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Matching up the suspension of electric vehicle with the supporting system of battery pack

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1. Introduction

Electric vehicles are a meaningful type of transportation to solve the environmental pollution problem and the worldwide energy crisis. The design of the electric vehicles is generally based on an existing prototype or an earlier vehicle platform [1]. However, with the increasing demands on vehicle dynamics and stability, the ride performance of the electric vehicle which is retrofitted by current vehicle architecture is insufficient after changing the overall layout. In addition, the property of the installed battery pack is also a critical influence factor for the electric vehicles.

As the source of power in the electric vehicle, the battery pack will determine the mechanical structure [1]. The shock and vibration affect the electrical and electronic components leading to energy loss and the structural failure [2-4]. In order to improve the current status, the paper proposes a supporting system with shock absorbers and bearing springs as a protective facility for the battery pack. Combined with the active suspension, which was proposed by Prof. Federspiel Labrosse and reviewed comprehensively by Hrovat [5-8], the vibration of battery pack and electric vehicle will be further restrained. Compared with the passive suspension, the active suspension shows a better performance with a serious of controller [9-12]. It has multiple sensors to acquire data and input to the microcomputer, which decides the control mode and uses the actuator to adjust the suspension movement. It is effective to restrain the vibration with an acting force and a reacting force.

Based on the above description, the purpose of the paper is to develop a 10-DOF model with the active suspensions and the supporting system to calculate the ideal position of the battery pack by Simulink and state space method, and show the effect of the supporting system for the electric vehicle.

2. 10-DOF Model

According to the analysis of the active suspension model and the supporting system of battery pack model, a multi-DOF full vehicle model and a supporting system model was developed. The electric vehicle is installed a single battery pack. The 10-DOF model is shown in Fig. 1.

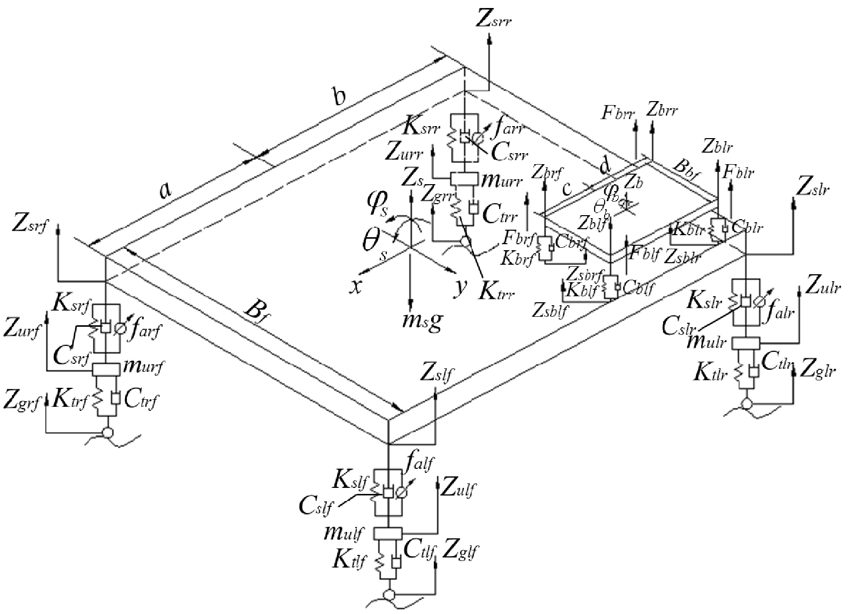


Fig. 1 10-DOF full vehicles model with a single battery pack

Based on the above 10-DOF model, the equations are established as follows:

1) The vertical motion equation at the center of mass:

$$m_s\ddot{z}_s = C_{slf}\left(\dot{z}_{ulf}-\dot{z}_{slf}\right)+k_{slf}\left(z_{ulf}-z_{slf}\right)+C_{srf}\left(\dot{z}_{urf}-\dot{z}_{srf}\right)+k_{srf}\left(z_{urf}-z_{srf}\right)+C_{slr}\left(\dot{z}_{ulr}-\dot{z}_{slr}\right)+k_{slr}\left(z_{ulr}-z_{slr}\right)+ \\ +C_{srr}\left(\dot{z}_{urr}-\dot{z}_{srr}\right)+k_{srr}\left(z_{urr}-z_{srr}\right)+f_{arf}+f_{alf}+f_{arr}+f_{alr}-m_s g-F_{brf}-F_{blf}-F_{brr}-F_{blr}, \tag{1}$$

where m_s is the sprung mass, kg; $\ddot{z}_s$ is the accelerated velocity, m/s^2; $z_{urf}, z_{ulf}, z_{urr}, z_{ulr}$ are the displacement of unsprung mass, mm; $z_{srf}, z_{slf}, z_{srr}, z_{slr}$ are the displacement of sprung mass, mm; $k_{srf}, k_{slf}, k_{srr}, k_{slr}$ are the suspension stiffness, N/m; $C_{srf}, C_{slf}, C_{srr}, C_{slr}$ are the suspension damping, Ns/m; $f_{arf}, f_{alf}, f_{arr}, f_{alr}$ are the actuator force of the active suspension, N; $F_{brf}, F_{blf}, F_{brr}, F_{blr}$ are the actuator force of battery, N.

