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Research Article

Vibration and Damping Analysis of Composite Fiber Reinforced Wind Blade with Viscoelastic Damping Control

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Composite materials are increasingly used in wind blade because of their superior mechanical properties such as high strength-to-weight and stiffness-to-weight ratio. This paper presents vibration and damping analysis of fiberreinforced composite wind turbine blade with viscoelastic damping treatment. The finite element method based on full layerwise displacement theory was employed to analyze the damping, natural frequency, and modal loss factor of composite shell structure. The lamination angle was considered in mathematical modeling. The curved geometry, transverse shear, and normal strains were exactly considered in present layerwise shell model, which can depict the zig-zag in-plane and out-of-plane displacements. The frequency response functions of curved composite shell structure and wind blade were calculated. The results show that the damping ratio of viscoelastic layer is found to be very sensitive to determination of magnitude of composite structures. The frequency response functions with variety of thickness of damping layer were investigated. Moreover, the natural frequency, modal loss factor, and mode shapes of composite fiber reinforced wind blade with viscoelastic damping control were calculated.

1. Introduction

Fiber reinforced composites are widely used in advanced structural applications such as aerospace and wind blade because of high strength-to-weight and stiffness-to-weight ratio. However, the fiber reinforced composites structures are usually subject to dynamic external loads during their operational life. Damping treated viscoelastic materials may serve as excellent vibration dampers to suppress the undesirable vibration and noise.

Numerical analysis of sandwiched shell structures has been studied by many researchers with different theories and methods [1–5]. Abarcar and Cunniff [6] investigated the free vibration response of laminated cantilever beams. Hodges et al. [7] studied the free vibration response for a general laminated beam by considering different boundary conditions. Khdeir and Reddy [8] and Abramovich [9] investigated the effects of rotary inertia and shear deformation of sandwich laminated shell structure. Love [10] developed a two-dimensional mathematical model that is used to determine the stresses and deformations in thin plates subjected to forces and moments. The natural frequencies corresponding to the forward and backward modes of thin rotating laminated cylindrical shells by using four common thin shell theories were determined by Lam and Loy [11].

Damping is an important factor for the dynamic design as it influences the vibration and noise levels significantly. Chandra et al. reviewed initial investigations on the damping analysis of fiber reinforced composite materials [12]. Typically, a viscoelastic or other damping material is sandwiched between two sheets of stiff materials that lack sufficient damping by themselves. Namely, viscoelastic sandwich structures consist of a soft viscoelastic layer that is confined between two identical elastic and stiff layers. Due to its high level of energy dissipation, the viscoelastic layer is provided to play a damping role and improves the dynamic response of the structure [13]. Yu and Huang [14] derived equations of motion of a three-layered circular plate with a thin viscoelastic layer based on the classical thin shell theory. Natural frequencies and modal loss factors of a three-layered annular plate with a viscoelastic core were studied by Wang and Chen [15], using the complex modulus concept.

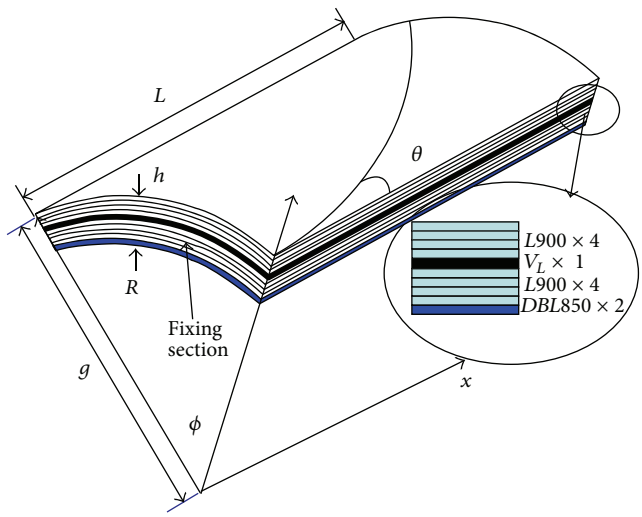

Figure 1: Geometry structure of fiber reinforced cylindrical composite shell with viscoelastic damping layer by considering the lamination angle.

