force 2 of the battery pack on the frame(counterforce)	F_{xb2}	N	Vertical load of right front wheel	F_{zf2}	N
Longitudinal force 3 of the battery pack on the frame(counterforce)	F_{xb3}	N	Vertical load of left rear 0wheel	F_{zf3}	N
Longitudinal force 4 of the battery pack on the frame(counterforce)	F_{xb4}	N	Vertical load of right rear wheel	F_{zf4}	N
Lateral force 1 of the battery pack on the frame(counterforce)	F_{yb1}	N	Longitudinal acceleration of the vehicle	a_x	m/s2
Lateral force 2 of the battery pack on the frame(counterforce)	F_{yb2}	N	Lateral acceleration of the vehicle	a_y	m/s2
Lateral force 3 of the battery pack on the frame(counterforce)	F_{yb3}	N	Distance between the center of gravity and ground	h	m
Lateral force 4 of the battery pack on the frame(counterforce)	F_{yb4}	N	Cornering stiffness of left front wheel	k_1	N/rad
Normal force 1 of the battery pack on the frame(counterforce)	F_{zb1}	N	Cornering stiffness of right front wheel	k_2	N/rad
Normal force 2 of the battery pack on the frame(counterforce)	F_{zb2}	N	Cornering stiffness of left rear wheel	k_3	N/rad
Normal force 3 of the battery pack on the frame(counterforce)	F_{zb3}	N	Cornering stiffness of right rear wheel	k_4	N/rad
Normal force 4 of the battery pack on the frame(counterforce)	F_{zb4}	N	Radius of wheel	r	m
Mass （without battery pack）	m_v	kg	Engine torque	T_{tq}	N·m
Yaw rate	ω	rad/s	Transmission ratio	i_g	
Sideslip angle	β	rad	Main reducing gear ratio	i_0	
Length of the battery pack	$2a$	m	Transmission efficiency	η_T	

The equation of yaw motion of the vehicle:

$$I_Z\dot{\omega} = 1_f\left(F_{y1}\cos\delta_1 + F_{y1}\cos\delta_2 + F_{x1}\sin\delta_1 + F_{x2}\sin\delta_2\right) + \frac{d_f}{2}\left(-F_{x1}\cos\delta_1 + F_{y1}\sin\delta_1 + F_{x2}\cos\delta_2 - F_{y2}\sin\delta_2\right) -$$

$$-l_r\left(F_{y3} + F_{y4}\right) + \left(F_{xb1} + F_{xb3} - F_{xb2} - F_{xb4}\right)b + \left(F_{yb1} + F_{yb2}\right)c + \left(F_{yb3} + F_{yb4}\right)\left(c + 2a\right). \tag{3}$$

The equation of longitudinal motion of the battery pack:

$$m_b\left(\dot{v}_x - v_y\omega\right) = F_{xb1} + F_{xb2} + F_{xb3} + F_{xb4}. \tag{4}$$

The equation of lateral motion of the battery pack:

$$m_b\left(\dot{v}_y + v_x\omega\right) = F_{yb1} + F_{yb2} + F_{yb3} + F_{yb4}. \tag{5}$$

The equation of yaw motion of the battery pack:

$$I_{zb}\dot{\omega} = a\left(F_{yb1} + F_{yb2} - F_{yb3} - F_{yb4}\right) +$$

$$+b\left(F_{xb2} - F_{xb1} + F_{xb4} - F_{xb3}\right). \tag{6}$$

Resolving the speed in the direction parallel to the body coordinate system, and then we can get:

$$v_{x1} = v_x - \frac{d_f}{2}\omega;\ v_{y1} = v_y + l_f\omega; \tag{7}$$

$$v_{x2} = v_x + \frac{d_f}{2}\omega;\ v_{y2} = v_y + l_f\omega; \tag{8}$$

$$v_{x3} = v_x - \frac{d_r}{2}\omega;\ v_{y3} = v_y - l_r\omega; \tag{9}$$

$$v_{x4} = v_x + \frac{d_r}{2}\omega;\ v_{y4} = v_y - l_r\omega. \tag{10}$$

The side slip angle of each tire:

$$\alpha_{f1} = \tan^{-1}\left(\frac{v_{y1}}{v_{x1}}\right) - \delta_1 = \tan^{-1}\left(\frac{v_y + l_f\omega}{v_x - \frac{d_f}{2}\omega}\right) - \delta_1; \tag{11}$$

$$\alpha_{f2} = \tan^{-1}\left(\frac{v_{y2}}{v_{x2}}\right) - \delta_2 = \tan^{-1}\left(\frac{v_y + l_f\omega}{v_x + \frac{d_f}{2}\omega}\right) - \delta_2; \tag{12}$$

$$\alpha_{f3} = \tan^{-1}\left(\frac{v_{y3}}{v_{x3}}\right) = \tan^{-1}\left(\frac{v_y - l_r\omega}{v_x - \frac{d_r}{2}\omega}\right); \tag{13}$$

$$\alpha_{f4} = \tan^{-1}\left(\frac{v_{y4}}{v_{x4}}\right) = \tan^{-1}\left(\frac{v_y - l_r\omega}{v_x + \frac{d_r}{2}\omega}\right). \tag{14}$$

