Influences Analysis of In-wheel Motor on EV Vibration Performance  

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Keywords: In-wheel motor EV, Vibration performance, In-wheel motor, Unsprung mass, One-quarter vehicle model.

Abstract. To analyse the influence of the increased unsprung mass on electric vehicle vibration performance as in-wheel motor embedded within the hub, Using one-quarter vehicle system with two degree-of-freedom, the vibration model of in-wheel motor electric vehicle is established, and the vibration performance indexes are presented. The frequency response characteristics and statistical characteristics of vibration response quantity are built by the method of frequency domain analysis. The influence of the increased unsprung mass on the vibration performance of electric vehicle is analysed based on B-level road and urban driving condition. The results show that vehicle speed variation has greater impact on the vibration response variables of in-wheel motor electric vehicle; and the increased unsprung mass of in-wheel motor electric vehicle exerts a little influence on body acceleration and wheel displacement, but has a serious impact on wheel acceleration and an evident influence on relative dynamic load of wheel, as well as a certain influence on suspension deflection.

Introduction  

In-wheel motor drived electric vehicle, which makes the driving motor embedded into hub, is simplest in arrangement and most efficient in transmission electric vehicle. Despite its remark-able advantages, in-wheel motor drived vehicle increases unsprung mass, which leads to a higher mass of unsprung mass. The increased unsprung mass directly affects the contact performance of tires, thus influences the driving performance of electric vehicle. Based on this problem, some studies were carried out at home and abroad [1-12].

A 1/4vehicle system with 2-DOF (Degree of Freedom) was used in reference [1-2]and show that reduction in unsprung mass can lead to a reduction in tire deformation and sprung mass acceleration, whose result was analysed by change in unsprung mass and simulation of suspension damping. However, the results of the reference[1] was obtained without showing how to choose pavement type and vehicle speed as well as the relationships between the unsprung mass and pavement type, references[2] did not explain to affect the vibration performance of in-wheel motor drive electric vehicles.

Based on foreign researches, the negative effect of vehicle vertical vibration caused by the increase in unsprung mass of in-wheel motor drive vehicle was put forward in Reference[3-5]. Active suspension was designed by using the one-quarter car model to overcome the negative effect. The influence of the unsprung mass on root mean squares of body acceleration, suspension dynamic deflection and wheel dynamic load was analyzed. However, the road type, which was between A and B level, used in reference [3] is not the representative in the time-domain simulation. Although reference [4-5] overcame the shortcoming of [3] by utlizaing B-level road type, simulation with vehicle speed at 36km/h could not consider the influence of the speed change.
In reference [6-8]. A new dynamic damper mechanism was proposed, based on the vibration analysis of the central motor drive and in-wheel motor drive structures, to achieve the same vibration performance of the two kinds of electric vehicles driven by wheel motor and central motor respectively. But the reason for choosing road type and vehicle speed was not explained. In reference[9-10], the RMS for body acceleration, suspension deflection and wheel load, motor acceleration of the micro electric vehicle were analyzed under the combination of vehicle parameters and the premise of B level road type and vehicle speed at 36km/h. However, the combination of the parameters brought so many changes. Besides, the results of the study were only suitable for one vehicle speed,

1/4 vehicle system with 2-DOF is established to evaluate the reason for the vibration performance of the in-wheel motor drive electric vehicle caused by the increase of the unsprung mass is not given clearly. In this paper, a vibration model is presented by using one-quarter system, and corresponding vibration performance indexes are proposed. By simlution in urban drive cycle, vibration performance of the in-wheel motor drive electric vehicle is obtained, and the result is analyzed to lay the foundation for the improvement, optimization and control of the vibration performance of the in-wheel motor drive electric vehicle.

**Vibration Model**

**1/4Vehicle System with in-wheel motor**

The mechanics description of the one-quarter vehicle model with wheel motor as shown in Fig.1, \( m_2 \) is sprung mass, \( m_1 \) is unsprung mass, \( k \) is vertical stiffness of the suspension, \( k_i \) is vertical stiffness of the wheel, \( c \) is the damping of the suspension, \( z_i \) is the vertical displacement of the wheel, \( z_2 \) is the vertical displacement of the body, and \( q \) is the road excitation.