2) The pitching motion equation:

$$I_{sp}\ddot{\theta}_s = \left[C_{slr}\left(\dot{z}_{ulr}-\dot{z}_{slr}\right)+k_{slr}\left(z_{ulr}-z_{slr}\right)+C_{srr}\left(\dot{z}_{urr}-\dot{z}_{srr}\right)+k_{srr}\left(z_{urr}-z_{srr}\right)+f_{alr}+f_{arr}\right]b- \\ -a\left[C_{slf}\left(\dot{z}_{ulf}-\dot{z}_{slf}\right)+k_{slf}\left(z_{ulf}-z_{slf}\right)+C_{srf}\left(\dot{z}_{urf}-\dot{z}_{srf}\right)+k_{srf}\left(z_{urf}-z_{srf}\right)+f_{alf}+f_{arf}\right]- \\ -\left(F_{brf}+F_{blf}\right)\left(-x-c\right)-\left(F_{brr}+F_{blr}\right)\left(-x+d\right), \tag{2}$$

where I_{sp} is the Y axel moment of inertia, kgm^2; θ_s is the pitching angle at the center of gravity; a is the distance from front axle to the barycenter, mm; b is the distance from the barycenter to rear axle, mm; c is the distance from the front edge to the barycenter of battery, mm; d is the distance from the barycenter of battery to the rear edge, mm; x is the abscissa of the battery position, mm.

3) The roll motion equation:

$$I_{sr}\ddot{\varphi}_s = \left[C_{slf}\left(\dot{z}_{ulf}-\dot{z}_{slf}\right)+k_{slf}\left(z_{ulf}-z_{slf}\right)-C_{srf}\left(\dot{z}_{urf}-\dot{z}_{srf}\right)-k_{srf}\left(z_{urf}-z_{srf}\right)+f_{alf}-f_{arf}\right]\frac{B_f}{2}+ \\ +\left[C_{slr}\left(\dot{z}_{ulr}-\dot{z}_{slr}\right)+k_{slr}\left(z_{ulr}-z_{slr}\right)-C_{srr}\left(\dot{z}_{urr}-\dot{z}_{srr}\right)-k_{srr}\left(z_{urr}-z_{srr}\right)+f_{alr}-f_{arr}\right]\frac{B_f}{2}- \\ -\left(F_{blf}+F_{blr}\right)\left(y+\frac{B_{bf}}{2}\right)-\left(F_{brf}+F_{brr}\right)\left(y-\frac{B_{bf}}{2}\right), \tag{3}$$

where I_{sr} is the X axel moment of inertia, kgm^2; φ_s is the roll angle at the center of gravity; y is the ordinate of the battery position, mm; B_f is the width of the electric vehicle, mm; B_{bf} is the width of the battery pack, mm.

4) The vertical motion equation of automotive four unsprung masses:

$$m_{ulf}\ddot{z}_{ulf} = k_{tlf}\left(z_{glf}-z_{ulf}\right)+C_{tlf}\left(\dot{z}_{glf}-\dot{z}_{ulf}\right)+k_{slf}\left(z_{slf}-z_{ulf}\right)+C_{slf}\left(\dot{z}_{slf}-\dot{z}_{ulf}\right)-f_{alf}; \tag{4}$$

$$m_{urf}\ddot{z}_{urf} = k_{trf}\left(z_{grf}-z_{urf}\right)+C_{trf}\left(\dot{z}_{grf}-\dot{z}_{urf}\right)+k_{srf}\left(z_{srf}-z_{urf}\right)+C_{srf}\left(\dot{z}_{srf}-\dot{z}_{urf}\right)-f_{arf}; \tag{5}$$

$$m_{ulr}\ddot{z}_{ulr} = k_{tlr}\left(z_{glr}-z_{ulr}\right)+C_{tlr}\left(\dot{z}_{glr}-\dot{z}_{ulr}\right)+k_{slr}\left(z_{slr}-z_{ulr}\right)+C_{slr}\left(\dot{z}_{slr}-\dot{z}_{ulr}\right)-f_{alr}; \tag{6}$$

$$m_{urr}\ddot{z}_{urr} = k_{trr}\left(z_{grr}-z_{urr}\right)+C_{trr}\left(\dot{z}_{grr}-\dot{z}_{urr}\right)+k_{srr}\left(z_{srr}-z_{urr}\right)+C_{srr}\left(\dot{z}_{srr}-\dot{z}_{urr}\right)-f_{arr}, \tag{7}$$

where $m_{urf}, m_{ulf}, m_{urr}, m_{ulr}$ are the unsprung masses, kg; $k_{trf}, k_{tlf}, k_{trr}, k_{tlr}$ are the stiffness of tire, N/m; $C_{trf}, C_{tlf}, C_{trr}, C_{tlr}$ are the tire damping, Ns/m; $z_{grf}, z_{glf}, z_{grr}, z_{glr}$ are the road profile input, mm.

