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Multi-objective optimization of active suspension system in electric vehicle with In-Wheel-Motor against the negative electromechanical coupling effects

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ABSTRACT

This paper presents a multi-objective optimization control method of active suspension system for solving the negative vibration issues emerged from In-Wheel-Motor (IWM) in electric vehicles. An integrated model which considering electromechanical coupling between electromagnetic excitation in motor and transient dynamics in vehicle is established and developed. The characteristics of electromagnetic excitation are discussed and its influences on vehicle dynamics are analyzed. The key factors are formulated and selected as the objective criteria for multi-objective optimization approach. The Pareto solution set of optimal parameters in active suspension system is generated by Particle Swarm Optimization (PSO) method, a comparison in vehicle dynamic performances is made to verify the targeted optimization method. The simulation results indicate that the optimized active suspension system can effectively reduce the vertical component of unbalanced electromagnetic excitation by maintaining the relative eccentricity of driving motor in a reasonable interval meanwhile attenuate the sensitivity of the vehicle system to electromagnetic excitation. Furthermore, active suspension system also preserve dynamical advantages in vehicle by means of a balance between the ride comfort and the road holding. The proposed multi-objective optimization method of active suspension system demonstrates a potential application in engineering in order to solve vibration issues in electric vehicle with in wheel motor.

1. Introduction

With the development of electrification and intellectualization in vehicle, In-Wheel-Motor Electric-Vehicles (IWM-EVs), which eliminates mechanical transmission system and integrates fast and accurate multidimensional dynamic control, has brought significant attention in automotive industry. However, vibration and noise issues in IWM are generated due to a special arrangement of propulsion system. The driving motor is connected to the wheel directly without any torsion damper or decelerator and transmission chain in the driveline, which will result in emergence of new electromechanical dynamic issues.

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In the past decades, research interests regarding IWM systems are mainly concentrated on the emerging vertical dynamic issues for IWM driven electric vehicle. One of the negative effects bought by power integration is the increased unsprung mass in electric vehicles. It will cause deterioration in tire road holding performance and ride quality evaluation. To solve this problem, the advanced dynamic-damper mechanism [1,2] and active control method [3] as well as design technology of driving motor [4] were proposed. The influence of intensified unsprung mass was abated from both aspects of vehicle structure re-design and motor structure re-design. Moreover, the negative electromechanical coupling in IWM system on vehicle dynamics has received great attention. The impact of unbalanced electromagnetic force on vehicle system dynamics was investigated in Refs. [5–7]. The results show that the vibration problems in motors not only causes deterioration of stability in vehicle but also has a considerable effect on the ride comfort in vehicle, and an appropriate control method will be desired. Some corresponding schemes to improve the vehicle vertical dynamics of IWM system had been proposed [8,9]. A novel rubber bushings IWM topology scheme was brought forward by Tan and Luo [10], aiming to absorb the vibration energy from the road surface and abate the MMG (motor magnet gap) deformation. The damping parameters in the proposed suspension system, the bushing stiffness, the bushing damping and the bushing deformation were re-matched by an optimal design subsequently [11].

The electromechanical coupling circle (Unbalanced Electromagnetic Excitation-Magnet Gap Deformation) has been demonstrated to be essential to the deterioration of vertical dynamic performance in this special structural layout in in-wheel motor driven electric vehicle. However, to date, little research has taken account of this negative effect from driven motor or the dynamic electromechanical coupling process in vehicle dynamics system. In previous researches, either the vertical unbalanced excitation in motor was neglected, or a constant magnet gap deformation was assumed [5,7,10,11]. On the other hand, the control method proposed for the electromechanical coupling effect is indirect control and the effectiveness is limited [6], meanwhile the re-design of IWM configuration is complex [10] and, difficult to develop in practice. Thus, the dynamic electromechanical coupling process and its specific control methodology need further research.

As well known, active suspension equipped with electromagnetic actuator can solve the contradiction between the ride comfort and the handing performance effectively. It demonstrates obvious dynamical advantages in its application process. In this paper, a multi-objective optimization method for the active suspension system is developed to solve the negative effect issue caused by the electromechanical coupling between IWM system and vehicle dynamic performance. By proposing an integrated working in a practical scenario, the electro-mechanical coupling process in IWM-EV is described in real-time. A comparison for dynamic performances in IWM-EVs is completed to verify the effectiveness of the proposed optimization approach. This paper is organized as follows: a literature is introduced in Section 1. After that, a Fourier series analytical Switched Reluctance (SR) in-wheel driven motor model is brought forward, followed by a preliminary discussion on the characteristics of unbalanced electromagnetic excitation. And then, the motor model is applied to subsequent developed real-time joint model of IWM-EV in Section 2. Then a Liner Quadratic Gaussian (LQG) controller for active suspension system is approached and a torque output time-varying case under random road roughness excitation is applied in the third section. Followed by, a multi-objective integrated parameter optimal process via PSO method after the targeted objective functions are formulated. Subsequently, the vehicle dynamic responses of the optimized results are compared and analyzed in both time and frequency domain. At last, some key conclusions are given in Section 5.

2. The electromechanical coupling model

As IWM-EV is composed of electric wheels with driven motor and vehicle dynamic system assembly, these critical parts are electromechanically coupled. This paper develops an integrated model for electric vehicle with IWMs in which two sub-models are included: one is SR-motor model in IWM system, which presents electromagnetic excitation to wheels. The other is vehicle model which emphasizes the dynamic responses in vehicle and outputs the transient electromechanical parameters back to the SR-IWM model in real-time. The sub-models are integrated on the basis of installation relationship of IWM-EV.

2.1. SR-motor modeling

SR-motor has wide application potentials in electric vehicle for its simple structure, high starting torque and wide operating range. These features make it easy to meet the needs of dynamic performance in electric vehicle. In this paper, SR-motor is adopted as the driving motor in IWM. Fig. 1(a) is a typical outer rotor SR-motor [12–14] which is mounted in the wheel hub to drive the vehicle directly. It is composed of an outer rotor, an inner stator, a winding coil and a supporting shaft. Magnetic circuit passes 6 outer rotor salient poles and 8 inner stator salient poles to form a loop by air gap. The power is 3 kW, the voltage is 220 V and the speed range is around 30–2000 rpm.

SR-motor is a typical electromechanical multi-field system. Its properties can be analyzed by finite element method, empirical table or analytical method. In this paper, Fourier series based on the virtual work principle and the electromechanical energy conversion are adopted to establish the electromechanical multi-field characteristic equations which include energy conversion equation, electromagnetic coupling equation, mechanical driving equation as well as air-gap eccentric equation.