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Nonlinear dynamic analysis for coupled vehicle-bridge vibration system on nonlinear foundation

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ABSTRACT

In this paper, the nonlinear dynamics of a parametrically excited coupled vehicle-bridge vibration system (CVBVS) is investigated, and the coupled system is subjected to a time-dependent transverse load including a constant value together with a harmonic time-variant component. The dynamic equations of the CVBVS are established by using the generalized Lagrange's equation. With the Galerkin truncation method, a set of nonlinear ordinary differential equations are derived by discretizing the continuous governing equation. The influences of parametric excitation with nonlinear support stiffness, mass ratio, excitation amplitude and position relation on the dynamic behaviors are studied for the interaction between vehicle and the bridge. The analysis results indicate that the nonlinear dynamic characteristics are strongly attributed to the interaction of the coupled system. Nonlinear support stiffness of foundation and mass ratio can lead to complex dynamic behaviors such as jump discontinuous phenomenon, periodic, quasi-periodic and chaotic motions. Vibration amplitude increases depending on the position, where the maximum vibration displacement does not occur at the center of the bridge. The excitation amplitude has an obvious influence on the nonlinear dynamic behaviors and the increase of the excitation amplitude makes the vibration strengthen. The bifurcation diagram and 3-D frequency spectrum are used to analyze the complex nonlinear dynamic behaviors of the CVBVS. The presented results can provide an insight to the understanding of the vibration characteristics of the coupled vehicle-bridge vibration system in engineering.

1. Introduction

Because heavy vehicles are widely used to communication and transportation with the development of the carrying capacity, the control technology and the configuration of vehicle suspension have been improved unceasingly. A detailed investigation on the vehicle suspension system to meet the industry development is required. Therefore, it is significant to establish and study the nonlinear dynamic behaviors of the vehicle suspension system by the nonlinear dynamic theory. Xiao [1] established a 4-DOF (degree of freedom) vehicle dynamic model considering the automobile suspension system with sinusoid excitation and hysteretic characteristic, and the chaotic movement was observed. Borowiec [2] carried out a dynamic analysis of the vehicle suspension system, numerical simulation and experiment were presented on three types of road surfaces. Borowiec [3] studied a quarter-car model by 2-DOF nonlinear oscillator and analyzed the transient vibration. Lindsey [4] described a new model for low-power active control of automotive suspension, and the steady state of the suspension system was investigated. ElMadany [5] developed a

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Nomenclature

m_0	eccentric mass
m_1	unsprung mass
m_2	sprung mass
ρ	density
I	moment of inertia
E	modulus of elasticity
L	length of the beam
A	cross section area of the beam
k_{b1}	linear stiffness of foundation
k_{b2}	nonlinear stiffness of foundation
c_b	damping of foundation
k_{t1}/c_{t1}	linear stiffness/damping of tire
k_{t2}/c_{t2}	nonlinear stiffness/damping of tire
k_{s1}/c_{s1}	linear stiffness/damping of suspension
k_{s2}/c_{s2}	nonlinear stiffness/damping of suspension
F_0	external excitation mean
F_p	external excitation amplitude
ω_0	rotational speed
B	location of vehicle
X_0	location of external excitation
Y_1	vibration displacement of unsprung
Y_2	vibration displacement of sprung
Y_b	vibration displacement of beam
τ	non-dimensional time

methodology for the design and evaluation of a slow-active vehicle suspension system. The vehicle dynamics, roadway excitations and performance measures were investigated. Lu [6] used numerical simulation and field test to investigate tire dynamic load with a nonlinear virtual prototype model of heavy duty vehicle. And the effects of vehicle speed, load, road surface roughness and tire stiffness on tire dynamic load and dynamic load coefficient were discussed. Dong [7] estimated the modal parameters and mass moments of inertia of an on-road vehicle by subspace identification method, and then the theoretical analysis was compared with Monte Carlo experiments. Múcka [8] used a linear planar model of automobile with 12-DOF to analyze the influence of tire–road contact model on the simulated vertical vibration response.