5) The vertical motion equation of battery pack:

$$m_b\ddot{z}_b = C_{blf}\left(\dot{z}_{sblf}-\dot{z}_{blf}\right)+k_{blf}\left(z_{sblf}-z_{blf}\right)+C_{brf}\left(\dot{z}_{sbrf}-\dot{z}_{brf}\right)+k_{brf}\left(z_{sbrf}-z_{brf}\right)+C_{blr}\left(\dot{z}_{sblr}-\dot{z}_{blr}\right)+k_{blr}\left(z_{sblr}-z_{blr}\right)+ \\ +C_{brr}\left(\dot{z}_{sbrr}-\dot{z}_{brr}\right)+k_{brr}\left(z_{sbrr}-z_{brr}\right)-m_b g, \tag{8}$$

where m_b is the battery mass, kg; $\ddot{z}_b$ is the accelerated velocity of battery, m/s^2; $z_{sbrf}, z_{sblf}, z_{sbrr}, z_{sblr}$ are the vertical displacement of suspension reacting force to the battery pack, mm; $z_{brf}, z_{blf}, z_{brr}, z_{blr}$ are the vertical displacement of battery pack, mm; $k_{brf}, k_{blf}, k_{brr}, k_{blr}$ are the battery stiffness, N/m; $C_{brf}, C_{blf}, C_{brr}, C_{blr}$ are the battery damping, Ns/m.

6) The pitching motion equation of battery pack:

$$I_{bp}\ddot{\theta}_b = \left[C_{blr}\left(\dot{z}_{sblr} - \dot{z}_{blr}\right) + k_{blr}\left(z_{sblr} - z_{blr}\right) + C_{brr}\left(\dot{z}_{sbrr} - \dot{z}_{brr}\right) + k_{brr}\left(z_{sbrr} - z_{brr}\right)\right]d - \\ -c\left[C_{blf}\left(\dot{z}_{sblf} - \dot{z}_{blf}\right) + k_{blf}\left(z_{sblf} - z_{blf}\right) + C_{brf}\left(\dot{z}_{sbrf} - \dot{z}_{brf}\right) + k_{brf}\left(z_{sbrf} - z_{brf}\right)\right], \tag{9}$$

where I_{bp} is the battery Y axel moment of inertia, kgm^2; θ_b is the pitching angle of battery.

7) The roll motion equation of battery pack:

$$I_{br}\ddot{\varphi}_b = \left[C_{blf}\left(\dot{z}_{sblf} - \dot{z}_{blf}\right) + k_{blf}\left(z_{sblf} - z_{blf}\right) - C_{brf}\left(\dot{z}_{sbrf} - \dot{z}_{brf}\right) - k_{brf}\left(z_{sbrf} - z_{brf}\right)\right]\frac{B_{bf}}{2} + \\ +\left[C_{blr}\left(\dot{z}_{sblr} - \dot{z}_{blr}\right) + k_{blr}\left(z_{sblr} - z_{blr}\right) - C_{brr}\left(\dot{z}_{sbrr} - \dot{z}_{brr}\right) - k_{brr}\left(z_{sbrr} - z_{brr}\right)\right]\frac{B_{bf}}{2}, \tag{10}$$

where I_{br} is the battery X axel moment of inertia, kgm^2; φ_b is the roll angle of the battery at the center of gravity.

According to the above equations, we can get the state space model of the vehicle-battery system. It is shown as follows:

$$\begin{cases} \dot{X} = AX + BQ + EU; \\ Y = CX + DQ + FU, \end{cases}$$

where $\dot{X}$ is a vector representing the displacement, velocity and accelerated velocity; Y is a scalar which representing the output. The matrices A, B, C, D, E and F can be derived from the mathematical model. It determines the relationship between the input and output variables. The state space model is a multiple inputs and multiple outputs (MIMO) system.

Fig. 2 shows a frame of the control system. It is a closed-loop system with feedback. Based on the control frame, its transfer function was obtained. Its controllability can be analyzed. Combined the above equations with the state space model, the ideal position of the battery pack can be calculated by Simulink.

