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Effect of Battery Pack Connection on Vehicle Ride Comfort

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Abstract: In improving the ride comfort of electric vehicle (EV), this paper studies the effect of rigid connection and flexible connection between battery pack and vehicle body on ride comfort. A quarter vehicle model and a road model in time domain are established. The root mean square (*RMS*) of vehicle body vertical acceleration is used as the index of ride comfort. Particle swarm optimization (PSO) algorithm is used to optimize the suspension parameters and connection parameters. A contrast experiment is designed with a prototype of a quarter vehicle to more realistically quantify the effect of battery pack connection on vehicle ride comfort. All the simulated and experimental results show that changing the rigid connection between vehicle body and battery pack to flexible connection can effectively reduce the *RMS* of vehicle body vertical acceleration, thereby improving the vehicle ride comfort, and can also reduce the *RMS* of vertical battery pack vertical acceleration to ensure the safety of battery pack.

Keywords: battery pack; electric vehicle; ride comfort; vehicle model

1 INTRODUCTION

Under the power of environmental pressure, oil resources and new technology, EV will gradually take the place of fuel vehicle [1, 2]. However, there are few studies on the ride comfort of EV. The ride comfort is one of the main indexes to evaluate vehicle performance, which directly affects occupant comfort [3].

For fuel vehicle, in improving vehicle ride comfort, many scholars have proposed various methods. For example, the use of active suspension or semiactive suspension and the use of various control algorithms to make it play a better role, so as to improve the ride comfort of vehicles [4-8]. Some scholars also use inerter or dynamic vibration absorbers (DVA) to absorb vibration energy for suspension, so as to improve vehicle ride comfort [9-11]. However, the above methods will increase the energy consumption of EV and affect the vehicle mileage.

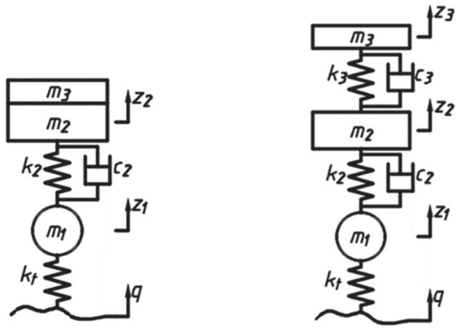
The vehicle mileage of EV is negatively correlated with vehicle mass. In improving the ride comfort of the vehicle without introducing too much extra mass, the existing parts of EV can be considered to be transformed into DVA. According to the theory of DVA, the greater the tuning mass of DVA, the better the vibration reduction effect of DVA. Mass of the EV battery pack is large, accounting for about 18% to 30% of the total vehicle mass. Therefore, the connection between the battery pack and the vehicle body can be changed from the rigid connection to the flexible connection, so that the battery pack acts as the tuning mass of DVA, and then improves the ride comfort of the vehicle.

Aiming to study the effect of battery pack connection mode on vehicle ride comfort, the quarter vehicle models of rigid connection and flexible connection between the battery pack and the vehicle body are established respectively in this paper. The filtered white noise method is used to establish road model, and the *RMS* of vertical acceleration of the vehicle body is used as the index of ride comfort. Using the above models, the effect of different suspension and connection parameters on vehicle ride comfort is studied, and the PSO algorithm is used to optimize the suspension and connection parameters. The optimal parameters are used in the model to further quantify the effect of battery pack connection mode on vehicle ride comfort.

2 QUARTER VEHICLE MODEL AND ROAD MODEL

2.1 Quarter Vehicle Model

The battery pack of the EV is generally located in the middle, the mass distribution coefficient value of the vehicle suspension is close to 1, and the vertical vibration of the front and rear suspension is almost independent. Therefore, the vehicle model can be simplified into a quarter vehicle model that ignores the tire damping coefficient. In the existing EVs, the battery pack and the vehicle body are rigidconnected, so the quarter vehicle model of the battery pack and the vehicle body in rigid connection is established, as shown in Fig. 1a, which is used as a cross reference. In Fig. 1b, the battery pack and the vehicle body are flexibly connected, that is, spring and damping are added between the vehicle body and the battery pack.



a) Model under rigid connection mode b) Model under flexible connection mode

Figure 1 Quarter vehicle model

where m_1 is the unsprung mass, m_2 is the vehicle body mass, m_3 is the battery pack mass. k_2 and c_2 are the suspension stiffness coefficient and the suspension damping coefficient. k_3 and c_3 are the battery pack connection stiffness coefficient and damping coefficient. k_t is the tire stiffness coefficient. z_3 is the vertical displacement of the battery pack under flexible connection mode, z_2 is the vertical displacement of the vehicle body, z_1 is the vertical displacement of the unsprung mass, and q is the road roughness excitation.