Considering the lateral load transfer and longitudinal acceleration, we can get vertical load of each wheel:

$$F_{zf1} = \frac{l_r}{2\left(l_f + l_r\right)}m_v g - \frac{h}{2\left(l_f + l_r\right)}m_v a_x - \frac{hl_r}{d\left(l_f + l_r\right)}m_v a_y; \tag{15}$$

$$F_{zf2} = \frac{l_r}{2\left(l_f + l_r\right)}m_v g - \frac{h}{2\left(l_f + l_r\right)}m_v a_x + \frac{hl_r}{d\left(l_f + l_r\right)}m_v a_y; \tag{16}$$

$$F_{zf3} = \frac{l_f}{2\left(l_f + l_r\right)}m_v g + \frac{h}{2\left(l_f + l_r\right)}m_v a_x - \frac{hl_f}{d\left(l_f + l_r\right)}m_v a_y; \tag{17}$$

$$F_{zf4} = \frac{l_f}{2\left(l_f + l_r\right)}m_v g + \frac{h}{2\left(l_f + l_r\right)}m_v a_x + \frac{hl_f}{d\left(l_f + l_r\right)}m_v a_y. \tag{18}$$

Ground reaction force to each wheel:

$$F_{y1} = k_1\alpha_{f1}; \tag{19}$$

$$F_{y2} = k_2\alpha_{f2}; \tag{20}$$

$$F_{y3} = k_3\alpha_{f3}; \tag{21}$$

$$F_{y4} = k_4\alpha_{f4}. \tag{22}$$

The expression of side slip angle β of the electric vehicle is $\tan^{-1}\frac{v_y}{v_x}$, normally, $|v_x|>>|v_y|$, so $|\beta| << 1$, when the vehicle drive uniformly, $v = \sqrt{v_x^2 + v_y^2} = constant$, then:

$$v_x = v\cos\beta \approx v;\ v_y = v\sin\beta \approx v\beta; \tag{23}$$

$$\dot{v}_x = -v\sin\beta\dot{\beta} \approx -v\beta\dot{\beta};\ \dot{v}_y = v\cos\beta\dot{\beta} \approx v\dot{\beta}. \tag{24}$$

So along X and Y axis, accelerations of the electric vehicle are:

$$a_x = \left(\dot{v}_x - v_y\omega\right) = \left(-v\beta\dot{\beta} - v\beta\omega\right) = -v\beta\left(\dot{\beta} + \omega\right); \quad (25)$$

$$a_y = \left(\dot{v}_y + v_x\omega\right) = \left(v\dot{\beta} + v\omega\right) = v\left(\dot{\beta} + \omega\right). \quad (26)$$

Because the side slip angle β is very small, we can consider the center of mass acceleration is perpendicular to the direction of the speed, about $v\left(\dot{\beta} + \omega\right)$. Because β is very small, the vehicle's speed and the longitudinal X axis direction are basically identical. At the same time, the acceleration and lateral Y axis direction are basically identical too.

Lateral speed produce the side slip angle in the location of the center of gravity, and then yaw movement produce side slip angle on the wheel too. The longitudinal velocity of each wheel is much larger than lateral velocity, what's more, because of $\left|\frac{l_f}{v}\right|\left|\frac{l_r}{v}\right|\left|\frac{d_f\omega}{2v}\right|\left|\frac{d_r\omega}{2v}\right| << 1$, the above formulas can be simplified and we can get the side slip of each wheel:

$$\alpha_{f1} = tan^{-1}\left(\frac{v_{y1}}{v_{x1}}\right) - \delta_1 = tan^{-1}\left(\frac{v_y + l_f\omega}{v_x - \frac{d_f}{2}\omega}\right) - \delta_1 = \frac{v\beta + l_f\omega}{v - \frac{d_f}{2}\omega} - \delta_1 \approx \beta + \frac{l_f\omega}{v} - \delta_1; \quad (27)$$