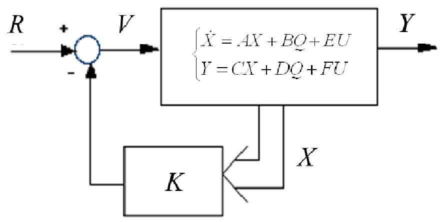


Fig. 2 A frame of control system

3. Simulation and results

3.1. Simulation conditions and vehicle parameters

White noise is the input of this simulation. Road roughness is the Power Spectral Density (PSD) Class D-1024 × 10^{-6} m^3. Simulation time is 10 seconds. Velocity is 20 m/s. There is a time delay between the front axles and the rear axles. It is 0.1274 seconds. Fig. 3 shows the curve of white noise for wheels. X coordinate axle represents time, s. Y coordinate axle represents velocity, m/s. Table 1 is a set of parameters from a remodeled vehicle and its battery pack.

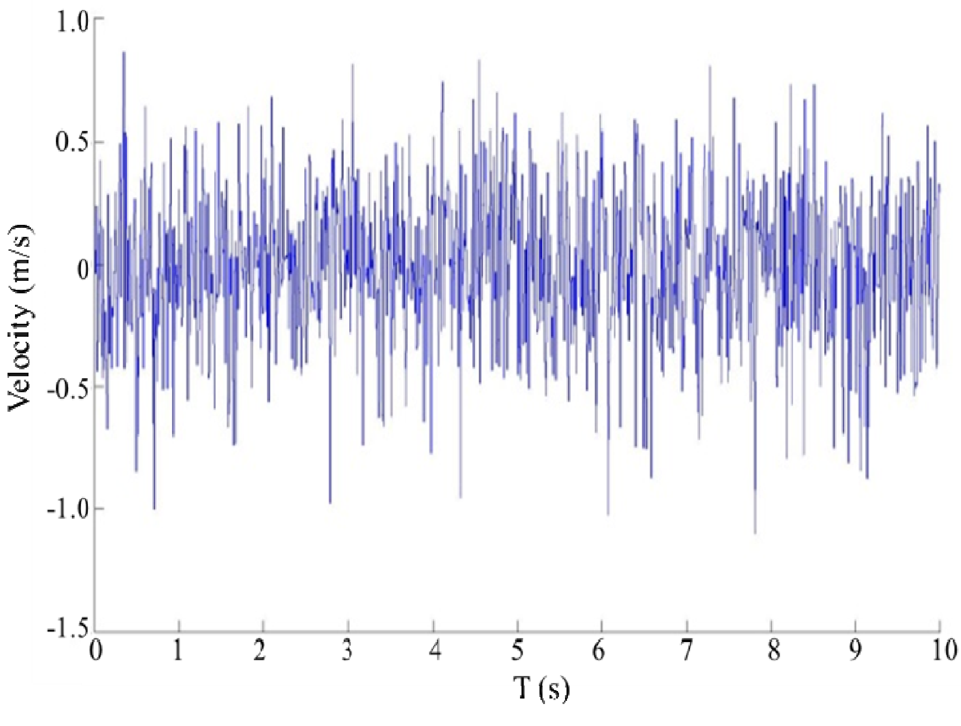


Fig. 3 Curve of white noise

Table 1

Parameters of a remodelled vehicle and its battery pack

Parameters	Definition	Value
m_s, kg	Sprung Mass	1800
L/W/H, mm	Length/Width/Height	4550*1700*1660
I_{sp} , kgm^2 I_{sr} , kgm^2	Y axel moment of inertia X axle moment of inertia	867 6210.75
m_{urf} , m_{ulf} , m_{urr} , m_{ulr} , kg	Unsprung mass	40
k_{srf} , k_{lf} , N/m k_{srr} , k_{slr} , N/m	The front bearing spring stiffness The rear bearing spring stiffness	66793 18606
k_{trf} , k_{tlf} , k_{trr} , k_{tlr} , N/m	Tire dynamic stiffness	201021
C_{srf} , C_{slf} , C_{srr} , C_{slr} , Ns/m	Shock absorber damping	1189
C_{trf} , C_{tlf} , C_{trr} , C_{tlr} , Ns/m	Tire shock absorber damping	14.6
Front wheel B_f , mm Rear wheel B_f , mm	Front axle width Rear axle width	1414 1422
a, mm b, mm	Front axle to the barycentre distance Rear axle to the barycentre distance	1154 1394
m_b, kg	Battery mass	300
L/W/H, mm	Battery Length/Width/Height	890*600*360
I_{bp} , kgm^2 I_{br} , kgm^2	Y axle battery moment of inertia X axle battery moment of inertia	24 52.81
C_{brf} , C_{blf} , C_{brr} , C_{blr} , Ns/m	Battery equivalent damping	1444
k_{brf} , k_{blf} , k_{brr} , k_{blr} , N/m	Battery equivalent stiffness	490000
B_{bf} , mm	Battery width	600
c, mm d, mm	Front edge to the barycentre distance Rear edge to the barycentre distance	445 445

3.2. Simulation results

In this section, there are five critical factors (automobile body acceleration, battery pack acceleration, suspension working space, battery pack working space and tire dynamic loads), which are emulated by different coordinate of the battery positions. The results affect the matching performance and the selection of ideal position for the battery pack. Based on the parameters of automotive cab layout and the size of battery pack, we changed x coordinate to be the first set of test points. The location parameters are the center of mass (0, 0, 0), front position (near by the front seat) (0.829, 0, 0) and rear position (near by the back seat) (-0.829, 0, 0).