By applying Newton's second law, the dynamic equations of the model under the rigid connection mode and the model under flexible connection mode are derived as follows:

$$\boldsymbol{m}\ddot{\boldsymbol{z}}+\boldsymbol{c}\dot{\boldsymbol{z}}+\boldsymbol{k}\boldsymbol{z}-\boldsymbol{k_q}q=0 \tag{1}$$

For the dynamic equation of the model under the rigid connection mode, each matrix in Eq. (1) is:

$$\boldsymbol{m}=\begin{bmatrix} m_1 & 0 \\ 0 & m_2+m_3 \end{bmatrix}, \boldsymbol{c}=\begin{bmatrix} c_2 & -c_2 \\ -c_2 & c_2 \end{bmatrix},$$

$$\boldsymbol{k}=\begin{bmatrix} k_2+k_t & -k_2 \\ -k_2 & k_2 \end{bmatrix}, \boldsymbol{k_q}=\begin{bmatrix} k_t \\ 0 \end{bmatrix},$$

$$\ddot{\boldsymbol{z}}=\left\{\ddot{z}_1 \quad \ddot{z}_2\right\}^T, \dot{\boldsymbol{z}}=\left\{\dot{z}_1 \quad \dot{z}_2\right\}^T, \boldsymbol{z}=\left\{z_1 \quad z_2\right\}^T.$$

For the dynamic equation of the model under the flexible connection mode, each matrix in Eq. (1) is:

$$\boldsymbol{k}=\begin{bmatrix} k_2+k_t & -k_2 & 0 \\ -k_2 & k_2+k_3 & -k_3 \\ 0 & -k_3 & k_3 \end{bmatrix}, \boldsymbol{k_q}=\begin{bmatrix} k_t \\ 0 \\ 0 \end{bmatrix},$$

$$\ddot{\boldsymbol{z}}=\left\{\ddot{z}_1 \quad \ddot{z}_2 \quad \ddot{z}_3\right\}^T, \dot{\boldsymbol{z}}=\left\{\dot{z}_1 \quad \dot{z}_2 \quad \dot{z}_3\right\}^T,$$

$$\boldsymbol{z}=\left\{z_1 \quad z_2 \quad z_3\right\}^T.$$

2.2 Road Model

The distance between the road surface and the base plate is typically defined as a function of road roughness, which is the excitation source in the vehicle model. The methodologies of constructing the road roughness model include harmonic superposition method, inverse Fourier transform method, auto regression (*AR*) model and autoregressive moving average model (*ARMA*) method, and the filtered white noise method. The filtered white noise method is relatively stable in calculation, and the road roughness is regarded as the response of the firstorder linear system excited by white noise. Compared with other methods, it is relatively simple and less computational, so it is the most commonly used method [12].

According to ISO/TC 108/SC2N67, the road roughness characteristic is an index to describe the degree of road relief. It can use the power spectral density (PSD) of road roughness to describe its statistical characteristics, and its PSD is expressed as Eq. (2).

$$G_q(n)=G_q(n_0)\left(\frac{n}{n_0}\right)^{-W} \tag{2}$$

where n is spatial frequency, m^{-1}, whose value is the reciprocal of wavelength; n_0 is reference spatial frequency, whose value is $n_0 = 0{,}1\ m^{-1}$; $G_q(n_0)$is the road surface PSD value at the reference spatial frequency is n_0; W is frequency index, usually W equal 2.

Use the filtered white noise method [12], Eq. (2) is transformed into the time domain function of road excitation:

$$\dot{q}(t)=-2\pi n_1 \upsilon q(t)+2\pi n_0\sqrt{G_q(n_0)v\omega(t)} \tag{3}$$

where n_1 is road space cutoff frequency, n_1 equal to $0.011\ m^{-1}$; υ is vehicle velocity, m/s; $q(t)$ is road excitation input, m; $\omega(t)$ is unit filtered white noise.

