International Core Journal of Engineering Volume 7 Issue 10, 2021
ISSN: 2414-1895 DOI: 10.6919/ICJE.202110_7(10).0003

Vibration Characteristics Analysis of EV Independently Driven by Hub Motor based on Electromechanical Coupling

Weihua Yang[1,2,a], Zifan Fang[1,2], Kongde He[1,2], Shaopeng Liu[1,2]

[1]Hubei Key Laboratory of Hydroelectric Machinery Design and Maintenance, China Three Gorges University, Yichang 443002, China;

[2]Yichang Key Laboratory of Robot and intelligent System, China Three Gorges University, Yichang 443002, China.

[a]ywhuactgu@126.com

Abstract

Selecting the electric vehicle independently driven by four electric wheels consisting of hub motor and wheel as studied object, the dynamic model of the electric vehicle is established in electromechanical coupling opinion, which takes into account the coupling effect between the electromagnetic force of hub motor and transient dynamics of electric vehicles. The vibration characteristics of electric vehicle is simulated under the different driving conditions, then the effect of the electromagnetic excitation of the hub motor on the vibration of the electric vehicle is discussed. The analysis results have some theoretical significance and reference value for improving the driving control performance, ride comfort and safety of the EV independently driven by electric wheels.

Keywords

Electric Vehicle; Hub Motor; Electromechanical Coupling; Vibration Characteristics; Simulation.

1. Introduction

Developing electric vehicle is an effective way to solve the energy shortage and environmental pollution. The electric vehicle independently driven by four electric wheels (4WD EV) has become the future development direction of electric vehicle because of its advantages in unique structure and good dynamic performance [1,2]. Electric wheel which integrates the hub motor with the wheel is the core part of this kind of EV. It is important that the electric wheel is a typical electro - mechanical system, so it is different from the ordinary vehicles both in the structure layout and dynamic performance [3]. On one hand, the introduction of the hub motor significantly causes the increase in quality of the unsprung mass, on the other hand, due to the magnetic gap deformation (MMG) inside the motor and the coupled effect of unbalanced electromagnetic force (UEF) and road excitation, the performance of electric vehicles deteriorate, which not only affects the vehicle ride comfort, but also reduces the driving safety [4].

Therefore, electromechanical coupling is the important factor causing the deterioration of the vertical dynamic performance of 4WD EV. How to reduce or even eliminate the above adverse effects has become one of the key problems to the development of this kind of electric vehicle. It is necessary to study the electromechanical coupled dynamics of electric wheel and suspension system accordingly.

Volume 7 Issue 10, 2021
DOI: 10.6919/ICJE.202110_7(10).0003

2. Dynamics model of vibration system of 4WD EV based on electromechanical coupling

In order to analyze the influence of electromechanical coupling on the vertical, pitching and rolling vibrations of 4WD EV, we need to establish its dynamics model considering the electromagnetic excitation of the hub motor. After making the necessary simplification and assumptions for the vehicle system, the 7-DOF vibration model of 4WD EV as shown in Figure 1 is established, which including three freedoms of the vertical, pitch and roll movement, and four vertical degrees of motion of 4 electric wheels (including hub motor). The model includes body's mass and four wheels' mass, each mass is connected by the elastic elements and damping elements , and the simplified model of the independent suspension is adopted. Not only the excitation of road roughness but also the unbalanced electromagnetic exciting force of the hub motor is considered in this model.

