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Influence of the Operating Conditions on Electric Vehicle Ride Comfort

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ABSTRACT

In order to evaluate the influence of the operating conditions on electric vehicle ride comfort, a dynamic model of quarter vehicle is established under the combination of in-wheel motor and road surface roughness. The weighted root-mean-square (r.m.s.) acceleration of the vertical vehicle body (a_{wb}) according to the international standard ISO 2631-1 (1997) is selected as an objective function to analyze the influence of the operating conditions on electric vehicle ride comfort. The obtained results indicate that the operating conditions of the vehicle greatly affect vehicle ride comfort. Especially the road surface conditions have large vibration amplitudes and low excitation frequencies.

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1. INTRODUCTION

The operating conditions of electric vehicles not only directly affect the durability of components, the life of the components of vehicle as well as the safety of vehicle movement, but also affect the electric vehicle ride comfort. A dynamic model of quarter vehicle was established with the combination of in-wheel motor and road surface roughness excitations to evaluate effect of in-wheel motor (IWM) suspension system on electric vehicle (EV) ride comfort according to the international standard ISO 2631-1 (1997) [1]. A 3-DOF quarter-vehicle dynamic model of an electric vehicle under two input excitation sources such as road surface roughness excitation and in-wheel motor excitation was established to evaluate the effects of design parameter of in-wheel motor suspension system (IMSs) on electric vehicle ride comfort according to the international standard ISO 2631-1 (1997) [2]. An electric vehicle dynamic model is established to evaluate the influence of the dynamics parameters of the electric vehicles on the ride comfort [3]. An electric dynamic model with the different battery mass distributions on the EV floor was established to increase the stability and movement safety of electric vehicles (EV) under various operation conditions [4]. A novel nonlinear dynamics model of the coupling system, which consists of the motor magnetic gap (MMG), was established to rearch the optimal parameter combination existing in the nonlinear dynamics model [5]. A simulation analysis on these four models: a sample car with no motor, a motor with fixed joint, and active/inactive control suspension for in-wheel motor was established to rearch the optimal parameter of inactive control suspension for in-wheel motor [6]. A 14-degree of freedom coupled vehicle dynamic model was established to rearch the optimal parameter of inactive control suspension for in-wheel motor [7]. A modified GPSO-LQG controller was proposed for one-quarter vehicle suspension with the purpose of optimizing suspension performance for entire speed ranges. After the introduction of one-quarter vehicle suspension model, road surface excitation model and magneto-rheological damper model, the GPSO-LQG controller was investigated with three weighted coefficients optimized by utilizing the Genetic Particle Swarm Optimization (GPSO) [8]. A semi-active air-suspension proportional–integral–derivative control system was proposed to study the influence of this change on ride comfort of vehicles driven by in-wheel motors using an 11 degrees of freedom of vehicle ride comfort model [9]. The major goal of this study is to establish a dynamic model of quarter vehicle under the combination of in-wheel motor and road surface roughness to analyze the influence of the operating conditions on electric vehicle ride comfort according to the international standard ISO 2631-1 (1997) [10].

2. ONE-QUARTER DYNAMIC MODEL OF ELECTRIC VEHICLE

A quarter-vehicle dynamic model of in-wheel-motor electric vehicle with three degrees of freedom and under two input excitation sources such as road surface roughness excitation is established to evaluate the influence of the operating conditions on electric vehicle ride comfort, as shown in Fig.1. In Fig.1, m_b is the vehicle body mass, m_m is in-wheel motor mass, m_a is vehicle axle mass, z_b, z_m and z_a are the vertical displacements of vehicle body, in-wheel motor, and vehicle axle masses, k,c, $k_{m1,2}$, c_m, and k_t, c_t are the stiffness and damping coefficients of the vehicle and in-wheel motor suspension systems and tire, q is input excitation function of road surface and F_{mz} is the excitation function of in-wheel motor in the vertical direction.

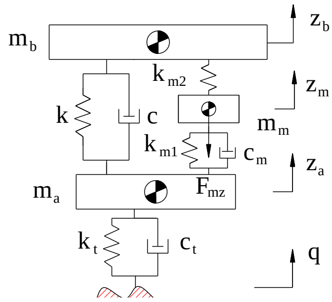

Fig.1. Quarter-vehicle dynamic model of in-wheel-motor electric vehicle

The equations of vehicle motion can be formulated in different ways such as Lagrange's equation, Newton-Euler equation, Jourdain's principle. In this study, Newton-Euler equation is chosen to describe the equations of vertical motion of electric vehicle. From quarter-vehicle dynamic model of in-wheel-motor electric vehicle as shown in Fig. 1, the dynamic equations of an electric vehicle are written as follows:

$$\begin{cases} m_b \ddot{z}_b = -\left[k(z_b - z_a) + c(\dot{z}_b - \dot{z}_a)\right] - k_{m2}(z_b - z_m) \\ m_m \ddot{z}_m = F_{mz} + k_{m2}(z_b - z_m) - \left[k_{m1}(z_m - z_a) + c_m(\dot{z}_m - \dot{z}_a)\right] \\ m_a \ddot{z}_a = \left[k_{m1}(z_m - z_a) + c_m(\dot{z}_m - \dot{z}_a)\right] + \left[k(z_b - z_a) + c(\dot{z}_b - \dot{z}_a)\right] - \left[k_t(z_a - q) + c_m(\dot{z}_a - \dot{q})\right] \end{cases} \quad (1)$$

