Effects of Suspension Design Parameters of an Electric Vehicle on Ride Comfort

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Abstract - *The suspension system plays an important role in improving vehicle comfort as well as reducing the dynamic load of the wheels acting on the road surface. Design parameters of an electric vehicle suspension system such as stiffness and damping coefficients are respectively analyzed to evaluate their effects on vehicle ride through the root-mean-square (r.m.s.) acceleration of the vehicle body according to the international standard ISO 2631-1 (1997) based on a quarter-vehicle model of the in-wheel motor (IWM) configuration with the motor. The obtained results indicate that the design parameters of suspension system have a significant effect on vehicle ride comfort. In addition, the research results also indicate the optimal parameters for the electric vehicle suspension system to improve vehicle ride comfort.*

Key Words: Electric vehicle, suspension system, stiffness coefficient, damping coefficient, dynamic model, ride comfort.

1. INTRODUCTION

Electric vehicles widely use in the market with outstanding advantages in terms of environmental pollution. The electric vehicle market has been competitive between car manufacturers in terms of both price and ride comfort quality. In order to improve vehicle ride comfort, the characteristics of the suspension system of electric vehicle play an important role to vehicle ride comfort. The effect of in-wheel motor (IWM) suspension system on electric vehicle (EV) ride comfort was conducted for analysis based on a dynamic model of quarter vehicle with the combination of IWM and road surface roughness excitations [1]. The amplitude-frequency and vibration response characteristics of the suspension of an electric mini off-road vehicle were analyzed with the natural frequencies of the front and rear suspensions selected in accordance with the required driving performance [2]. A novel in-wheel (IW) active vibration system for an IW motor (IWM)-driven electric vehicle was proposed and analyzed via a fuzzy optimal sliding mode (FOSM) control method based on a 6 degree-of-freedom (DOF) vehicle model to improve electric vehicle ride comfort [3]. A magnetorheological semi active suspension system of an electric vehicle was proposed and controlled to improve the EV conversion ride comfort performance based on a dynamic model of an electric vehicle with 7 degrees of freedom [4]. An active suspension of hub-driven electric vehicles (EVs) was proposed and controlled using a robust control method to improve vehicle ride comfort [5]. A SAS-Controlled Active Suspension System was proposed and controlled using a validated 7 degrees of freedom of vehicle's ride model and vehicle's ride comfort performance was evaluated by improvement with an active suspension system [6]. An active suspension system in EV conversions ride model was proposed and controlled to further improve the EV conversion's ride comfort performance [7]. An in-wheel vibration absorber for in-wheel-motor electric vehicles (IWM EVs) was proposed and optimized via a particle swarm optimization (IPSO) and then a linear quadratic regulator (LQR) algorithm was developed to control suspension damper to improve vehicle ride comfort [8].

In this paper, a quarter-vehicle model of the in-wheel motor (IWM) configuration with the motor of an electric vehicle with three degrees of freedom is proposed under two combined excitation sources of road surface and electric motor to investigate the effects on the design parameters of an electric vehicle suspension system on the value of the root-mean-square (r.m.s.) acceleration of the vertical vehicle body according to the international standard ISO 2631-1 (1997) [15]

2. QUARTER -VEHICLE RIDE DYNAMIC MODEL

A quarter-vehicle model of an in-wheel motor (IWM) electric vehicle with three degrees of freedom is established under two combined excitation sources of road surface and electric motor based on reference [8], as shown in Fig-1, where m_b, m_t, and m_m are vehicle body mass, wheel assembly mass, electric motor mass, respectively; k, k_{m1}, k_{m2}, and k_t are the suspension stiffness, in-wheel spring stiffness, bolt stiffness, and tire vertical stiffness, respectively; c, c_m and c_t are the vehicle suspension damping coefficient, in-wheel damper damping coefficient, tire damping coefficient, respectively and F_{mz} is the in-wheel motor excitation function and q is road surface excitation function

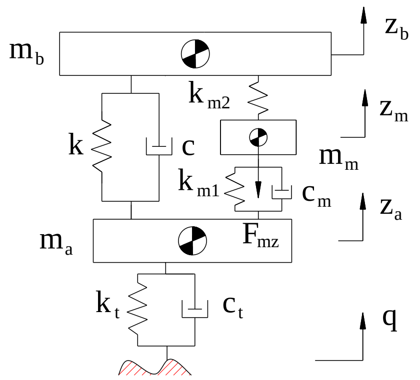

Fig-1: Quarter-vehicle model of an in-wheel motor (IWM) electric vehicle

The equations of motion: The equations of motion for Fig-1 using Newton's second law of motion are written below

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

Road surface excitation function[1],[9],[10]: The road surface roughness is usually assumed to be a zero-mean stationary Gaussian random process and can be generated through an inverse Fourier transformation based on a power spectral density (PSD) function. The time domain excitation of the uneven road surface is generated as the sum of a series of harmonics:

$$q(t) = \sum_{k=1}^{N} \sqrt{2G_q\left(f_{mid-k}\right)\Delta f_k}\,\sin\left(2\pi f_{mid-k}t + \varphi_k\right) \tag{2}$$

where, $G_q(f_{mid-k})$ is power spectrum according to ISO 8608:2016[16], m²/Hz; Δf is the frequency range, Hz; t is time, s; φ_k is the random phase uniformly distributed from 0 to 2π.