$$\alpha_{f2} = tan^{-1}\left(\frac{v_{y2}}{v_{x2}}\right) - \delta_2 = tan^{-1}\left(\frac{v_y + l_f\omega}{v_x + \frac{d_f}{2}\omega}\right) - \delta_2 = \frac{v\beta + l_f\omega}{v + \frac{d_f}{2}\omega} - \delta_2 \approx \beta + \frac{l_f\omega}{v} - \delta_2; \quad (28)$$

$$\alpha_{f3} = tan^{-1}\left(\frac{v_{y3}}{v_{x3}}\right) = tan^{-1}\left(\frac{v_y \text{ - } l_r\omega}{v_x - \frac{d_f}{2}\omega}\right) = \frac{v\beta - l_r\omega}{v - \frac{d_f}{2}\omega} \approx \beta - \frac{l_r\omega}{v}; \quad (29)$$

$$\alpha_{f4} = tan^{-1}\left(\frac{v_{y4}}{v_{x4}}\right) = tan^{-1}\left(\frac{v_y \text{ - } l_r\omega}{v_x + \frac{d_r}{2}\omega}\right) = \frac{v\beta - l_r\omega}{v + \frac{d_r}{2}\omega} \approx \beta - \frac{lr\omega}{v}. \quad (30)$$

The longitudinal forces can be gotten by two front wheels:

$$F_{x1} = F_{x2} = \frac{T_{tq}i_g i_0\eta_T}{2r}. \quad (31)$$

And then we can get three degrees of freedom for movement differential equations of the electric vehicle.

The equation of longitudinal motion of the vehicle:

$$\text{-}m_v v\beta\left(\dot{\beta} + \omega\right) = -\left(k_1\delta_1 + k_2\delta_2\right)\beta - \left(k_1\delta_1\frac{l_f}{v} + k_2\delta_2\frac{l_f}{v}\right)\omega + \frac{T_{tq}i_g i_0\eta_T}{r} + k_1\delta_1^2 + k_2\delta_2^2 - F_{xb1} - F_{xb2} - F_{xb3} - F_{xb4}. \quad (32)$$

The equation of lateral motion of the vehicle:

$$m_v v\left(\dot{\beta} + \omega\right) = \left(k_1 + k_2 + k_3 + k_4\right)\beta + \left(k_1\frac{l_f}{v} + k_2\frac{l_f}{v} - k_3\frac{l_r}{v} - k_4\frac{l_r}{v}\right)\omega +$$

$$+\frac{T_{tq}i_g i_0\eta_T}{2r}\delta_1 + \frac{T_{tq}i_g i_0\eta_T}{2r}\delta_2 \text{-} k_1\delta_1 \text{-} k_2\delta_2 - F_{yb1} - F_{yb2} - F_{yb3} - F_{yxb4}. \quad (33)$$

The equation of yaw motion of the vehicle:

$$\left[l_f\left(k_1 + k_2\right) + \frac{d_f}{2}\left(k_1\delta_1 - k_2\delta_2\right) - l_r\left(k_3 + k_4\right)\right]\beta + \frac{2\left(k_1 + k_2\right)l_f^2 + 2\left(k_3 + k_4\right)l_r^2 + \left(k_1\delta_1 - k_2\delta_2\right)l_f d_f}{2v}\omega -$$

$$-l_f\left(k_1\delta_1 + k_2\delta_2 \text{ - } \frac{T_{tq}i_g i_0\eta_T}{2r}\delta_1 \text{ - } \frac{T_{tq}i_g i_0\eta_T}{2r}\delta_2\right) - \frac{d_f}{2}\left(\frac{T_{tq}i_g i_0\eta_T}{2r} + k_1\delta_1^2 \text{ - } \frac{T_{tq}i_g i_0\eta_T}{2r} - k_2\delta_2^2\right) + \quad (34)$$

$$+\left(F_{xb1} + F_{xb3} - F_{xb2} - F_{xb4}\right)b + \left(F_{yb1} + F_{yb2}\right)c + \left(F_{yb3} + F_{yb4}\right)\left(c + 2a\right) = I_z\dot{\omega}.$$

3. Simulation

Matlab/Simulink used to solve mathematical model, as shown below [9].