Road surface excitation: It is described by various mathematical functions. In this study, the random road surface function is selected as the input function of the vehicle dynamic analysis problem. The random road surface roughness of random white noise is used as excitation source waveform for vehicle [1], the random road profile is produced by filtering the white noise using the following mathematical model of the road roughness.

$$\dot{q}(t) + 2\pi f_0 q(t) = 2\pi n_0 \sqrt{G_q(n_0) v(t)}\, w(t) \quad (2)$$

where, $G_q(n_0)$ is the road roughness coefficient which is defined for typical road classes from A to H according to ISO 8068(1995) [10], n_0 is a reference spatial frequency which is equal to 0.1 m, v(t) is the speed of vehicle; f_0 is a minimal boundary frequency with a value of 0.0628 Hz, n_0 is a reference spatial frequency which is equal to 0.1 m, w(t) is a white noise signal.

In-wheel motor excitation function: The excitation function of in-wheel motor in the vertical direction [1-2] is determined by

$$F_{mz} = m_s e \omega_R^2 \sin \omega_R t \quad (3)$$

where, m_s is the total mass of the tire, the rim and the motor rotor; e is the eccentricity of the rotor; ω_R is the angular velocity of the rotor.

3. VEHICLE RIDE COMFORT CRITERIA [2]

The time-domain method can be applied to evaluate the vehicle ride comfort according to ISO 2631-1 (1997) [11], in this study, the vibration evaluation based on the basic evaluation methods including measurements of the weighted root-mean-square (r.m.s.) acceleration defined as

$$a_{wz} = \left[\frac{1}{T}\int_0^T a_z^2(t)\,dt\right]^{1/2} \quad (4)$$

Where, $a_z(t)$ is the weighted acceleration (translational and rotational) as a function of time, m/s^2; *T* is the duration of the measurement, s.

For indications of the likely reactions to various magnitudes of overall vibration in the public transport and vehicle, a synthetic index-called the root-mean-square (RMS) acceleration, a_{wz} can be calculated from formula

Eq. (4); besides, the RMS value of the acceleration in vehicle would be compared with the values in Tab.1.

Tab.1: Comfort levels related to aw threshold values [11]

$a_w/(m/s^2)$	Comfort level
< 0.315	Not uncomfortable
0.315÷0.63	A little uncomfortable
0.5 ÷ 1.0	Fairly uncomfortable
0.8 ÷ 1.6	Uncomfortable
1.25 ÷ 2.5	Very uncomfortable
> 2	Extremely uncomfortable

4. RESULTS AND DISCUSSION

In order to evaluate the influence of the operating conditions on electric vehicle ride comfort. The equations of motion of Eq. (1) are simulated and analyzed in the Matlab/Simulink environment with a set of parameters referenced in the documentation [12] when vehicle moves on ISO class B road surface at vehicle speed of 80 km/h and in-wheel motor vertical exciting force F_{mz0}=2295cos(100πt)/N and full load. Time domain acceleration response of vehicle body is shown in Fig.2.

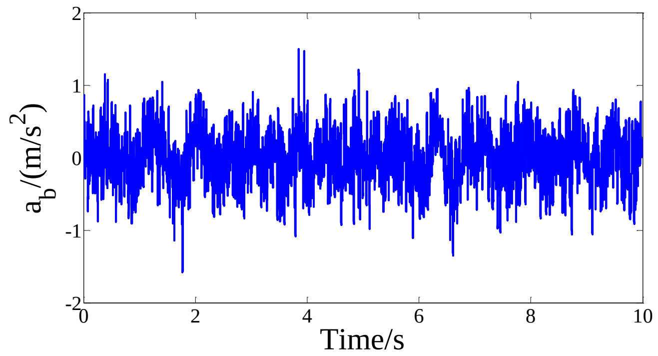

Fig.2. Time domain acceleration response of in-wheel-motor electric vehicle body

From the results of Fig. 2, we could determine the value of the RMS acceleration of the vertical vehicle body (a_{wz}) through Eq. (4) according to the international standard ISO 2631-1 is 0.3716 m/s^2. This result, compared with Tab.1, shows that human may feel a little uncomfortable. The vehicle's operating conditions will continue to be reviewed and evaluated in in the following section.