In-wheel motor excitation function [1], [11]: The nonlinear forces of the bearing in the X direction and Z direction can be obtained according to Eq. (3), as follows.

$$\begin{cases} F_{mz} = m_s e \omega_r^2 \sin\left(\omega_r t\right) \\ F_{mx} = m_s e \omega_r^2 \cos\left(\omega_r t\right) \end{cases} \tag{3}$$

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

Currently there are many methods to evaluate the vehicle ride comfort such frequency-domain method, time-domain method [12], [13], [14]. This study is based on ISO 2631-1 (1997), the vibration evaluation based on the basic evaluation method including measurements of the weighted root-mean-square (r.m.s.) acceleration is defined by:

$$a_w = \left[\frac{1}{T}\int_0^T a_w^2(t)dt\right]^{1/2} \tag{4}$$

where, $a_w(t)$ is the weighted acceleration (translational and rotational) as a function of time, m/s²; T is the duration of the measurement, s.

In this way, a synthetic index-called vertical weighted r.m.s. acceleration, a_w can be calculated from formula Eq. (4) and the r.m.s. value of the vertical acceleration in vehicle would be compared with the values in Tab-1, for indications of likely reactions to various magnitudes of overall vibration in the public transport.

Table- 1: Comfort levels related to a_w threshold values

a_w/(m.s²)	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

The equations of motion of Eq.(1) are simulated and calculated by Matlab/Simulink software according to the reference [8] when vehicle moves on ISO class B road surface at vehicle v=87 km/h and IWM excitation force of F_{mz}= 2398sin188t (N). Time domain acceleration of response vehicle body is shown in Fig-2. The value of the root-mean-square (r.m.s.) acceleration of the vehicle body is determined by Eq.(4) which achieved as a_{wb}=0.67 m/s² and this value satisfies uncomfortable condition for human (according to Tab-1).

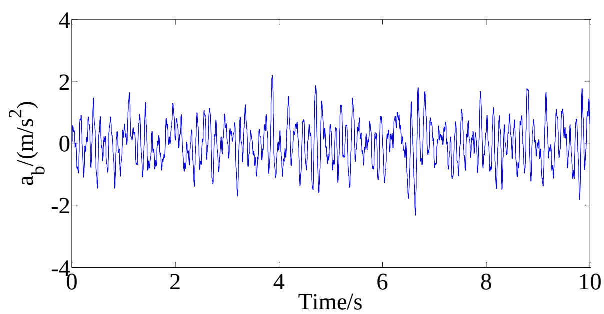

Fig-2: Time domain acceleration of response vehicle body

The suspension stiffness coefficient values from 0.2xk value to 2.0xk (k is the value of the stiffness coefficient of the original suspension system of an electric vehicle) are investigated its effects on the value of the root-mean-square (r.m.s.) acceleration of the vehicle body (a_{wb}) when vehicle moves on ISO class B road surface at vehicle v=87 km/h and IWM excitation force of F_{mz}= 2398sin188t (N). The a_{wb} value with variable stiffness coefficient of the original suspension system is shown in Fig-3. From the result of Fig- 3 we see that the value of the stiffness suspension system increases, a_{wb} value increases which leads to reduce vehicle ride comfort.

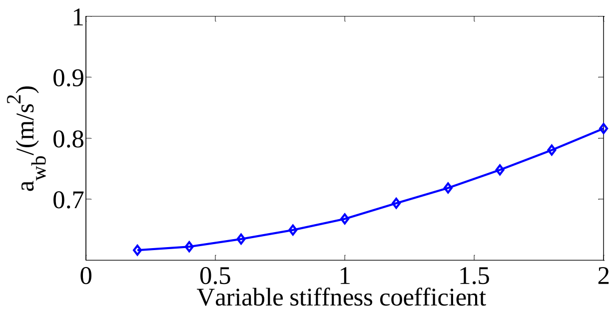

Fig-3: a_{wb} value with variable stiffness coefficient of the original suspension system

The suspension damping coefficient values from 0.2xc value to 2.0xc (c is the value of damping coefficient of the original suspension system of an electric vehicle) are investigated its effects on the value of the root-mean-square (r.m.s.) acceleration of the vehicle body (a_{wb}) when vehicle moves on ISO class B road surface at vehicle v=87 km/h and IWM excitation force of F_{mz}= 2398sin188t (N). The a_{wb} value with variable damping coefficient of the original suspension system is shown in Fig-4. From the result of Fig- 4, we see that the value of the damping suspension system increases, a_{wb} value reduce and then it increases. The optimal value of a_{wb} =0.55 m/s² at 0.4xc value which reduce by 21.8% in compared with parameters of the original suspension system.

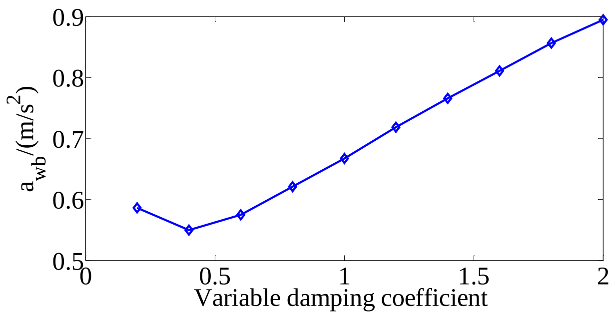

Fig-4: a_{wb} value with variable damping coefficient of the original suspension system

5. CONCLUSIONS

In this study, the effects on the design parameters of an electric vehicle suspension system on the value of the root-mean-square (r.m.s.) acceleration of the vertical vehicle body are analyzed for evaluating efficiency based on a 3-DOFs quarter-vehicle model of an electric vehicle under two combined excitation sources of road surface and electric motor. The obtained results indicated that suspension design parameters of an electric vehicle suspension system have a significant effect on vehicle ride comfort. In addition, the study result has shown that the optimal value of a_{wb} =0.55 m/s² at 0.4xc value which reduce by 21.8% in compared with parameters of the original suspension system.

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