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Bifurcation and Chaos of Functionally Graded Carbon Nanotube Reinforced Composite Beam with Piezoelectric Layer

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Abstract. This paper investigates bifurcation and chaos of functionally graded carbon nanotube-reinforced composites (FG-CNTRCs) beam containing piezoelectric layer (PL) under combined electro-thermo-mechanical loads. We assumed that FG-CNTRC material properties were graded along thickness direction and determined them using mixtures' law. Governing equations of structures were derived according to the theory of Euler-Bernoulli beam, PL with thermal effects and von Kármán geometric nonlinearity. Next, the governing equations were transformed into second order nonlinear ordinary differential equations (SNODE) with cubic terms through Galerkin procedure and further into first order nonlinear ordinary differential equations (FNODE) through introducing additional state variables. Complex system dynamic behavior was qualitatively examined using fourth order Runge-Kutta method. The effects of different factors including applied voltage, volume fraction, temperature change, and distribution of carbon nanotubes (CNTs) on bifurcation and chaos of FG-CNTRC beams with PL were comprehensively studied.

AMS subject classifications: 73K52
Key words: FG-CNTRC beam, bifurcation and chaos, piezoelectric, Runge-Kutta method, Galerkin procedure.

1 Introduction

CNTs possess excellent electrical, mechanical and thermal characteristics and can be considered as a great reinforcement material in multifunctional composites and high performance structures. Therefore, the research on CNTs has been in progress in the last few years.

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Recently, many dynamic researches have been carried out on carbon nanotubes reinforced composites (CNTRC). CNTRC have wide application prospects in information materials, biomedical materials, stealth materials, catalysts, high-performance structural materials, multifunctional materials, etc. At present, the main methods to fabricate CNTRC are physical blending and in-situ polymerization. Civalek et al. [1] used discrete singular convolution method to present the numerical solution and modeling of free vibrations of annular sector plate of CNTRC. Nonlinear vibration of CNTRC plates exposed to the parametric and forced excitations was improved by Guo et al. [2]. Jorge et al. [3] investigated a 3D multiscale finite element (FE) model and exploited dynamic response of polymer material reinforced with CNTs. In view of Donald shell theory and the effective model of multi-walled CNTs, Wang et al. [4] provided an analytical method for studying the dynamic stability of composites reinforced with multi-walled CNTs. Moumen et al. [5] investigated polymer composite impact responses with random distributions of CNTs. Mohandes et al. [6] evaluated free vibration behavior of a thin cylindrical shells made of single-walled CNTs reinforced fiber-metal composite. Fiorenzo et al. [7] investigated stability and thermoelastic vibrations of CNTRC structures in thermal environments. Thai et al. [8] analyzed free vibration and bending of CNTRC plates. Considering agglomeration effect of CNTs, Kamarian et al. [9] studied free vibration behavior of CNTRC conical shells. Vinyas [10] studied effect of free vibrations of CNTs reinforced inclined and magneto-electro-elastic rectangular plates by FE method.

However, weak interface of matrix and CNTs limits the use of CNTs in nanocomposites. Subsequently, functionally graded FG-CNTRC emerged and gained considerable research interest. Shen [11] investigated non-linear bending of single-walled CNT-reinforced functionally gradient nanocomposite plates and discovered that strength bonding interface could be enhanced by using gradient distribution of CNT in the matrix. Dynamic behaviors of FG-CNTRC shells were exploited by some researcher [12] using a linear discrete dual-controller FE model. Jiao et al. [13] applied a semi-analytical method and addressed dynamic buckling of cylindrical shells made of FG-CNTRC exposed to dynamic displacement loading. Chakraborty et al. [14] applied semi-analytical method to examine vibration and stability of CNTs reinforced FG laminated composite cylindrical shells. Zhao [15] used modified Fourier series of field variables and exploited free vibrations behavior of FG-CNTRC truncated conical plates under general boundary conditions. Qin et al. [16] provides a general method for analyzing effect of free vibration of rotating cylindrical shells made of FG-CNTRC under arbitrary boundary conditions. Mirzaei et al. [17] used Donnell kinematics assumption and first-order shear deformation shell theory (FSDT) to deal with free vibration of single-walled CNTRC plates. Moradi et al. [18] adopted a mesh-free method and dynamically analyzed SWCNT reinforced nanocomposite cylinder under an impact load. Heshmati et al. [19] employed Timoshenko beam theory (TBT) to discuss dynamic responses of nanocomposite beams made of FG multi-walled CNT polystyrene under multiple moving loads. Using semi-analytical method, Zhong et al. [20] discussed the vibrations of sector, circular and annular plates made of FG-CNTRC with arbitrary boundary conditions. Nguyen et al. [21] de-