3 EFFECT OF RELEVANT PARAMETERS ON VEHICLE RIDE COMFORT

For EV with conventional rigid connection mode of battery pack, the effect of suspension parameters on vehicle ride comfort has been fully studied by scholars. Under flexible connection mode of the battery pack with vehicle body, however, suspension and connection parameters on the influence of vehicle ride comfort study is less. In the case, using the vehicle model under flexible connection mode established in previous section, some of its parameters are as shown in Tab. 1. Herein, the vehicle is assumed to be traveling on C-level road at a velocity of 40 km/h. According to the reference [13], the *RMS* of vertical acceleration of the vehicle body is selected as the index of vehicle ride comfort. In addition, the vertical acceleration of the battery pack also affects the safety of the battery pack, so the vertical acceleration of the battery pack is also studied. The effects of suspension stiffness coefficient, damping coefficient and connection stiffness coefficient and damping coefficient on vehicle ride comfort and the *RMS* of battery pack vertical acceleration are studied, which provided theoretical guidance for the subsequent parameters' optimization design.

Table 1 Vehicle parameters table

Parameters	Value
m_1 / kg	40
m_2 / kg	287
m_3 / kg	108
k_t / N/m	190000

3.1 Stiffness Coefficient and Damping Coefficient of Suspension

Considering that the natural frequency of human bodyseat in the vehicle is generally about 3 Hz, the natural frequency of the body part is generally within the range of 1,2 Hz - 2 Hz to prevent its resonance. For vehicle ride comfort and safety, the damping ratio of the vehicle suspension system is generally within 0,5. Combined with Tab. 1, it is converted into suspension stiffness coefficient and damping coefficient, where the range of stiffness coefficient is 16315,64 N/m to 45321 N/m, the damping coefficient is 0 to 2978 Ns/m. Taking the above parameters into the model under flexible connection mode, the effects of suspension stiffness coefficient and damping coefficient on the *RMS* of vertical acceleration of the vehicle body and the battery pack are obtained respectively, as shown in Fig. 2 and Fig. 3.

Fig. 2 shows that the *RMS* of the vehicle body and battery pack vertical acceleration are consistent with the variation trend of suspension stiffness coefficient. With the change of suspension stiffness, the plot of the *RMS* of vertical acceleration is saddle shaped.

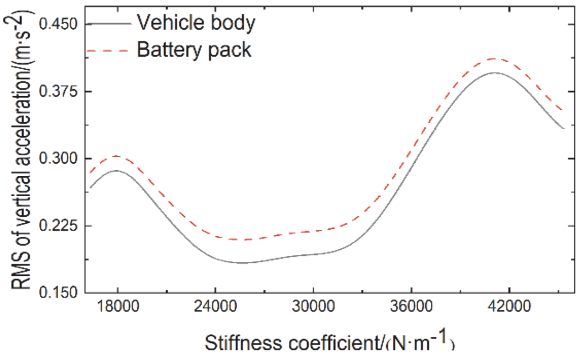


Figure 2 Effect of suspension stiffness coefficient on *RMS* of vertical acceleration

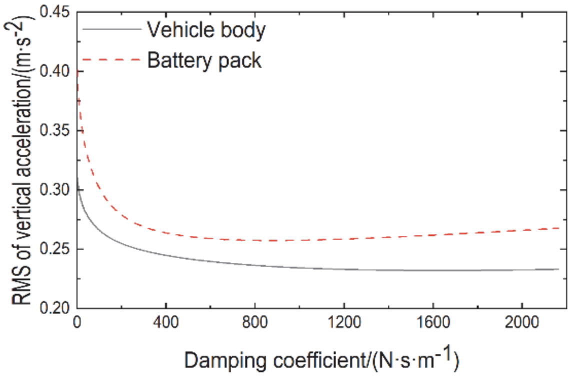


Figure 3 Effect of suspension damping coefficient on *RMS* of vertical acceleration

Fig. 3 shows that with the change of damping coefficient, the *RMS* of the vehicle body vertical acceleration decreases with the increase of damping coefficient, but the decreasing speed becomes slower. With the increase of damping coefficient, the *RMS* of battery pack vertical accelerations decreases rapidly at first and then increases slowly.

