Journal of Sound and Vibration 412 (2018) 74–94

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Dynamic interaction of monowheel inclined vehicle-vibration platform coupled system with quadratic and cubic nonlinearities

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ARTICLE INFO

Article history:
Received 7 March 2017
Received in revised form 15 September 2017
Accepted 24 September 2017

Keywords:
MIV-VPCS
Nonlinear dynamics
Interaction
Intermediate nonlinearity support
Coupled vibration

ABSTRACT

In order to analyze the nonlinear dynamics and stability of a novel design for the monowheel inclined vehicle-vibration platform coupled system (MIV-VPCS) with intermediate nonlinearity support subjected to a harmonic excitation, a multi-degree of freedom lumped parameter dynamic model taking into account the dynamic interaction of the MIV-VPCS with quadratic and cubic nonlinearities is presented. The dynamical equations of the coupled system are derived by applying the displacement relationship, interaction force relationship at the contact position and Lagrange's equation, which are further discretized into a set of nonlinear ordinary differential equations with coupled terms by Galerkin's truncation. Based on the mathematical model, the coupled multi-body nonlinear dynamics of the vibration system is investigated by numerical method, and the parameters influences of excitation amplitude, mass ratio and inclined angle on the dynamic characteristics are precisely analyzed and discussed by bifurcation diagram, Largest Lyapunov exponent and 3-D frequency spectrum. Depending on different ranges of system parameters, the results show that the different motions and jump discontinuity appear, and the coupled system enters into chaotic behavior through different routes (period-doubling bifurcation, inverse period-doubling bifurcation, saddle-node bifurcation and Hopf bifurcation), which are strongly attributed to the dynamic interaction of the MIV-VPCS. The decreasing excitation amplitude and inclined angle could reduce the higher order bifurcations, and effectively control the complicated nonlinear dynamic behaviors under the perturbation of low rotational speed. The first bifurcation and chaotic motion occur at lower value of inclined angle, and the chaotic behavior lasts for larger intervals with higher rotational speed. The investigation results could provide a better understanding of the nonlinear dynamic behaviors for the dynamic interaction of the MIV-VPCS.
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1. Introduction

The monowheel inclined vehicle-vibration platform coupled system was comprehensively investigated by engineers and scientists in the last few decades. To further strengthen and increase the advances and carrying capacity of the coupled

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https://doi.org/10.1016/j.jsv.2017.09.027
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system, the nonlinear vibration and stability became the key to the theoretical research and experimental analysis. Due to the strong nonlinearity of the suspension system, tire and the vibration platform with intermediate nonlinearity support and geometric nonlinearity, the dynamic interaction of the MIV-VPCS subjected to a harmonic excitation become quite complicated. Therefore, to enhance and increase advantages and avoid unstable vibration under different operation conditions of the coupled system, more attention should be payed to the nonlinear dynamics of the MIV-VPCS.

