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Nonlinear dynamic analysis of a unilateral vibration vehicle system with structural nonlinearity under harmonic excitation

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ABSTRACT

In this paper, the nonlinear dynamics and vibration transmission characteristics of a multi-body dynamic model are investigated to examine the performance of a unilateral vibration vehicle system. The nonlinear equation of motion, considering the suspension and tyre characterized by quadratic and cubic nonlinearities, is deduced by Lagrange's equation. Based on the dynamic equation, the nonlinear dynamic behaviors of the vibration system are investigated more precisely by bifurcation diagram, the largest Lyapunov exponent and 3-D frequency spectrum with the effects of external excitation amplitude, tyre nonlinearity and inclined angle. The numerical analysis indicates that the vibration system exhibits a wide variety of rich and interesting dynamic behaviors, namely different motion states and jump discontinuity are observed, and the different routes to chaotic motion via period-doubling bifurcation, inverse period-doubling bifurcation, Hopf bifurcation and saddle-node bifurcation are presented depending on the different system parameters.

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1. Introduction

Modern transport vehicles are designed for heavy-industrialization, high stability, high safety and low consumption, therefore, it is necessary to establish a more realistic vehicle dynamic model and investigate the dynamic behaviors, which not only play an important role in the theoretical development of vehicle dynamics, but also have important application value to design and control of vehicle system. Due to the strong nonlinearities of suspension system and tyre and the coupled influences of internal and external excitations, the vehicle system appears complicated dynamic characteristics, more and more attention has been payed to the nonlinear dynamics and vibration transmission of the vehicle system in order to avoid unstable vibration and noise. Therefore, it is necessary to be able to predict the vibration behaviors, coupled interaction and understanding the mechanism of vibration generation and the propagation rule between suspension system and tyre subjected to internal and external excitations. However, the tyre nonlinearity and coupled relationship among the components of the vehicle system have significant effect on vehicle dynamics with larger excitation, which are often neglected in the previous studies and may lead to the actual dynamics of the vehicle system lose. In addition, the suspension system is often modeled as piecewise linear structure, which will lead to serious mistake under the condition. Limited work has been done to research the dynamic responses of the vehicle system with structural nonlinearity. Therefore, the focus of this work is on establishing a more accurate and practical unilateral vibration vehicle dynamic model and understanding the dynamic behaviors with quadratic and cubic nonlinearities.

