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Nonlinear dynamic analysis of a quarter vehicle system with external periodic excitation

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ABSTRACT

In this paper, a nonlinear dynamic model of a quarter vehicle with nonlinear spring and damping is established. The dynamic characteristics of the vehicle system with external periodic excitation are theoretically investigated by the incremental harmonic balance method and Newmark method, and the accuracy of the incremental harmonic balance method is verified by comparing with the result of Newmark method. The influences of the damping coefficient, excitation amplitude and excitation frequency on the dynamic responses are analyzed. The results show that the vibration behaviors of the vehicle system can be control by adjusting appropriately system parameters with the damping coefficient, excitation amplitude and excitation frequency. The multi-valued properties, spur-harmonic response and hardening type nonlinear behavior are revealed in the presented amplitude-frequency curves. With the changing parameters, the transformation of chaotic motion, quasi-periodic motion and periodic motion is also observed. The conclusions can provide some available evidences for the design and improvement of the vehicle system.

1. Introduction

The vehicle dynamics plays an important role in the development of vehicle industry, and the vibration [1] and noise of vehicle system caused by external excitation is still a subject of research. The vehicle system is a strong nonlinear system interactions among suspension, tires and other components, which may become uncontrollability and instability caused by the vibration and impact. In addition, Suspension system, as one of the key components, can absorb the most of energy between the tire and vehicle body. Thus, it is important to analyze the dynamic behaviors of the vehicle system. The vehicle system is a typically complicated multi-body nonlinear system, and the nonlinearity degree can be embodied via the number of degree of freedom (DOF) with the established model. Several models have been developed by the researches related to the dynamic behavior of vehicle system [2]. The 2-DOF/1-DOF model (quarter-car model) is use for analyzing the vertical vibration of the body, the 4-DOF model (half-car model) with two-wheel (front and rear, left and right) for studying the vertical and pitch motions, and the 7-DOF full 3-D vehicle model (full-vehicle model) as a four-wheel model for investigating the vertical, pitch and roll motions.

With the increasing demand for high comfort and high safety, the dynamic behaviors of vehicle system have been extensively studied in the past years, Liang [3] established a 2-DOF nonlinear vehicle suspension model, and analyzed the chaotic behavior of the vehicle passing the consecutive speed control humps on a highway with different parameters. A quarter vehicle system with nonlinear spring and damper was analyzed by Liu [4], which investigated the effects of the consecutive speed control humps on the dynamic behaviors of the vehicle passing the consecutive speed control humps. Zheng [5] discussed the dynamic responses of a 2-DOF nonlinear suspension system and the chaotic motion could be controlled by using state variable feedback. Li [6] presented a vehicle suspension system with hysteretic nonlinearity and the chaotic motion was derived by the Melnikov function [7], which was subjected to the multi-frequency excitation from road surface. Litak [8–9] used the Melnikov criterion to examine a global homoclinic bifurcation and transition to chaos in the case of a SDOF (single degree of freedom) car model excited kinematically by a road surface profile consisting of harmonic and noisy components. Zhu investigated the dynamic responses of 4-DOF [10] and 7-DOF [11] ground vehicle model, and the disturbances from the road were assumed to be sinusoid. The results showed that the chaotic response may appear in the unstable region of frequency response diagram. Zhu [12] studied the nonlinear dynamics of a 2-DOF vibration system with nonlinear damping and nonlinear spring, and the amplitude and vibration can be reduced by adjusting properly system parameters and considering the value of excitation frequency. Ikenaga [13] developed a full-vehicle

