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Dynamic modeling of a multilayer rotating blade via quadratic layerwise theory

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ABSTRACT

A novel dynamic model for a multilayer rotating blade mounted at an arbitrary stagger angle using a quadratic layerwise theory is developed to study structural dynamics of the blade, particularly damping properties, using various coating layer configurations. A reduced two-dimensional (2D) model is used to describe the dynamic behavior of each layer in the weak form, while the quadratic layerwise theory is applied to interpolate the transverse shear stresses along the thickness direction. Results of numerical simulations with the reduced 2D model are compared to the full three-dimensional (3D) model showing an excellent agreement, comparable to the cubic layerwise theory, for both modal analysis and frequency response calculations. Moreover, damping analyses are performed on two types of multilayer blades: two-layer (free damping) and three-layer (constrained layer), in both non-rotating and rotating situations, and, parametric analyses with varying coating thickness and rotation speed are carried out. It is shown that damping decreases as the rotation speed increases due to inertial and Coriolis effects. Furthermore, frequency loci veering as a result of the rotation speed is observed. The proposed model gives an efficient and accurate way to study the dynamic behavior of rotating multilayer structures, such as compressor blades.

1. Introduction

Nowadays, turbomachineries are widely used in industry, such as gas turbines and aero engines. Compressor blades as the key component are responsible for supplying high pressure to the flow while operating at a high rotation speed. Undertaking such severe operation environment, the high speed aero flow generates an unsteady aerodynamic force which acts on the blade body with combinations of both centrifugal and Coriolis forces. It is well known that when the aerodynamic force coincides with the natural frequencies of the compressor blade, the flutter phenomenon will appear, causing extremely large resonance peaks, and eventually resulting in structural failure. Therefore, solutions to suppress the resonance peaks and avoid flutter become a significant and interesting research subject, where the traditional solution is to increase the structural damping of compressor blades. For the sake of the feasibility in industrial applications, a convenient method is to apply a thin damping layer over the blade surface. The damping layer can consist of hard coating materials, viscoelastic materials, epoxy resin, etc. Alternatively, composite materials can be used. Composite compressor blades have several advantages: lightweight, high stiffness and high damping effect.

To give an accurate prediction of the vibration of blades, multilayer structure modeling methods have been widely developed. For composite structures, in each laminate layer, the out of plane shear stress components can be assumed constant. Since typical composite structures consist of a large number of thin laminate layers, with increasing number of layers, the transverse shear stresses tend to an approximately continuous profile along the thickness direction [1]. However, this assumption based on large number of laminate layers is not suitable for two-layer or three-layer structures, because the continuity of the transverse shear stresses cannot be satisfied. Cremer et al. [2] give a simplified two-layer model, where the transverse shear is neglected and Euler–Bernoulli bending theory is considered. However, the model is not suitable to describe two layers with similar material properties. To conquer this challenge, layerwise theories, such as Robbins and Reddy [3], Reddy [4], Castro et al. [5], and Moleiro et al. [6], are applied. In the early research, the linear layerwise theory is developed to predict the vibration behavior of multilayer structures with thin laminate, where the transverse shear stresses are small enough to be neglected. Furthermore, high order interpolation is used on the layerwise theory to improve accuracy. Cho et al. [7] use a high order interpolation function to approximate the displacement components of each layer for a laminated composite plate and predict the eigenfrequencies for various laminated configurations but only considering the simply supported situation. Basar and Omurtag [8] apply a shell element via the layerwise theory to predict the vibration characteristics of

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both the thin and thick laminated plate in a static situation. Ferreira [9] uses a first order shear deformation layerwise theory to describe the composite plates while applying the multiquadrics method for the numerical discretization.

In the prediction of the dynamic behavior of a cantilever multilayer structure (non-rotating and rotating cases), many papers are presented. Nabi and Ganesan [10] utilized a layered two-dimensional (2D) element to predict damping of a twisted blade with various pretwisted angles in an non-rotating state. Lee et al. [11] applied a global zig–zag layerwise theory to model a multilayer rotating disk in both the frequency and time domains. He et al. [12] adopted the thin shell model to describe a pretwisted composite cantilever blade with referring to Qatu and Leissa [13]. However, only the non-rotating case is studied. By means of the finite element method, Chen and Chen [14] studied a response characteristic of a composite rotating blade due to the random excitation. Kee and Kim [15] applied a thick shell finite element model to simulate a twisted composite blade with the rotation speed. However, only the geometry of the cylindrical shell is considered. Malekzadeh et al. [16] researched on the dynamic response of a simply supported composite plate loaded by a moving excitation source, where a global layerwise theory is applied. Xie and Xue [17] used a Zapfe's element to model a straight constrained layer blade at an arbitrary rotation speed, where parametric analyses account for the variation of damping structure configurations and rotation speed but not for the stagger angle.

In this paper, a new quadratic layerwise theory is applied to a reduced 2D dynamic model of a rotating blade, where the blade is considered to be mounted at an arbitrary stagger angle. The main objective is to investigate the damping of a pure blade treated by various coating configurations in the non-rotating and rotating situations. The model is validated by comparison to a full 3D model and the loss factor of the damped blade is calculated for several configurations. It is shown that loss factors decrease when the rotational velocity increases and the apparently irregular patterns are caused by frequency loci veering. The current reduced model is a fast tool to predict the dynamic behavior and loss factor in the early design stage of compressor blades coated with damping materials.