3.2 Stiffness Coefficient and Damping Coefficient of Connection

According to the technical requirements of battery pack support for EV, the firstorder mode of the battery pack support is greater than 30 Hz, and the battery pack support has no obvious resonance peak in the range of 5 - 30 Hz.

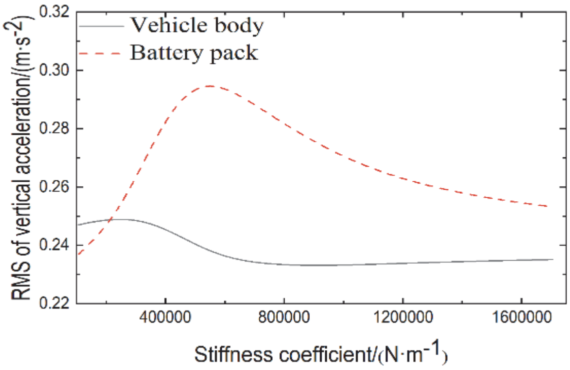


Figure 4 Effect of connection stiffness coefficient on *RMS* of vertical acceleration

In order to avoid resonance with the battery pack support, the natural frequency f_B range of the battery pack is 5 - 30Hz. In order to make it consume more vibration energy and reduce the vertical acceleration of the body, and due to the lack of relevant research data, the damping ratio of the battery pack holder is set wide, and its damping ratio is set within 0,8. Combined with Tab. 1, the damping ratio is transformed into the stiffness coefficient and damping coefficient of the connection, where the range of the stiffness coefficient is 106592 N/m to 1705468 N/m, the damping value is 0 to 3393 Ns/m.

Taking the above parameters into the model under flexible connection mode, the effects of connection stiffness coefficient and damping coefficient on the *RMS* of vertical acceleration of the vehicle body and battery pack are obtained respectively, as shown in Fig. 4 and Fig. 5.

Fig. 4 shows that the *RMS* of the vehicle body vertical acceleration increases first, then decreases, and then increases slowly with the increase of connection stiffness coefficient. The *RMS* of the battery pack vertical acceleration increases first and then decreases.

Fig. 5 shows that the *RMS* of the vehicle body vertical acceleration and battery pack vertical acceleration have the same trend with damping coefficient, which is always decreasing, but the decreasing speed tends to be slowly.

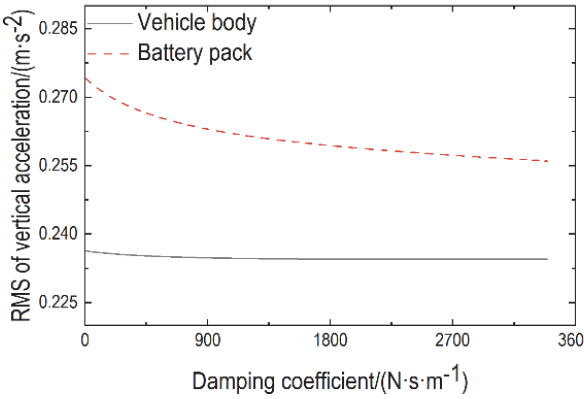


Figure 5 Effect of connection damping coefficient on *RMS* of vertical acceleration

Based on the above changes of *RMS* of the vehicle body and battery pack vertical acceleration with relevant parameters, it can be seen that suspension stiffness coefficient and connection stiffness coefficient have a great effect on the ride comfort under flexible connection mode of the battery pack with vehicle body, and there is an optimal stiffness coefficient for the best ride comfort of the vehicle. The ride comfort of the vehicle can be improved to a certain extent by increasing the damping coefficient of suspension and connection. The suspension stiffness coefficient and connection stiffness coefficient have great effect on the *RMS* of the battery pack vertical acceleration, and there is an optimal stiffness coefficient to minimize the *RMS* of the battery pack vertical acceleration. The effect of damping coefficient on the *RMS* of battery pack vertical acceleration is roughly the same as that of vehicle body.

4 VEHICLE RIDE COMFORT OPTIMIZATION

It can be seen from the above section that suspension parameters and connection parameters jointly affect vehicle ride comfort, and are not simply increasing or decreasing functions, which provides space for optimization. In order to eliminate the factors that the model under rigid connection mode is not set the best parameters, and to quantify the effect of battery pack connection on vehicle ride comfort. The model under rigid connection mode is used as the control group. The models under rigid and flexible connection mode are optimized respectively in the same parameter range, and the best index of ride comfort under the two connection modes is compared.