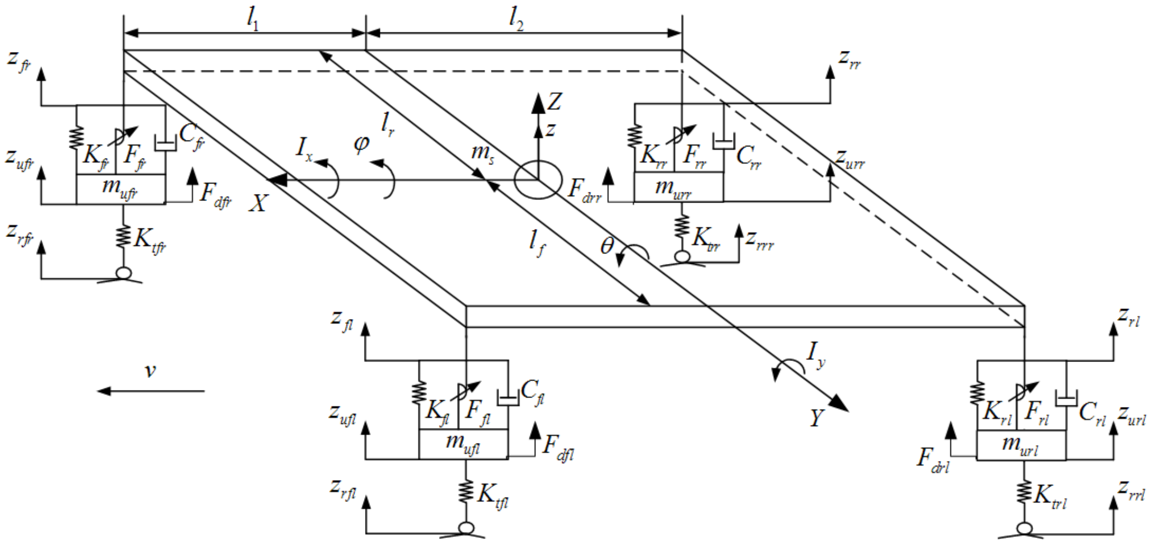

Fig. 1 7-DOF vibration model of 4WD EV

According to the Newton's laws of motion, 7-DOF dynamic model of vehicle vibration system is established, then the state -space model is obtained using state-space method. The status vector of the system is established as follows:

$$X=[x_1,x_2,x_3,x_4,x_5,x_6,x_7,x_8,x_9,x_{10},x_{11},x_{12},x_{13},x_{14}]^T=[z,\dot{z},\theta,\dot{\theta},\varphi,\dot{\varphi},z_{ufl},\dot{z}_{ufl},z_{ufr},\dot{z}_{ufr},z_{url},\dot{z}_{url},z_{urr},\dot{z}_{urr}]^T$$

Input vector:

$$u=[F_{fl},F_{fr},F_{rl},F_{rr},z_{rfl},z_{rfr},z_{rrl},z_{rrr}]^T$$

Output vector:

$$\begin{aligned}Y&=[y_1,y_2,y_3,y_4,y_5,y_6,y_7,y_8,y_9,y_{10},y_{11}]^T\\&=[\ddot{z},\ddot{\theta},\ddot{\varphi},z_{fl}-z_{ufl},z_{fr}-z_{ufr},z_{rl}-z_{url},z_{rr}-z_{urr},z_{ufl}-z_{rfl}\ ,z_{ufr}-z_{rfr},z_{url}-z_{rrl},z_{urr}-z_{rrr}]^T\end{aligned}$$

The state equation and output equation are as follows:

$$\dot{X}=A_7X+B_7u,\ \ Y=C_7X+D_7u \tag{1}$$

Where, F_{ij} is the controllable output damping force of semi-active suspension, F_{dij} is the vertical unbalanced electromagnetic exciting force of the hub motor, *i*=*f*,*r*(front, back), *j*=*r*,*l*(right, left). A_7 is the system matrix, B_7 is the output matrix, C_7 is the control matrix, D_7 is the direct transfer matrix. The meanings of other parameters are consistent with those in the usual literature, so it will not be repeated in the paper. Parameters of vehicle's vibration system and other Parameters have the same meaning with relative literature [5], the related parameters of system are taken from a certain type of 4WD EV in the literature [6].

