Analytical development of single crystal Macro Fiber Composite actuators for active twist rotor blades

This content has been downloaded from IOPscience. Please scroll down to see the full text.
2005 Smart Mater. Struct. 14 745
(http://iopscience.iop.org/0964-1726/14/4/033)
View the table of contents for this issue, or go to the journal homepage for more

Download details:

IP Address: 147.46.119.246
This content was downloaded on 06/07/2015 at 06:31

Please note that terms and conditions apply.
Analytical development of single crystal Macro Fiber Composite actuators for active twist rotor blades

Jae-Sang Park and Ji-Hwan Kim

School of Mechanical and Aerospace Engineering, Seoul National University, San 56-1, Sillim-dong, Gwanak-gu, Seoul 151-742, Korea

Received 10 September 2004, in final form 14 April 2005
Published 14 July 2005
Online at stacks.iop.org/SMS/14/745

Abstract

A Macro Fiber Composite (MFC) is a piezoelectric fiber composite which has an interdigitated electrode, rectangular cross-section and unidirectional polycrystalline piezoceramic (PZT) fibers embedded in the polymer matrix. A MFC actuator has much higher actuation performance and flexibility than a monolithic piezoceramic actuator. Moreover, the single crystal piezoelectric material exhibits much higher induced strain levels, energy density and coupling than those of polycrystalline piezoceramic materials. Thus, the performance of an MFC can be improved by using single crystal piezoelectric fiber instead of polycrystalline piezoceramic fiber. This study investigates the analytical modeling, material properties and actuation performance of an MFC using single crystal piezoelectric material (single crystal MFC). For single crystal MFC, the mechanical properties are calculated by the classical lamination theory, and the uniform fields model (UFM) is adopted to predict piezoelectric strain constants. In addition, the actuation performance of the single crystal MFC with the active twist rotor blade is studied. The material properties and actuation performance of single crystal MFC are compared with those of standard MFC.

1. Introduction

A number of studies of smart materials and structures have been performed in the past few decades. Although there are many kinds of smart materials, piezoelectric material is considered as the most representative smart material because it is capable of altering the response of the structure through sensing, actuation and control. Various researches of smart structures using piezoceramics (PZT) have been performed. However, monolithic piezoceramics have some significant drawbacks. Monolithic piezoceramics are vulnerable to impact and can hardly conform to a curved surface due to the brittle nature of the ceramics. To overcome these drawbacks of monolithic piezoceramics, Active Fiber Composite (AFC, figure 1(a)) was developed at MIT [1]. AFC is an anisotropic actuator which employs round cross-section PZT fibers in the epoxy matrix. AFC uses the interdigitated electrodes to produce much higher in-plane actuation than traditional PZT actuators with through-the-thickness poling. In addition, the combination of PZT fibers and soft matrix provides the load transfer mechanism which increases robustness to damage, and offers conformability and flexibility. AFC was applied to reduce the vibration of helicopter rotor blades at MIT. The static twisting performance of the active rotor blade using AFC was investigated through numerical and experimental methods [2]. Rodgers [3] studied an integral twist-actuated rotor blade. The twist actuation performance of the active rotor blade with AFC was investigated over a range of rotor speeds, actuation frequencies and blade loading conditions in hover. Shin [4] investigated the active integral twist control for vibration reduction of helicopter rotors during forward flight through numerical and experimental methods. In the study, the hub vibratory load of rotor blades could be reduced by using the active twist rotor blade. AFC material characterization for helicopter rotor blade applications was studied [5]. Although the AFC had many improvements over monolithic PZT, there were some defects. First, the circular cross-section PZT fibers of the AFC had very little contact area between the
interdigitated electrodes and the fibers, which resulted in the transfer of the electric field into the PZT fibers inefficiently. Second, the cost to manufacture the PZT fibers used in the AFC was high. Finally, the AFC needed to operate at high voltage.

