Research Article

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

Tai-Hong Cheng, Ming Ren, Zhen-Zhe Li, and Yun-De Shen

College of Mechanical and Electrical Engineering, Wenzhou University, Higher Education Park, Wenzhou, Zhejiang 325035, China

Correspondence should be addressed to Yun-De Shen; shenyunde63@163.com

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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 fiber reinforced 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.
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]:

$$
u(x, \phi, z, t) = \sum_{J=1}^{N_i} V^J(x, \phi, t) \Phi^J(z),$$

$$w(x, \phi, z, t) = \sum_{J=1}^{N_i} W^J(x, \phi, t) \Phi^J(z),$$

where $\Phi^J(z)$ 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:

$$\begin{bmatrix}
\sigma_{xx} \\
\sigma_{yy} \\
\sigma_{zz} \\
\sigma_{xy} \\
\sigma_{xz} \\
\sigma_{yz}
\end{bmatrix}
= \begin{bmatrix}
Q_{11} & Q_{12} & Q_{13} & 0 & 0 & \tilde{Q}_{16} \\
Q_{12} & Q_{22} & Q_{23} & 0 & 0 & \tilde{Q}_{26} \\
Q_{13} & Q_{23} & Q_{33} & 0 & 0 & \tilde{Q}_{36} \\
0 & 0 & 0 & Q_{44} & Q_{45} & 0 \\
0 & 0 & 0 & Q_{45} & Q_{55} & 0 \\
Q_{16} & \tilde{Q}_{26} & \tilde{Q}_{36} & 0 & 0 & Q_{66}
\end{bmatrix}
\begin{bmatrix}
\varepsilon_{xx} \\
\varepsilon_{yy} \\
\varepsilon_{zz} \\
\varepsilon_{xy} \\
\varepsilon_{xz} \\
\varepsilon_{yz}
\end{bmatrix},$$

where

$$\begin{align*}
\tilde{Q}_{11} &= Q_{11}m^4 + 2m^2n^2(Q_{12} + 2Q_{66}) + C_{22}n^4, \quad (3a) \\
\tilde{Q}_{12} &= m^2n^2(Q_{11} + Q_{22} - 4Q_{66}) + C_{12}(m^4 + n^4), \quad (3b) \\
\tilde{Q}_{13} &= Q_{13}m^2 + Q_{23}n^2, \quad (3c) \\
\tilde{Q}_{16} &= -2Q_{66}mn(m^2 - n^2) + mn(Q_{11}m^2 + Q_{12}n^2) \\
&\quad - mn(Q_{12}m^2 + Q_{22}n^2), \quad (3d) \\
\tilde{Q}_{22} &= Q_{11}n^4 + 2m^2n^2(Q_{12} + 2Q_{66}) + C_{22}m^4, \quad (3e) \\
\tilde{Q}_{23} &= Q_{13}n^2 + Q_{23}m^2, \quad (3f) \\
\tilde{Q}_{26} &= 2Q_{66}mn(m^2 - n^2) + mn(Q_{12}m^2 + Q_{11}n^2) \\
&\quad - mn(Q_{22}m^2 + Q_{12}n^2), \quad (3g)
\end{align*}$$
Table 1: Material properties.

<table>
<thead>
<tr>
<th>Materials</th>
<th>$E_1$ (Gpa)</th>
<th>$E_2$ (Gpa)</th>
<th>$G_{12}$ (Gpa)</th>
<th>$G_{23}$ (Gpa)</th>
<th>$\nu$</th>
<th>Density (kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DBL800</td>
<td>20.3</td>
<td>9.9</td>
<td>7.3</td>
<td>3.8</td>
<td>0.3</td>
<td>1633.32</td>
</tr>
<tr>
<td>L900</td>
<td>27.9</td>
<td>8.5</td>
<td>4.05</td>
<td>3.26</td>
<td>0.3</td>
<td>1638.6</td>
</tr>
<tr>
<td>Viscoelastic material</td>
<td>0.0021</td>
<td>0.0021</td>
<td>0.0007</td>
<td>0.0007</td>
<td>0.49</td>
<td>972</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Materials</th>
<th>Layer</th>
<th>Lamination angle</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>DBL850</td>
<td>1</td>
<td>0</td>
<td>0.45 mm</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0</td>
<td>0.45 mm</td>
</tr>
<tr>
<td>L900</td>
<td>3</td>
<td>0</td>
<td>0.9 mm</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0</td>
<td>0.9 mm</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0</td>
<td>0.9 mm</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0</td>
<td>0.9 mm</td>
</tr>
<tr>
<td>Viscoelastic material</td>
<td>7</td>
<td>0</td>
<td>$T_v = 0.5, 1, 1.5$ (mm)</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0</td>
<td>0.9 mm</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>0</td>
<td>0.9 mm</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0</td>
<td>0.9 mm</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>0</td>
<td>0.9 mm</td>
</tr>
</tbody>
</table>

$$
\tilde{Q}_{33} = Q_{33},
$$

$$
\tilde{Q}_{36} = (Q_{13} - Q_{23})mn,
$$

$$
\tilde{Q}_{44} = Q_{44}m^2 + Q_{55}n^2,
$$

$$
\tilde{Q}_{45} = (Q_{55} - Q_{44})mn,
$$

$$
\tilde{Q}_{55} = Q_{55}m^2 + Q_{44}n^2,
$$

$$
\tilde{Q}_{66} = mn(Q_{11}mn - Q_{12}mn) - mn(Q_{12}nn - Q_{22}nn) + Q_{66}(m^2 - n^2)^2,
$$

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]:

$$
\int_V \rho \ddot{u}_i \delta u_i dV + \int_V \sigma_{ij} \delta \epsilon_{ij} dV
= \int_V f_i \delta u_i dV + \int_S \tau_{ij} \delta u_i dS.
$$

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

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

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 $9 \times 9$ 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
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

Figure 4: Mode shapes of fiber reinforced cylindrical composite panel with variation of damping ratio $\eta$ of viscoelastic layer.

Figure 5: Frequency response functions of fiber reinforced composite wind blade with variation of damping ratio $\eta$ 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 ($\eta = 1$).

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 $\eta_i$ increases with increasing of damping factor $\eta$ 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.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Damping factor of viscoelastic material = 0.2</th>
<th>Damping factor of viscoelastic material = 0.4</th>
<th>Damping factor of viscoelastic material = 0.8</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Freq. (Hz)</td>
<td>$\bar{\eta}_i$</td>
<td>Freq. (Hz)</td>
</tr>
<tr>
<td>1</td>
<td>84.87</td>
<td>0.03747</td>
<td>84.89</td>
</tr>
<tr>
<td>2</td>
<td>123.90</td>
<td>0.02619</td>
<td>124.09</td>
</tr>
<tr>
<td>3</td>
<td>211.62</td>
<td>0.04058</td>
<td>211.52</td>
</tr>
<tr>
<td>4</td>
<td>311.41</td>
<td>0.02369</td>
<td>311.45</td>
</tr>
<tr>
<td>5</td>
<td>335.05</td>
<td>0.02570</td>
<td>335.10</td>
</tr>
<tr>
<td>6</td>
<td>388.39</td>
<td>0.03696</td>
<td>388.38</td>
</tr>
</tbody>
</table>

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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