The wind turbine as a most important part of wind power generation system accounts for more than 23% of total design coast. The geometry large deflection has influence on the vibration characteristics and stability of aeroelasticity of composite wind turbine. Therefore, investigation of the vibration and damping characteristics of composite wind blade is very important. In this study, the vibration and damping characteristics of composite fiber reinforced wind blade with viscoelastic damping control were studied using finite element method. The frequency response functions of curved composite shell structure and wind blade were calculated for investigation of damping and modal properties of structures.

2. Finite Element Modeling

Figure 1 shows a geometry structure of fiber reinforced cylindrical composite shell with viscoelastic damping layer, where $L900$ and $DBL850$ are glass fiber layer and V_L is viscoelastic damping layer where D is the −45-degree aligned continuous fibers, B the 45-degree aligned continuous fibers, and L the 0-degree aligned continuous fibers. Based on the full layerwise shell theory, the displacement fields (u, v, and w) on the cylindrical coordinate system can be expressed by containing the piecewise interpolation function along thickness z-direction and finite element shape functions as below [16, 17]:

$$\begin{aligned} u(x,\phi,z,t) &= \sum_{J=1}^{Ni} U^J(x,\phi,t)\,\Phi^J(z), \\ v(x,\phi,z,t) &= \sum_{J=1}^{Ni} V^J(x,\phi,t)\,\Phi^J(z), \\ w(x,\phi,z,t) &= \sum_{J=1}^{Ni} W^J(x,\phi,t)\,\Phi^J(z), \end{aligned} \tag{1}$$

where the $\Phi^J(z)$ is linear interpolation function.

The linear constitutive equations between stresses and strains of viscoelastic orthotropic materials can be written with respect to material coordinates $(1,2,3)$ as shown as follows:

$$\begin{Bmatrix} \sigma_{xx} \\ \sigma_{\phi\phi} \\ \sigma_{zz} \\ \sigma_{\phi z} \\ \sigma_{xz} \\ \sigma_{x\phi} \end{Bmatrix}_k = \begin{bmatrix} \widehat{Q}_{11} & \widehat{Q}_{12} & \widehat{Q}_{13} & 0 & 0 & \widehat{Q}_{16} \\ \widehat{Q}_{12} & \widehat{Q}_{22} & \widehat{Q}_{23} & 0 & 0 & \widehat{Q}_{26} \\ \widehat{Q}_{13} & \widehat{Q}_{23} & \widehat{Q}_{33} & 0 & 0 & \widehat{Q}_{36} \\ 0 & 0 & 0 & \widehat{Q}_{44} & \widehat{Q}_{45} & 0 \\ 0 & 0 & 0 & \widehat{Q}_{45} & \widehat{Q}_{55} & 0 \\ \widehat{Q}_{16} & \widehat{Q}_{26} & \widehat{Q}_{36} & 0 & 0 & \widehat{Q}_{66} \end{bmatrix}_k \begin{Bmatrix} \varepsilon_{xx} \\ \varepsilon_{\phi\phi} \\ \varepsilon_{zz} \\ \varepsilon_{\phi z} \\ \varepsilon_{xz} \\ \varepsilon_{x\phi} \end{Bmatrix}_k, \tag{2}$$

where

$$\widehat{Q}_{11} = Q_{11}m^4 + 2m^2n^2(Q_{12} + 2Q_{66}) + C_{22}n^4, \tag{3a}$$

$$\widehat{Q}_{12} = m^2n^2(Q_{11} + Q_{22} - 4Q_{66}) + C_{12}(m^4 + n^4), \tag{3b}$$

$$\widehat{Q}_{13} = Q_{13}m^2 + Q_{23}n^2, \tag{3c}$$

$$\begin{aligned} \widehat{Q}_{16} = {} & -2Q_{66}mn(m^2 - n^2) + mn(Q_{11}m^2 + Q_{12}n^2) \\ & - mn(Q_{12}m^2 + Q_{22}n^2), \end{aligned} \tag{3d}$$

$$\widehat{Q}_{22} = Q_{11}n^4 + 2m^2n^2(Q_{12} + 2Q_{66}) + C_{22}m^4, \tag{3e}$$

$$\widehat{Q}_{23} = Q_{13}n^2 + Q_{23}m^2, \tag{3f}$$

$$\begin{aligned} \widehat{Q}_{26} = {} & 2Q_{66}mn(m^2 - n^2) + mn(Q_{12}m^2 + Q_{11}n^2) \\ & - mn(Q_{22}m^2 + Q_{12}n^2), \end{aligned} \tag{3g}$$

Table 1: Material properties.