To remedy these defects of the AFC, a Macro Fiber Composite (MFC, figure 1(b)) was developed at NASA Langley Research Center [6]. MFC is a piezoelectric fiber composite which has a rectangular cross-section; unidirectional piezoceramic fibers are embedded in the polymer matrix and it uses an interdigitated electrode. In contrast to AFC, the rectangular PZT fiber of the MFC improved the maximum contact area between the PZT fibers and the interdigitated electrodes. Furthermore, the PZT fiber of the MFC was obtained from dicing lower cost monolithic PZT wafers. Williams et al [7] investigated the mechanical properties of a MFC using the classical lamination theory. Nonlinear mechanical behaviors of the MFC were studied by experiment, and the linear mechanical properties of the MFC were compared with the result of the analytical method [8]. In addition, Williams et al [9] measured the nonlinear actuation properties of a MFC under various loads. There have been some researches for the application of a MFC to a structure. Azzouz et al [10] studied the finite element modeling of an MFC actuator and compared the performance of the MFC with that of a traditional PZT actuator. Their results showed that the MFC actuator outperformed the typical piezoceramic actuator. Ruggerio et al [11] used several MFCs as both actuators and sensors to measure the dynamic behavior of an inflatable satellite structure. The flexibility of the MFC made for convenient attachment to the curved surface and MFC outperformed the other actuators. Jha and Inman [12] researched optimal sizes and placements of the MFC actuator for the inflatable toroidal structure. Schultz and Hyer [13] studied the snapthrough behavior of an unsymmetric laminate using a MFC.

The recent development of single crystal piezoelectric material [14, 15] could elevate the actuation performance of an anisotropic piezocomposite actuator [16, 17]. The single crystal piezoelectric material can produce strain levels in excess of 1% and exhibit five times the strain energy density of polycrystalline piezoelectric material (conventional piezoceramics). In addition, the single crystal piezoelectric material has a high coupling of up to 90%.

There have been limited researches for material properties and the actuation performance of MFC using single crystal piezoelectric material (single crystal MFC). Therefore, this paper studies the variations of mechanical and electromechanical properties of single crystal MFC with the variation of volume fraction or angle of fibers. The predicted material properties of single crystal MFC are compared with those of standard MFC. In addition, the active twisting actuation performance of rotor blades using single crystal MFC is compared with that using AFC and standard MFC.

2. Analytical method for single crystal MFC

In this section, the analytical method for the material properties of standard and single crystal MFC is presented. For simplicity, we will refer to the single crystal piezoelectric material as PMN-PT throughout the remainder of this paper. In addition, the standard notation for the composite materials is used for the material properties of the MFC instead of the standard piezoelectric notation.

The MFC is a symmetric and cross-ply laminate which consists of PMN-PT (or PZT) fiber, epoxy, copper electrode, Acrylic and Kapton as shown in figure 2. The poled PMN-PT and PZT fiber are assumed to be transversely isotropic and the other constituent materials are isotropic. The basic lamination for the MFC is [Kapton/Acrylic/90°copper/0°PMN−PT(0°PZT)]. The PMN-PT (or PZT) fiber has an arbitrary angle; however, the copper electrode is always perpendicular to the PMN-PT (or PZT) fiber. Further, the poling direction for the PMN-PT (or PZT) fiber is the fiber direction.

2.1. Mechanical properties

2.1.1. Rule of mixture. There are two types of orthotropic layers of the MFC, PMN-PT (or PZT)/epoxy and copper/epoxy
layers. All of the PMN-PT (or PZT) and copper fibers are rectangular, uniformly distributed and aligned in the orthotropic layers. The rule of mixture is used to calculate the effective mechanical properties of the orthotropic layers of the MFC.

The fiber direction and the direction normal to the fiber are denoted as 1 and 2, respectively. By the rule of mixture, Young’s modulus for the 1 and 2 directions, the in-plane shear modulus, the major Poisson’s ratio and the density of the PMN-PT (or PZT)/epoxy and copper/epoxy layers of the MFC are denoted as 1 and 2, respectively. By the rule of mixture, the effective mechanical properties of orthotropic layers of the MFC are obtained by analogy with equations (2) and (5) as

\[
E_{r}^{MFC} = \frac{E_{1}A_{12} - E_{2}A_{22}^{2}}{A_{MFC}A_{22}} \quad E_{y}^{MFC} = \frac{A_{11}A_{22} - A_{12}^{2}}{A_{MFC}A_{11}}
\]