Due to the complexity of road excitation, parameters optimization cannot be carried out by solving the analytical solution of the dynamic equation, so the PSO algorithm is used to find the optimal parameters. Compared with other genetic algorithms, PSO is simple, easy to implement, and has a faster convergence velocity, so it is widely used in the field of suspension parameters optimization.

4.1 Optimization Variables

Taking an EV as an example, some of its parameters are shown in Tab. 1. For model under the rigid connection, the parameters to be optimized include suspension stiffness coefficient and damping coefficient, whose range is obtained according to the calculation method in the previous section. The results are shown in Tab. 2. For the flexible connection model, the parameters to be optimized include suspension stiffness and damping coefficient and the stiffness and damping coefficient at the connection of the battery pack, whose range is the calculation range in the previous section.

Table 2 Variable range of the model under rigid connection mode

Parameters	Lower limit	Upper limit
k_2 / N/m	224,55	623,75
c_2 / Ns/m	0	297,8

4.2 Objective Function

Taking the *RMS* of the vehicle body vertical acceleration as the optimization objective, its value is the smallest within the constraints; the objective function can be written as Eq. (4) and Eq. (5).

$$J_1 = \min\left(S_{RMS}\left(k_2, c_2\right)\right) \tag{4}$$

$$J_2 = \min\left(S_{RMS}\left(k_2, c_2, k_3, c_3\right)\right) \tag{5}$$

where $S_{RMS}\left(k_2, c_2\right), S_{RMS}\left(k_2, c_2, k_3, c_3\right)$ is the *RMS* of vehicle body vertical acceleration.

4.3 Constraint Conditions

In order to prevent the suspension from frequently colliding with the buffer block when the vehicle is running, the constraints on the suspension dynamic deflection are set $\left|f_d\right| \le 90 \text{ mm}$, and the suspension dynamic deflection is set $\left|f_{Bd}\right| \le 10 \text{ mm}$ considering the safety of the battery pack.

4.4 Optimization Solution

The optimization model of rigid connection model and flexible connection model can finally be written as Eq. (6) and Eq. (7). The other parameters of the model are shown in Tab. 1. In the optimization process, the road roughness of C-class road at 40 km/h is selected as the excitation. Using PSO algorithm for vehicle model parameter optimization and the previous section on the effect of law of relevant parameters on the vehicle ride comfort, and testing for many times, to set the population of 500, the largest number of iterations for 150 generations. In order to improve the global search ability of the algorithm, individual learning factor and social factor from 0,92 to 1,49 as the number of iterations linear additive, the coefficient of inertia decreases linearly from 0,9 to 0,3. The optimization results are shown in Tab. 3.

$$\begin{cases} \min\left(S_{RMS}\left(k_2, c_2\right)\right) \\ s.t.\ \left|f_d\right| \le 90 \text{ mm} \end{cases} \tag{6}$$

$$\begin{cases} \min\left(S_{RMS}\left(k_2, c_2, k_3, c_3\right)\right) \\ s.t.\ \ \left|f_d\right| \le 90 \text{ mm} \\ \qquad \left|f_{Bd}\right| \le 10 \text{ mm} \end{cases} \tag{7}$$

Table 3 Optimization results

	Model under rigid connection mode	Model under flexible connection mode
k_2 / N/m	339,56	339,85
c_2 / Ns/m	620	980
k_3 / N/m		142020
c_3 / Ns/m		255

4.5 Simulation Analysis of Optimization Results

Take the optimized variable values into the two models respectively, the simulation time is set as 30 s, and the 40 km/h road roughness of C-grade road is selected as the excitation. The vertical acceleration responses of the vehicle body and the battery pack of the two models are obtained, as shown in Fig. 6 and Fig. 7.

It can be seen from Fig. 6 that the vertical acceleration of the vehicle body under flexible connection mode decreases compared with that of the model under rigid connection mode. By calculating the *RMS* of the vehicle body vertical acceleration, the *RMS* of the vertical acceleration under flexible connection mode is 5,12% lower than that of the model under rigid connection mode.