![Figure 1. The Dynamic model of one-quarter vehicle System.](image)

For the dynamic model in Fig.1, Newton’s second law or Lagrange Equation can be used to obtain the vibration equations of the system:

\[
[m] \{\ddot{z}\} + [c] \{\dot{z}\} + [k] \{z\} = \{f\} \tag{1}
\]

\[
[m] = \begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}, \quad [c] = \begin{bmatrix} c & -c \\ -c & c \end{bmatrix}
\]
\[ [k] = \begin{bmatrix} k + k_i & -k \\ -k & k \end{bmatrix}, \{k_f\} = \begin{bmatrix} k_i \\ 0 \end{bmatrix} \]

\[ \{z\} = \begin{bmatrix} z_1, z_2 \end{bmatrix}^T, \{f\} = \begin{bmatrix} k \end{bmatrix} q \]

**Vibration Performance Indicators**

Vibration characteristic parameters of the one-quarter vehicle system, including body damping ratio \( \zeta_0 \), body partial frequency \( f_0 \), wheel damping ratio \( \zeta_i \), wheel partial frequency \( f_i \), and body main frequency \( f_1 \), wheel main frequency \( f_2 \), are given as follows:

\[ \zeta_0 = \frac{c}{2\sqrt{km_2}}, f_0 = \frac{1}{2\pi} \sqrt{\frac{k}{m_2}} \]

\[ \zeta_i = \frac{c}{2\sqrt{(k + k_i)m_1}}, f_i = \frac{1}{2\pi} \sqrt{\frac{k + k_i}{m_1}} \]

\[ f_i = \frac{a}{\sqrt{2} - \sqrt{\left(\frac{a}{2}\right)^2 - b}}, f_2 = \frac{a}{\sqrt{2} + \sqrt{\left(\frac{a}{2}\right)^2 - b}} \]

\[ a = f_0^2 + f_i^2, b = \frac{kk_i}{(2\pi)^4 m_1m_2} \]

The vibration response of the one-quarter vehicle system with 2-DOF consists of body vertical acceleration \( \ddot{z}_2 \), suspension dynamic deflection \( f_d \), and wheel relative dynamic load \( F_d/G \), where \( f_d \) and \( F_d/G \) can be expressed respectively as follows:

\[ f_d = z_2 - z_1 \]

\[ F_d = m_1\ddot{z}_1 + m_2\ddot{z}_2, G = (m_1 + m_2)g \]

Considering the fact that in-wheel motor increases the unsprung mass, wheel displacement \( z_i \) and wheel acceleration \( \ddot{z}_i \) are further presented to be additional vibration responses.

**Frequency Domain Analysis Method**

**System Frequency and vibration response Characteristics**

By taking Fourier Transform for both sides of the Eq (1), system frequency response characteristics can be obtained as in Eq (8).
\[ H(\omega) = \frac{\{z(\omega)\}}{q(\omega)} = ([k] - \omega^2 [m] + j\omega [c])^{-1} \{k_f\} \] (8)

Frequency response characteristics of vibration response are calculated based on the Fourier Transform as follows:

\[ H(\omega)_{z_{2-q}} = \frac{\ddot{z}_2(\omega)}{\dot{q}(\omega)} = -\omega^2 \frac{\dot{z}_1(\omega)}{\dot{q}(\omega)} = -\omega^2 H(\omega)_{z_{2-q}} \] (9)

\[ H(\omega)_{f_{j-q}} = \frac{\dot{f}_d(\omega)}{\dot{q}(\omega)} = H(\omega)_{z_{2-q}} - H(\omega)_{z_{1-q}} \] (10)

\[ H(\omega)_{F_{j/G-q}} = \frac{\ddot{F}_d(\omega)}{\dot{q}(\omega)G} = \frac{m_1\ddot{z}_1(\omega) + m_2\ddot{z}_2(\omega)}{\dot{q}(\omega)G} \]
\[ = -\frac{\omega^2}{G} \{m_1H(\omega)_{z_{1-q}} + m_2H(\omega)_{z_{2-q}}\} \] (11)

\[ H(\omega)_{z_{1-q}} = \frac{\ddot{z}_1(\omega)}{\dot{q}(\omega)} = -\omega^2 \frac{\dot{z}_1(\omega)}{\dot{q}(\omega)} = -\omega^2 H(\omega)_{z_{1-q}} \] (12)

**Statistical Characteristics of Vibration Response**

On the premise of assuming that vehicle system is linear, PSD of the vibration response can be expressed in the form

\[ G_x(f) = |H(\omega)_{x-q}^2 G_q(f), \omega = 2\pi f \] (13)

Where, \( G_x(f) \) is the PSD of vibration response \( x \).

