Ocean Engineering 115 (2016) 196–209

Contents lists available at ScienceDirect

Ocean Engineering

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

Effects of in-plane loads on free vibration of symmetrically cross-ply laminated plates resting on Pasternak foundation and coupled with fluid

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ARTICLE INFO

Article history:
Received 24 July 2015
Accepted 5 February 2016
Available online 23 February 2016

Keywords:
Free vibration
Laminated composite plate
Fluid–plate interaction
Ritz method
In-plane loading

ABSTRACT

The aim of present work is to investigate the effects of uniform in-plane loads on vibratory characteristics of symmetrically cross-ply laminated composite plates on elastic foundation and vertically in contact with fluid based on the first order shear deformation theory. The fluid is assumed to be ideal, incompressible and inviscid with small amplitude motion and the effects of hydrostatic pressure and free surface waves are negligible. The fluid domain is considered to be finite in depth and width but it is infinite in length direction. The Rayleigh–Ritz method is applied to derive the eigenvalue equation of the fluid–plate system and Chebyshev polynomials multiplied by a boundary function are adopted as the admissible functions in the procedure. The accuracy of the proposed method is examined via comparison studies with the available data in the literature. The effects of different parameters on natural frequencies such as, thickness-span ratios, aspect ratios, fluid depth ratios, load intensities, elastic foundation coefficients and various types of in-plane loads and boundary conditions are discussed in tabular and graphical forms.

1. Introduction

Over the past few decades, application of composite plates as one of the structural components has developed in various engineering fields namely, marine, aerospace, civil and etc. high strength-to-weight ratio, modulus-to-weight ratio and low production cost are some of the significant features of composite materials that have attracted the attention of many engineering designers. In addition, elastic foundation is a model to represent relatively soft material in contact with plate surface. The oldest model of the soil–structure interaction was proposed by Winkler. Pasternak is a two-parameter elastic foundation model which the interaction of adjacent springs is considered by connecting the ends of the springs to a shear layer. A considerable volume of literature is available for bending, buckling and vibration of composite plates with and without foundation based on the various laminated plate theories namely, equivalent single-layer, 3D elasticity theory and multiple model methods. It could be mentioned that solution based on the three-dimensional elasticity theories such as layer-wised theory is often computationally expensive. These theories require numerous unknowns for multilayered plates and are often computationally expensive to obtain the accurate solutions. The total number of unknowns depends on the number of layers in a laminate and will increase dramatically as the number of layers increases. The first-order shear deformation theory (FSDT) is simple to implement and applied for both thick and thin laminate composite plates. However the accuracy of solutions will be strongly dependent on the shear correction factors. Without requiring the specification of a shear correction factor in the first-order shear deformation plate theory, various higher-order plate theories have been developed. A number of single-layer higher-order plate theories that include the effects of transverse shear deformations have been published in the literature. Remarkable published papers have been presented by Reddy (1997,1984), Qatu (2004), Khdeir (1988), Kant and Swaminathan (2001), Matsunaga (2001), Mantari et al. (2011), Cui et al. (2011), Senthilnathan et al., (1987), Whitney and Pagano (1970), Shojaee et al. (2012), Khalili et al. (2013), Vosoughi et al. (2013), Aiello and Ombres (1999), Ferreira and Fasshauer (2007), Akavci (2007), and Timarci and Aydogdu (2005) based on the equivalent single-layer theories and Carrera (2003a,2003b,2000) based on the layer-wised theory.

On the other hand, many structural components are often subjected to various types of in-plane stresses. These stresses not only cause the buckling phenomenon but also affect the vibration modes of the structures. The vibration problem of plates in the presence of in-plane stresses is important to the aeronautical, naval and structural engineers. Some numerical and analytical works have been devoted to

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http://dx.doi.org/10.1016/j.oceaneng.2016.02.014
0029-8018/

this problem. Dawe and Craig (1986) studied the vibration and stability of symmetrically laminated plates subjected to in-plane stresses based on the first-order shear deformation plate theory by using the Ritz and finite strip method. Xiang et al. (1996) investigated the free vibration and buckling of thick simply supported symmetrically cross-ply laminated rectangular plates resting on elastic foundation. Hasani Baferani and Saidi (2013) presented an exact analytical approach to examine the effects of different in-plane loads on the vibration of laminated thick rectangular plates resting on elastic foundation. Leissa and Kang (2002) presented an exact solution for vibration and buckling of SS-C-SS-C isotropic rectangular plates subjected to linearly varying in-plane stresses based on the Classical plate theory. Dickinson (1971) by using the Ritz method studied the vibration of thin isotropic plates subjected to both direct and shearing in-plane forces. Singh and Dey (1990) applied the finite difference method to analyze the vibration of the rectangular plates subjected to in-plane forces.