Materials	$E1$ (Gpa)	$E2$ (Gpa)	$G12$ (Gpa)	$G23$ (Gpa)	ν	Density (kg/m^3)
*DBL*800	20.3	9.9	7.3	3.8	0.3	1633.32
*L*900	27.9	8.5	4.05	3.26	0.3	1638.6
Viscoelastic material	0.0021	0.0021	0.0007	0.0007	0.49	972

Table 2: Lamination type of clamped free shell structure and blade.

Materials	Layer	Lamination angle	Thickness
*DBL*850	1	0	0.45 mm
	2	0	0.45 mm
*L*900	3	0	0.9 mm
	4	0	0.9 mm
	5	0	0.9 mm
	6	0	0.9 mm
Viscoelastic material	7	0	T_v = 0.5, 1, 1.5 (mm)
*L*900	8	0	0.9 mm
	9	0	0.9 mm
	10	0	0.9 mm
	11	0	0.9 mm

$$\widehat{Q}_{33} = Q_{33}, \tag{3h}$$

$$\widehat{Q}_{36} = (Q_{13} - Q_{23})\, mn, \tag{3i}$$

$$\widehat{Q}_{44} = Q_{44}m^2 + Q_{55}n^2, \tag{3j}$$

$$\widehat{Q}_{45} = (Q_{55} - Q_{44})\, mn, \tag{3k}$$

$$\widehat{Q}_{55} = Q_{55}m^2 + Q_{44}n^2, \tag{3l}$$

$$\begin{aligned}\widehat{Q}_{66} &= mn\,(Q_{11}mn - Q_{12}mn) \\ &\quad - mn\,(Q_{12}mn - Q_{22}mn) + Q_{66}\left(m^2 - n^2\right)^2,\end{aligned} \tag{3m}$$

where $m = \cos\theta$ and $m = \cos\theta$.

To derive the governing equation of motion for the composite cylindrical shell with viscoelastic damping layers can be obtained as the following equation [17]:

$$\begin{aligned}&\int_V \rho \ddot{u}_i \delta u_i dV + \int_V \sigma_{ij}\delta\varepsilon_{ij} dV \\ &\quad = \int_V f_i \delta u_i dV + \int_S \tau_i \delta u_i dS.\end{aligned} \tag{4}$$

Finally, the frequency response function can be expressed as the following form:

$$H = \frac{U}{F_0}, \tag{5}$$

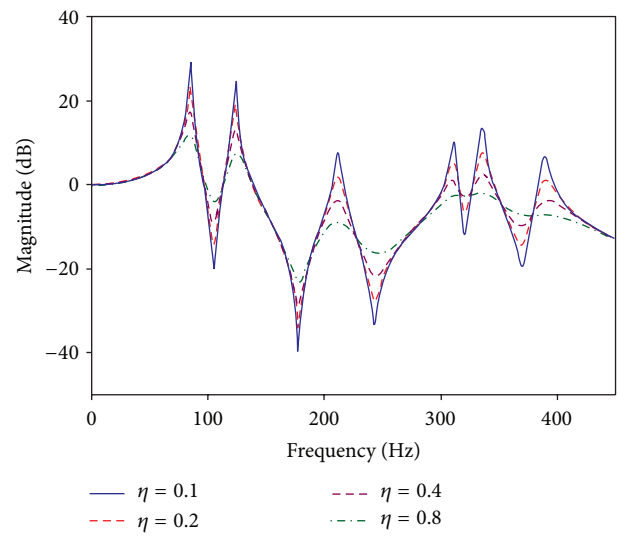

Figure 2: Frequency response functions of fiber reinforced cylindrical composite panel with variation of damping ratio η of viscoelastic layer.