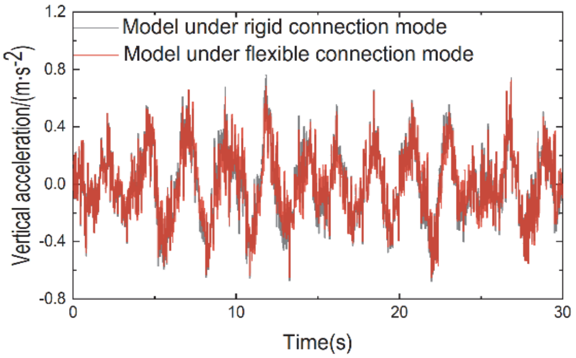


Figure 6 The vertical acceleration of the vehicle body

It can be seen from Fig. 7 that the vertical acceleration of the battery pack is almost the same under the flexible connection mode and the rigid connection mode of the battery pack. By calculating the *RMS* of the battery pack vertical acceleration, the *RMS* of the battery pack vertical acceleration under the rigid connection mode and under the flexible connection mode have little change, and the *RMS* has only decreased by 0,41%.

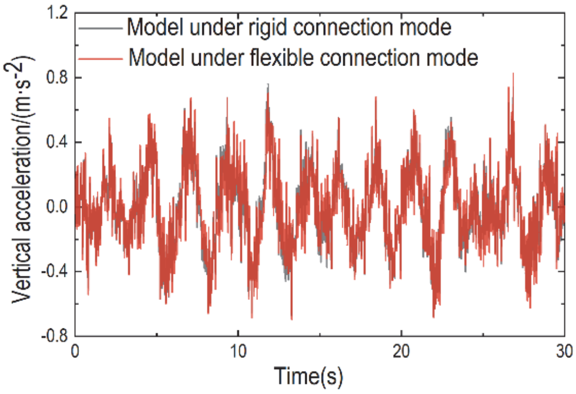


Figure 7 The vertical acceleration of battery pack

Based on the above results, the flexible connection between the battery pack and the body can improve the ride comfort of the vehicle, and has little impact on the vertical acceleration of the battery pack, which ensures the safety of the battery pack.

5 PROTOTYPE EXPERIMENTAL VERIFICATION

Considering the complexity of reality, the virtual model simulation method cannot fully reflect the effect of battery pack connection mode on vehicle ride comfort. Therefore, the prototypes of quarter vehicle model under battery pack rigid connection mode and flexible connection mode are established respectively and relevant experiences are designed. The experimental process is shown in Fig. 8.

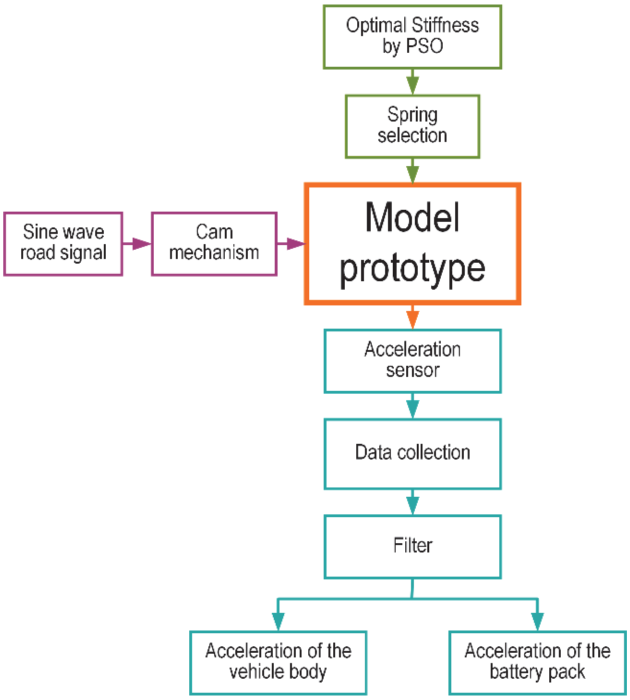


Figure 8 Experimental process

It should be noted that, limited by the experimental conditions, the road roughness model is excited by the cam mechanism to generate the sine wave road roughness. The advantage of the sine wave road roughness is that it can highlight the vibration characteristics of the vibration system more. Due to the complexity of damping regulation and the little effect of damping elements on the vibration system, damping elements are omitted in the model prototype. The unsprung mass, body mass and battery pack mass ratio of the model prototype are the same as those of the original vehicle. Under the same natural frequency range as the original vehicle, PSO algorithm is used to optimize the suspension stiffness coefficient and battery pack connection stiffness coefficient, and the optimal stiffness coefficient is obtained to select the appropriate spring. The acceleration sensor is used to collect the vertical acceleration of the vehicle body and the battery pack, and the collected results are filtered to obtain the effective results.