Furthermore, the fluid–structure interaction problems have also received much attention due to their importance in nuclear reactor elements, ship or submarine hulls and propellant storage tanks in airplanes, missiles and space vehicles (Hosseini-Hashemi et al., 2010a). Many notable investigations related to the fluid–structure interaction problem have been done by researches. Amabili (1997) studied vibration of structures coupled with heavy fluid by the Ritz method. Ergin and Ugurlu (2003) investigated the dynamic characteristics of a vertical cantilever plate partially in contact with fluid. Ugurlu et al. (2008) examined the effects of elastic foundation and fluid on the dynamic response characteristics of rectangular Kirchhoff plates using a mixed-type finite element formulation. Hosseini-Hashemi et al. (2010b) studied free vibration of vertical isotropic rectangular Mindlin plates resting on Pasternak elastic foundation and fully or partially in contact with fluid on their one side. In their study, the effects of free surface waves does not considered and a set of static Timoshenko beam functions have been employed as the admissible functions in the Ritz procedure. Zhou and Cheung (2000) analyzed the vibratory characteristics of a rectangular plate in contact with water on one side. Kerboua et al. (2008) by using a combination of the finite element method and Sanders' shell theory studied the Vibration analysis of rectangular plates in contact with fluid. By applying the Ritz method, free vibration analysis of a laminated composite rectangular plate coupled with a bounded fluid was carried out by Khorshidi and Farhadi (2013). Their investigation was based on the CPT, FSDT and third-order shear deformation theory (TSDT). They only considered the simply supported boundary condition with movable (SSM) and immovable edges (SSI) and clamped one. The effect of free surface waves was taken into account in their study. Jeong and Kang (2013) by using the Ritz method and a set of orthogonal polynomials examined the free vibration of CCFF multiple rectangular plates coupled with a liquid.

From aforementioned research works, it could be deduced that the research on dynamic response of the laminated composite rectangular plates in contact with fluid has been restricted to very few papers and there is a gap in this area of research. Moreover, as mentioned above, it is well known that the presence of in-plane loads as well as the elastic foundation parameters has significant effects on the natural frequencies of the plate. In present study, as the first endeavor, the effects of uniform in-plane loads on the natural frequencies of symmetrically cross-ply laminated rectangular plates on two parameter elastic foundation and in contact with fluid based on the first-order shear deformation plate theory (FSDT) is investigated. The fluid is assumed to be ideal, incompressible and inviscid (i.e., the fluid flow is potential) with small amplitude motion. The fluid domain is finite in depth and width but it is infinite in length direction. The effects of hydrostatic pressure and free surface waves of fluid does not consider in present work. The Rayleigh–Ritz method is applied to derive the eigenvalue equation of the fluid–plate system and Chebyshev polynomials multiplied by a boundary function are adopted as the admissible functions in the procedure. It could be mentioned that the Ritz method is a powerful technic in the study of vibration analysis of structures. In this method, resulting frequency is an upper bound solution, unless an appropriate shape functions is employed. Therefore, convergence should be monotonic from above as the number of terms of the admissible functions increases. It is well known that the accuracy and the applicability of the Ritz method greatly depend on the adopted basic functions. One of the advantages of the Chebyshev polynomials is that these are a set of orthogonal functions in the interval $[-1, 1]$, so rapid convergence is anticipated. The accuracy and eligibility of the proposed method is examined via comparison studies with the available data in the literature. The effects of different parameters on natural frequencies such as, thickness-span ratios, aspect ratios, fluid depth ratios as well as elastic foundation coefficients, load intensities and various types of in-plane loads are discussed thoroughly.

2. Theoretical formulation

2.1. Basic analysis

Let us consider a symmetrically laminated thick rectangular plate with length a, width b and total uniform thickness h, resting on a two-parameter elastic foundation of Pasternak type and in contact with fluid. The geometry of the plate–fluid and the coordinate systems are depicted in Fig. 1. The plate consists of N layers which are assumed to be homogeneous and made of orthotropic material. The fluid is considered to be in a rectangular domain with width a, depth H and infinite length. The fluid is assumed to be ideal, incompressible and inviscid (i.e., the fluid flow is potential) with small amplitude motion so that the potential of the velocity exists according to the linearized theory of small movement of fluid.

On the basis of the first-order shear deformation plate theory the displacement fields are assumed to be given Reddy (1997) and Qatu (2004):

$$\overline{u}(x,y,z,t) = u_0(x,y,t) + z\psi_x(x,y,t)$$

$$\overline{v}(x,y,z,t) = v_0(x,y,t) + z\psi_y(x,y,t)$$

$$\overline{w}(x,y,z,t) = w(x,y,t) \quad (1)$$

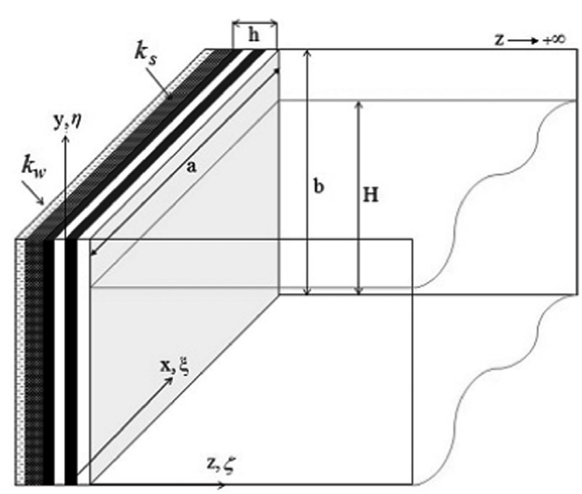

Fig. 1. Geometry and coordinates of laminated rectangular plate on Pasternak foundation and in contact with fluid.