Volume 7 Issue 10, 2021
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3. Electromagnetic exciting force of the hub motor

3.1 Analysis of electromagnetic torque of permanent magnet disc-type coreless DC motor

In order to make sure the tangential force between the rotor and the stator when the hub motor rotates, the magnetic circuit should be analyzed firstly. The permanent magnet disc-type coreless DC motor is double external rotors and single stator in the structure in the paper. Because the length of the magnetic path of this motor varies with diameter, the air gap magnetic density is distributed uniformly, which will lead to the complexity of magnetic circuit calculation. Owing to the air gap of the permanent disk motor is long, the main magnetic circuit is generally unsaturated. Normally, the magnetic circuit at the average radius is taken as the main magnetic circuit to be analysed in engineering, moreover, the calculating method is made according to cylindrical motor. The simplified section of permanent magnet disc-type coreless DC motor is shown in Figure 2. Where, δ_0 is the length of single-side air gap, l is the axial length of the armature winding, h_M is the thickness of the magnetization direction of the one-sided permanent magnet, and magnetic steel is circular shape, D_o and D_i are the outer and inner diameter of the permanent magnet respectively.

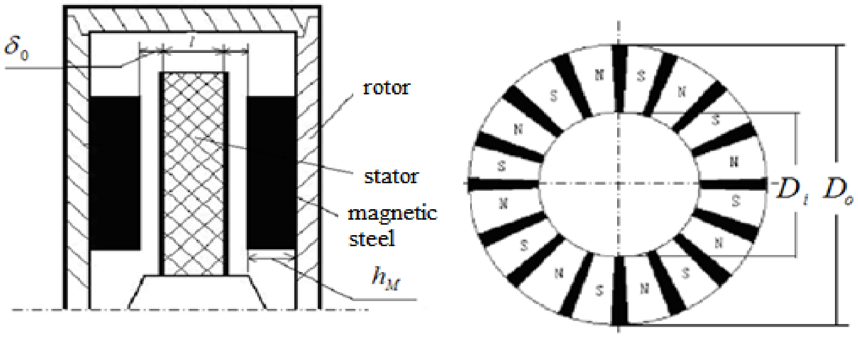

Fig. 2 Section diagram of permanent magnet disc-type coreless DC motor

Compared with the radial magnetic field motor, permanent magnet disc-type coreless DC motor is only different in the structure; the basic electromagnetic relationship has not been changed. Therefore, the formula of electromagnetic torque can be derived using the analytic method of cylindrical motor with the radial magnetic field, then the electromagnetic torque (T_{em}) of the disk motor is established as follows:

$$T_{em} = p/\Omega = \frac{\pi^2}{32\sqrt{2}}\alpha_i B_\delta A_{av}({D_o}^2 - {D_i}^2)(D_o + D_i) \tag{2}$$

3.2 Vertical electromagnetic exciting force of the hub motor

Considering the vertical dynamic performance of electric wheel vehicle vibration system is the main research content, the vertical excitation model of disk iron-free permanent magnetic motor will be established. Because the tangent force ($F_\tau(t)$) is produced when the disk motor rotates under the electromagnetic torque, the tangential force between the rotor and the stator when the motor is rotating can be determined firstly, and then takes the separation force of tangential force in the vertical direction as the excitation source, which can used to be the response of the body vibration system. In short, the relation between the tangent force and the time caused by the electromagnetic torque is as follows [8]:

$$F_\tau(t) = \begin{cases} \dfrac{T_{em}}{R} & \mathrm{z}T \le t \le (z+\dfrac{\beta_s}{T})T \\ 0 & (z+\dfrac{\beta_s}{T})T \le t \le (\mathrm{z}+1)T \end{cases} \quad (\mathrm{z}=1,2......) \tag{3}$$

Where, T_{em} is electromagnetic torque. R is the average radius of the stator is action period of the force. For the disk motor with three-phase winding, the rotor turns around a rotor pole distance when the

Volume 7 Issue 10, 2021
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current is switched on the stator three-phase winding once, then the action cycle (T) of the exciting force is 2π/, where, m is the motor number of poles, n is the motor speed, then T can be calculated by the formula 60/*n*π.

