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Response of moderately thick laminated composite plates on elastic foundation subjected to moving load

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ABSTRACT

Dynamic response of moderately thick antisymmetric cross-ply laminated rectangular plates on elastic foundation is investigated. The governing equations are based on the higher order shear deformation theory (HSDT). Two-parameter elastic foundation (Pasternak type) is considered. Modal analysis in conjunction with the incremental differential quadrature method (IDQM), as an efficient and stable numerical tool for temporal domain discretization, are employed to solve the governing differential equations. Much lower computational time of the DQM with respect to Newmark's method is exhibited. The convergence of the method is demonstrated and its accuracy is shown by comparing the results with those of exact solution for thin plate obtained using the classical plate theory (CPT). Also, comparison between the results of different theories, i.e. the classical thin plate theory (CPT), the first order shear deformation theory (FSDT) and the higher order shear deformation theory (HSDT), is made. The effects of different parameters on dynamic response of the antisymmetric cross-ply plates are studied. The results can be used as benchmark solution for future works.

1. Introduction

The problem of structures subjected to traversing loads is sometimes encountered in modern engineering such as: bridges, overhead cranes and airport runaways.

The study of dynamic response of plates resting on elastic foundation subjected to moving loads is interesting and important, as some of the results may be applicable in understanding the dynamic behavior of roadways and runways. In the analysis of roadways and runways of airports, the structure is usually modeled as a plate resting on an elastic foundation. In general, loads on these types of structures are moving loads or moving masses such as the wheel loads from moving vehicles and planes.

Most of the previous studies on the plates subjected to moving loads are based on the classical plate theory (CPT) or the first order shear deformation theory (FSDT) and for plates without elastic foundations. Chonan [1] studied the dynamic response of a pre-stressed, orthotropic thick strip to a moving load based on the FSDT. The strip is of infinite length and subjected to initial in-plane stresses parallel and perpendicular to the edges. Agrawal et al. [2] analyzed the dynamic response of orthotropic thin plates subjected to moving mass using Green's function based on the CPT. Taheri and Ting [3,4] analyzed the dynamic response of thin plate subjected to moving loads using the finite element method [3] and structural impedance approach [4]. The Newmark's *p*-method was used in time domain. Geannakakes and Wang [5] reviewed the B_3-spline finite strip method and its application extended to the moving load analysis of arbitrarily shaped thin plates. Zhu and Law [6] analyzed the dynamic behavior of an orthotropic thin plate simply supported on a pair of parallel edges and under a system of moving loads, based on the Lagrange equation and modal superposition. de Faria and Oguamanam [7] investigated the vibration of Mindlin plates with moving concentrated load, using the finite element method (FEM) and they proposed a new strategy which is based on an adaptive mesh scheme and the use of perturbation technique in the structural vibration simulation. de Faria [8] carried out the vibration of a cylindrical panel with a moving force or mass, using the finite element method. The panels considered are assumed to be thin such that out-of-plane shear effects can be disregarded and the classical theory of shells can be applied. A perturbation technique is used to simplify the numerical problem. Wu [9] presented a technique for predicting the dynamic responses of a two-dimensional (2-D) full-size rectangular plate undergoing a transverse moving line load (i.e., multiple concentrated loads located in a straight line). They employed the one-dimensional (1-D) equivalent beam model or the scale beams

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Nomenclature

A_{ij}	component of extensional stiffness of laminate
a	plate dimension in the x-direction
b	plate dimension in the$y$-direction
D_{ij}	bending stiffness of laminate
E_i	Young's modulus of lamina
G_{ij}	shear modulus of lamina
h	total thickness of plate
k_w	coefficients of foundation stiffness along z direction
K_w	non-dimensional Coefficients of foundation stiffness along z direction [$=k_wD_{11}/a^4$]
k_g	coefficients of shearing layer of elastic foundation
K_g	non-dimensional coefficient of shearing layer of elastic foundation [$=k_gD_{11}/a^2$]
M_{xx}, M_{yy}	bending moment about y and x-axis and twisting moment, respectively
N_x,N_y	number of series terms in the x- and y-directions
N_{xx}, N_{yy}	in-plane normal force resultant in the x- and y-directions
$P_0(t)$	moving load magnitude
$\overline{Q}_{ij}^{(k)}$	generalized stiffness of kth layer
u_0, v_0, w_0	displacement component in the x-, y- and z-direction of a point on mid-plane of plate, respectively
V_P	moving load velocity
W_c	non-dimensional center deflection [$=w(a/2,b/2)E_1h^3/(P_oa^2)$]
x, y, z	the Cartesian coordinate variables
φ^x	rotation about y-axis
φ^y	rotation about x-axis
v_{ij}	the Poisson's ratio of laminate
ρ	mass density

