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Homoclinic orbits and chaos of a supercritical composite panel with free-layer damping treatment in subsonic flow

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ABSTRACT

Multi-pulse homoclinic orbits and chaotic dynamics of a supercritical composite panel with free layer damping treatment in subsonic flow are investigated considering one to two internal resonance. Inviscid potential flow theory is employed to exhibit the aerodynamic pressure and Kelvin's model is used to describe the viscoelastic property of the free damping layer. By Hamilton's principle, the governing equation of the composite panel in the subcritical regime is derived. In the supercritical regime, the buckling configuration is solved analytically and the PDE is obtained by introducing a displacement transformation for nontrivial equilibrium configuration. Then the governing equation in the first supercritical region is transformed into a discretized nonlinear gyroscopic system via assumed modes and then Galerkin's method. The method of multiple scales and canonical transformation are applied to reduce the equations of motions to the near-integrable Hamiltonian standard forms. The Energy-Phase method is employed to demonstrate the existence of chaotic dynamics by identifying the existence of multi-pulse jumping orbits in the perturbed phase space. The global solutions are finally interpreted in terms of the physical motion of the gyroscopic continua and the dynamical mechanism of chaotic pattern conversion between the forward traveling wave motion and the complex bidirectional traveling wave motion are discussed.

1. Introduction

Aeroelasticity is concerned with those physical phenomena which involve significant mutual interaction among inertial, elastic and aerodynamic forces [1]. The aeroelasticity of panels on a variety of high performance operational and research aircraft is a subject which has been intensely studied for the past half century. Because of structural nonlinearities, the dynamic aeroelastic instability of panels does not usually lead to immediate catastrophic failure, as often the case for lifting surfaces, but rather is frequently a limited amplitude oscillation which may lead to long time fatigue failure [2].

In fact, the type of aeroelastic instability of panels, whether divergence or flutter, depends on the boundary conditions and Mach number [3]. For example, if a panel is simply supported or clamped at both edges, it undergoes divergence in subsonic flow but flutters in supersonic flow; whereas, a cantilevered panel clamped at one end and free at the other flutters in subsonic flow and undergoes divergence in supersonic flow. The instability of panels with different boundary conditions in the subsonic flow have been studied by Dugundji et al. [4], Oyibo [5] and Tang et al. [6,7]. Dowell et al. [8] discussed the nonlinear aeroelastic behavior, summarized the primary physical sources of fluid and structural nonlinearities that can lead to nonlinear aeroelastic response and they offered a few suggestions for future work. Recently, some researchers [9–11] carried out the active aeroelastic analysis with piezoelectric actuation and time-delayed feedback control.

Damping refers to the extraction of mechanical energy from a vibrating system usually by conversion into heat. Damping serves to control the steady state resonant response in engineering field as passive vibration suppression mechanism. In this paper, we will see that the interaction between damping and excitation may generate complex chaotic motions under certain parameter conditions. Passive damping, especially the use of surface damping treatments in the automotive, commercial airplane, has emerged in recent years. Rao [12] described some of recent industrial applications of passive damping using viscoelstic materials to reduce noise and vibration. The damping effects are also one of the most important and interesting aspects of the theory of stability for elastic non-conservative systems (including panel flutter). Contrary to

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the normal sense, some research [4,5,13,14] has indicated that the structural damping destabilize the dynamical aeroelastic systems. The authors of this study [15] found a phenomenon of dual effect of viscoelastic damping on the composite panel flutter.

In recent years, there have been a number of investigations related to the issue of post-buckling composite structures which could improve the design envelope [16–18]. The panel structure in subsonic flow is actually a gyroscopic continua due to the presence of the skew-symmetric gyroscopic operator in the expression of aerodynamic force. Readers who are interested in the dynamics of gyroscopic continua in the supercritical regime can refer to the monograph by Païdoussis [19] and the papers by Zhang and Chen [20], Yang and Yang [21], Dai et al. [22] and Chen et al. [23]. One significant distinction of the gyroscopic dynamics is the involvement of the complex modes: we will see that gyroscopic nature influences the chaotic response profoundly as studied in this paper.

Pourtakdoust and Fazelzadeh [24] investigated the chaotic behavior of nonlinear viscoelastic panels in supersonic flow using numerical method. Several conventional criteria were applied to detect the chaotic motions and they indicated the important influence of structural damping on the domain of chaotic region. In recent decades, many researchers develop some global perturbation methods for detecting chaotic dynamics. The idea that homoclinic bifurcations in a dynamical system can be used to predict the occurrence of chaotic motions was originally introduced by Melnikov [25], and later was further developed by Holmes [26]. By using the classical Melnikov method, several papers were contributed to the global bifurcations and chaos of the forced excited panels in the subsonic flow [27–29] as the panels and shells were widely used in the design of external skin of high-speed vehicles.

