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Parametric study of dynamic response of sandwich plate under moving loads

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ABSTRACT

Constrained layer damper is widely used in engineering applications to suppress the severe vibration of structural systems, especially for the cases with moving loads, such as sandwich beam or sandwich plate. The response analysis and parametric analysis of these sandwich structures under moving loads have not still understood comprehensively. To do this, a hybrid approach based on extended Rayleigh-Ritz solution together with penalty method and differential quadrature method is presented to predict the dynamic responses of sandwich plate with isotropic face plate and a viscoelastic core subjected to moving loads. Both the energy terms related to the sandwich plate and the energy terms introduced by boundary conditions are derived based on the first order shear deformation theory (FSDT) and expressed using the Rayleigh-Ritz solutions, and then the governing equation of motion of sandwich plate is obtained through Lagrange equation, which can model a sandwich plate with various boundary conditions. Different with classical Rayleigh-Ritz solutions, the admissible functions adopted here is a set of combination of simple polynomials and trigonometric functions, which just satisfy a totally unconstrained boundary condition, and penalty method is applied to handle constraints. Then the variations of the natural frequency, associated modal loss factor and vibration response with the parameters (such as thicknesses of constrained layer and damping layer, elastic modulus of constrained layer material, and shear modulus and loss factor of damping layer material) of sandwich plate are studied. Moreover, the variations of maximum dynamic deflections with different boundary conditions as well as moving speeds are investigated.

1. Introduction

Sandwich structures which contain two stiffer layers and a viscoelastic mid-layer, have been widely used in engineering applications, such as aerospace, mechanical and civil engineering, due to the lighter structures with higher stiffness and desirable mechanical properties [1]. Additional damping by using higher damping materials is the simplest way to reduce vibrations of structures. Viscoelastic materials have the typical complex modulus due to both elastic and viscous characteristics of these materials. The dynamic behavior of sandwich structures under moving loads could be improved by using high damping viscoelastic core.

The flexural vibration of sandwich structures (e.g. beams and plates) has been investigated since the 1950s. Kerwin [2] analyzed a simply supported sandwich beam with complex modulus and presented the transverse traveling wave of sandwich beam. Mead et al. [3] investigated the forced vibration of a three-layer damping sandwich beam with arbitrary boundary condition. Johnson et al. [4] predicted the damping in structures with constrained viscoelastic layers using finite element method. Lall et al. [5] applied the Rayleigh-Ritz method to analyze the damping performance of flexural vibrations of a simply supported and partially covered plate with constrained viscoelastic damping treatment. Cupial et al. [6] investigated the natural frequencies and loss of factors of a rectangular three-layered plate with a viscoelastic core layer and laminated face layers based on the first order shear deformation theory (FSDT). Wang et al. [7] presented a Galerkin assumed modes analysis of sandwich plates. Banerjee et al. [8] investigated the free vibration of sandwich beam using dynamic stiffness method based on the Timoshenko beam theory. Ferreira et al. [9] presented a layerwise finite element model to treat the dynamic problem of sandwich plates with a viscoelastic core and laminated anisotropic face layers, where the Carrera's unified formulation is used to derive the stiffness and mass matrices of element. Khalfi et al. [10] obtained the harmonic and transient responses of a plate with partial constrained layer damping due to an impact based on the Lagrange's equations and fast Fourier transform, where Prony series was used to account for core properties. Hernandez et al. [11] investigated the influences of uncertainties on the modal parameters of a sandwich structure with a viscoelastic core using Monte Carlo simulation analysis, where two sources of uncertainties, associated with physical

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parameters of the constitutive model of viscoelastic core and with a set of geometrical parameters, were included.

Recently, the optimization of loss factor of sandwich plate is focused on. Arujo et al. [12] and Moita et al. [13] presented a new mixed layerwise finite element model to optimize hybrid active-passive laminated sandwich plates through maximization of modal loss factors. The design variables are viscoelastic core thickness, constraining elastic layers ply thicknesses and orientation angles, and the position of co-located sensor and actuator pairs. Aumjaud et al. [14] developed a novel double shear lap-joint damper produced the highest modal loss factor and amplitude reduction for least added mass for honeycomb sandwich structures. Additionally, Mahmoudkhani et al. [15] investigated the nonlinear free and forced bending vibrations of sandwich plates with incompressible viscoelastic core by using the method of eigenfunction expansion and the extended Green's formula.