Fig. 4 shows the automobile body acceleration curves in the different positions. The green solid line stands for the calculated results at the center of mass; the blue dashed line stands for the calculated results in the rear position; the red dash-dotted line stands for the calculated results in the front position. It is clear that the three curves fluctuate obviously, but the solid line is more close to the X coordinate axle than the rest of two curves. The root mean square value is shown in the Table 2. The acceleration at the center of mass is the least value. Because of involving the acceleration of gravity, the results are more accurate. Therefore the center of mass is superior to the other positions by the preliminary judgment.

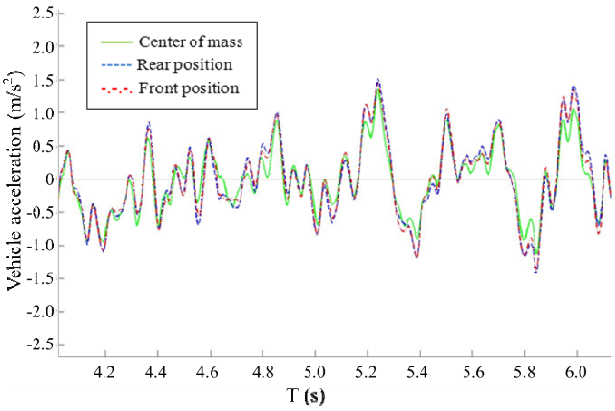


Fig. 4 Automobile body acceleration curves

Table 2

Root mean square value of automobile body acceleration

Location parameter	Automobile body acceleration Root mean square, m/s^2
Center of mass (0,0,0)	0.5199
Rear (-0.829,0,0)	0.5974
Front (0.829,0,0)	0.5869

The battery pack acceleration curves are described in Fig. 5. The location parameters and the type of lines are same to Fig. 4. It is clear that the dash-dotted line almost overlap the dash line. The solid line is involved in two curves area. Therefore the position at the center of mass fluctuates in the narrowest range than the others. Compared with Fig. 4, the range of Fig. 5 is wider. The root mean square values of the battery pack acceleration prove the phenomenon that is shown in Table 3. The results show that the battery pack acceleration is approximately double of the automobile body acceleration due to the supporting system of the battery pack.

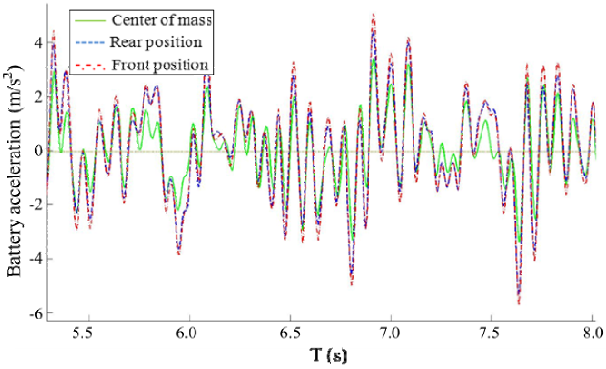


Fig. 5 Battery pack acceleration curve

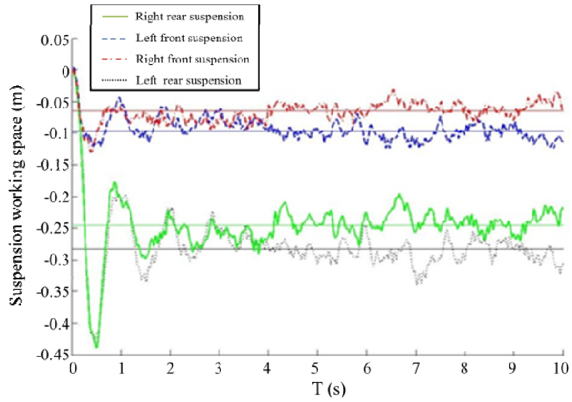
Table 3

Root mean square value of the battery pack acceleration

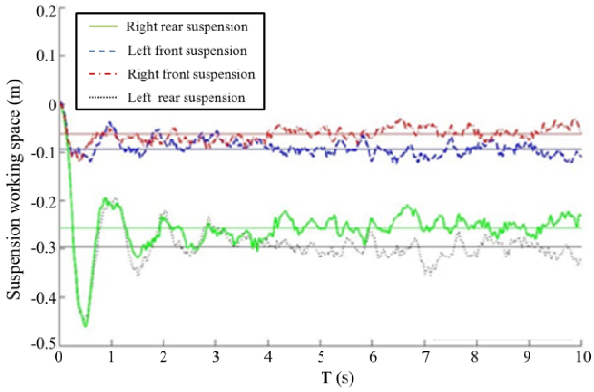
Location parameter	Battery pack acceleration Root mean square, m/s^2
Center of mass (0,0,0)	1.2451
Rear (-0.829,0,0)	1.6280
Front (0.829,0,0)	1.8044

