https://doi.org/10.31871/WJRR.12.6.10
World Journal of Research and Review (WJRR)
ISSN: 2455-3956, Volume-12, Issue-6, June 2021 Pages 29-32

Effects of Design Parameter of In-Wheel Motor Suspension System on Electric Vehicle Ride Comfort

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***Abstract*- The main goal of this paper is to evaluate the effects of design parameter of in-wheel motor suspension system (IMSs) on electric vehicle ride comfort. In order to achieve this goal, 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 is established for simulation and evaluation. The equations of vertical motion of electric vehicle are described using Newton-Euler equation which are solved via Matlab/Simulink software. The root-mean-square (RMS) acceleration of the vertical vehicle body according to the international standard ISO 2631-1 (1997) is selected as an evaluation criteria of vehicle ride comfort. In-wheel suspension parameters such as stiffness and damping coefficients are respectively analyzed and evaluated its effect on vehicle ride comfort. The study results indicate that these parameters of IMSs have a great effect on vehicle ride comfort. The stiffness values of IMSs increase, vehicle ride comfort is going to be worse and vice versa vehicle ride comfort is improved. The study results provide a theoretical basis for designing IMSs for electric vehicles.**

***Index Terms*—Electric vehicle, In-wheel motor, Suspension, Ride comfort.**

I. INTRODUCTION

Electric vehicles are a popular alternative to vehicles using internal combustion engines. Therefore, the competition between electric vehicle manufacturers is becoming more and more fierce on both the price and the quality of the vehicle. The suspension system of an electric vehicle plays an important role in improving the comfort of the vehicle which is an interesting topic for researchers in recent years. A study on the effect of in-wheel motor suspension on vehicle ride comfort was analyzed and evaluated based on a dynamic model of quarter vehicle with the combination of IWM and road surface roughness excitations [1]. The vertical performance of electrical vehicles driven by suspended in-wheel motors was proposed to search for optimal parameters for the suspension to improve the ride comfort based on multi-objective optimization method [2]. The parameters of the in-wheel spring and rubber bushing of in-wheel-motor electric vehicle (IWM EV) were optimized through an improved particle swarm optimization (IPSO) algorithm and then in-wheel damper was controlled via a fuzzy proportional-integral-derivative (PID) method to enhance ride comfort of electric vehicle [3]. A semi-active air-suspension proportional–integral–derivative control system was proposed and analyzed for improving the vehicle ride comfort using a vehicle ride comfort model with 11 degrees of freedom [4]. In-wheel motor- (IWM-) suspensions coupling system of an electric vehicle were optimized through an artificial fish swarm algorithm (AFSA) to enhance ride comfort of electric vehicle [5]. The evaluation of effect of in-wheel electric motors mass on the performance of active suspension system by using one of more common control methods which is Linear Quadratic Regulator (LQR) was proposed and analyzed in the direction of improving vehicle ride comfort [6]. The dynamic vibration-absorbing structures (DVAS) for EVs driven by in-wheel motors (IWM) were proposed and optimized by a multi-objective optimization problem via a particle swarm optimization approach to improve vehicle ride comfort [13]. The optimal parameters in active suspension system were found out using Particle Swarm Optimization (PSO) method and then a Liner Quadratic Gaussian (LQG) controller was used to control for an active suspension system [14]. The effects of design parameter of in-wheel motor suspension system (IMSs) on electric vehicle ride comfort surveyed and evaluated its effects on vehicle ride comfort based 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 and the root-mean-square (RMS) acceleration of the vertical vehicle body according to the international standard ISO 2631-1 (1997).

II. MATHEMATICAL MODEL OF IWM EV

A. *Quarter-Vehicle Dynamic Model*

A quarter-vehicle dynamic model of in-wheel-motor electric vehicle (IWM EV) with three degrees of freedom and under two input excitation sources such as road surface roughness excitation is established to evaluate the effect of design parameter of in-wheel motor suspension system (IMSs) on electric vehicle ride comfort, as shown in Fig.1.

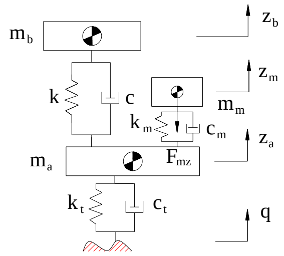

Figure.1: Quarter-vehicle dynamic model of IWM EV

Explanation of Fig.1, m_b is the vehicle body mass, m_m is

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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_m, 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.