Compare and analyze the vertical acceleration of the vehicle body and the battery pack, obtained from the vehicle model prototypes experiments under rigid and flexible connection mode, as shown in Fig. 9 and Fig. 10. Meanwhile, the suspension parameters and the connection parameters used in the above experiments are also used to simulate the sine wave road excitation used in the experiments. The simulation results show that the *RMS* of the vertical acceleration of the vehicle body under flexible mode is 43,64% lower than that under the rigid mode. The *RMS* of the vertical acceleration of the battery pack under flexible mode is 25,68% lower than that under the rigid model. The reason why this result is obviously superior to the simulation result under the excitation of road roughness is that the frequency distribution of road roughness excitation is uneven, while the frequency of sine wave road excitation is single, which can better improve the vehicle ride comfort within a specific frequency.

It can be seen from Fig. 9 that the vertical acceleration of the vehicle body under flexible mode is significantly lower than that under the rigid mode. The *RMS* of the vertical acceleration of the vehicle body under flexible mode is 48,58% lower than that under the rigid mode. It can be seen from Fig. 10 that the vertical acceleration of the battery pack under flexible mode is significantly lower than that under the rigid model, and the *RMS* of the vertical acceleration of the battery pack under flexible mode is 33,80% lower than that under the rigid mode.

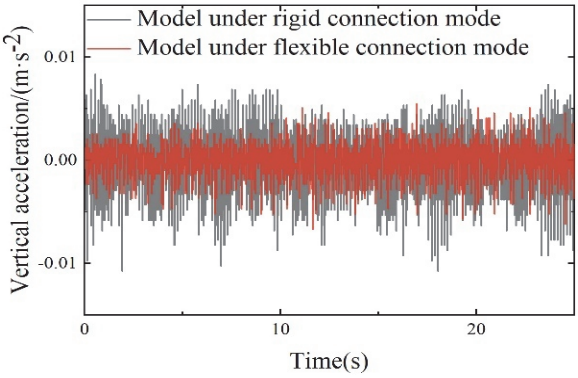


Figure 9 The vertical acceleration of the vehicle body

This result is superior to the simulation results under the same conditions, possibly because the influence of damping cannot be completely eliminated in the experimental prototype. In a word, whether from the simulation or the model prototype experiment, the results show that the vehicle ride comfort can be improved by using the flexible connection between the vehicle body and the battery pack under the appropriate parameters.

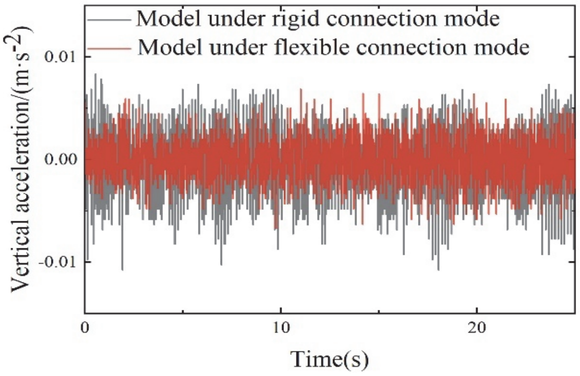


Figure 10 The vertical acceleration of the battery pack

6 CONCLUSIONS

Through the simulation and prototype experiment of the rigid connection model and flexible connection model between the vehicle body and the battery pack, the following conclusions can be drawn.

(1) For EV, changing the connection mode between the body and battery pack from rigid connection to flexible connection can reduce the *RMS* of the body acceleration and improve the ride comfort of the vehicle under appropriate suspension parameters and connection parameters.

(2) Changing the connection mode between the body and the battery pack to flexible connection can also reduce the vertical vibration acceleration of the battery pack and improve the safety of the battery pack under appropriate parameters.

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