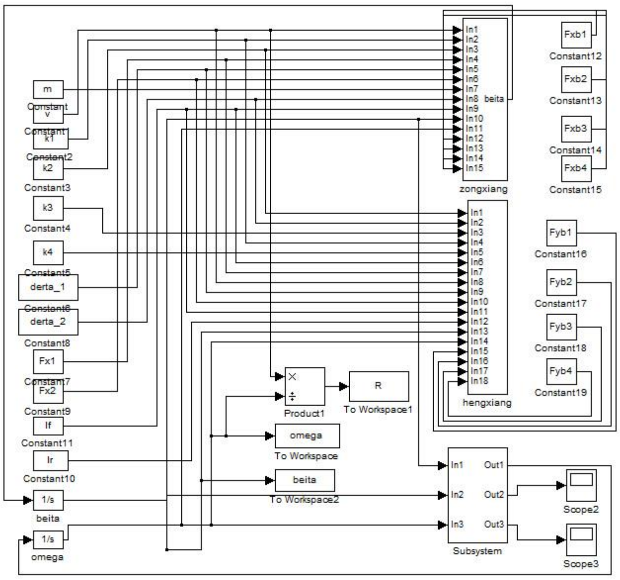

Fig. 4 Simulation model of steering characteristic of the electric vehicle

Table 2

The parameters of the electric vehicle

Name	Parameter
Electric vehicle’s length*width*height, mm	4550*1700*1660
The whole mass (except the battery pack) m_v, kg	1800
The mass of battery pack m_b, kg	300
Battery pack’s length*width*height, mm	890*600*360
Front tread d_f, mm	1414
Rear tread d_r, mm	1422
Radius of wheel r, mm	367
Distance between front axle and the center of gravity l_f, mm	1154
Distance between rear axle and the center of gravity l_r, mm	1394
Moment of inertia of the Z axis I_Z, kg·m^2	5000
Moment of inertia of the Y axis I_Y, kg·m^2	867
Moment of inertia of the Z axis I_X, kg·m^2	6210
Cornering stiffness of left front wheel k_1, N/rad	-50000
Cornering stiffness of right front wheel k_2, N/rad	-50000
Cornering stiffness of left rear wheel k_3, N/rad	-50000
Cornering stiffness of right rear wheel k_4, N/rad	-50000

3.1. Steering transient response of the electric vehicle

The front wheel angle step input test: while the vehicle is driving straight with steady-state, turning the steering wheel sharply to a corner, then stop turning the steering wheel and keep the angle of the same, after that the vehicle is driving along the uniform circular road. This test can reflect the transient response characteristics and steady state response characteristics, and we can observe changes of the yaw rate and the side slip angle in the whole process.

Setting the velocity of the electric vehicle is 15m/s ,inner steered angle $\delta_1 = 19.47°$, the vehicle begin to turn from the start ,and then we can get graphs of the yaw rate and the side slip angle ,as shown in Figs. 5 and 6 .