2. Dynamic modeling

As shown in Fig. 1, following the authors' previous work [18], a multilayer rotating blade is modeled as a rectangular plate at an arbitrary rotation speed Ω. The blade is a cantilever plate which is clamped at the disk with radius of R. The stagger angle is denoted θ; the dimensions of the blade are the length L, width b and thickness h.

The high order layerwise theory by Plagianakos and Saravanos [1] is extended to the dynamic modeling of a multilayer rotating compressor blade mounted at an arbitrary stagger angle, where a quadratic shape function is used for the interpolation along the thickness direction. As illustrated in Fig. 2, at each interface, the in-plane displacement components (u_j, v_j) and for each laminate layer, two hyper rotation angles $(\theta_{\alpha j}, \theta_{\beta j})$ are defined as the independent variables; the transverse displacement w_0 is assumed constant along the thickness direction. Hence, the displacement at an arbitrary position of the multilayered structure is written as three orthogonal displacement components

$$\begin{cases} u^{(j)} = \Theta_1 u_j + \Theta_2 u_{j+1} + \Theta_3 \theta_{\alpha j} \\ v^{(j)} = \Theta_1 v_j + \Theta_2 v_{j+1} + \Theta_3 \theta_{\beta j} \\ w^{(j)} = w_0, \end{cases} \tag{1}$$

where $(\cdot)^{(j)}$ denotes the variable of the jth layer; Θ_1, Θ_2 are linear shape functions and Θ_3 is a quadratic shape function.

As shown in Fig. 2, the xy-plane of the global coordinate system is located at a distance d off the jth interface along the z-axis, where the distance d is arbitrary. The constant d_j denotes the distance from the jth interface to the xy-plane along z-axis. Thus, the shape functions are written [1,19]

$$\begin{cases} \Theta_1 = 1/2 - [2z - (d_j + d_{j+1})]/2h_j \\ \Theta_2 = 1/2 + [2z - (d_j + d_{j+1})]/2h_j \\ \Theta_3 = [2z - (d_j + d_{j+1})]^2/2h_j - h_j/2. \end{cases} \tag{2}$$

In terms of the elasticity theory, the strain components read

$$\begin{cases} \epsilon_{xx} = u_{,x} \\ \epsilon_{yy} = v_{,y} \\ \epsilon_{xy} = u_{,y} + v_{,x} \\ \epsilon_{xz} = w_{,x} + u_{,z} \\ \epsilon_{yz} = w_{,y} + v_{,z}. \end{cases} \tag{3}$$

The tensor of the elastic moduli is used to calculate the stress components of an arbitrary material which satisfies the Cauchy generalized Hooke's law [20]. In this paper, only homogeneous materials are considered to simplify the case study. The strain–stress relations read

$$\begin{cases} \sigma_{xx} = \frac{E}{1-\mu^2}(\epsilon_{xx} + \mu\epsilon_{yy}) \\ \sigma_{yy} = \frac{E}{1-\mu^2}(\epsilon_{yy} + \mu\epsilon_{xx}) \\ \sigma_{xy} = \frac{E}{2(1+\mu)}\epsilon_{xy} \\ \sigma_{xz} = \frac{E}{2(1+\mu)}\epsilon_{xz} \\ \sigma_{yz} = \frac{E}{2(1+\mu)}\epsilon_{yz}, \end{cases} \tag{4}$$

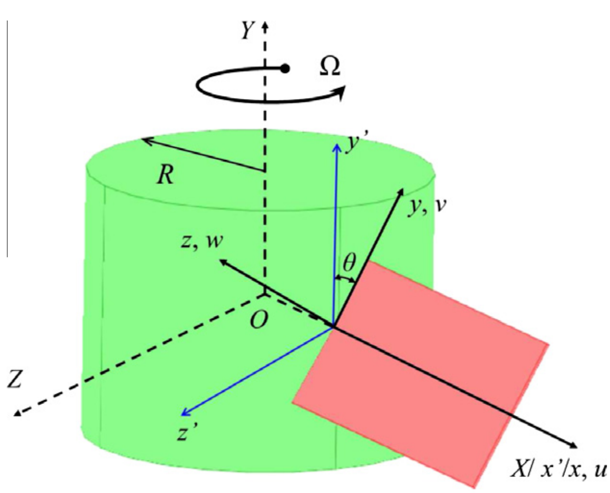

Fig. 1. Rotating blade model.

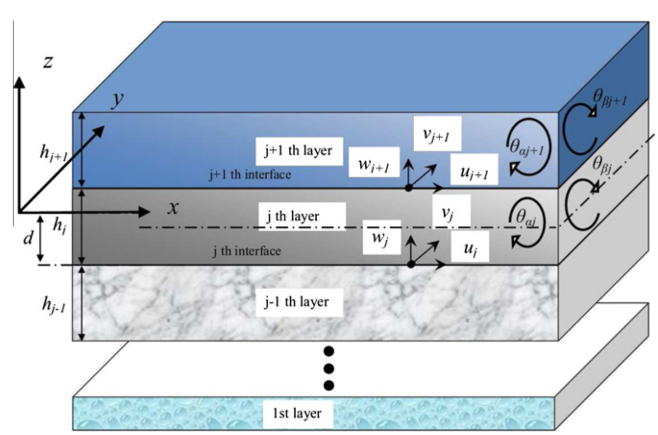

Fig. 2. Multilayered structure.