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High frequency vibration characteristics of electric wheel system under in-wheel motor torque ripple

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A B S T R A C T

With the introduction of in-wheel motor, the electric wheel system encounters new vibration problems brought by motor torque ripple excitation. In order to analyze new vibration characteristics of electric wheel system, torque ripple of in-wheel motor based on motor module and vector control system is primarily analyzed, and frequency/order features of the torque ripple are discussed. Then quarter vehicle-electric wheel system (QV-EWS) dynamics model based on the rigid ring tire assumption is established and the main parameters of the model are identified according to tire free modal test. Modal characteristics of the model are further analyzed. The analysis indicates that torque excitation of in-wheel motor is prone to arouse horizontal vibration, in which in-phase rotational, anti-phase rotational and horizontal translational modes of electric wheel system mainly participate. Based on the model, vibration responses of the QV-EWS under torque ripple are simulated. The results show that unlike vertical low frequency (lower than 20 Hz) vibration excited by road roughness, broadband torque ripple will arouse horizontal high frequency (50–100 Hz) vibration of electric wheel system due to participation of the three aforementioned modes. To verify the theoretical analysis, the bench experiment of electric wheel system is conducted and vibration responses are acquired. The experiment demonstrates the high frequency vibration phenomenon of electric wheel system and the measured order features as well as main resonant frequencies agree with simulation results. Through theoretical modeling, analysis and experiments this paper reveals and explains the high frequency vibration characteristics of electric wheel system, providing references for the dynamic analysis, optimal design of QV-EWS.

1. Introduction

The extraordinary growth of vehicle population has brought the shortage of energy, environmental pollution and traffic safety problems. Developing the electric vehicles (EVs) is an effective solution to these problems. Compared with central motor driven EVs, in-wheel motor driven EVs have obvious advantages in structure layout, integrated chassis control and manipulation, which stand for the developing trends of EVs in the future [1].

Electric wheel system of in-wheel motor driven EVs consists of in-wheel motor, wheel and tire. Due to coupling of in-wheel motor and wheel/tire, the electric wheel system is different from the wheel/tire system of internal combustion engine vehicles both in the excitation source and structural dynamics. The electric wheel system encounters not only low

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frequency (lower than 20 Hz) vibration excited by road roughness [2] but also high frequency electromagnetic excitation from in-wheel motor. Most of the current researches related to electric wheel system dynamics focus on the low frequency vibration problems, among which the vertical negative effects caused by increase of in-wheel motor in unsprung mass have gained extensive attention. In [3,4], it is pointed out that indices for vehicle comfort and safety deteriorate evidently on account of the increase in unsprung mass. In [5,6], the in-wheel motor is flexibly isolated from the wheel and acts as a dynamic vibration absorber to abate the vibration of the unsprung mass. In [7,8], methods of suspension configuration and parameters optimization are presented. In [9], active suspension control method is adopted to address this problem and favorable effects are achieved. Other related literatures deals with the problem of unsprung mass increase from the perspective of development and design of high power density motor type for in-wheel motor use[10,11].

There are few researches on the vibration that arises from electromagnetic excitation of in-wheel motor. In [12], a novel in-wheel motor driven topology scheme is brought forward and based on this scheme the vehicle vertical dynamics under road roughness and radial magnetic force are studied. On this basis, an 11-degree of freedom dynamics model is developed to study the influence of magnetic force on vehicle vertical and lateral coupling dynamics in [13]. These two studies have paid attention to motor magnetic force excitation, the frequency range of which can vary with motor rotation speed up to 200 Hz. However, traditional low frequency vehicle model is still used. The applicability of the model needs to be verified. In [14,15] the estimation error of wheel slip ratio resulting from driving wheel dynamic deformation under driving torque of in-wheel motor is analyzed. Although the model applicable frequency has been extended by considering tire deformation dynamics, these two papers don't focus on vibration response and also lack essential validation of the model, detailed analysis and rational explanation of the results. In [16] the characteristics of the unbalanced residual lateral force of in-wheel switched reluctance motor, the negative vibration effect of the force on vehicle and the control methods of this effect are analyzed and proposed, but the high frequency vibration characteristics of the vehicle are not reflected due to model reduction.

Torque ripple of the internal combustion engine suffers energy attenuation by mechanical parts in the transmission to wheel, whereas torque ripple of in-wheel motor is directly imposed on the wheel. As a result, emerging vibration problem of electric wheel system under torque ripple is highlighted. Currently, researches related to this problem have fresh quest. It is necessary to make an effort in theoretical modeling, analysis and experimental study of electric wheel system high frequency vibration problem.

In order to analyze new vibration problems of electric wheel system under torque ripple of in-wheel motor, this paper is organized as follows. In Section 2, torque ripple of in-wheel motor is analyzed based on motor module and motor vector control system considering dead-time effect of the inverter. In Section 3, the quarter vehicle-electric wheel system (QV-EWS) dynamics model based on rigid ring tire assumptions is established and the main parameters of the model are identified. In Section 4, modal analysis of QV-EWS is conducted. Then vibration responses of the QV-EWS under torque ripple are simulated and the high frequency vibration characteristics are discussed based on the modal features. In Section 5, bench experiment of electric wheel system is conducted. High frequency vibration phenomenon of electric wheel system is revealed and the theoretical model is verified. Finally the conclusions come out in Section 6.

2. Torque ripple of in-wheel motor

Permanent magnet synchronous motor (PMSM) is considered to be optimal choice for in-wheel motor as its considerable advantages in power density and efficiency. This paper targets an in-wheel surface-mounted PMSM with concentrated fractional-slot windings, shown in Fig. 1. Torque ripple of this motor mainly derives from non-sinusoidal magnetic field distribution, cogging torque and phase current harmonics. Due to structural optimization such as skewed slot, the contribution of non-sinusoidal distribution of magnetic field and cogging torque to torque ripple is minor. For this reason, only phase current harmonics are considered and the following assumptions are made:

1) Saturation of the motor iron core is neglected [17,18].
2) The distribution of air gap magnetic field due to permanent magnet is sinusoidal without harmonics.

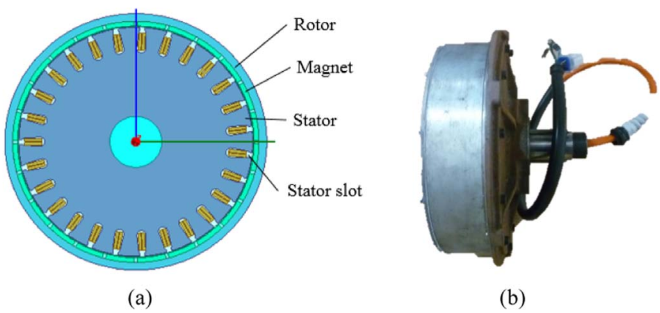

Fig. 1. In-wheel PMSM (a) Cross section of PMSM; (b) physical entity.