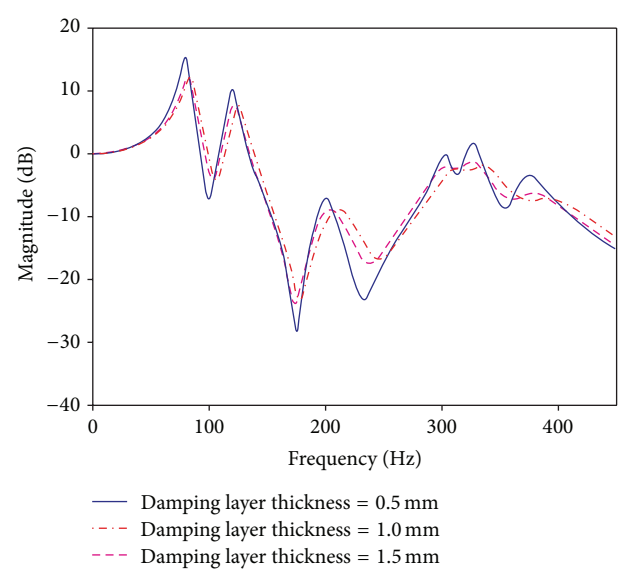

Figure 3: Frequency response functions of fiber reinforced cylindrical composite panel with variation of thickness of damping layer.

where U is the modal displacement and F_0 is the magnitude of external harmonic excitation force.

3. Results and Discussions

To carry out a finite element analysis of cylindrical composite shell, the nine-node 9×9 meshes were used for the composite cylindrical shell structure. Table 1 shows the material properties of fiber materials and viscoelastic damping material and Table 2 shows the lamination type of composite shell structure and blade. The size of the panel was $L = 0.3$ m, $R = 0.5$ m, and $\phi = 0.6$ rad. The output power of proposed

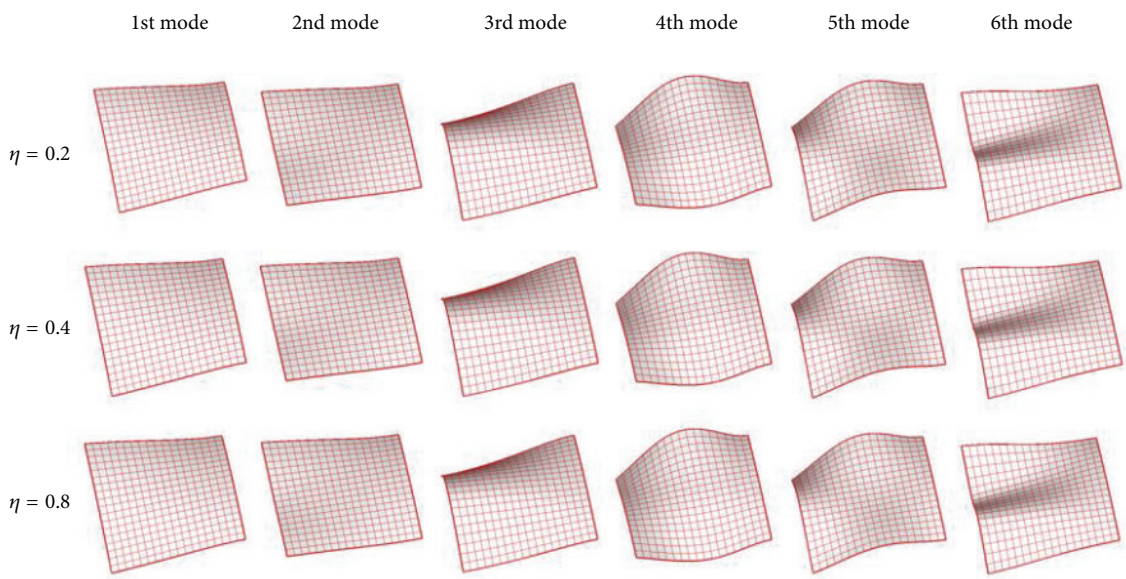

FIGURE 4: Mode shapes of fiber reinforced cylindrical composite panel with variation of damping ratio η of viscoelastic layer.