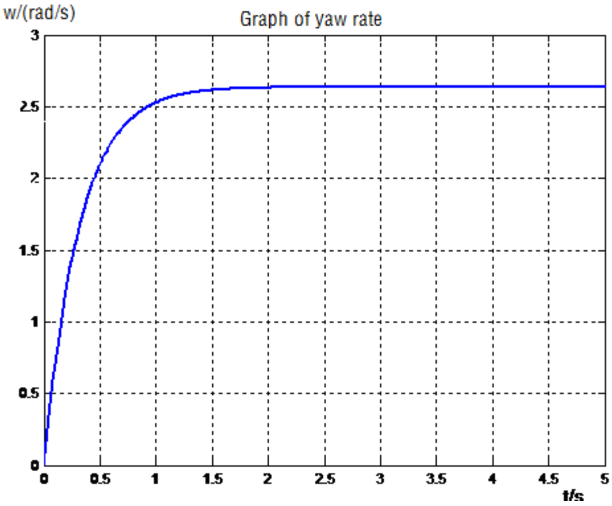

Fig. 5 Graph of yaw rate

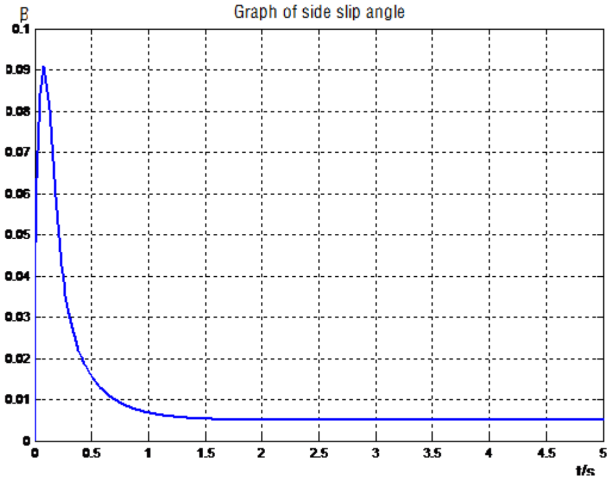

Fig. 6 Graph of side slip angle

3.2. The steady-state response of the electric vehicle

3-DOF model was used to study the motion of the electric vehicle. When the electric vehicle is driving with constant velocity, we analyzed the steady state response under the front-wheel-step input. The vehicle drives along the 9m-radius of circle with the lowest stable speed. And inside and outside front wheel angle are δ_1, δ_2 respectively. Because of the low speed, the centrifugal force is small, and the tire side-slip angle can be neglected, then the turning radius $R_0 = u_0 / \omega_0$. Keep the front wheel angles (δ_1, δ_2) constant, and make the vehicle speed slowly and continuously (the longitudinal acceleration is less than 0.25 m/s^2), until the vehicle lateral acceleration up to 6.5 m/s^2. Measuring speed (u) and yaw rate (ω) continuously, according to the formula $R = u / \omega$, we can get turning radius with side-slip angle, R / R_0-V can represent steering characteristics of the vehicle.

When the vehicle is driving with uniform circular motion, the side slip angle and yaw rate are constant, it means $\dot{\beta} = 0$, $\dot{\omega} = 0$, then we can get the steady-state differential equations of the electric vehicle.

The equation of longitudinal motion of the vehicle:

$$-m_v v\beta\omega = -\left(k_1\delta_1 + k_2\delta_2\right)\beta - \left(k_1\delta_1 \frac{l_f}{v} + k_2\delta_2 \frac{l_f}{v}\right)\omega + \frac{T_{\mathrm{d}1} - I_\omega \dot{\omega}_{f1}}{\mathrm{r}} + \frac{T_{\mathrm{d}2} - I_\omega \dot{\omega}_{f2}}{\mathrm{r}} + k_1\delta_1^2 + k_2\delta_2^2 . \tag{35}$$

The equation of lateral motion of the vehicle:

$$m_v v\omega = \left(k_1 + k_2 + k_3 + k_4\right)\beta + \left(k_1 \frac{l_f}{v} + k_2 \frac{l_f}{v} - k_3 \frac{l_{\mathrm{r}}}{v} \text{-} k_4 \frac{l_r}{v}\right)\omega + \frac{T_{\mathrm{d}1} - I_\omega \dot{\omega}_{f1}}{\mathrm{r}}\delta_1 + \frac{T_{\mathrm{d}2} - I_\omega \dot{\omega}_{f2}}{\mathrm{r}}\delta_2 -$$

$$-k_1\delta_1 - k_2\delta_2 - F_{yb1} - F_{yb2} - F_{yb3} - F_{yxb4} . \tag{36}$$

The equation of yaw motion of the vehicle:

$$\left[l_f\left(k_1 + k_2\right) + \frac{d_f}{2}\left(k_1\delta_1 - k_2\delta_2\right) - l_r\left(k_3 + k_4\right)\right]\beta + \frac{2\left(k_1 + k_2\right)l_f^2 + 2\left(k_3 + k_4\right)l_r^2 + \left(k_1\delta_1 - k_2\delta_2\right)l_f d_f}{2v}\omega -$$

$$-l_f\left(k_1\delta_1 + k_2\delta_2 \text{ - } \frac{T_{d1} - I_\omega \dot{\omega}_{f1}}{r}\delta_1 \text{ - } \frac{T_{d2} - I_\omega \dot{\omega}_{f2}}{r}\delta_2\right) - \frac{d_f}{2}\left(\frac{T_{d1} - I_\omega \dot{\omega}_{f1}}{r} + k_1\delta_1^2 \text{ - } \frac{T_{d2} - I_\omega \dot{\omega}_{f2}}{r} - k_2\delta_2^2\right) +$$

$$+\left(F_{yb1} + F_{yb2}\right)c + \left(F_{yb3} + F_{yb4}\right)\left(c + 2a\right) = 0. \tag{37}$$

By MATLAB/Simulink simulation, we can get curves about the ratio of turning radius (R / R_0) and yawing rate along with the change of speed, as shown in Figs. 7 and 8.

Keeping the front wheel angles δ_1, δ_2 constant, and making the vehicle speed up continuously and evenly (the longitudinal acceleration is less than 0.25 m/s^2), until the vehicle lateral acceleration up to 6.5 m/s^2. Measuring speed (u) and yaw rate (ω) continuously, and according to formulas $R = u / \omega$ and $a_y = u\omega$, we can get corresponding values of R and a_y. Then we get the curve of R / R_0-$a_y$with different lateral acceleration, shown in Fig. 9. It shows that under the condition of the steady-state, with speeding up slowly, the electric vehicle's turning radius become bigger and bigger, and the turning characteristic is understeer .

