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Electric vehicles with in-wheel switched reluctance motors: Coupling effects between road excitation and the unbalanced radial force

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ABSTRACT

The switched reluctance motor (SRM) has great application potential in in-wheel motor electric vehicle (IWM-EV) due to its advantages, such as a high starting torque for initial acceleration, a wide operating speed range and high efficiency to extend the battery service life. However, these advantages are overshadowed by its inherent vibration and noise due to the unbalanced radial force. For the vehicle vibration system, the vertical component of SRM unbalanced radial force, namely SRM vertical force, is one of the major concerns. This paper analytically investigates the coupling effect of SRM vertical force and road excitation on IWM-EV vibration. First, the system dynamics model of IWM-EV and IWM driving EV controller are proposed to include SRM vertical force; then the analytical models are solved to predict the vehicle dynamic responses at different speeds on periodic and stochastic road inputs with various amplitudes and coherence functions between left- and right-sides of the vehicle. It is concluded that SRM vertical force is highly coupled with road excitation and SRM airgap eccentricity, and such coupling effects yield a great impact on vehicle vertical vibration dynamics.

1. Introduction

Recently, in-wheel motor electric vehicle (IWM-EV) has brought significant attention in automotive industry due to its remarkable merits: integrated configuration, tiny space and weight, efficient power transfer, fast and precise independent speed and torque control, as well as its convenience to implement X-by-Wire chassis control system (ABS, ESP and TCS), etc. To maximize these advantages and performance of IWM-EV, many studies have been conducted, including the driving torque control [1,2], vehicle state estimation methods [3,4], the drive-by-wire controller and electric differential control of in-wheel motor for electric vehicle [5], as well as energy management approach [6,7], etc.

As one of the key components of propulsion system, electric motor plays a critical role in IWM-EV dynamics. Nowadays, Switched Reluctance Motor (SRM) has received more and more attentions for in-wheel motor applications due to its advantages: a high starting torque for initial acceleration, a wide operating speed range and high efficiency to extend the battery service life [8,9]. However, these advantages are overshadowed by its inherent torque ripple, vibration and noise, which seriously hindered the applications of SRM for in-wheel motor [10–13]. The residual unbalanced radial force caused

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by airgap eccentricity is one of the main reasons for SRM vibration [12–14]. To suppress SRM vibration, some structures and controllers [15–17] have been investigated by eliminating SRM torque ripple and radial force. These studies contribute to suppress SRM vibration, however the SRM effect on vehicle vibration characteristic has not been considered enough.

For the electric vehicle vibration system, the vertical component of SRM residual unbalanced radial force, namely SRM vertical force, is one of the major concerns. The SRM vertical force, airgap eccentricity and road excitation may be highly coupled as shown in Fig. 1, where the road excitation induces SRM stator and rotor vibration, which will cause airgap deformation, i.e. airgap eccentricity. The airgap eccentricity yields SRM vertical force. Meanwhile, SRM vertical force has negative effect on stator and rotor vibration which will eventually aggravate airgap eccentricity. So the airgap eccentricity and SRM vertical force is coupled with each other along with the road excitation. Unlike the traditional vehicle propulsion systems with a torque vibration damper, the SRM applies the SRM vertical force excitation directly on wheel, which will induce great negative effect on IWM-EV vibration performance. It is thus imperative to consider such coupling effects in the analysis of IWM-EV vibration performance.

In the previous work [18,19], the SRM vibration and corresponding control methodology has been investigated assuming constant SRM eccentricity, but the coupling between road excitation, SRM airgap eccentricity and vertical force was not considered. Following the previous work, this study will consider such coupling effect, with the organization as follows: a full IWM-EV model and SRM driving EV controller are proposed followed by a preliminary analysis of SRM vertical force. Then the IWM-EV vibration coupling effect between the SRM airgap eccentricity, its vertical force, and road excitation is analyzed followed by the conclusions drawn from this study.

2. IWM-EV modeling

The primary objective of this study is to understand the coupling effects mentioned above, the required vehicle dynamics model thus needs to reflect the contributions of those coupling factors. In this study, the IWM-EV model consists of three sub-models: (i) the nonlinear vehicle model that highlights the effect of SRM vertical force on vehicle vibration; (ii) the SRM controller model that provides the desired torque for IWM-EV according to the desired vehicle speed; and (iii) SRM vertical force model used to predict SRM vertical force that is derived from the driving torque acting on the wheel.

2.1. Vehicle model

To simulate the vehicle dynamic responses subjected to various types of road excitations at different speeds, a vehicle model is developed as shown in Fig. 2, where the vertical force of SRM is brought into IWM-EV. The model consists of 11 degrees of freedom (DOF) including the vertical, pitch and roll motion of the sprung mass (M_b), the vertical motion of the aggregate mass of tyre, rim and SRM rotor (M_{uij}), and vertical motion of the aggregate mass of SRM stator and housing (M_{msij}) at the four corners, respectively. The major assumptions of this model include (i) the suspension compliances in longitudinal and lateral directions are negligible; (ii) the applied effective road profile remain unchanged at different speeds and tyre normal loads; and (iii) the front and rear suspensions have linear stiffness and damping characteristics, the tyres have only linear stiffness and do not lift off.

Based on the assumptions mentioned above, the governing equations of the vehicle motions can be described as

$$M_b\ddot{z} = S_{zfl} + S_{zfr} + S_{zrl} + S_{zrr} \tag{1}$$

$$I_x\ddot{\rho} = c_f(S_{zfl} - S_{zfr}) + c_r(S_{zrl} - S_{zrr}) \tag{2}$$

$$I_y\ddot{\theta} = -a(S_{zfl} + S_{zfr}) + b(S_{zrl} + S_{zrr}) + M_b g(h_{cg} - h_p)\sin\theta \tag{3}$$

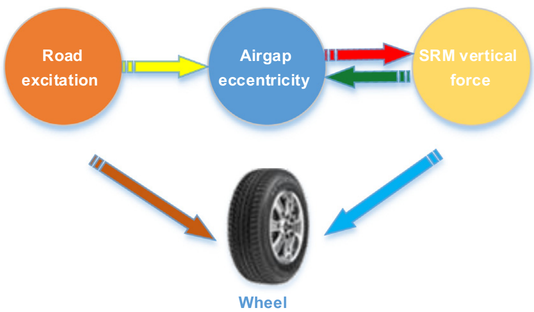

Fig. 1. The conceptual relationship between road excitation, airgap eccentricity and SRM vertical force.