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Vibration Control of a Rotating Composite Blade Using Sliding Mode Control
슬라이딩 모드 제어 기법을 이용한 복합재료 블레이드의 진동제어

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1. Introduction

Composites blades have many applications in helicopter rotors, turbine engines, wind turbines, only to name a few. As a result of the recent study, the application of a composite thin-walled beam model is aimed to enhance the understanding of the dynamic response performance of the blade, and to obtain better representative models capturing non classical features. In order to avoid vibration-induced fatigue failure and increase the efficiency of blade, vibration reduction technology should be implemented. But only few studies on vibration control of rotating thin-walled beam have found in the previous literatures. In the present study a Sliding Mode Control (SMC) methodology is developed and applied to control the vibration characteristics of the rotating beam under external distributed load and design characteristics. The active capability is achieved through the converse piezoelectric effect that consisted of the generation of localized strains in response to an applied voltage. Comparative study with a Linear Quadratic Gaussian (LQG), under various dynamic conditions, shows that the SMC offers desirable features with respect to the system with uncertainties and external load.

2. Structural modeling of composite thin-walled beam

The geometrical configuration of a single cell composite thin-walled beam is shown by Fig. 1. The beam model is mounted on a rigid hub (radius R_0) and rotates with constant angular velocity Ω about origin O. The single cell thin-walled beam mode includes the primary and secondary warping effects and incorporates transverse shear, Coriolis effect, and centrifugal acceleration. The beam consists of orthotropic composite material, a circumferentially uniform stiffness(CUS) configuration is selected as to include bending-bending elastic coupling. According to the above assumption, the dynamic equation of rotating composite

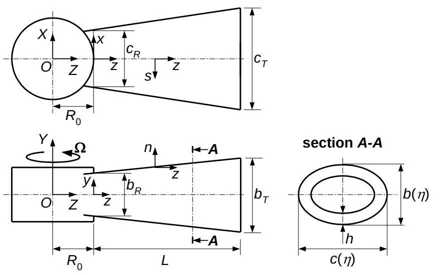

Fig. 1 Geometric configuration of the rotating blade

thin-walled beam in term of displacement variable, considered 3-D displacement, are expressed as

$$\begin{aligned} u(x,y,z,t) &= u_0 - y\phi(z,t) \\ v(x,y,z,t) &= v_0 + x\phi(z,t) \\ w(x,y,z,t) &= w_0(z,t) + \theta_x(z,t)[y(s) - n\frac{dx}{ds}] \\ &+\theta_y(z,t)[x(s) + n\frac{dy}{ds}] - \phi'(z,t)[F_w(s) + na(s)] \end{aligned} \tag{1}$$

where

$$\begin{aligned} \theta_x(z,t) &= \gamma_{yz}(z,t) - v_0'(z,t) \\ \theta_y(z,t) &= \gamma_{xz}(z,t) - u_0'(z,t) \end{aligned} \tag{2}$$

In the above equations, u_0 (z,t), v_0 (z,t), and w_0 (z,t) denote the rigid body translations along the x, y, and z axes, while $\theta_x(z,t)$, $\theta_y(z,t)$, and $\phi(z,t)$ denotes the rotation about the x, y, and z axes, respectively. Furthermore, γ_{yz} and γ_{xz} represent the transverse shear stress in the yz plane and xz plan, respectively. While represents the primary warping function and represents the secondary warping function. In order to obtain coupled bending equation and boundary condition of the thin-walled beam, Hamilton's principle is used such as

$$\begin{aligned} &\int_{t0}^{t1}(\delta K - \delta V + \delta W)dt = 0 \\ &\delta u_0 = \delta v_0 = \delta\theta_x = \delta\theta_y = 0 \quad \text{at} \quad t = t_1, t_2 \end{aligned} \tag{3}$$

where δK, δV denote variation of kinetic and strain energy, respectively, and δW is expression of the virtual work done by the external force. From Eqs. (1), (2), and (3) the governing equation of the bending-transverse (flap-lag) motion are obtained as Eq. (4). In Eq. (4) u_0, v_0 are the lag and flap displacements, respectively; p_x, p_y are surface load in each direction (x, y), and m_x, m_y are moments about x- and y-axes, respectively; $a_{ij}(z)$ and $b_j(z)$ denote global stiffness and inertia terms, respectively.