Influence of road surface conditions: The vehicle moving on the different road surface conditions, five road surface conditions from ISO class A road surface to ISO class E road surface according to ISO 8068(1995) are selected for evaluation when vehicle moves at speed of 80 km/h and in-wheel motor vertical exciting force F_{mz0}=2295cos(100πt)/N and full load. The values of the root mean square (r.m.s) acceleration responses the vertical in-wheel-motor electric vehicle body (a_{wb}) with variable road surface conditions based on the International Standard ISO 2631-1: 1997 which are determined through Eq. (4), as shown in Fig 3. From the results of Fig 3, it shows that the a_{wb} values increase height fast when electric vehicle moves on poor and very poor road surface conditions, especially ISO class D road surface and ISO class E road surface. The a_{wb} values respectively increase 52.80%, 44.67%, 43.06% and 44.89 % when electric vehicle moves on from ISO class A road surface to ISO class E road surface which make the electric vehicle comfort worse, when the road surface conditions become worse.

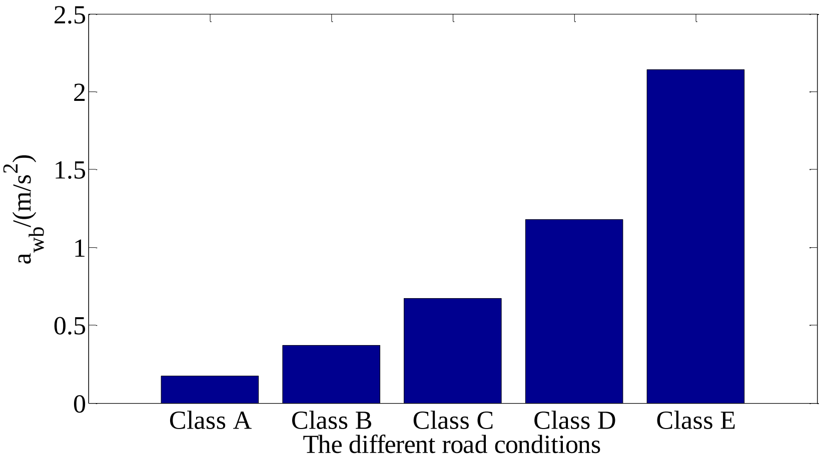

Fig.3. a_{wb} values with variable road surface conditions

Influence of electric vehicle conditions: The different electric vehicle speed conditions from 40 km/h to 90 km/h are selected to evaluate the influence of the operating conditions on electric vehicle ride comfort when vehicle moves on ISO class B road surface and full load. The a_{wb} values with variable vehicle velocity conditions are shown in Fig.4. From the results Fig 4, we show that the a_{wb} values respectively increase when the value of the electric vehicle speed increases. The a_{wb} values respectively increase 10.23%, 8.61%, 7.45%, 6.08% and 5.45 % when the velocity increases which make the electric vehicle comfort become worse, when the velocity increases.

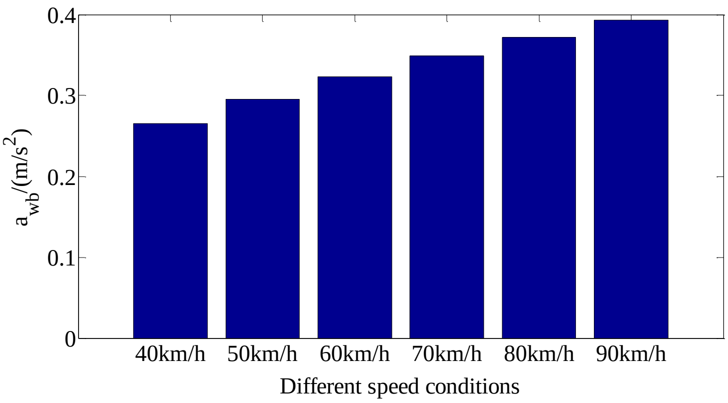

Fig.4. a_{wb} values with variable vehicle velocity conditions

5. CONCLUSION

In this paper, a dynamic model of quarter vehicle is established under the combination of in-wheel motor and road surface roughness to evaluate the influence of the operating conditions on electric vehicle ride comfort according to the international standard ISO 2631-1 (1997). The major conclusions drawn from the analysis can be summarized as follows: (1) The a_{wb} values increase height fast when electric vehicle moves on poor and very poor road surface conditions, especially ISO class D road surface and ISO class E road surface; (2) The a_{wb} values respectively increase when the value of the electric vehicle speed increases and the a_{wb} values respectively increase 10.23%, 8.61%, 7.45%, 6.08% and 5.45 % when the velocity increases. The study results provide a useful document for designers and manufacturers in the field of the in-wheel-motor electric vehicle suspension design.

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