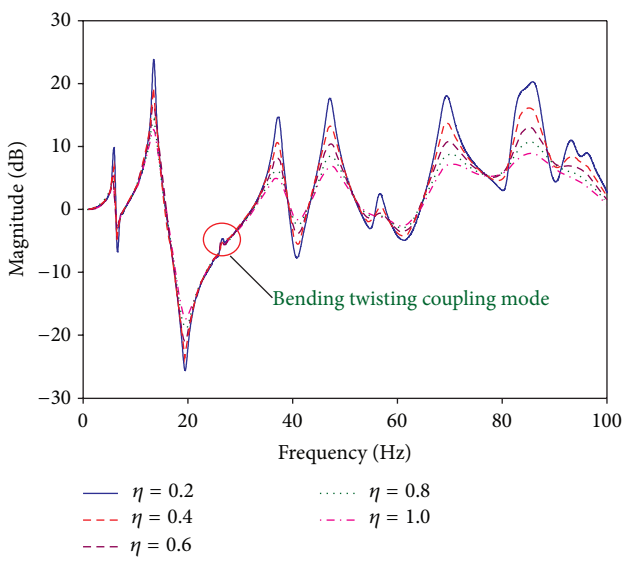

FIGURE 5: Frequency response functions of fiber reinforced composite wind blade with variation of damping ratio η of viscoelastic layer (T_v = 1 mm).

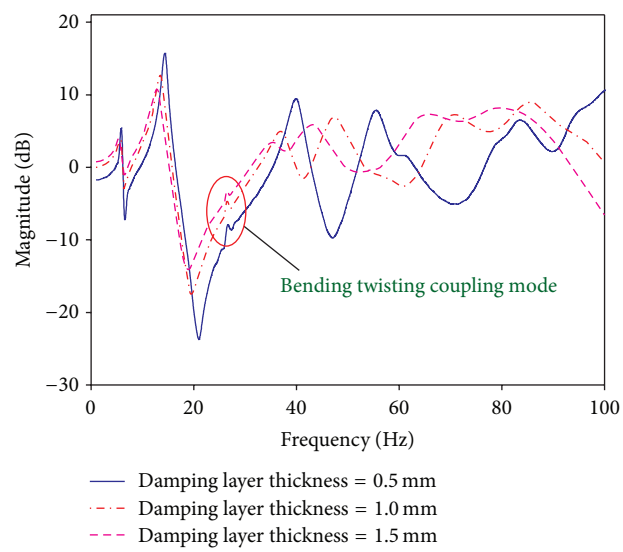

FIGURE 6: Frequency response functions of fiber reinforced composite wind blade with variation of thickness of damping layer (η = 1).

wind blade is 10 kW and total length of the wind blade is 3.7 m.

The damping ratio and thickness of viscoelastic damping layer are the important parameters for controlling the magnitude of structural vibration. Figure 2 shows the frequency responses of such panels with different damping ratio of viscoelastic layer by numerical analysis. The amplitudes of the peaks significantly decrease with the increasing of the damping ratio of viscoelastic layers. The results show that the viscoelastic damping layer can efficiently reduce the first six mode vibrations of sandwich composite panel, and it could be used as a method of obtaining light weight and other multifunctional benefits. Figure 3 shows the frequency response functions of composite panel with different thickness of viscoelastic layer by numerical analysis. The amplitudes of the peaks show that a certain amount is decreased with increasing of the thickness of viscoelastic layers. Table 3 shows the comparison of natural frequencies and modal loss factors of composite laminated clamped free shell structure with different damping factor of viscoelastic damping layer. The modal loss factor $\overline{\eta}_i$ increases with increasing of damping factor η in same mode. But the natural frequency is almost no changes with variety of damping factors. Figure 4 shows the first six mode shapes of fiber reinforced cylindrical composite panel with variation of damping ratio of viscoelastic layer.

Table 3: Comparison of natural frequencies and loss factors of composite laminated clamped free shell structure.