B. *Equation of motion*

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 IWM EV as shown in Fig. 1, the dynamic equations of an electric vehicle are written as follows:

$$\begin{cases} m_b\ddot{z}_b = -\left[k(z_b - z_a) + c(\dot{z}_b - \dot{z}_a)\right] \\ m_m\ddot{z}_m = F_0 \sin\omega t - \left[k_m(z_m - z_a) + c_m(\dot{z}_m - \dot{z}_a)\right] \\ m_a\ddot{z}_a = \left[k_m(z_m - z_a) + c_m(\dot{z}_m - \dot{z}_a)\right] + \\ +\left[k(z_b - z_a) + c(\dot{z}_b - \dot{z}_a)\right] - \left[k_t(z_a - q) + c_m(\dot{z}_a - \dot{q})\right] \end{cases} \quad (1)$$

C. *Input excitation*

Road surface excitation function: There are many mathematical functions that describe road surface roughness such as harmonic function, random function, etc. In this study, the random road surface function of random white noise is selected as input excitation source waveform for an electric vehicle [7], the random road function 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 (very good) to F (very poor) according to ISO 8068(1995) [8], 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 [1,11, 12] is determined by

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

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.

III. VEHICLE RIDE COMFORT CRITERIA

The time-domain method can be applied to evaluate the vehicle ride comfort according to ISO 2631-1 (1997) [9], in this study, the vibration evaluation based on the basic evaluation methods including measurements of the weighted root-mean-square (RMS.) 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 Table-1.

Table 1: Comfort levels related to a_w threshold values [9]

$a_w/(m/s^2)$	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

IV. ANALYSIS AND DISCUSSION

In order to evaluate the effects of design parameter of in-wheel motor suspension system (IMSs) 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 [10] when vehicle moves on ISO class B road surface at vehicle speed v=72 km/h and IWM vertical exciting force F_{mz0}=2295cos(100πt)/N. Time domain acceleration response of vehicle body is shown in Fig.2.

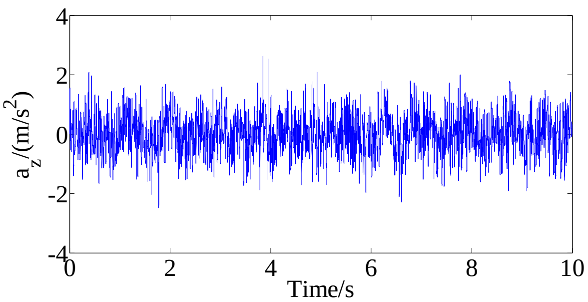


Figure 2: Time domain acceleration response of vehicle body

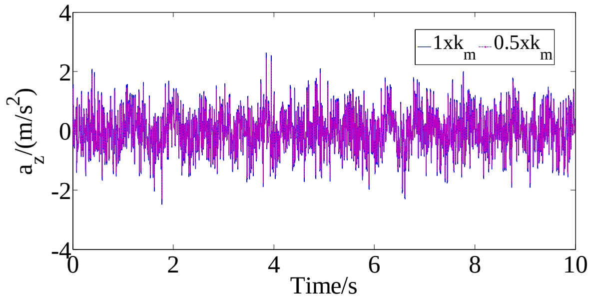
From the results of Fig. 2, we could determine the value of the RMS acceleration of the vertical vehicle body (a_{wz}) through Eq. (4) according to the international standard ISO 2631-1 is 0.62 m/s^2. This result, compared with Tab.1, shows that human may feel a little uncomfortable.

Three values of IMSs stiffness k_m= [0.5, 1.0 2.0]xk_{m0} with k_{m0} is the stiffness value of the original IMSs[10] are selected to investigate its effects on electric vehicle ride comfort. Time domain acceleration response of vehicle body with three values of IMSs stiffness when vehicle moves under the same condition as above is shown in Fig.3. The values of the RMS acceleration of the vertical vehicle body with variable stiffness values of IMSs are shown in Tab.2.