subjected to a moving concentrated load, where the structural sizes and the external-load magnitude of the beam model are not necessarily equal to the corresponding ones of the plate model. Sun [10] studied the dynamic displacement of thin plate caused by a moving harmonic line and point load. The solution is represented by the convolution of dynamic Green's function of plate. An approximate relationship between critical load velocity and critical frequency is established analytically. Au and Wang [11] investigated the sound radiation from the forced vibration of rectangular orthotropic thin plates under moving loads. Lawa et al. [12] studied different aspects of dynamic identification of moving loads from a vehicle traveling on top of a beam-slab type bridge deck. The bridge deck is modeled as an orthotropic plate and the loads are modeled as a group of wheel loads or a group of axle loads moving on top of the bridge deck at a fixed spacing. Wu [13] presented a moving mass element to perform the dynamic analysis of an inclined thin isotropic plate subjected to moving loads and by considering the effects of inertia force, Coriolis force and centrifugal force.

Mohebpour et al. [14] investigated dynamic behavior of laminated composite plates traversed by a moving oscillator. They used finite element method to solve the governing equations based on the FSDT.

Regards to the response of plate on elastic foundation and subjected to moving load, Zaman et al. [15] presented a finite element algorithm to evaluate the dynamic response of a thick isotropic plate on viscoelastic foundation subjected to moving loads. Huang and Thambiratnam [16,17] developed a procedure incorporating the finite strip method, together with a spring system and applied to treat the response of rectangular thin plate structures resting on elastic foundation. Kim and McCullough [18] carried out the dynamic displacement and stress responses of a plate of infinite extent on a viscous Winkler foundation subjected to moving tandem-axle loads with amplitude variation. Formulations developed in the transformed field domain using a triple Fourier transform in time, space, and moving space for moving loads with arbitrary amplitude variation, and a double Fourier transform in space and moving space for the steady-state response to moving harmonic loads.

Lee and Yhim [19] carried out reports on a dynamic analysis of single and two-span continuous composite plate structures subjected to multi-moving loads based on the third order shear deformation theory. They used the finite element to solve the problem.

In particular, as a first endeavor, the dynamic response of anti-symmetric cross-ply rectangular laminated moderately thick plates on two-parameter elastic foundation (Pasternak type) is studied based on the higher order shear deformation theory. Modal analysis in conjunction with the differential quadrature method (DQM) in temporal domain are employed to obtain the solution. The effects of different parameters on the response of the plate are studied. This work in addition to represent a solution for the topic problem, establishes the applicability of the DQ method as an unconditionally stable and efficient numerical method for time dependent structural problems.

2. Governing equations and solution procedure

A composite plate composed of perfectly bonded orthotropic layers of length a, width b and total thickness h rested on the two-parameter elastic foundation is considered (see Fig. 1). Based on the higher order shear deformation plate theory, the equations of motion become [20],

In-plane equation of motion in the x-direction:

$$\begin{aligned}&A_{11}\frac{\partial^2 u_o}{\partial x^2}+A_{66}\frac{\partial^2 u_o}{\partial y^2}+(A_{12}+A_{66})\frac{\partial^2 v_o}{\partial x\partial y}+(B_{11}-c_1E_{11})\frac{\partial^2\varphi^x}{\partial x^2}\\&+(B_{66}-c_1E_{66})\frac{\partial^2\varphi^x}{\partial y^2}+(B_{12}+B_{66}-c_1E_{12}-c_1E_{66})\frac{\partial^2\varphi^y}{\partial x\partial y}\\&-c_1E_{11}\frac{\partial^3 w_o}{\partial x^3}-c_1(E_{12}+2E_{66})\frac{\partial^3 w_o}{\partial x\partial y^2}\\&=I_o\frac{\partial^2 u_o}{\partial t^2}+J_1\frac{\partial^2\varphi^x}{\partial t^2}-c_1I_3\frac{\partial^3 w_o}{\partial x\partial t^2}\end{aligned}\quad(1)$$

In-plane equation of motion in the y-direction:

$$\begin{aligned}&(A_{12}+A_{66})\frac{\partial^2 u_o}{\partial x\partial y}+A_{22}\frac{\partial^2 v_o}{\partial y^2}+A_{66}\frac{\partial^2 v_o}{\partial x^2}+(B_{12}+B_{66}-c_1E_{12}\\&-c_1E_66)\frac{\partial^2\varphi^x}{\partial x\partial y}+(B_{66}-c_1E_{66})\frac{\partial^2\varphi^y}{\partial x^2}-(c_1E_{22}-B_{22})\frac{\partial^2\varphi^y}{\partial y^2}\\&-c_1E_{22}\frac{\partial^3 w_o}{\partial y^3}-c_1(E_{12}+2E_{66})\frac{\partial^3 w_o}{\partial x^2\partial y}\\&=I_o\frac{\partial^2 v_o}{\partial t^2}+J_1\frac{\partial^2\varphi^y}{\partial t^2}-c_1I_3\frac{\partial^3 w_o}{\partial y\partial t^2}\end{aligned}\quad(2)$$