Suspension working space (SWS) describes a vertical displacement of endpoints. Fig. 6 shows the SWS of four endpoints in the different position of the battery pack. The green solid line stands for the calculated results of the right rear suspension; the blue dashed line stands for the calculated results of the left front suspension; the red dash-dotted line stands for the calculated results of the right front suspension; the black dotted line stands for the calculated results of the left rear suspension.

The results show that four suspensions are in compression mode and the value in the front is less than the suspension in the rear. The reason is that the distance from the front axle to the center of mass is shorter than the rear axle. The value of right and left value is different due to the different inputs. Changing the inputs to the same value, the curves of right and left overlaps in a same line (Fig. 6, d). Compared with Fig. 6, a-c, the position of the battery pack affects the results. Especially in the rear position, it is obviously that the values of the rear suspension working space are changed greater than the others. The root mean square values are shown in Table 4. According to the calculated results, the suspension working space at the center of mass is the least value.



a



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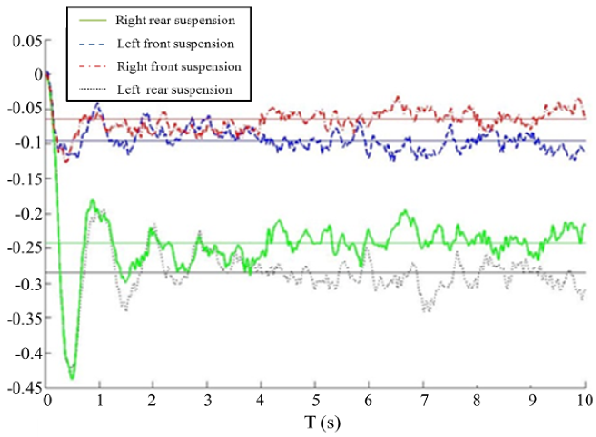

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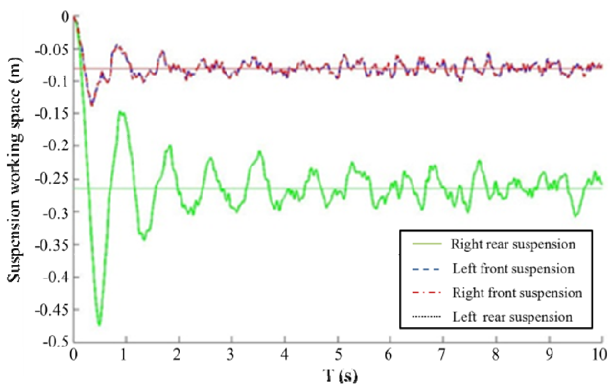
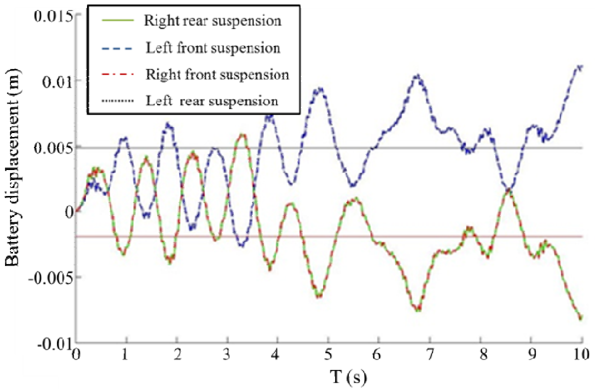


d

Fig. 6 Suspension working space: a) centre of mass; b) rear position; c) front position; d) reference diagram

Table 4
Root mean square value of the suspension working space

Location parameter	Suspension working space Root mean square, mm
Center of mass(0,0,0)	23.5
Rear (-0.829,0,0)	24.7
Front (0.829,0,0)	24.6



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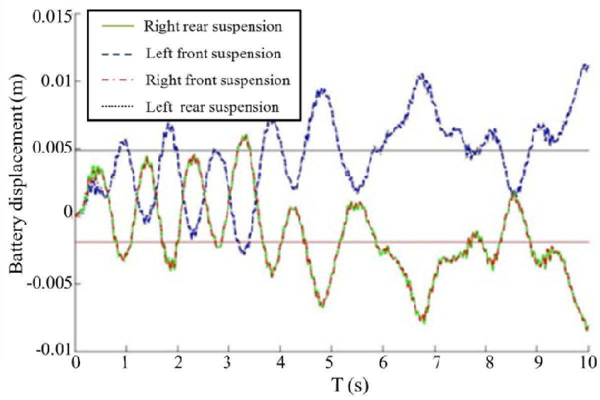