When the electric vehicle is driving normally, the direction of $F_\tau(t)$ will change with angular displacement of the rotor or time. Therefore, $F_\tau(t)$ can be decomposed in the vertical direction based on the principle of synthesis and decomposition of the force, Then the changing status of electromagnetic excitation force of the motor is obtained . Final we can develop the expression for the electromagnetic exciting force of the hub disk-type permanent magnetic DC motor in the vertical direction as followed:

$$F_\tau^y(t)=\begin{cases}\frac{T_{em}}{R}\cos\frac{n\pi}{30}t & zT\le t\le (z+\frac{7}{15})T \\ 0 & (z+\frac{7}{15})T \le t\le (z+1)T\end{cases} \quad (z=1,2......) \tag{4}$$

4. Analysis of vibration characteristic

Because the motor integrates with the wheel, the unbalanced electromagnetic exciting force of the motor will cause the vibration of the motor, and vibration is transmitted to the car body through the wheel, causing body vibration and affecting the ride comfort of the vehicle. Therefore, the coupling vibration of the hub motor and the car should be considered. The 7-DOF dynamics model of the vehicle has been established previously, so the vibration characteristics of the whole vehicle will be analyzed below. Simulating Analysis by programming based on the platform of Matlab software is conducted. The program includes the state space model of vehicle vibration system, four-wheel input road spectrum model of B level, and electromagnetic exciting force calculation model of hub motor.

Four-order Rung Kutter algorithm is used to solute the state space model of vehicle vibration system during the simulation, the driving speed is 40km/h, and simulation time is 10 seconds and sampling interval is 0.005 seconds. Statistics about values of performance indexes in Time Domain of the vibration response are shown in Table 1.

Table 1. Statistics about values of performance indexes in time domain

Name (unit)	RMS	maximum
vertical acceleration of the center of mass (m/s^2)	0.3858	1.2967
pitching angular acceleration of the center of mass (rad/s^2)	0.4803	1.4488
rolling angular acceleration of the center of mass (rad/s^2)	0.3519	0.9226
suspension deflection of front-left suspension (m)	0.0061	0.0177
dynamic displacement of front-left tire (m)	0.0039	0.0081

It can be seen from Table 1 that the electromagnetic exciting force has obvious effect on vibration characteristics of the vehicle. Due to the coupled action of electromagnetic excitation and road uneven excitation, the root - mean – square (RMS) statistical results of three directions exceed 0.315, which will cause passengers feel more uncomfortable, especially, the maximum value of the vertical acceleration exceeds 0.8, which will cause ride discomfort obviously. Results show that the vibration characteristics of the system are changed significantly. These changes must affect the ride comfort adversely.

The results of amplitude frequency response are shown in Figure 3,where Figure 3(a) is the amplitude frequency response of vertical acceleration of the center of mass, Figure 3(b) is the amplitude frequency response of pitching angular acceleration of the center of mass, Figure 3(c) is the amplitude frequency response of rolling angular acceleration of the center of mass, Figure 3(d) is the amplitude frequency response of deflection offront-left suspension, Figure 3(e) is the amplitude frequency response of dynamic displacementof front-left tire. As it can be seen from Figure 3, there is a resonance peak between 1 Hz frequency and 10 Hz frequency caused by the electromagnetic exciting