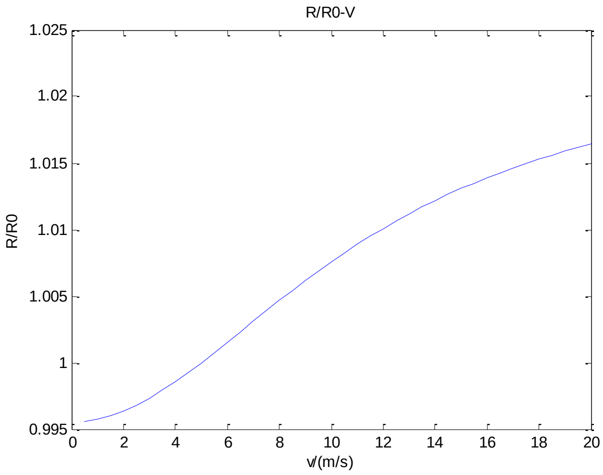

Fig. 7 R / R_0-V curve of steady-state responses of the electric vehicle

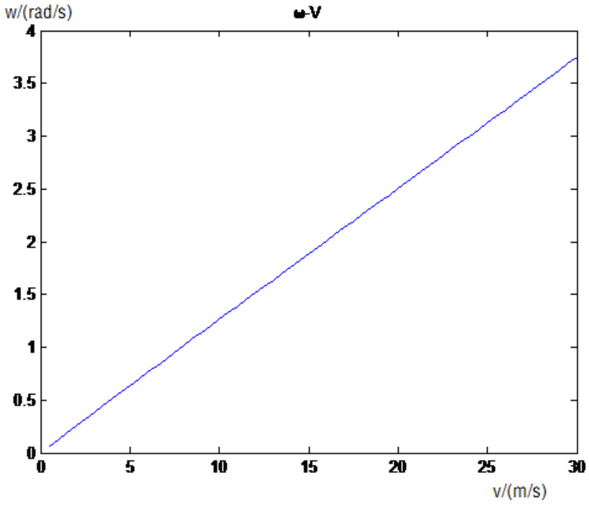

Fig. 8 ω-V curve of steady-state responses of the electric vehicle

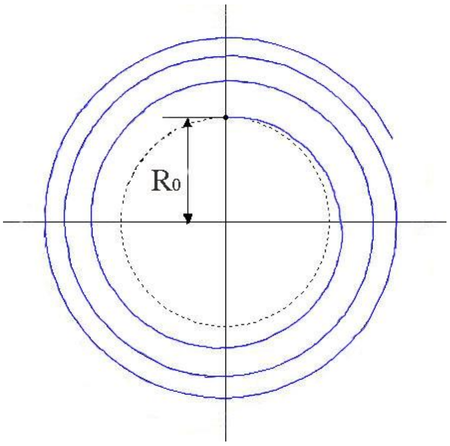

Fig. 9 Traveling track under continuous accelerated driving

with fixed front wheel angle

3.3. The influence of different speed for steering characteristics of electric vehicle

When the vehicle is driving with a slowly speed, giving a front wheel angle, the vehicle's turning should be sensitive. When the vehicle is driving with a high speed, we gave a front wheel angle, which makes vehicle changing lanes. Carrying on front-wheel-angle-step input simulation test with speed of 10 m/s, 15 m/s, 20 m/s respectively, then we can get responds curves of yaw rate and side slip angle, as shown in Figs. 10 and 11.