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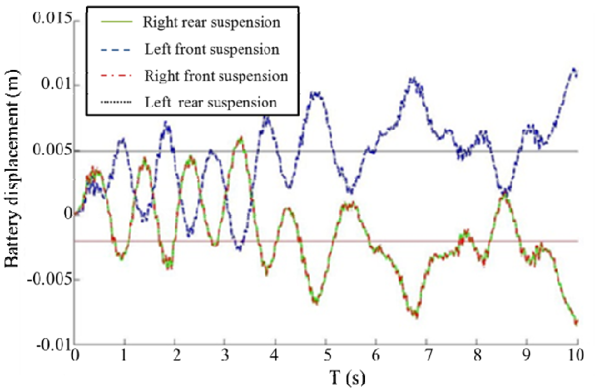


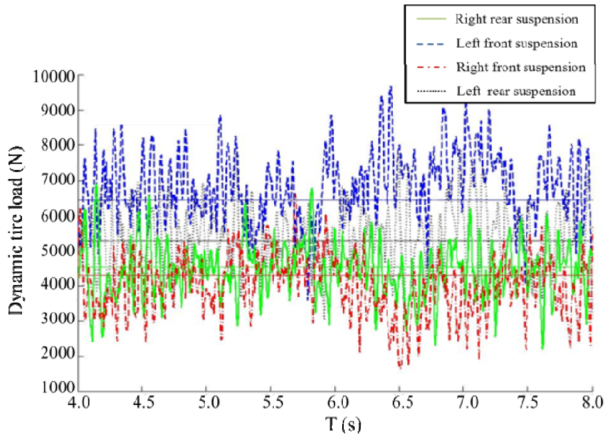
c

Fig. 7 the battery pack working space: a) Centre of mass; b) Rear position; c) Front position

The battery pack working space is a parameter of the supporting system. It describes the vertical displacement of the battery pack four endpoints and the influence by the suspension working space. Fig. 7 shows the simulated results. The location parameters and the type of line are same to Fig. 6. The left endpoints show the different direction of motion with the right endpoints. It depends on the motion of the suspension system. Combined with the calculated results in Table 5, the battery pack working space at the center of battery is the least value.

Table 5
Root mean square value of the battery pack working space

Location parameter	Battery pack working space Root mean square, mm
Center of mass (0,0,0)	4.5
Rear (-0.829,0,0)	4.6
Front (0.829,0,0)	4.6



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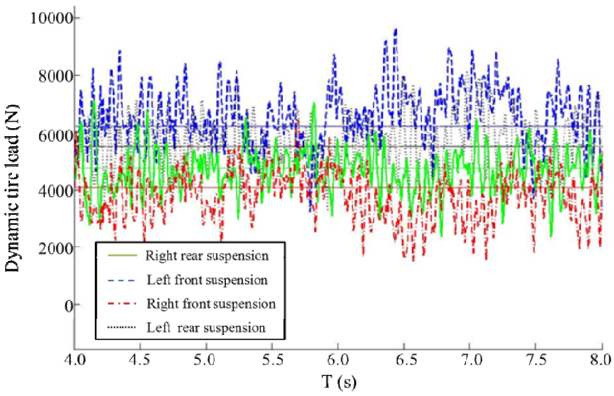

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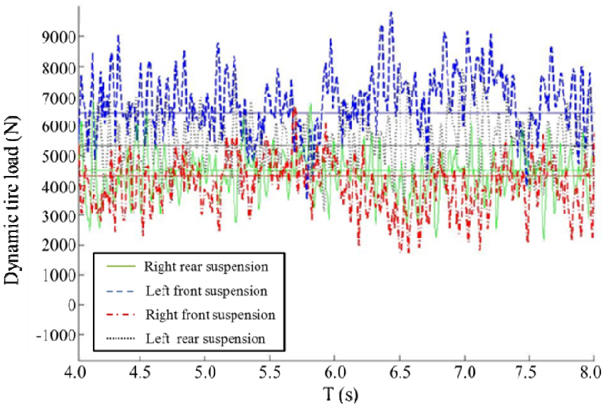

c

Fig. 8 Tire dynamic loads: a) centre of mass; b) rear position; c) front position

Fig. 8 describes the tire dynamic loads. The location parameters and line style are same to the above figures. The positions of the battery pack affect the simulated results. When the battery pack is installed in the rear position, the front tire dynamic load is decreased and vice versa. Table 6 is the root mean square value of the tire dynamic loads. Depends on the barycenter divided the automobile into two parts. Because the barycenter locates at front of the geometric center, the weight of the latter part greater than the first parts. Therefore, the calculated result of the battery pack which installed in the rear position is the maximum value. In addition, the center of the mass is the best place for the battery pack.