ISSN: 2414-1895
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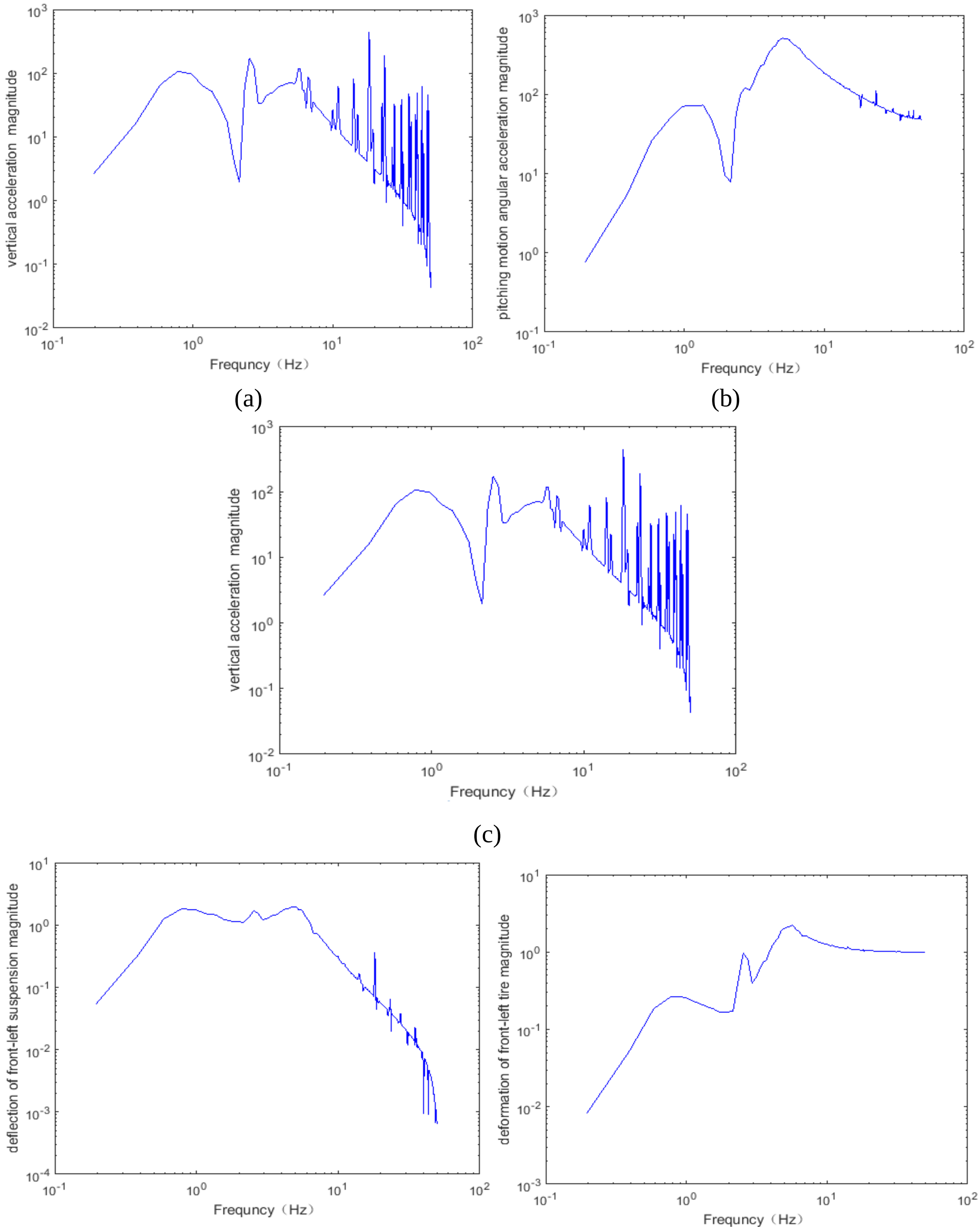
force of hub motor. Obviously, the resonance in this human sensitive frequency range will have an adverse impact on the ride comfort of the vehicle; meanwhile, the electromagnetic exciting forces also motivate the high frequency oscillations of the system. In particular, the high frequency resonance peak of the vertical vibration acceleration of the body is exceeded the vibration amplitude of the low frequency resonance region, which will cause the high frequency resonance to be the main vibration domain of the system.



(a) (b)

(c)

(d) (e)

Fig. 3 The results of amplitude frequency response

5. Conclusion

In view of the above analysis, the conclusions which we can draw are as followed: Under the coupling of road excitation and electromagnetic excitation, the vibration characteristics of EV driven by hub motor have been changed greatly. Electromagnetic excitation will motivate the vibration in the most sensitive frequency of human, and the large high-frequency oscillation will also have an adverse impact on ride comfort. Therefore, in order to solve the negative impact of the vibration of the hub motor, it is important for reasonable installation of the motor and the matching of the suspension. The above analysis conclusions can give the reference significance for the improvement of suspension and control strategy, and provide theoretical basis and guidance direction for the research of semi-active suspension control strategy of EV driven by hub motor.

Acknowledgments

This work was financially supported by Hubei Key Laboratory of Hydroelectric Machinery Design and Maintenance fund (2018KJX09) and Yichang Key Laboratory of Robot and intelligent System fund (JXYC00014).

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