The literature concerning the dynamic responses of the vehicle system were large. Most of these studies were concentrated in suspension system and tire, which were modeled as nonlinear springs and nonlinear dampers. Zhang et al. [1,2] established a 2-DOF (degree of freedom) magneto-rheological damper suspension system via using modified dynamic model. The nonlinear dynamic behaviors of the suspension system were analyzed with different external excitations from stochastic road surface. Taffo et al. [3] examined the vibration responses of a nonlinear oscillator with symmetric potential that modeled a quarter-car forced by the road profile under parametric excitation. The parametric resonance of a harmonically excited nonlinear quarter-car model with position and velocity time-delayed active control was investigated. Li et al. [4] investigated the possible chaotic behavior of a single-DOF vehicle suspension system under multi-frequency excitations from road surface. And the influence of nonlinear damping on the chaotic motion was studied. In order to investigate the effect of asymmetrical viscous damping (AVD) on the dynamic characteristic with vehicle system, Silveira et al. [5] analyzed the dynamic behaviors of a 2-DOF suspension system subjected to harmonic load with AVD. The approximate analytical solution of the vibration system was obtained by harmonic balance method (HBM). Zhou et al. [6] researched the vibration responses of a quarter vehicle system subjected to an external load with strong nonlinearity. The key system parameters were investigated by incremental harmonic balance method (IHBM) and numerical integration method. Silveira et al. [7] compared the dynamic behaviors of a passenger vehicle with symmetrical and asymmetrical damping coefficients, which indicated that the asymmetrical system of vibration reduction was more advantage. Taffo et al. [8] investigated a 2-DOF vehicle suspension system with time-delayed feedback control. The stability of the nonlinear system was analyzed with different system parameters. The comparison of the dynamic responses between uncoupled and coupled suspension system was presented by Jerrelind et al. [9], which showed that the coupled model could better reflect the practical dynamic behaviors. Litak et al. [10] utilized the Melnikov criterion to analyze the different bifurcation routes with single-DOF vehicle system subjected external load. The transition was analyzed for different levels of noise and illustrated by numerical simulations. Maher et al. [11] compared the dynamic behaviors with the linear suspension model and nonlinear suspension model of a quarter car system. In addition, the experiment was carried out to prove the accuracy of the nonlinear dynamic model. Zhu et al. [12] investigated the chaotic response and bifurcations of multi-DOF ground vehicle system under sinusoid excitation with time delay. Sekulić et al. [13] analyzed the vibration properties of intercity bus with 10-DOF, it indicated that the vibration exposure time decreased with increasing seat stiffness. Zhong et al. [14] established a 2-DOF vehicle suspension system with piecewise-linear spring. And the nonlinear dynamics was researched with different system parameters. Fakhraei et al. [15] analyzed the chaotic behavior of a multi-DOF vehicle system with driver subjected to sinusoidal disturbance by using the identification techniques of the chaotic motion, the effects of amplitude and frequency on the speed control bumps were discussed.

With the development of technology, the vibration and stability of vibration platform and beam structures had drawn increasing attention in many engineering applications, which were studied extensively in the literature. Ghayesh et al. [16,17] examined the geometric nonlinear dynamics of an axially moving plate in the sub and supercritical regimes by applying von Kármán plate theory. And the dynamic responses were presented by bifurcation diagrams and frequency-response curves. Xu et al. [18] established a two and three spans finite element models of stiffened panels, and analyzed the influence of a central dented imperfection on the load carrying capacity. Bhattiprolu et al. [19] built a pinned-pinned beam model resting on a nonlinear foundation which could react both in tension and compression to be capable of predicting the dynamic behaviors. By using the IHBM and numerical simulation method, the effects of key system parameters on the vibration characteristics for the beam were studied. Dai et al. [20] used the modified coupled stress theory to establish a new cantilevered microbeam model. The transition between softening nonlinear behavior and hardening nonlinear behavior was analyzed. Hasan et al. [21] investigated the dynamic behaviors of multi-mode flexible beam on nonlinear foundation subjected to external load by applying multi-level residue HBM. The influences of different system parameters on the nonlinear behaviors were investigated. Huang et al. [22] analyzed the dynamic characteristics of a curved beam under external excitation with quadratic and cubic nonlinearities. The softening behavior and hardening behavior were presented by IHBM. Ansari et al. [23,24] studied the nonlinear dynamics of beam model subjected to a moving excitation on a nonlinear foundation. And the dynamic responses with key system parameters were obtained by the multiple scales method. Vatankhah et al. [25] utilized the strain gradient and non-classical continuum theories to analyze the dynamic responses of microbeams. The primary, super/sub-harmonic resonances were studied. Cui et al. [26] analyzed the nonlinear vibration of Euler beam with a sliding end, and the analytical solution and numerical simulation were presented. In addition, the effects of key parameters were studied. Emam et al. [27] studied the nonlinear vibration of beam with simple support. And the research results indicated that the first mode had the important contribution on dynamic behavior of the simply supported beam. Zhou et al. [28] established a nonlinear Euler-Bernoulli beam model under a concentrated harmonic excitation with intermediate nonlinearity support, and the effects of the system parameters on the dynamic behaviors were studied and discussed by multi-dimensional IHBM. Ghayesh et al. [29–31] made a series of research on the nonlinear vibration of beam subjected to harmonic excitation force with or without intermediate support. And the dynamic responses were presented by frequency-response curves, force-response curves and bifurcation diagrams.

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