Mode	Damping factor of viscoelastic material = 0.2		Damping factor of viscoelastic material = 0.4		Damping factor of viscoelastic material = 0.8	
	Freq. (Hz)	$\overline{\eta}_i$	Freq. (Hz)	$\overline{\eta}_i$	Freq. (Hz)	$\overline{\eta}_i$
1	84.87	0.03747	84.89	0.07490	84.96	0.14942
2	123.90	0.02619	124.09	0.05192	124.82	0.10031
3	211.62	0.04058	211.52	0.08134	211.15	0.16404
4	311.41	0.02369	311.45	0.04736	311.60	0.09449
5	335.05	0.02570	335.10	0.05140	335.31	0.10267
6	388.39	0.03696	388.38	0.07393	388.33	0.14797

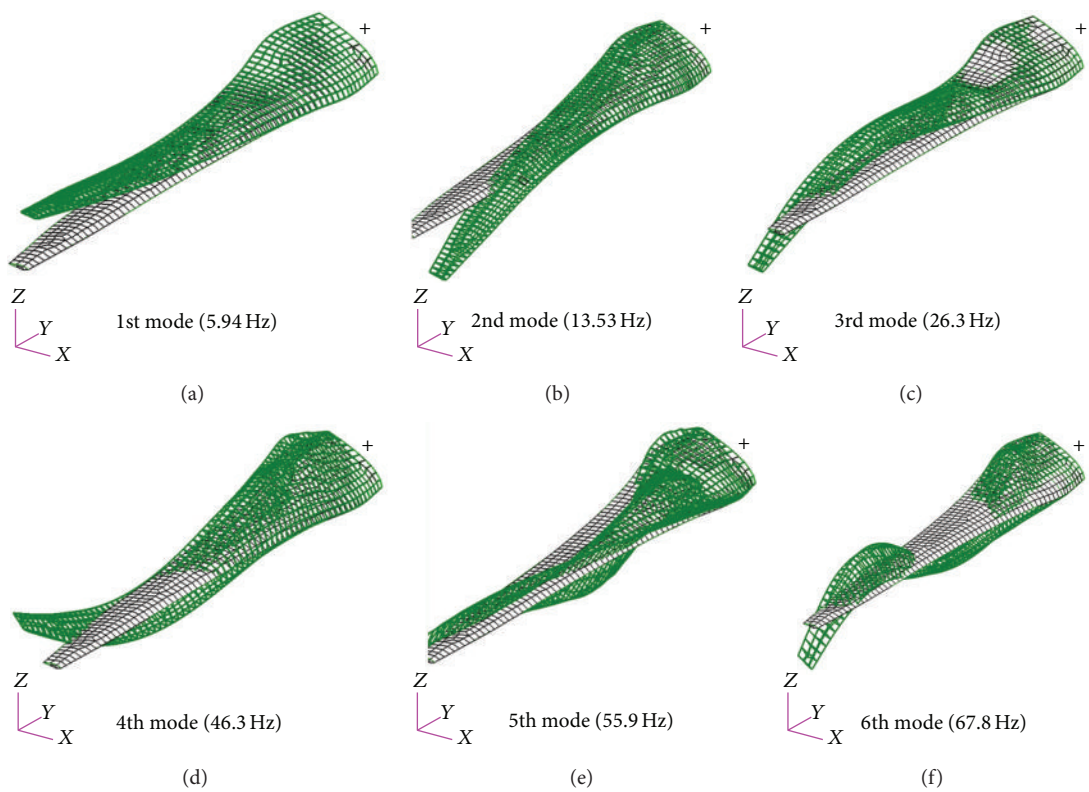

Figure 7: Mode shapes of fiber reinforced composite wind blade with damping ratio of 0.2.

The mode shapes are no differences with variety of damping ratio. Figure 5 shows the frequency response functions of fiber reinforced composite wind blade with variation of damping ratio of viscoelastic layer. The results show that as the damping ratio of viscoelastic layer increases, the damping increases. Figure 6 shows the frequency response functions of fiber reinforced composite wind blade with variation of thickness of damping layer. The magnitude of peak value was decreased with increasing of thickness and the frequency minimizing occurred at higher mode. Moreover, because of bending twisting effect the third mode showed a very low pick value.

Figure 7 shows the first six mode shapes of fiber reinforced cylindrical composite wind blade with viscoelastic damping treatment with damping ratio of 0.2. Mode 3 is a bending twisting coupling mode and other mode shapes present the bending modes.