The details of the framework of higher-dimensional Melnikov method can be found in Wiggins [30]. Then, Haller and Wiggins [31–33] developed an analytical global perturbation method, Energy-Phase method, to detect multi-pulse orbits homoclinic to a slow manifold in the perturbed resonant Hamiltonian systems which provide the mechanism how energy flow between modes. Haller [34] summarized the Energy-Phase method and presented a detailed procedure of applications to problems in mechanics and physics. Malhotra et al. [35] used the method to examine the global dynamics of flexible spinning discs, which was parametrically excited in spin rate, and had imperfections that cause symmetry-breaking. McDonald and Namachchivaya [36] studied the global dynamics of parametrically excited pipes conveying fluid near a zero to one resonance. Yu and Chen [37,38] researched the global bifurcations and chaos in externally excited cyclic system and harmonically excited undamped circular plate.

In this paper, we apply the Energy-Phase method to investigate the multi-pulse homoclinic orbits and chaotic dynamics of an externally excited supercritical composite panel with free layer damping treatment in subsonic flow considering one to two internal resonance. The organization of this paper is as follows: In Section 2, Hamilton's principle is employed to derive the governing equation in the subcritical regime considering nonlinear stretching of the composite panel. In the supercritical regime, the buckled static configuration is solved analytically and the PDE is obtained by introducing a displacement transformation for nontrivial equilibrium configuration. Then, the governing equation is transformed into a discretized nonlinear gyroscopic system via assumed modes and Galerkin's method. In Section 3, in the presence of one to two internal resonance, the near-integrable Hamiltonian standard formulations appropriate for applying the Energy-Phase method are obtained by using the method of multiple scales and canonical transformation. In the next section, we study the global dynamics of such gyroscopic systems. Specifically, in Section 4.1. The dynamics of unperturbed systems is investigated. In Section 4.2, under small perturbations, the Energy-Phase method is employed to show the existence of chaotic motions by identifying the existence of multi-pulse jumping orbits in the perturbed phase space. In Section 4.3, the existence of a Šilnikov homoclinic orbit for the dissipative gyroscopic system is proved and its approximate parameter set are presented. In Section 5, the global solutions are interpreted in terms of the physical motion. In Section 6, we end the paper with concluding remarks.

2. Governing equations of motion

We consider a flat rectangular composite panel of length a, width b and thickness h, with one surface exposed to a subsonic airflow of velocity V_∞. The composite panel consists of a base layer and a free damping layer. The base layer are assumed to be purely elastic, with Young's moduli E_e and the damping layer is viscoelastic with a dynamic modulus of the Kelvin-Voigt type $E_d = E(1 + \eta \frac{\partial}{\partial t})$, where η represents the viscos coefficient. In addition, the panel is subjected to external in-plane loadings F_x and horizontal excitation $F_b = A_b \cos \omega_b t$ by the motion of the base, as shown in Figs. 1 and 2. We assume that there is no delamination between the elastic and viscoelastic layer at their interface. Since the transverse vibrations are dominant in the panel dynamic problem, the effects of longitudinal and rotary inertia are also negligible.

Based on the static equilibrium condition in the longitudinal direction of the composite panel, the neutral location of the cross section can be determined by

$$h_0 = \frac{(1-\upsilon_d^2)E_e h_e^2 - (1-\upsilon_e^2)E_d h_d^2}{2(1-\upsilon_d^2)E_e h_e + 2(1-\upsilon_e^2)E_d h_d} \tag{1}$$

where υ_e and υ_d is the Poisson ratio of the elastic layer and damping layer, respectively.

The equations of motion are obtained by using the Kirchhoff's hypothesis of classical thin-plate theory and considering von Karman geometric nonlinearity, which describes the stretching in the neutral plane of the composite panel. The total strains are expressed as [39]

$$\varepsilon_{xx} = \frac{1}{2}\left(\frac{\partial w}{\partial x}\right)^2 - z\frac{\partial^2 w}{\partial x^2}, \quad \varepsilon_{yy} = \frac{1}{2}\left(\frac{\partial w}{\partial y}\right)^2 - z\frac{\partial^2 w}{\partial y^2},$$
$$\gamma_{xy} = \frac{1}{2}\frac{\partial w}{\partial x}\frac{\partial w}{\partial y} - 2z\frac{\partial^2 w}{\partial x \partial y} \tag{2}$$

Since the subsonic flow is along the x direction, in this paper, we only consider a two-dimensional simply supported composite panel. So, the terms corresponding to the y direction are omitted in the following analysis, and subscript e and d represents the elastic layer and the damping layer, respectively.

The kinetic energy and strain energy can be expressed as follows

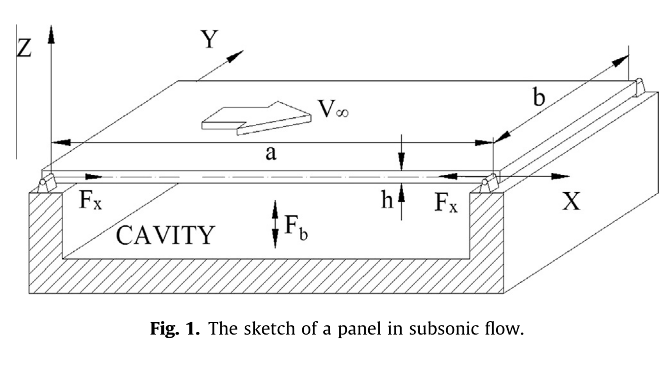

Fig. 1. The sketch of a panel in subsonic flow.