where \(N_{j}^{MFC}\) is the thickness of the MFC. If the PMN-PT (or PZT) fiber is aligned in the \(x\) direction, the effective mechanical properties of the MFC in the material coordinates can be obtained. Therefore,

\[
E_{1}^{MFC} = E_{1}^{MFC}, \quad E_{2}^{MFC} = E_{y}^{MFC},
\]

in addition, the density of the MFC can be represented as

\[
\rho^{MFC} = \sum_{k=1}^{N} \rho_{k}(S_{x+k} - z_{k}).
\]

2.2. Electromechanical properties

The electromechanical properties, i.e. the piezoelectric strain constants of the MFC, are calculated using the uniform fields model (UFM, [1]). The UFM is a generalization of the rule of mixture, and the concept of the UFM is shown in figure 3. The representative volume element is divided into three separate cases, that is, Case A, Case B and Case C. The total combination model represents a combination of the three cases. In each case, the effective material properties of a completed case are substituted for the material properties of the PMN-PT (or PZT) fiber in the next case. In this section, the superscripts or subscripts \(p\) and \(m\) indicate the PMN-PT (or PZT) fiber and matrix, respectively.

The linear piezoelectric constitutive equation for the PMN-PT (or PZT)/epoxy layer of the MFC in each case A,
where the upper bar means the average material properties.

The detailed derivation for the effective material properties at each case is summarized in [1]; thus, it is not shown in this paper. The effective material properties in each case are given as follows.

For Case A,

\[
C_{11}^{\text{eff}} = \frac{c_{13}^p c_{11}^m V_{33}^{p} - ((c_{13}^m - c_{13}^p)^2 - c_{11}^m c_{33}^m - c_{11}^p c_{33}^p) V_{33}^{m} V_{33}^{p}}{c_{11}^{p} V_{33}^{p} + c_{11}^{m} V_{33}^{m}}
\]

\[
C_{12}^{\text{eff}} = \frac{(c_{12}^m c_{13}^m + c_{13}^p c_{12}^p) C_{33}^{p} - (c_{12}^m C_{33}^m - c_{12}^p C_{33}^p) V_{33}^{m} V_{33}^{p}}{C_{33}^{p} V_{33}^{p} + C_{33}^{m} V_{33}^{m}}
\]

\[
C_{13}^{\text{eff}} = \frac{c_{13}^{p} c_{13}^{m} V_{33}^{p} + c_{13}^{m} V_{33}^{m} V_{33}^{p}}{c_{13}^{p} V_{33}^{p} + c_{13}^{m} V_{33}^{m}}
\]

\[
C_{22}^{\text{eff}} = \frac{c_{22}^{p} c_{22}^{m} V_{33}^{p} - (c_{22}^{m} c_{22}^{p})^2 - c_{22}^{m} c_{33}^{m} - c_{22}^{p} c_{33}^{p}) V_{33}^{m} V_{33}^{p}}{c_{22}^{p} V_{33}^{p} + c_{22}^{m} V_{33}^{m}}
\]

\[
C_{33}^{\text{eff}} = \frac{c_{33}^{p} c_{33}^{m} V_{33}^{p} + c_{33}^{m} V_{33}^{m} V_{33}^{p}}{c_{33}^{p} V_{33}^{p} + c_{33}^{m} V_{33}^{m}}
\]

The piezoelectric strain constants of the MFC can be calculated from the final completed combination model as

\[
\begin{pmatrix}
\tilde{e}_{11}^{\text{eff}} \\
\tilde{e}_{12}^{\text{eff}} \\
\tilde{e}_{13}^{\text{eff}}
\end{pmatrix}
= \begin{bmatrix}
C_{11}^{\text{eff}} & C_{12}^{\text{eff}} & C_{13}^{\text{eff}} \\
C_{12}^{\text{eff}} & C_{22}^{\text{eff}} & C_{23}^{\text{eff}} \\
C_{13}^{\text{eff}} & C_{23}^{\text{eff}} & C_{33}^{\text{eff}}
\end{bmatrix}^{-1}
\begin{pmatrix}
\tilde{e}_{11} \\
\tilde{e}_{12} \\
\tilde{e}_{13}
\end{pmatrix}
\]