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$$\delta u_0 : [a_{43}\theta_x' + a_{44}(u_0' + \theta_y)]' + \Omega^2\{P(z)u_0'\}' - b_1\Omega^2 u_0 - b_1\ddot{u}_0 + p_x = 0,$$
$$\delta v_0 : [a_{52}\theta_y' + a_{55}(v_0' + \theta_x)]' + \Omega^2\{P(z)v_0'\}' - b_1\ddot{v}_0 + p_y = 0, \quad (4)$$
$$\delta\theta_y : [a_{22}\theta_y' + a_{25}(v_0' + \theta_x)]' - a_{44}(u_0' + \theta_y) - a_{43}\theta_x' - (b_5 + b_{15})(\ddot{\theta}_y - \Omega^2\theta_y) + m_y = 0,$$
$$\delta\theta_x : [a_{33}\theta_x' + a_{34}(u_0' + \theta_y)]' - a_{55}(v_0' + \theta_x) - a_{52}\theta_y' - (b_4 + b_{14})(\ddot{\theta}_x - \Omega^2\theta_x) + m_x = 0$$

3. Robust Sliding Mode Control methodology

The Sliding Mode Control (SMC) is well known for the robust control scheme that works well under even in the presence of severe environment conditions, such as the model uncertainties and various external loads. In order to design sliding mode control, the state space equation is represented by

$$\dot{\mathbf{x}}(t) = \boldsymbol{A}\mathbf{x}(t) + \boldsymbol{B}u(t) + \boldsymbol{F}$$
$$\mathbf{y}(t) = \boldsymbol{C}\mathbf{x}(t) \quad (5)$$

In eq. (5), A and B matrix consist of mass and stiffness; ***C*** is the output feedback matrix and ***F*** denotes the external load vector, while **x**(t) defines state vector of the rotating blade. The control feedback input u(t) obtained by SMC is defined as the summation of linear control input (u_l) and non-linear control input (u_{nl}), as described

$$u = u_l + u_{nl} \quad (6)$$

These control inputs, u_l and u_{nl}, represented by

$$u_l(t) = -(\mathbf{SB})^{-1}\mathbf{SA}x(t) + (\mathbf{SB})^{-1}\Phi\mathbf{S}x(t)$$
$$u_{nl}(t) = -\rho(t,x)(\mathbf{SB})^{-1}\frac{\mathbf{P}_2 s(t)}{\|\mathbf{P}_2 s(t)\|} \quad (7)$$

define a state feedback law and a discontinuous or switched component, respectively. In Eq. (7), **S** and Φ denotes switch function matrix and any stable design matrix, respectively. *ρ (t,x)* is a scalar function depending on the magnitude of the uncertainties in the rotating blade system and P_2 is a symmetric positive definite matrix satisfying a Lyapunov equation

$$\mathbf{P_2\Phi + \Phi^T P_2 = -I} \quad (8)$$

where **I** denotes the identity matrix. Since the above robustness properties of the sliding mode control, overcomes external disturbance, this control methodology is selected as a reliable control system for rotating blade.

4. Result and discussion

Using extended Galerkin method, the numerical simulation of composite thin-walled rotating blade is implemented. As concerns the characteristics of the piezoactuators, the ones madeup from PZT-4 piezoceramic.

The sliding mode observer based control will be illustrated through numerical simulations. Figs. 2 and 3 display uncontrolled and controlled dynamic response of the blade subjected to distribute load using Linear Quadratic Gaussian controller and Sliding Mode Control, respectively. The results show that sliding mode controller provides better control performance than Linear Quadratic Gaussian.

5. Conclusion

In this study, the vibration control of rotating blade in the form of composite thin-walled beam subjected to a distributed load was presented. Through the result of simulation [see Figs. 2 and 3], it is convinced that the Sliding Mode Control strategy appears to be very effective to reduce vibration amplitude and possess robustness properties. The results presented here are likely to provide valuable information to the engineers involved in the design and control of advance turbine blades.

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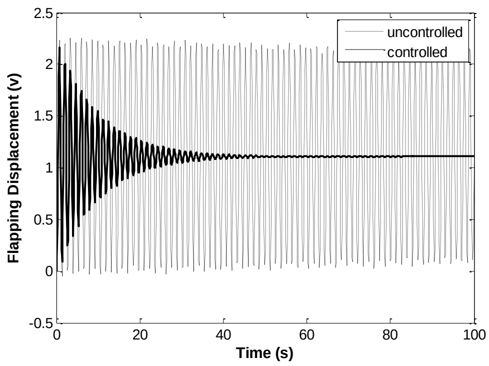

Fig. 2 Uncontrolled and controlled flapping response via LQG controller (Ω = 200 rad/s, θ=60o , σ = 1.0)

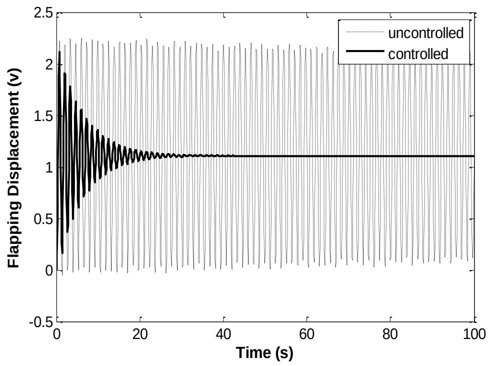

Fig. 3 Uncontrolled and controlled flapping response via SMC controller (Ω = 200 rad/s, θ=60o , σ = 1.0)