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Dynamic analysis for cracked fiber-metal laminated beams carrying moving loads and its application for wavelet based crack detection

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ABSTRACT

The present study considered the free and forced vibration of cracked fiber metal laminated (FML) beams with a damper subjected to a moving load, and the detection of the cracks by using continuous wavelet transform (CWT). The beam is regarded as multi segments which are assumed to obey the Euler-Bernoulli beam hypothesis and the crack is modeled as rotational spring with sectional flexibility. The modal expansion theory and Newmark method are employed to solve the dynamic responses of FML beam numerically. Two classes of boundary conditions are considered and the dynamic responses at the tip of a FML cantilever beam with a single crack are obtained for various load velocity, and the outcome results have been compared to the results obtained by literature. The influences of crack depth, crack location, ply angle of the fiber layer, stiffness coefficient of the damper and velocity of the moving load on free vibration and forced vibration of FML cantilever beams are investigated. Numerical results indicate that the above-mentioned effects play a very important role on both free vibration and dynamic responses of the beam. In the end of the numerical examples, continuous wavelet transform is used to detect the location of the cracks of a clamped-clamped FML beam.

1. Introduction

Structures under the action of the moving load or mass are easy to find in engineering such as bridges, roads and some aerospace equipment. Due to the diversities of structures and materials and the complexity of loads, the dynamic behaviors of suchlike mechanical models become interesting topics for both structural and material researchers. Quite a few investigations have been reported in the analyses of dynamic responses of the structures subjected to moving loads. For homogeneous isotropic structures, a typical example, Frýba [1] took overall consideration of the dynamic deflections and stresses of all kinds of beams, rectangular plates and three-dimensional structures under the action of moving constant load, harmonic load and multi-axle system. Many investigators focus attentions on composite structures subjected to moving loads. Simsek [2–4] studied dynamic responses of the functionally graded material beam subjected to moving constant load and harmonic load either analytically or numerically. For the laminated composite structures, Malekzadeh [5] investigated the three-dimensional dynamic analysis of laminated composite plates subjected to moving load by using differential quadrature method.

The literatures mentioned above are concerned with the intact structures. But in fact, due to the manufacturing processes and operating conditions, cracks always exist in structures, which can introduce local flexibilities, reduce the stiffness and change the dynamic behavior of the structure. For dynamic behavior of structures with a crack or multi cracks under the action of moving loads, numerous studies [6–11] have been reported based on different crack model. The most popular model for the crack in beam is a massless rotational spring with sectional flexibility. Based on this model and Euler-Bernoulli beam theory, Lin and Chang [12] studied the forced responses of cantilever beams with a single-sided open crack subjected to a moving point load. Shafiei et. al [13] proposed an analytical solutions for free and forced vibrations of a multiple cracked Timoshenko beam subject to a concentrated moving load. For cracked inhomogeneous beams, Yang et. al [14] investigated their dynamic behavior under an axial force and a moving load based on classical Euler-Bernoulli beam hypothesis and rotational spring model and modal expansion technique. Yan et al. [15] studied the dynamic behavior of edge-cracked Timoshenko functionally graded beams on an elastic foundation under a moving load.

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Cracks make structures more flexible, as concluded by all of the literature concerned with crack problems mentioned above. Hence, it is necessary to detect cracks in structures. The crack identification turns into another pop topic which has attracted a great many researchers. One of the most used methods to study damages in structures, especially in bridges, is the wavelet transform. For example, Zhu and Law [16] studied the crack identification of bridge beam from operational deflection time history based on wavelet transform and the results are validated by both simulation and experiment; Khorram et. al [17] identified the location of the crack of a simply supported beam by applying continuous wavelet transform (CWT) to the displacement at midspan during the time used in the fixed sensor approach, and the displacement of the moving load during the time used in the moving sensor approach, respectively, and inferred that moving sensor approach is more sensitive. In the last few years, it is common occurrence in the literature [18–21] for damage detection for beam-type structure based on wavelet transform and moving load.

Fiber-metal laminates (FMLs) are high-performance hybrid structures comprised of metal alloy sheets and fiber-reinforced plies, originally invented by Delft University of Technology [22] in the 1980s. The combination of good impact resistance of the metals and the better lightweight property of the fiber-reinforced composites has made it of great use in aerospace and satellite structures. Theoretical and experimental studies have been performed on the analysis of fiber metal laminated (FML) structures by many researchers. As examples, Reyes et. al [23] studied the quasi-static and impact behaviors of fiber metal laminates by experiment; Shooshtari and Razavi [24] investigated the linear and nonlinear free vibrations of fiber metal laminated rectangular plates by using the Galerkin method and multiple time scales method. In FML structures, crack damage can often result in stiffness degradation and has evident influence on the mechanical properties of the structures. Considering the wide applications of FML structures, it is important to study the dynamic response of FMLs with crack damage subjected to moving loads and detect the crack of the structures.