The Root Mean Square value of the vibration response can be got by Eq(14)

\[ \sigma_p = \sqrt{\int_{f_l}^{f_u} G_p(f) df} \] (14)

Where, \( f_l \) is the lower frequency limit, and \( f_u \) is the upper frequency limit.

**Vibration Performance Study**

**Simulation Research on Vibration Performance**

In order to investigate in-wheel motor drive electric vehicle on vibration performance, a simulation model was built based on the in-wheel motor drive electric vehicle prototype from references [5-6], whose simulation parameters are given in Table 1.

In order to analyze the variation of the unsprung mass, in-wheel motor mass changes from 20kg to 50kg with 3kg as the step size. And B level road type is chosen to study the vertical performance of the in-wheel motor drive electric vehicle. Besides, in the view of urban
driving condition and in-wheel motor drive electric vehicle speed limited to 60km/h in downtown, vehicle speed varies from 10km/h to 60km/h with 10km/h as the step size.

Table 1. Simulation Parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Body Mass $m_2$/kg</td>
<td>202</td>
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<tr>
<td>Wheel Mass $m_1$/kg</td>
<td>38</td>
</tr>
<tr>
<td>Stif. of Susp. $k$/Nm(^{-1})</td>
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<td>Damp of Susp. $c$/Nsm(^{-1})</td>
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<td>Stif. of Tire $k_f$/Nm(^{-1})</td>
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Simulation Result and Analysis

Based on previous theoretical analysis, the simulation software is developed on the basis of Matlab to evaluate vibration performance of in-wheel motor electric vehicle.

Table 2. Vibration characteristic parameters of the in-wheel motor drive Electric Vehicle.

<table>
<thead>
<tr>
<th>Wheel Mass/kg</th>
<th>Body damping ratio</th>
<th>Wheel partial frequency/Hz</th>
<th>Body main frequency/Hz</th>
<th>Wheel damping ratio</th>
<th>Wheel partial frequency/Hz</th>
<th>Wheel main frequency/Hz</th>
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</table>

The vibration characteristics parameters of the in-wheel motor drive electric vehicle are shown in Table 2. With the increase in the wheel mass, body damping ratio and body partial frequency remain unchanged, but body main decreases slightly, wheel damping ratio, wheel partial frequency and wheel main frequency reduce obviously.

On the B level road, the relationships between vibration performance RMS of in-wheel motor drive electric vehicle and vehicle speed and wheel mass are shown in Fig.2. From Fig.2, with the increase in vehicle speed, the vibration performance RMS enlarges gradually, but the increment decreases. Wheel mass variation has little influence on body acceleration and wheel displacement, but has great impact on suspension deflection, wheel relative dynamic load and wheel acceleration. With the increase in wheel motor, the RMS of suspension deflection and wheel relative dynamic load increase gradually, but the wheel acceleration RMS decrease.
Figure 2. The influence of vehicle speed and wheel mass on vibration response.

Under the standard parameter of the wheel mass 38kg, vehicle speed changes from 10 km/h to 60km/h with step size of 10km/h, the change rate of the RMS of the body acceleration are 41.421%, 22.475%, 15.470%, 11.803% and 9.544% respectively. The change rates of the RMS of other vibration responses are similar to body acceleration.

Under the vehicle speed of 60km/h, wheel mass changes from 20kg to 50kg with step size of 3kg, the average change rate of the RMS of the body acceleration and body displacement are 1.18% and 1.59% respectively, namely unchanged. Average change rate of the RMS of suspension deflection and wheel acceleration are 6.24%, 19.00% and 35.74%.
Conclusion

(1) Because of the in-wheel motor, the unsprung mass increased, which changes the vibration performance indicators such as wheel damping ratio $\zeta_i$, wheel partial frequency $f_i$, and wheel main frequency $f_2$.

(2) Vibration performance of in-wheel motor drive electric vehicle is influenced by vehicle variation heavily. The peak value of RMS of the vibration response occurs at the highest speed.

(3) The increase in the unsprung mass of the vehicle, which weakens ride comfort barely and wheel displacement mildly, deteriorates wheel acceleration obviously, which means the reduction of the tire grounding and vehicle safety. Besides, it has some influence on suspension dynamic deflection and affcts the space layout of the suspension.

References


