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A modified Fourier solution for vibration analysis of moderately thick laminated plates with general boundary restraints and internal line supports

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ABSTRACT

In this investigation, a modified Fourier solution based on the first-order shear deformation theory is developed for the free vibration problems of moderately thick composite laminated plates with general boundary restraints and internal line supports. In this solution approach, regardless of boundary conditions, the displacements and rotation components of the plate are invariantly expressed as a new form of trigonometric series expansions in which several supplementary terms introduced to ensure and accelerate the convergence of the series expansion. All the unknown coefficients are treated as the generalized coordinates and determined using the Raleigh–Ritz method. A systematic comparison including classical boundaries, elastic restraints, and internal line supports between the current solutions and numerical results published by other researchers is carried out to validate the excellent accuracy, reliability and feasibility of the proposed method. Excellent agreements are achieved. Comprehensive studies on the effects of elastic restraint parameters, layout schemes and locations of line supports are also reported. New results are obtained for plates subjected to elastic boundary restraints and arbitrary internal line supports in both directions, which may serve as benchmark solutions for future researches.
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1. Introduction

As one of the important structural components, composite laminated plates are widely used in aerospace crafts, naval vessels, civil construction and other fields of modern technology. Notably, these plates frequently work in complex environments and may suffer to arbitrary boundary restraints. In addition, intermediate line supports may be placed to reduce the magnitude of dynamic and static stresses and displacements of the plates as well as satisfy special functional requirements. Therefore a thorough understanding of the vibration behaviors of composite laminated plates with general boundary restraints and internal line supports is of great interest for the designers to realize proper and comparatively accurate design of machines and structures.

In recent decades, the wide use of composite plate structures has motivated a huge amount of research efforts in developing more accurate and applicable model and methods for analyzing their dynamic behaviors. Over decades of research, various plate theories and computational methods have been proposed by researchers, and a large number of researches have been carried out based on these theories and approaches. In the early stage, the classical plate theory (CPT), in which transverse normal and shear deformations are neglected, has been employed to predict the vibration behavior of composite laminated plates [1–14,28]. However, the CPT is limited to thin plates. For composite plates which are rather thick or when they are made from materials with a high degree of anisotropic, the CPT underestimate deflection and overestimates natural frequency due to ignoring the transverse shear deformation effect. To overcome this drawback, the classical plate theory has been modified to include the transverse shear deformation in plate bending, which resulted in a number of the so-called first-order shear deformation theories (FSDTs). Many of the previous studies regarding composite plates are based on the FSDTs [15–29]. It should be noted that shear correction factors have to be incorporated in the conventional FSDTs to adjust the transverse shear stiffness due to the transverse shear strains in these theories are assumed to be constant through the thickness. To overcome the deficiency of the FSDTs and further improve the dynamic analysis of plate structures, a number of higher order shear deformation theories (HSDTs) were developed, where the higher order variation of in-plane displacements through the thickness is considered to represent the actual warping of the plate cross-section. In such a case, HSDTs are free from shear correction factor. Noticeably, many of the contributions about dynamic analysis of composite plates are based on the HSDTs [28,30–39]. As pointed out by Qu et al. [40], although the HSDTs

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are capable of solving the global dynamic problem of plates more accurately, they introduce rather sophisticated formulations and boundary terms that are not easily applicable or yet understood. And these theories require more computational demanding compared to those FSDTs. Furthermore, from the existing literature, we can know that the FSDTs with proper shear correction factors are adequate for the prediction of the global behaviors of moderately thick laminated plates. Since the purpose of the analysis is to predict the free vibration characteristics of composite plates, the FSDTs may be a recommendable compromise between the solution accuracy and effort. Therefore, in the present work, the first-order shear deformation plate theory is just employed to formulate the theoretical model.

Apart from aforementioned plate theories, some other laminated plate theories such as layer-wise theories [41–47], zig-zag theories [48–54] have been developed. It has also been of great interest for researchers to develop an accurate and efficient method which can be used to determine the vibration behaviors of composite laminated plates. So far, many computational methods are available for the vibration analysis of these structures, such as the Ritz method, Galerkin method, differential quadrature (DQ) method, RBF method, Fourier series solution, finite element method (FEM), discrete singular convolution (DSC) approach, etc. The development of research on this subject has been well documented in several monographs respectively by Qatu [55], Reddy [56], Carrera et al. [57], Ye [58], and review or survey articles [53,59–61].