Table 6

Root mean square value of the tire dynamic loads

Location parameter	Tire dynamic loads Root mean square, kN
Center of mass (0,0,0)	1.2181
Rear (-0.829,0,0)	1.2421
Front (0.829,0,0)	1.2271

Combined the calculated results from Table 2-6, the position of battery pack decides the automobile performance. Compared with the results from front position (0.829, 0, 0) and the rear position (-0.829, 0, 0), the center of mass shows the advantage for installing the battery pack. Therefore, for the electric vehicle, which developed on the prototype, the best position to install the battery pack is near by the center of mass. It will not only improve the automobile performance, but also goods for the battery life to work longer time. In addition, the supporting system for the battery pack shows the same function. It protects batteries and suspensions.

The calculated results are summarized in Table 7. It shows the impact of supporting system for the electric vehicle. We select three parameters to compare the differences (automobile body acceleration, suspension working space, tire dynamic loads) between installed supporting system and without supporting system. When the battery pack is installed the supporting system, the value of three parameters change obviously, especially the suspension working space and tire dynamic loads, they reduced over 40%. The result affects the ride performance seriously.

According to Table 7, the functions of the supporting system are protection the battery pack and improvement the performance of the suspension system. Furthermore, it also solves a part of the battery problem, which the customers worried about. It will prolong the battery life and reduce costs to a certain extent, because it will decrease the maintenance and repair times. Moreover, it will be good news for the company who provide the maintenance and repair service. To summarize, the initial test which simulated a set of location parameters show a well beginning, when the battery pack and the supporting system with springs and shock absorbers installed near by the centre of mass. The next step for the research is to simulate more different location parameters in order to figure out the accurate ideal coordinate position.

Table 7

The root mean square value comparison

Parameters/Unit	Without supporting system	Center of mass (0,0,0)
Automobile body acceleration, m/s^2	0.6440	0.5199
Suspension working space, mm	54.1	23.5
Tire dynamic loads, kN	2.13	1.2181

4. Conclusions

To improve the performance of the suspension system and protect the battery pack, the initial fixed frame system of the battery pack is changed to a supporting system with springs and shock absorbers. A 10-DOF model was developed based on the new system. The ideal position of the battery pack was simulated by applying the different location parameters. According to the calculated results, the center of mass is the ideal position for the battery pack. When installed the supporting system, the suspension working space decreases over 50% and the vibration is controlled. It is an initial result to know the installing range of the battery pack and test the feasibility of the supporting system, but more accurate and reasonable location coordinate need to be studied further.

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ELEKTROMOBILIO PAKABOS IR MAITINIMO ELEMENTŲ TVIRTINIMO SISTEMOS SUDERINAMUMAS

R e z i u m ė

Sprendžiant energijos sąnaudų mažinimo elektromobiliuose problemą, šiek tiek daugiau dėmesio skiriama maitinimo elementų sistemai nei automobilio dinamikai. Siekiant patobulinti elektromobilio pakabos sistemos darbą ir apsaugoti maitinimo elementus, straipsnyje siūloma jų tvirtinimo sistemą derinti su elektromobilio pakaba. Pradinė kietai įtvirtinta rėminė maitinimo elementų sistema pakeista į pakabinamą ant spyruoklių ir apsaugotą nuo smūgio amortizatoriais. Pasiūlytas10 laisvės laipsnių pilnas automobilio dinaminis modelis. Naudojant Simulink ir būvio erdvėje modelį, išbandytas tvirtinimo sistemos tinkamumas ir nustatyta ideali maitinimo elementų padėtis automobilyje esant skirtingiems jų išdėstymo parametrams. Rezultatai byloja, kad automobilio masių centras yra ideali maitinimo elementų padėtis. Įmontavus pakabinamą sistemą, automobilio korpuso pagreitis, pakabos darbo zona ir padangų dinaminės apkrovos akivaizdžiai pagerėja.

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MATCHING UP THE SUSPENSION OF ELECTRIC VEHICLE WITH THE SUPPORTING SYSTEM OF BATTERY PACK

S u m m a r y

As a solution for reducing emissions, electric vehicles are focused on battery system rather than vehicle dynamics. To improve the performance of suspension systems of the electric vehicle and protect battery packs, the paper proposed a supporting system to match up with the electric vehicle suspension. The initial fixed frame system of the battery pack is changed to a supporting system with springs and shock absorbers. A 10-DOF model was developed based on the full vehicle model. Applying Simulink and the state space model, the feasibility of the supporting system is tested and the ideal position of the battery pack is calculated by the different location parameters. The results show that the centre of mass is the ideal position for the battery pack. When the supporting system is installed, the automobile body acceleration, suspension working space and tire dynamic loads are improved obviously.

Keywords: electric vehicle suspension; supporting system; ideal position.

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