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The lumped mass model of the vehicle system, the suspension and tyre are equivalent to linear or nonlinear spring and damping elements, is often modeled as spring-damper-mass vibration system with different degrees of freedom, which is mainly divided into quarter vehicle dynamic model with 1-DOF/2-DOF (only including the vertical vibration), half vehicle dynamic model with 4-DOF/5-DOF (including vertical vibration and sidesway of sprung mass, vertical vibration of unsprung mass) and full vehicle dynamic model with M-DOF (including vertical, pitching, sidesway vibrations of sprung mass, four vertical vibrations of the unsprung mass etc.), according to different research conditions. In order to reasonably simplify the model for the complex vehicle system, many researchers did a lot of theoretical analysis and experimental research. Litak [1] examined a global homoclinic bifurcation and transition to chaos of a quarter car model excited kinematically by the road surface profile. Andrzejewski [3] provided an overview of the theory of stability analysis and applications of wheeled vehicle, which focused on various methods devoted to analyzing wheeled vehicle behavior, and provided both basic and advanced knowledge. Zhang [4] investigated the nonlinear behaviors of a 2-DOF Magneto-rheological (MR) vibration isolation system, the transitions between distinct regimes of stable motion and chaotic motion of the suspension system for variations in frequency of external excitation were analyzed. Zhong [5] established 2-DOF suspension system considering the piecewise-linear nonlinearity. Based on the relationship between parameters and the topological bifurcation solutions, the motion characteristics with different parameters were obtained. Taffo [6] analyzed a nonlinear quarter-car model with time-delayed feedback control, and explored the vibration behaviors, which indicated a time delay could be both stabilizing and destabilizing. Jia [7] and Lu [8] studied amplitude-frequency responses and vibration characteristics of a 2-DOF bilinear suspension system. The effects of nonlinear spring stiffness, coefficient of damping, roughness of ground and spring clearance on response curves were further discussed. Jazar [9] gave a detailed introduction of the vehicle dynamics, he addressed fundamental and advanced topics, and a basic knowledge of vehicle motion, vehicle kinematics, vehicle dynamics and vehicle vibration, as well as numerical methods, was expected. Li [10] researched the chaotic motion of a vehicle suspension system with hysteretic nonlinearity subjected to quasi-periodic excitation by road surface, and the influence of each coefficient on chaos was investigated. Pacejka [11] explained the relationship between operational variables, vehicle variables and tire modeling to well-known the effective modeling of complex tire and vehicle dynamics problems. Jenny [12] established a two degrees of freedom model of coupled/uncoupled suspension systems characterized by piecewise linear stiffness, which indicated the coupled system had a more irregular behavior with larger motions than the uncoupled suspension system. Because Magnetorheological dampers can reduce the dynamic tire forces, improve the ride quality of the passengers and protect of the vehicle from rollover, Dehghani [13] focused on studying the active control of the chaotic behavior generated by the nonlinear model of the MR dampers in a typical heavy articulated vehicle. Fakhraei [14] analyzed the chaotic behavior of a ground vehicle system with driver subjected to road disturbances, and the relationship between the nonlinear vibration of the vehicle and ride comfort was evaluated. Zhu [15] studied the chaotic response and bifurcations of a 4-DOF vehicle model that was subjected to two sinusoid disturbance with time delay. The bifurcation diagrams showed that the chaotic response could be sensitive to variation of damping of the suspension. Whereafter, Zhu [16] investigated the chaotic response of a nonlinear 7-DOF ground vehicle model. Yang [17] investigated the possibility of chaotic vibration of the 4-DOF half vehicle model under consecutive speed control humps on the highway. And then a direct variable feedback control was proposed to eliminate the influence of chaos on vehicle nonlinear vibration. Based on multi-body dynamics theory, Lu [18] modeled a nonlinear virtual prototype model of heavy duty vehicle, and the nonlinear characteristics of shock absorber and leaf springs were precisely studied. In order to investigate the longitudinal, lateral and vertical dynamics of vehicle system simultaneously, Li [19] proposed a nonlinear three-directional coupled vehicle model. The system responses were calculated by numerical integration and compared with the Functional Virtual Prototyping model and the test data. Liu [20] analyzed the phenomenon of internal resonance in high-speed vehicle system under high frequency periodic excitations, and parametric studies on the internal resonance were further explored. Silveira [21] studied the dynamic behavior of a quarter-car model with asymmetrical viscous damping under harmonic excitation. The response was obtained with an analytical approximation via harmonic balance method. Zhou [22] theoretically investigated the dynamic characteristics of a quarter vehicle with external periodic excitation by the incremental harmonic balance method and Newmark method. The influences of the damping coefficient, excitation amplitude and excitation frequency on the dynamic responses were investigated. Sun [23] presented the hybrid modeling with damping multi-mode switching damper, which could be used to optimize the switching sequences of the damping modes by taking into account the suspension performance requirements. To research the suspension vibration energy conversion mechanism and energy harvest potential, Zhang [24] analyzed the energy flow of regenerative suspension system and explored the suspension energy regenerate potential based on the quarter vehicle model and road roughness model. Burdzik [25] developed a novel method for research on exposure to nonlinear vibration of passenger car suspension as nonlinear dynamical system, and provided a discussion on the results of studies addressing the impact exerted by damping properties of shock absorber on the vibrations being generated. Szymański [26] used the time-spectrum analysis to determine the frequency band connected with car body free vibration generated by impacts of suspension elements in case of clearance in suspension elements fixing to the car body. Wang [27] compared the effects of the linear/nonlinear tyre model, which showed that the nonlinearity of tyre importantly influenced the dynamic characteristics of the automotive suspension.

The finite element model (FEM) of the vehicle system is discretized the structures into link elements, beam elements, elastic element, solid elements and assembly elements, which can provide more detailed and accurate investigation the dynamic behaviors of vehicle system [28]. To analyze the contribution of vehicle body on the strength of the frame, Zhou [29] developed two kinds of FEM models according as whether the body was considered or not. Jonsson [30] modeled a

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