Despite a large number of studies have been carried out based on aforementioned theories and methods, it appears that the information available about the vibration characteristics of thick composite laminated plates is very limited. Most of the contributions on plates with elastically edges are confined to isotropic and thin plates. The only work is available in the open literature is that of Karami et al. [21] based on DQ formulation, to the authors′ knowledge. In addition, laminated plates with internal line supports are widely encountered in the engineering practices. Without these intermediate supports, the plates may undergo large deformation and acute shaking and eventually lead to structural failure. The only work is focused on this subject is that of Cheung and Zhou [5,6] based on static beam functions and that of Abrate and Foster [62], that presented the vibrations of thin isotropic and composite plates with classical boundary conditions. Moreover, most of the available solution procedures in the open literature are often only customized for a specific set of restraint conditions, which may not be appropriate for practical application because there are hundreds of different combinations of boundary conditions for a plate. It is desirable to develop a unified, efficient method which is capable of dealing with composite plates subjected to arbitrary boundary restraints and intermediate line supports.

The purpose of the present study is to develop an efficient and accurate solution for free vibration analysis of moderately thick, composite laminated plates subjected to general boundary restraints and internal line supports and provide a unified and reasonable accurate alternative to other analytical and numerical techniques. This paper can be considered as an extension of the modified Fourier series method previously developed for vibration analysis of isotropic plates [63] and composite laminated shells [64–66]. For the sake of brevity, the moderately thick composite laminated plates with rectangular platform which are most frequently used in the engineering applications are considered. The first-order shear deformation plate theory is adopted to formulate the theoretical model. The displacements and rotation components of the plate, regardless of boundary conditions, are invariantly expressed as a new form of trigonometric series expansions in which several supplementary terms introduced to ensure and accelerate the convergence of the solution. At each edge of the plate, the general restraint condition is implemented by introducing three groups of linear springs and two groups of rotational springs, which are continuously distributed along the edge. Instead of seeking a solution in strong forms in the previous studies, all the Fourier coefficients will be treated equally and independently as the generalized coordinates and solved directly from the Rayleigh–Ritz technique. A variety of free vibration results for thin and moderately thick composite laminated plates with different boundary conditions, geometric properties and material parameters are presented and compared with those solutions reported by other contributors, aiming to validate the convergence, efficiency and accuracy of the present analysis, as well as to explore the limits of its applicability. New results are obtained for plates subjected to elastic boundary restraints and arbitrary internal line supports in both the directions. The effects of the elastic restraint parameters, layout schemes, number of lamina and locations of line supports are also examined and reported.

2. Theoretical formulations

2.1. Description of the model

As shown in Fig. 1, the length, width and thickness of the thick, elastically restrained composite laminated plate under consideration are represented by a, b and h, respectively. The middle surface displacements of the plate in the x, y and z directions are denoted by u_0, v_0 and w_0, respectively, and ϕ_x and ϕ_y separately represent the rotations of transverse normal respect to y- and x-axes. At each edge of the plate, the general restraint condition is implemented by introducing three groups of linear springs (k_u, k_v and k_w) and

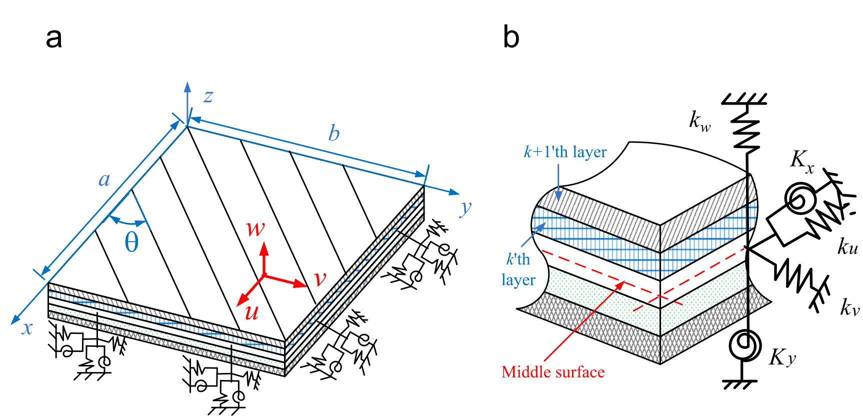

Fig. 1. Geometry and notations of a laminated plate: (a) co-ordinate system; and (b) partial view.

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