Furthermore, the piezoelectric strain constants of the MFC can be predicted by using the following equations [17] as well as the UFM.

\[
d_{11}^{\text{eff}} = \frac{d_{11}^{p}}{1 + \frac{c_{11}^{m}}{c_{11}^{p}}}
\]

\[
d_{12}^{\text{eff}} = V_{33}^{p} d_{12}^{p}
\]

In section 4, the piezoelectric strain constants of the MFC by the UFM will be compared with those by equation (13).
3. Modeling of active twist rotor blades

The modeling of an active twist rotor (ATR) blade using a single crystal MFC actuator is presented in this section. The ATR blade is modeled as a thin-walled single cell composite beam based on Rehfield’s model [2, 23]. The assumptions for the single cell composite beam are as follows.

- Cross-sectional shape is maintained during deformation, but out-of-plane displacements are allowed.
- The wall thickness is small compared with the other dimensions so that the problem can be treated as a thin-walled, plane stress problem.
- The transverse in-plane normal stresses are negligible (no internal pressure).
- The rate of twist can vary along the length of the beam and it acts as a measure of the torsional warping of the cross-section.
- Properties along the longitudinal axis of the beam are constant.

3.1. Strain–displacement relationship

The definitions of the coordinate and position vectors for the thin-walled beam are shown in figure 4(a). \( r_p \) is the point position vector, \( r_n \) is the mid-plane position vector, and \( r_w \) is the normal projection vector of the mid-plane position vector \( r_n \).

The coordinate \( x \) is the spanwise coordinate, whereas \( y \) and \( z \) are the transverse coordinates of any point in the cross-section. \( X(x), Y(s) \) and \( Z(s) \) are the mid-plane contour coordinates of the cross-section, in global coordinates. Global displacements are defined as shown in figure 4(b). \( U(x), V(x) \) and \( W(x) \) are the rotational displacements, and \( \beta \) are the translational displacements, and \( \phi(s) \) and \( \phi_x(s) \) are the twist angle and twist rate for the cross-section.

The displacements at any point in the beam wall are

\[
\begin{align*}
  u(x) &= U(x) - (Y - nZ)\beta_y(x) \\
  v(x) &= V(x) - (Z + nY)\phi(x) \\
  w(x) &= W(x) + (Y - nZ)\phi_x(x)
\end{align*}
\]

where \( \phi(s) \) is the warping function defined as

\[
\phi(s) = -\frac{2A}{\Gamma} \alpha^s(s) + \int_0^s r_n \, ds
\]

with

\[
\alpha^s(s) = \int_0^s \alpha \, ds, \quad \text{and} \quad \alpha(s) = \frac{\Gamma}{G_{eff}} \frac{1}{f_Y} \frac{1}{\kappa_{eff}}
\]

where \( \Gamma \) represents both the contour and the actual mid-plane contour length. The effective shear stiffness \( G_{eff} \) is the thickness-averaged shear stiffness at a specific point in the beam wall, and \( t \) and \( A \) are the wall thickness and the area of the mid-plane contour, respectively.

The axial normal strain is decomposed into the mid-plane strain and the local bending curvature strain as

\[
\varepsilon_x = U_{,x} - Y\beta_{y,}\gamma_x + Z\beta_{y,} + \psi\phi_{,x} + n(Y_{,x}\beta_{y,} + Z_{,x}\beta_{y,})
\]

\[
= \varepsilon_x + n\kappa_x.
\]

The shear strain in the wall of the beam is constant and is not a function of the thickness coordinate \( n \). Thus,

\[
\gamma_{xy} = (V_{,y} - \beta_x)Y_{,y} + (W_{,z} + \beta_{y,})Z_{,z} - \frac{2A}{\Gamma} \alpha \phi_{,y} = \gamma_{xy}^\alpha.
\]