The current study is to present the free and forced vibration of FML beams with a damper carrying a moving load and the detection of locations of cracks by using CWT. The beam is regarded as multi segments which are assumed to obey the Euler-Bernoulli beam hypothesis and the crack is modeled as rotational spring with sectional flexibility. Two classes of boundary conditions will be considered, and the influences of crack depth, crack location, stiffness coefficient of the damper and velocity of the moving load on both free vibration and dynamic responses of FML cantilever beams will be investigated. The conclusions of this research may be a useful theoretical reference to optimal design as well as damage detection of FML structures.

2. Dynamic behavior of a multi-cracked FML beam

Consider a fiber-metal laminated beam having length L, width b and thickness h with N cracks connected to a viscous damper of stiffness k, damping coefficient c, and mass m_e shown in Fig. 1. The Cartesian coordinate system O-xz is established on the geometric middle plane of the beam ($z = 0$). The N single-sided open cracks of the beam located at x_i of depth d_i ($i = 1, 2, \ldots, N$). The beam is divided into $(N + 1)$ segments by the N cracks and the length of the ith segment is l_i ($i = 1, 2, \ldots, N + 1$).

2.1. Governing equation of motion

Based on Euler-Bernoulli beam theory, the governing equation of motion for the whole beam is

$$D\frac{\partial^4 w}{\partial x^4} + I_0\frac{\partial^2 w}{\partial t^2} + \left[k(w - r) + c\left(\frac{\partial w}{\partial t} - \frac{\partial r}{\partial t}\right)\right]\delta(x - a) = F\delta(x - vt)H\left(\frac{L}{v} - t\right) \quad (1)$$

where $w = w(x, t)$ and $r = r(t)$ are the deflection of the whole beam and absolute position of the damper, respectively; $\delta(x)$ and $H(x)$ are the so-called Dirac and Heaviside functions which can be defined as

$$\int_{-\infty}^{\infty}\delta(x)\mathrm{d}x = 1, \quad \begin{cases}\delta(x) = 0, & \text{for } x \neq 0\\ \text{indefinite}, & \text{for } x = 0\end{cases} \quad (2)$$

$$H(x) = \begin{cases}0, & x < 0\\ 1, & x > 0\end{cases} \quad (3)$$

k and c are the stiffness and damping coefficients of the damper, respectively; t denotes the time; $I_0 = b\int_{-\frac{h}{2}}^{\frac{h}{2}}\rho^{(j)}\mathrm{d}z$ is the inertia of the beam and $\rho^{(j)}$ is the material density for jth layer; D is the reduced bending stiffness of the beam given as

$$D = D_{11} - \frac{B_{11}^2}{A_{11}} \quad (4)$$

where $\{A_{11}, B_{11}, D_{11}\} = b\int_{-\frac{h}{2}}^{\frac{h}{2}}\bar{Q}_{11}^{(j)}\{1, z, z^2\}\mathrm{d}z$. $\bar{Q}_{11}^{(j)}$ is the stiffness coefficient of the jth layer given as

$$\bar{Q}_{11}^{(j)} = E_{11}\cos^4\theta_j + 2(E_{12} + 2E_{66})\cos^2\theta_j\sin^2\theta_j + E_{22}\sin^4\theta_j \quad (5)$$

where, θ_j is the angle of the jth ply orientation of the fiber and the elastic modulus E_{ij} are given by follows:

$$E_{11} = \frac{E_1}{1 - v_{12}v_{21}}, \quad E_{22} = \frac{E_2}{1 - v_{12}v_{21}}$$
$$E_{12} = \frac{v_{12}E_2}{1 - v_{12}v_{21}}, \quad E_{66} = G_{12}, \quad v_{21}E_1 = v_{12}E_2 \quad (6)$$

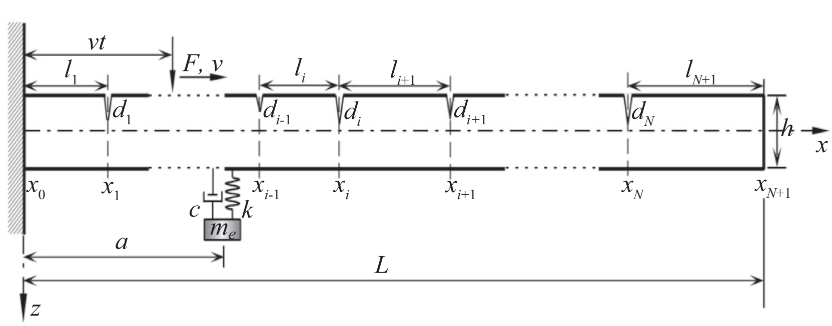

Fig. 1. Structural schematic for a cracked fiber-metal laminated beam with a damper.