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suspension system with an active suspension control approach combining a filtered feedback control scheme and an input decoupling transformation. Zhang [14] proposed a semi-active sliding mode controller based magneto-rheological quarter vehicle suspension through comparing the time and frequency domain responses of the sprung mass and unsprung mass accelerations, suspension travel and the tire dynamic force with those of the passive quarter vehicle suspension, under three kinds of varied amplitude harmonic, rounded pulse and real-road measured random excitations. Borowiec [15] established a SDOF nonlinear model, representing a quarter automobile with semi-active, nonlinear suspension, and the chaotic vibrations and bifurcations of the system were studied with changing excitation frequency and road profile amplitude. Turkay [16] used a quarter-car model to study the response of the vehicle to profile imposed excitation with randomly varying traverse velocity and variable vehicle forward velocity. In addition, root-mean-square responses of the vehicle to white and colored noise velocity road inputs were analyzed. Wagner [17] presented a quarter-car model with nonlinear damping, which was subjected to white or colored noise excitation by using high-dimensional probability density functions. Wu [18] reviewed on the application of chaos theory in automobile nonlinear system, which indicated that the automobile nonlinear system had very abundant and complicated dynamic phenomena. Chaos motion could happen even in the simplest single-freedom nonlinear vertical vibration system of automobile. Verros [19] investigated the dynamics of a controlled quarter-car model by applying an appropriate methodology for obtaining exact periodic motions for the case of forced resulting from a road with harmonic profile. Kropáč [20] build two models: a planar model of a personal car with a driver and one passenger, and a planar model of a three-axle truck. The dynamic behaviors were evaluated caused by passing an isolated obstacle and a number of randomly distributed obstacles. Bum [21] proposed multi-body dynamics model of complete vehicle, and investigated the effects of individual and overall design variable uncertainties on the ride comfort uncertainty. Yang [22] established a 7-DOF nonlinear full-vehicle model and then used numerical simulation to analyze chaotic vibration excited by consecutive speed control humps. Yang [23] studied the possibility of chaotic vibration with the 4-DOF half vehicle model under consecutive speed control humps on the highway. Then, a direct variable feedback control was proposed to eliminate the influence of chaos on vehicle nonlinear vibration and how to select proper control parameters was discussed. Shen [24] analyzed the effects of the time delay on the dynamic responses by four semi-active dynamic vibration absorbers and the comparisons between the analytical and the numerical solutions were presented. Eimadany [25–26] developed an integrated investigation of vehicle dynamics, roadway excitations and performance measures in order to study the dynamic behaviors and design of vehicle suspension systems and the consequences of vehicle ride quality. Sheng [27] studied the chaotic motion of the SDOF nonlinear suspension mathematical model under single frequency sine, multi-frequency harmonic and random road excitation, and the dynamic behaviors were analyzed by using central manifold theorem. Safety analysis and the forced vibration characteristic of a SDOF vehicle suspension system with hysteretic nonlinearity characteristic under road quasi-period multi-frequency excitations were carried out by Yu [28]. Zhuang [29] researched a vehicle model with nonlinear suspension spring and hysteretic damping element, which exhibited multiple heteroclinic orbits in the unperturbed system. Zhong [30] and Lu [31] investigated a kinetic model of the piecewise-linear nonlinear suspension system that consists of a dominant spring and an assistant spring, and the topological bifurcation solutions, motion characteristics with different parameters were obtained. Jerrelnd [32] studied a 2-DOF model of with coupled suspension systems characterized by piecewise-linear stiffness, which indicated that the coupled system had a more irregular behavior with larger motions than the uncoupled suspension system. Hamed [33] analyzed the dynamic behavior of a quarter-car system with 2-DOF, where the tire was modeled as a nonlinear hardening spring and the disturbance of road assumed to be sinusoid. Ren [34] deduced a 2-DOF system with piecewise and smooth nonlinear coupled differential equations, which were calculated by using Shooting-Method. The results showed that the jump phenomenon would happen with road conditions change suddenly or carrying capacity change hugely. Marzbanrad [35] established a quarter-car nonlinear model with nonlinear air spring and nonlinear damper and then studied the possibility of chaotic vibration of this model under consecutive speed control humps on the highway. Borowiec [36] studied the dynamics of a 2-DOF nonlinear oscillator representing a quarter-car model excited by a road roughness profile, which was modeled by means of a harmonic function. Sheng [37] build a nonlinear dynamic model of automobile heave vibration system with 2-DOF based on an analysis of nonlinear spring force and damping force for automotive suspension and tire by the incremental harmonic balance method (IHBM). The IHBM is a very effective method for solving nonlinear problems, but little work is used to analyze the dynamic behavior of vehicle nonlinear system. The key factor of IHBM is the computation of steady state solution with very short time. Meanwhile, it is well designed for system under periodic excitation, which is very fit for the vehicle nonlinear system. Although there are a lot of literatures concerned with the vehicle system, the studies on nonlinear dynamic characteristics of the forced vibration vehicle system based on IHBM are still very limited. So it is important to research the dynamic characteristics influenced by the system parameters based on the IHBM.

The above cited references have presented the vibration characteristics with the suspension system, the disturbances usually come from the changing random road surface and consecutive speed control hump under running vehicle. However, the vehicle system may similarly suffer from the complexity vibration and harshness problem and especially the vibration property of the vehicle system on offload platform. In this study, a SDOF nonlinear vehicle suspension system with external excitation caused by double eccentric shaft vibration exciter is presented, which is used to investigate the nonlinear dynamic behaviors of the vibration system with the deflection of tire and suspension. The differential equation of the vehicle system is calculated using the IHBM and NMM (Newmark method). The dynamic behaviors of the vehicle system are characterized using time domain, frequency domain, phase diagrams, Poincaré maps, bifurcation diagram and frequency-amplitude curves. The influences of the damping coefficient, excitation amplitude and excitation frequency on the dynamic characteristics are studied, which provide to understand the vibration properties of the vehicle system.

The paper is organized into five sections. Section 2 presents the external excitation and the mathematical modeling of a SDOF nonlinear vehicle system. In Section 3, the IHBM is introduced. The dynamic behaviors of the vehicle system are analyzed in Section 4, and discuss the effects of the key parameters. Finally, Section 5 presents some brief conclusions.

2. Nonlinear dynamic model of vehicle suspension system

The dynamic behaviors of vehicle suspension system with external excitation require an integrated investigation. In this section, a SDOF vehicle nonlinear dynamic model is established with nonlinear spring and nonlinear damping. And the external