The beam is one of the significant structures widely used in many technological devices and machines components. The dynamic behaviors of bridge or vibration platform, which are usually modeled as beam, have been investigated extensively with the influences on harmonic displacement excitation or stationary random excitation. However, due to.

the different support materials or support position, the foundation often has the strong nonlinear characteristics. Therefore, the dynamic analysis of the beam resting on nonlinear foundation becomes an important research topic. Calım [9] analyzed the dynamic behaviors of beam on Pasternak-type viscoelastic foundation subjected to time-dependent loads. The dynamic responses of beam were investigated through various examples. Ansari [10] used the multiple scales method to study the vibration characteristics of a finite Euler-Bernoulli beam. The effects of damping and non-linear stiffness of the foundation as well as the magnitude of the moving load on the frequency responses were discussed. Huang [11] presented nonlinear vibration analysis of a curved beam subjected to uniform base harmonic excitation with both quadratic and cubic nonlinearities. Particular attention was paid to the anti-symmetric response with and without excitation by using incremental harmonic balance method (IHBM). A boundary element method formulation was developed for the dynamic analysis of Timoshenko beams by Carrer [12]. The four kinds of beams that were pinned-pinned, fixed-fixed, fixed-pinned and fixed-free, under uniformly distributed, concentrated, harmonic concentrated and impulsive loading, were analyzed. Akour [13] established a nonlinear beam model resting on linear elastic foundation and subjected to harmonic excitation with simply support at both ends. The damping coefficient, natural frequency and coefficient of the nonlinearity were investigated. Ghayesh [14] investigated the nonlinear forced vibration of a microbeam by employing the strain gradient elasticity theory, and frequency–response curves of the vibration system were demonstrated. Yang [15] analyzed the dynamic response of finite Timoshenko beam resting on a six parameter foundation subjected to a moving load. The effects of different truncation terms on the dynamic responses were discussed via the Runge–Kutta method. Zhao [16] focused on obtaining the direct expressions of steady-state two dimension temperature and displacement responses for the coupled thermoelastic vibrations of Timoshenko beam subjected to a heat flux and an external force, and the influences of some important physical parameters on the coupled multi-physics problem were discussed. Jorge [17] analyzed the vibration characteristics of beam on nonlinear elastic foundation, subjected to moving loads. The effects of the load's intensity and velocity and the foundation's stiffness were researched. Mbong [18] established a single-DOF nonlinear beam model, which is subjected to a combination of both low-frequency force and high-frequency force. The critical values of perturbation parameters for the onset of the chaotic motion were specified using Melnikov's method. Hasan [19] studied the nonlinear vibration of multi-mode flexible beam on an elastic foundation subjected to external harmonic excitation by using multi-level residue harmonic balance. The effects of various parameters such as vibration amplitude, foundation modulus coefficient, damping factor and excitation level etc., on the nonlinear behaviors were examined.

Dynamic analysis of the CVBVS subjected to a load is significant in the design stage or during the assessment of coupled structures. And energy transfer from a bridge system to a nonlinear vehicle system has been a very important issue in recent studies. The dynamic behaviors of coupled system between vehicle and bridge have been studied by a number of researchers. Asnachinda [20] presented an identification of multiple vehicle dynamic axle loads on multi-span continuous bridge, and the accuracy of identified dynamic axle loads for all cases of study was within a relative percentage error of 13%. Zhang [21] analyzed the coupled vehicle-bridge system with vertical track irregularity by a new nonstationary, random vibration method. It showed that the proposed PEM-PIM method performed nonstationary random vibration analysis of coupled vehicle-bridge systems efficiently and accurately. Liu [22] studied the dynamic behavior of a suspension bridge due to moving vehicle loads with vertical support motion caused by earthquake. The interaction of both the moving loads and the seismic forces can substantially amplify the vibration response of long-span suspension bridge system. Xu [23] developed a new optimization method for the coupled vehicle-bridge system subjected to an uneven road surface excitation. The precise integration method was used to compute the vertical random vibrations for the coupled