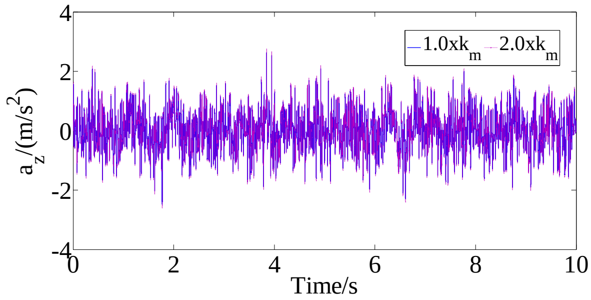
Table.2. The values of the RMS acceleration of the vertical vehicle body with variable stiffness values of IMSs

Parameters	0.5xk_m	1.0xk_m	2.0xk_m
$a_{wz}/(m/s^2)$	0.57	0.62	0.69

From the results of Fig.2, we can see that the peak values of time domain acceleration response of vehicle body respectively decrease with the decrease of k_{m0}. The value of the RMS acceleration of the vertical vehicle body with $1.0xk_{m0}$ value reduces by 6.9% in comparison with $0.5xk_{m0}$ value, which makes vehicle ride comfort improve. The peak values of a_z respectively increase with the increase of k_{m0}. The a_{wz} value with $1.0xk_{m0}$ increases by 8.8% in comparison with $0.5xk_{m0}$ value. This makes vehicle ride comfort decline.



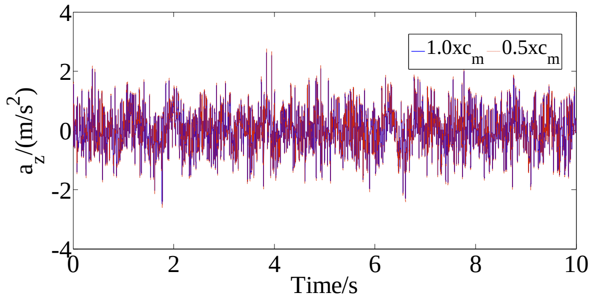
(a) With the decrease of k_m



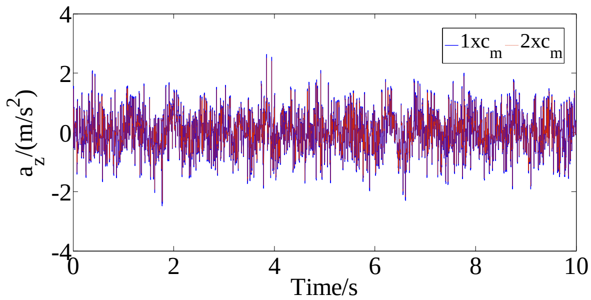
(b) With the with the increase of k_m

Figure 3: Time domain acceleration response of vehicle body with variable stiffness values of IMSs

Three values of damping IMSs c_m=[0.5, 1.0 2.0]xc_{m0} with c_{m0} is the damping value of the original IMSs[10] are selected to investigate its effects on electric vehicle ride comfort. Time domain acceleration response of vehicle body with three values of damping IMSs when vehicle moves under the same condition as above is shown in Fig.4. The values of the RMS acceleration of the vertical vehicle body with variable stiffness values of IMSs are shown in Tab.3.



(a) With the decrease of c_m



(b) With the with the increase of c_m

Figure 4: Time domain acceleration response of vehicle body with variable damping values of IMSs

Table.3. The values of the RMS acceleration of the vertical vehicle body with variable damping values of IMSs

Parameters	$0.5xc_m$	$1.0xc_m$	$2.0xc_m$
$a_{wz}/(m/s^2)$	0.71	0.62	0.55

From the results of Fig.3, we can see that the peak values of a_z respectively increases with the decrease of c_{m0}. The a_{wz} value with $1.0xc_{m0}$ value increases by 14.5% in comparison with $0.5xc_{m0}$ value. This makes vehicle ride comfort decline. The peak values of a_z respectively reduce with the increase of c_{m0}. The a_{wz} value with $1.0xc_{m0}$ reduces by 12.7% in comparison with $2.0xc_{m0}$ value, which makes vehicle ride comfort improve.

V. CONCLUSION

A quarter-vehicle dynamic model of in-wheel-motor electric vehicle (IWM EV) with three degrees of freedom and under two input excitation sources such as road surface roughness excitation is proposed to evaluate the effects of design parameter of in-wheel motor suspension system (IMSs) on electric vehicle ride comfort. The major conclusions that can be drawn from the analysis can be summarized as follows: (1) The peak values of a_z respectively increase with the increase of k_{m0} and a_{wz} values increase with the increase of $k_{m0,}$ which makes vehicle ride comfort to be getting worse and (2) the peak values of a_z respectively reduce with the increase of c_{m0} and a_{wz} value reduces with the increase of $c_{m0,}$ which makes vehicle ride comfort improve. The study results are the theoretical basis for the optimal design of the electric vehicle suspension system.

ACKNOWLEDGMENT

This research was financially supported by Thai Nguyen University of Technology, TNUT, Vietnam.

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