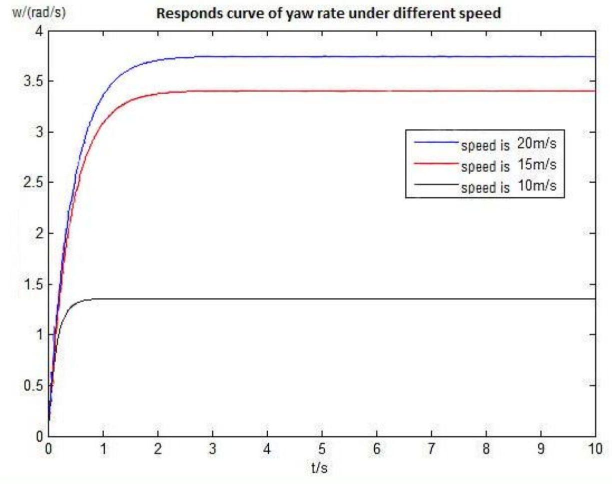

Fig. 10 Responds curve of yaw rate under different speed

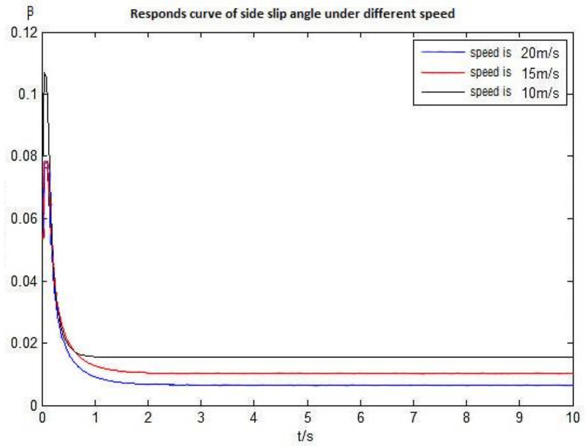

Fig. 11 Responds curve of side slip angle under different speed

According to Fig. 10, we know that with the increase of the speed of the vehicle, the stability value of yaw rate is increased. When the vehicle speed up, the reason giving a specific front wheel angle is to change lanes, then we hope the vehicle is stable. In the case of the same front wheel angle, the higher speed the more sensitive of turning.

From side slip angle curve (Fig. 11), we know that with the increase of the speed of the vehicle, the overshoot of side-slip angle is increased, reaction time was shortened, and the steady-state value decreased. According to our normal driving experience, speed reduced when the vehicle is turning to decrease the side slip angle, so that the vehicle body vertical direction is the same as the vehicle forward direction. Therefore, the tested electric vehicle has good stability.

3.4. The influence of the center of gravity to steering characteristics

It is an important characteristics that the changes in location of the center of gravity, and then we analyze the influence of different mass center position to the electric vehicle handling stability. Before the change of the center of gravity, according to the load between front axle and rare axle, we can get the location of the center of mass, that is l_f = 1.154 m and l_r = 1.394 m, and the vehicle mass center is located before the center of the vehicle size.

To study the effect of the center of gravity, fixed speed, we can get response curves of constant location, center of mass forward 0.1 m and center of mass back 0.1 m by changing the longitudinal position of the battery pack, shown in Figs. 12 and 13.

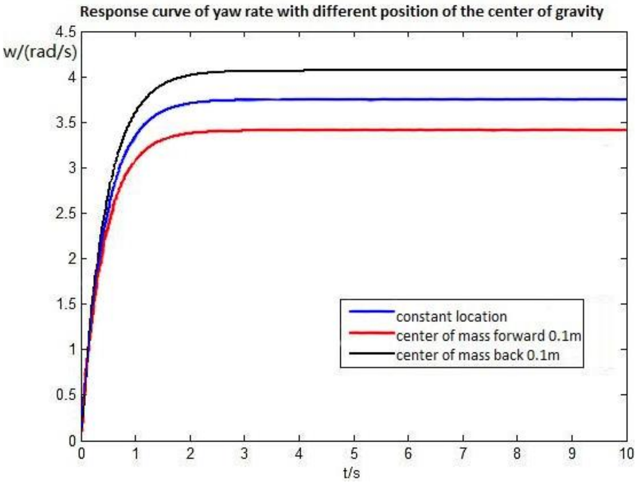

Fig. 12 Center of mass in the front-response curve of yaw rate with different position of the center of gravity

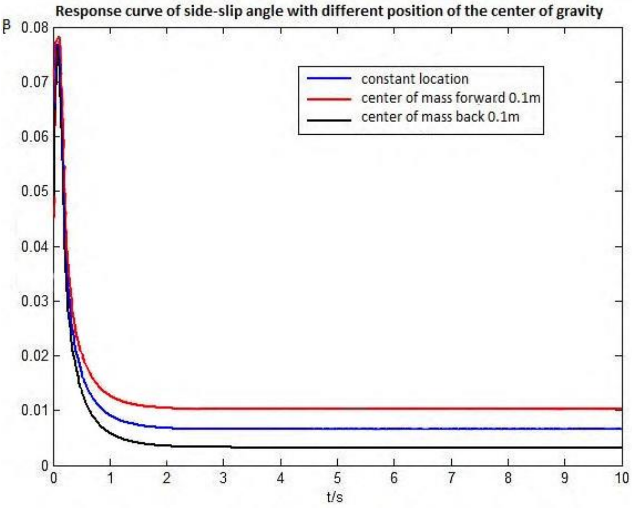

Fig. 13 Center of mass in the front-response curve of side-slip angle with different position of the center of gravity

By contrasting and analyzing three groups of curve about yaw rate, we can get conclusions: when the center of mass is located before the center of vehicle size, changing the position of the battery pack, as the center of mass going backward, the stable time of yaw rate is shorten, but the stable value is increased. The result of mass center forward is opposite.