On the other hand, structures subjected to moving loads are commonly countered in engineering applications, such as roads and bridges, submarines and mechanical engineering. The dynamic behaviors of such structures with moving loads have been studied by many researchers in past decades. The comprehensive studies on the moving load problem have been performed by Fryba [16], and several analytical methods were proposed. Many engineering applications referred to moving load problems have been reviewed by Ouyang [17]. In the following section, here a brief review of the linear vibration behavior of plate under moving loads is introduced. As known, the governing equation of such problem is partial differential equation which is generally based on the classical plate theory (CPT) or FSDT and higher order shear deformation theory (HSDT), so the eigenfunction and integral scheme are often used to deal with the special and temporal derivatives, respectively. For homogenous plates, Gbadeyan et al. [18] proposed a versatile solution technique to solve the response of beams and plates under moving loads, based on modified generalized finite integral transforms and the modified Struble's method. Takabataka [19] considered the discontinuous variation of bending stiffness and mass of the plate with variation of the thickness using a characteristic function and presented an analytical method for rectangular plates under moving loads. Shadnam et al. [20] analyzed the response of rectangular plate subjected to moving mass and force by using a series of eigenfunctions. Ghazvini et al. [21] presented a robust computational approach to predict the transverse deflection of a thin rectangular plate with varying thickness under a traveling mass using eigenfunction expansion method. Nikkhoo et al. [22] proposed a semi-analytical model to study the response of a thin rectangular plate subjected to series of moving inertial loads by using eigenfunction expansion method, which was then applied to predict the response of Mindlin elastic plate [23]. Eftekhari et al. [24] presented a combined application of Ritz method, differential quadrature method (DQM) and integral quadrature method (IQM) to conduct the vibration response of rectangular plate subjected to accelerated traveling masses. In this paper, the Ritz method with beam eigenfunctions is used to discretize the spatial partial derivatives, and the DQM and IQM are employed to analogize the resultant system of partial differential equations, then the Newmark time integration scheme is used to solve the ordinary differential equations. Song et al. [25] presented a comprehensive method to predict the dynamic behavior of flat plate of arbitrary boundary conditions under moving loads based on Rayleigh-Ritz solution with penalty method and DQM, which was then extended to determine the responses of functionally graded plates [26]. For composite plates, Malekzadeh et al. [27] presented a solution procedure based on the three-dimensional (3D) elasticity theory to accurately predict the vibration response of cross-ply laminated thick plates under moving load. Vosoughi et al. [28] investigated the dynamic response of moderately thick antisymmetric cross-ply laminated rectangular plates on elastic foundation based on the HSDT, where Pasternak type elastic foundation was considered.

Finite element method (FEM), which is one of the most versatile methods to solve the spatial problem, is often applied in the vibration problem of plate under moving loads. Wu [29] investigated vibration of a rectangular plate under moving force along a circular path using FEM associated with equivalent forces (and moments). Wu [30] presented a moving mass element to perform the dynamic analysis of an inclined plate under moving loads using FEM. Esen [31] presented an equivalent finite element to analyze the transverse vibration of the plate under a moving point mass, which was then extended to predict both the transverse and longitudinal vibration responses of thin rectangular plates under a variable velocity moving load along an arbitrary trajectory [32]. Lee et al. [33] proposed a 7-DOF finite element model of composite plate to determine the vibration response under moving loads and analyze the influences of different plate theories, layup sequences and conditions on responses. Ghafoori et al. [34] described a FEM based on the FSDT to investigate the dynamic response of angle-ply laminated composite plates under a moving load. Mohebpour et al. [35] investigated the dynamic behavior of laminated composite plates traversed by a moving oscillator using FEM based on FSDT. However, the response analysis and parametric study of the sandwich structures (e.g., plate) under moving loads have not still understood comprehensively.

To the best of author's knowledge, there are little studies carried out so far in the literature into dynamic responses of sandwich plate under moving loads, and the information is not available in open literatures. As a first endeavor, thus, this paper presents a mixed Rayleigh-Ritz method (RRM) associated with penalty method (PM) method to treat the dynamic problem of sandwich plate with isotropic face plate and a viscoelastic core subjected to moving loads based on thin plate theory. The admissible functions adopted here just satisfy a totally unconstrained condition, so the method can be used to model the sandwich plate with various boundary conditions. Finally, the parametric study of sandwich plate are performed.

2. Dynamic model of sandwich plate under moving load

2.1. Energy formulas

A sandwich plate with a viscoelastic core carrying a moving mass is shown in Fig. 1. The sandwich plate consists of three layers, namely constrained layer (CL), damping layer (DL) and base layer (BL) plates. Without loss of generality, it is assumed that the mass moves with a constant velocity v_L along *o-x* axis, that is, the location of the mass is ($v_L t$, y_L), where y_L is constant. In this paper, the following widely adopted assumptions [3] are raised to derive the energy expression of the sandwich plate: (a) For BL and CL, effect of rotatory inertia and normal stresses along thickness are taken to be negligibly small; (b) Normal to the undeformed middle surface remains straight and normal to the deformed middle surface and unstretched in length; (c) The transverse displacement at a section is considered not to vary along the thickness and the longitudinal displacements are assumed to vary linearly along the thickness; (d) No slip occurs at the interfaces between

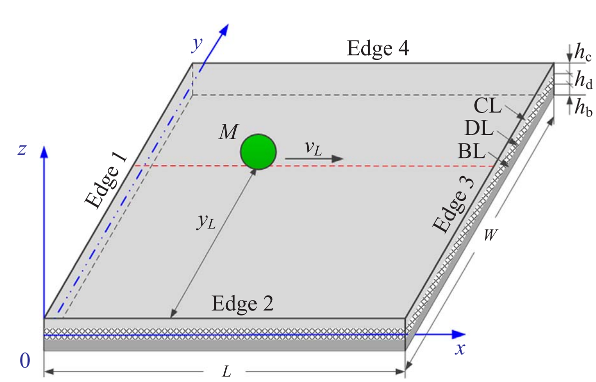

Fig. 1. Geometry and moving load of a sandwich plate with a viscoelastic core.