4. Conclusion

In this paper, the vibration characteristics of fiber reinforced composite wind turbine blade with viscoelastic damping treatment were investigated using layerwise theory and finite element method. The frequency response functions, mode shapes, and modal loss factor of composite panel with viscoelastic damping layer were calculated. The results show that the damping ratio of viscoelastic layer was found to be very sensitive to determination of magnitude of composite

structures. The amplitudes of the peaks in frequency response functions of composite wind blade significantly decreased with the increasing of the damping ratio of viscoelastic layers. The amplitudes of the peaks show that a certain amount was decreased with increasing of the thickness of viscoelastic layers. Present results show that the sandwiched viscoelastic damping layer can effectively suppress vibration of composite wind turbine blade.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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References

[1] M. S. Qatu, R. W. Sullivan, and W. Wang, "Recent research advances on the dynamic analysis of composite shells: 2000–2009," *Composite Structures*, vol. 93, no. 1, pp. 14–31, 2010.

[2] T.-S. Lok and Q.-H. Cheng, "Free and forced vibration of simply supported, orthotropic sandwich panel," *Computers and Structures*, vol. 79, no. 3, pp. 301–312, 2001.

[3] M. R. Maheri, R. D. Adams, and J. Hugon, "Vibration damping in sandwich panels," *Journal of Materials Science*, vol. 43, no. 20, pp. 6604–6618, 2008.

[4] K. H. Ip, W. K. Chan, P. C. Tse, and T. C. Lai, "Vibration analysis of orthotropic thin cylindrical shells with free ends by the Rayleigh-Ritz method," *Journal of Sound and Vibration*, vol. 195, no. 1, pp. 117–135, 1996.

[5] M. R. Maheri and R. D. Adams, "Finite-element prediction of modal response of damped layered composite panels," *Composites Science and Technology*, vol. 55, no. 1, pp. 13–23, 1995.

[6] R. B. Abarcar and P. F. Cunniff, "The vibration of cantilevered beam of fiber reinforced materials," *Journal of Composite Materials*, vol. 6, no. 3, pp. 504–517, 1972.

[7] D. H. Hodges, A. R. Atilgan, M. V. Fulton, and L. W. Rehfield, "Free-vibration analysis of composite beams," *Journal of the American Helicopter Society*, vol. 36, no. 3, pp. 36–47, 1991.

[8] A. A. Khdeir and J. N. Reddy, "Free vibration of cross-ply laminated beams with arbitrary boundary conditions," *International Journal of Engineering Science*, vol. 32, no. 12, pp. 1971–1980, 1994.

[9] H. Abramovich, "Shear deformation and rotary inertia effects of vibrating composite beams," *Composite Structures*, vol. 20, no. 3, pp. 165–173, 1992.

[10] A. E. H. Love, "On the small free vibrations and deformations of thins shells," *Philosophical Transactions of the Royal Society of London A*, vol. 179, pp. 491–546, 1888.

[11] K. Y. Lam and C. T. Loy, "Analysis of rotating laminated cylindrical shells by different thin shell theories," *Journal of Sound and Vibration*, vol. 186, no. 1, pp. 23–35, 1995.

[12] R. Chandra, S. P. Singh, and K. Gupta, "Damping studies in fiber-reinforced composites—a review," *Composite Structures*, vol. 46, no. 1, pp. 41–51, 1999.

[13] M. Bilasse, L. Azrar, and E. M. Daya, "Complex modes based numerical analysis of viscoelastic sandwich plates vibrations," *Computers and Structures*, vol. 89, pp. 539–555, 2011.

[14] S.-C. Yu and S.-C. Huang, "Vibration of a three-layered viscoelastic sandwich circular plate," *International Journal of Mechanical Sciences*, vol. 43, no. 10, pp. 2215–2236, 2001.

[15] H. J. Wang and L. W. Chen, "Vibration and damping analysis of a three-layered composite annular plate with a viscoelastic midlayer," *Composite Structures*, vol. 58, no. 4, pp. 563–570, 2002.

[16] J. N. Reddy, *Mechanics of Laminated Composite Plates and Shells: Theory and Analysis*, CRC Press, Boca Raton, Fla, USA, 2004.

[17] T. H. Cheng, Z. Z. Li, and Y. D. Shen, "Vibration analysis of cylindrical sandwich aluminum shell with viscoelastic damping treatment," *Advances in Materials Science and Engineering*, vol. 2013, Article ID 130438, 7 pages, 2013.