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Multi-pulse chaotic dynamics of non-autonomous nonlinear system for a laminated composite piezoelectric rectangular plate

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Abstract The global bifurcations and multi-pulse chaotic dynamics of a simply supported laminated composite piezoelectric rectangular thin plate under combined parametric and transverse excitations are investigated in this paper for the first time. The formulas of the laminated composite piezoelectric rectangular plate are derived by using the von Karman-type equation, the Reddy’s third-order shear deformation plate theory and the Galerkin’s approach. The extended Melnikov method is improved to enable us to analyze directly the non-autonomous nonlinear dynamical system, which is applied to the non-autonomous governing equations of motion for the laminated composite piezoelectric rectangular thin plate. The results obtained here indicate that multi-pulse chaotic motions can occur in the laminated composite piezoelectric rectangular thin plate. Numerical simulation is also employed to find the multi-pulse chaotic motions of the laminated composite piezoelectric rectangular thin plate.

1 Introduction

A laminated composite piezoelectric plate is a smart structure, which can be employed to integrate actuators and sensors into a structural component. Research works and development on the responses of laminated composite piezoelectric plates have experienced tremendous growth in the last two decades because they are widely applied to many engineering structures, especially in airplane and launch vehicles. In some applications, for example morphing structures or morphing wings, laminated composite plates with piezoelectric materials can undergo a large oscillating deformation, which leads to nonlinear oscillations of the plates. However, few research works deal with the complex nonlinear dynamics of laminated composite piezoelectric plates, such as the bifurcations and multi-pulse chaotic dynamics. With the development of the theories of nonlinear dynamics and chaos, prediction, understanding and control become possible for more complicated nonlinear phenomena in laminated composite piezoelectric plates.

Several research works focused on the responses of laminated composite piezoelectric plates. Tzou and Ye [1] analyzed distributed control of a piezoelectric laminated square plate with a temperature-induced deflection and demonstrated that the piezoelectric effect of piezoelectric polyvinylidene fluoride (PVDF) sensors is much more prominent than the thermal strain effect. Reddy [2] presented theoretical formulations, the Navier solutions and finite element models on laminated composite plates with integrated sensors and actuators and subjected to both mechanical and electrical loadings. The results indicated that the dynamic responses of laminated composite plates can be controlled by using piezoelectric materials. Later, Ye and Tzou [3] developed
a new piezoelectric composite finite element and gave a comparison between finite element solutions of a laminated composite piezoelectric plate and experimental data. Gopinathan et al. [4] gave a review on different laminate theories used for the modeling and analysis of laminated composite beams or plate structures. Oh et al. [5] studied the postbuckling and nonlinear vibrations of fully symmetric and partially eccentric piezolaminated composite plates subjected to thermo-piezoelectric loads. Shen [6] utilized a mixed Galerkin-perturbation technique to analyze thermal postbuckling of a simply supported, shear-deformable laminated plate with piezoelectric actuators and subjected to the combined action of thermal and electric loads. Moita et al. [7] gave the geometrically nonlinear analysis of laminated adaptive thin plates with embedded integrated piezoelectric actuators or sensors layers. Varelis and Saravanos [8] presented a theoretical framework for analyzing the prebuckling and postbuckling responses of laminated composite plates with piezoelectric actuators and sensors. Varelis and Saravanos [9] used the nonlinear laminate theory to analyze nonlinear effects of laminated composite piezoelectric plates as a result of large displacements and rotations. Liew et al. [10] investigated the dynamic response controlling of laminated composite plates with piezoelectric sensor/actuator patches using an efficient mesh-free Galerkin method. Shen [11] analyzed nonlinear bending of a simply supported, shear deformable cross-ply laminated plate with piezoelectric actuators and subjected to a transverse uniform or sinusoidal load combined with electrical loads and thermal environments based on higher order shear deformation plate theory and perturbation technique.

Recently, Ishihara and Noda [12] investigated the nonlinear dynamic behavior of a symmetric cross-ply piezothermoelastic laminated plate subjected to mechanical, thermal and electrical load. Huang and Shen [13] investigated the nonlinear vibrations of simply supported shear deformable cross-ply laminated plates with piezoelectric actuators and subjected to mechanical, electrical and thermal loads. Cheng et al. [14] analyzed the larger-amplitude deflection effect of a laminated composite plate integrated with randomly poled piezoelectric layers. Rabinovitch [15] studied the geometrically nonlinear behavior of piezo-laminated plates actuated with isotropic or anisotropic piezoelectric layers. Ye et al. [16] investigated the nonlinear oscillations and chaotic dynamics of a simply supported antisymmetric cross-ply laminated composite rectangular thin plate under parametric excitation. Zhang et al. [17] investigated the nonlinear oscillations and chaotic dynamics of a parametrically excited simply supported symmetric cross-ply laminated composite rectangular thin plate with the geometric nonlinearity and nonlinear damping. Huang and Liu [18] studied the dynamic electroelastic responses of a laminated composite plate with piezoelectric sensors and actuators. Abe et al. [19] analyzed the nonlinear dynamic responses of clamped laminated shallow shells with 1:1 internal resonance using the combination of the Galerkin’s procedure and the shooting method. Hao et al. [20] analyzed the nonlinear oscillations, bifurcations and chaos of a functionally graded material (FGM) plate and found that the periodic, quasi-periodic and chaotic motions exist for the FGM rectangular plate under certain conditions. Zhu and Fu [21] used the finite difference method to study nonlinear dynamic responses of piezoelectric laminated plates with matrix cracks. Zhang et al. [22] established the nonlinear governing equations of motion for a simply supported laminated composite piezoelectric rectangular plate under combined parametric and transverse excitations and studied the periodic and chaotic dynamics in the case of one-to-two internal resonance.

The theories of the global bifurcations and chaotic dynamics for high-dimensional nonlinear systems can be used to discover new phenomena such as the multi-pulse chaotic motions. It is well known that the Melnikov method enables us to detect both homoclinic and heteroclinic bifurcations of nonlinear dynamical systems. Following the studies given by Wiggins [23], a new global perturbation method was developed by Kovacic and Wiggins [24], which may be used to detect the Shilnikov type single-pulse homoclinic and heteroclinic orbits of four-dimensional autonomous ordinary differential equations. Kaper and Kovacic [25] employed a modified Melnikov method to investigate the existence of several multi-bump homoclinic orbits to resonance bands for completely integral Hamiltonian systems with perturbations. Subsequently, Camassa et al. [26] proposed an extended Melnikov method to study the multi-pulse jumping of homoclinic and heteroclinic orbits in a class of perturbed Hamiltonian systems. In addition to the above mentioned concluding points, the extended Melnikov method proposed in [26] also offers great contribution in dealing with four-dimensional autonomous ordinary differential equations. Recently, the extended Melnikov method has also been applied to engineering systems. Zhang et al. [27] used the extended Melnikov method to investigate the multi-pulse global bifurcations and chaos for nonlinear nonplanar oscillations of a parametrically excited cantilever beam. Zhang et al. [28] improved the extended Melnikov method and employed it to study the multi-pulse Shilnikov type chaotic dynamics for a non-autonomous buckled rectangular thin plate under parametric excitation.

This paper generalizes the extended Melnikov method to non-autonomous nonlinear dynamical systems and uses it to investigate the multi-pulse chaotic dynamics of a simply supported laminated composite piezoelectric rectangular plate under combined parametric and transverse excitations for the first time. The nonlinear