To side-slip angle, we can get conclusions: as the center of mass going backward, the overshoot of side-slip angle is decreased, and the stable time is shorten. The result of mass center forward is opposite.

Changing the position of battery pack to make the center of mass is located in the center of the vehicle size. So $l_f = 1.394$ m and $l_r = 1.154$ m, then we can get response curves of constant location, center of mass forward 0.1 m and center of mass back 0.1 m by changing the longitudinal position of the battery pack, shown in Figs. 14 and 15.

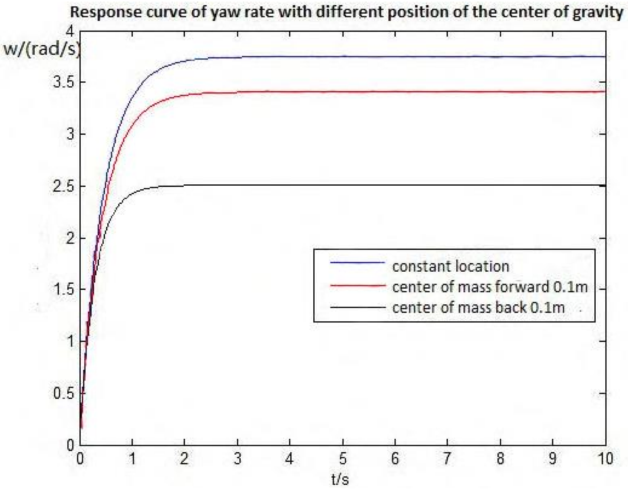

Fig. 14 Center of mass in the back-Response curve of yaw rate with different position of the center of gravity

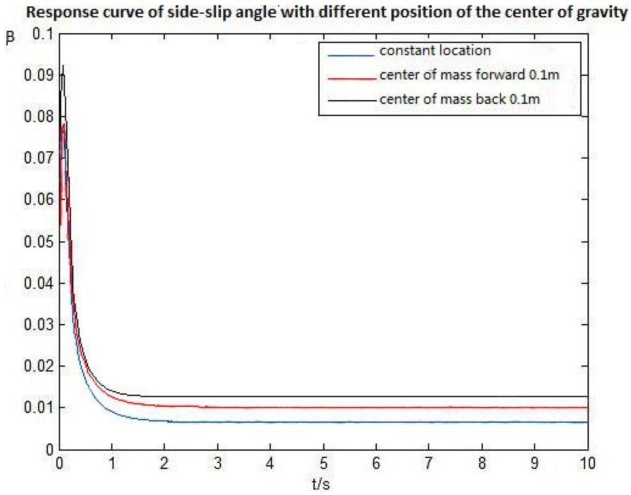

Fig. 15 Center of mass in the back-response curve of side-slip angle with different position of the center of gravity

According to Figs. 14 and 15, we can know when the center of mass is located after the center of vehicle size, changing the position of the battery pack, as the center of mass go backward, the response time of yaw rate is extended, but the time reaches a stable is shorten, and the steady-state value is decreased. The overshoot of side-slip angle is decreased, the response time extend, and the steady-state value is decreased.

Usually, when the mass of center go backward, rear wheels' vertical load and cornering stiffness are increasing, and side-slip angle is decreasing. But front wheels' side-slip angle is increasing, so the different value of slip angle between front and rear wheel is increasing, and the tendency of understeer is increasing. If the front wheel angle is constant, the corresponding yaw rate and side-slip angle are decreasing [10].

4. Conclusions

This paper studied turning characteristic simulation model of the electric vehicle, conducting simulations with side-slip angle and yaw rate, and simulation with different location in center of mass, then input the result of simulation to the workspace to map the response curves. By analyzing the simulation results of the system model, we can see that there is certain understeer when the electric vehicle is turning. Changing the position of the battery pack, to make the vehicle's mass center is located back in the center of vehicle size is more stable than front in the center of vehicle size.

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STUDY ON THE INFLUENCE OF THE ARRANGEMENT OF BATTERY PACK ON THE STEERING CHARACTERISTICS OF ELECTRIC VEHICLE

Summary

This paper established the three degree of freedom mathematical model, based on the two degree of freedom linear model with two wheel steering. Then the dynamics differential equation is obtained. With a step input of the front wheel, observing and analyzing the yaw rate response and the side slip angle response in the whole process based on MATLAB/Simulink. Finally, by changing the position of the battery pack to transform the location of the gravity center of the whole vehicle, analyzing the impact on the electric vehicle's steering characteristic while the location of battery pack changed.

Keywords: electric vehicle, dynamic model, simulation, battery pack.

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