Therefore, the strain vector can be represented as

\[
\left\{ \begin{array}{c}
\varepsilon_x \\
\varepsilon_y \\
\gamma_{xy}
\end{array} \right\} = \left\{ \begin{array}{c}
\varepsilon_x^\alpha \\
\varepsilon_y^\alpha \\
\gamma_{xy}^\alpha
\end{array} \right\} + n \left\{ \begin{array}{c}
\kappa_x \\
\kappa_y \\
\kappa_{xy}
\end{array} \right\} = \varepsilon^\alpha + n\kappa.
\]

3.2. Constitutive equations

The wall of the active beam consists of active or non-active materials. Under the plane stress assumption, the linear piezoelectric constitutive equation for the \( k \)th layer of the wall of the active beam is given as

\[
\sigma_k = \begin{bmatrix}
\sigma_{xx} \\
\sigma_{yy} \\
\tau_{xy}
\end{bmatrix}_k = \begin{bmatrix}
\bar{Q}_{11} & \bar{Q}_{12} & \bar{Q}_{16} \\
\bar{Q}_{12} & \bar{Q}_{22} & \bar{Q}_{26} \\
\bar{Q}_{16} & \bar{Q}_{26} & \bar{Q}_{66}
\end{bmatrix}_k \begin{bmatrix}
\varepsilon_{xx} \\
\varepsilon_{yy} \\
\gamma_{xy}
\end{bmatrix}_k + \begin{bmatrix}
d_{11} \\
d_{12} \\
d_{16}
\end{bmatrix}_k E_k
\]

where \( \begin{bmatrix} d_{11} & d_{12} & d_{16} \end{bmatrix}^T \) is the transformed piezoelectric strain constant vector. In addition, the electric field is defined as...
$E_k = -\frac{V}{d}$, where $V_k$ and $p_k$ are the applied voltage and the electrode spacing of the interdigitated electrode for the $k$th layer, respectively.

The force and moment resultant vectors are defined as

$$\mathbf{N} = \int_{-1/2}^{1/2} \sigma \begin{bmatrix} 1 & n \end{bmatrix} \, dn. \quad (20)$$

The constitutive equation can be represented by using equations (19) and (20) as

$$\begin{bmatrix} \mathbf{N} \\ \mathbf{M} \end{bmatrix} = \begin{bmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{B} & \mathbf{D} \end{bmatrix} \begin{bmatrix} \varepsilon^n \\ \kappa \end{bmatrix} - \begin{bmatrix} \mathbf{N}^u \\ \mathbf{M}^u \end{bmatrix}. \quad (21)$$

Because the hoop stress $\sigma_n$ is zero, $N_i$ is zero. In addition, the cross-section is infinitely rigid in its own plane, which results in zero transverse and twisting curvatures ($\kappa_n = 0$).

Therefore, equation (21) can be reduced as

$$\begin{bmatrix} N_i \\ N_{i, x} \end{bmatrix} = \begin{bmatrix} L_{11} & L_{12} \\ L_{12} & L_{22} \end{bmatrix} \begin{bmatrix} e_{i, x} \\ \gamma_{i, y} \end{bmatrix} - \begin{bmatrix} \tilde{N}_i \\ \tilde{N}_{i, x} \end{bmatrix}$$

$$= \mathbf{Le} - \mathbf{F}^u \quad (22)$$

where the reduced laminate stiffness and piezoelectric stress resultant vectors are defined as

$$L_{11} = A_{11} - \frac{A_{12}^2}{A_{22}} \quad L_{12} = A_{16} - \frac{A_{12}A_{26}}{A_{22}}$$

$$L_{22} = B_{11} - \frac{A_{12}B_{12}}{A_{22}} \quad L_{22} = A_{66} - \frac{A_{26}^2}{A_{22}}$$

$$L_{23} = B_{16} - \frac{A_{26}B_{12}}{A_{22}} \quad L_{33} = D_{11} - \frac{B_{12}^2}{A_{22}}$$

$$\tilde{N}_i = N_i - \frac{A_{12}}{A_{22}} N_{i, x} \quad \tilde{N}_{i, x} = N_{i, x} - \frac{A_{26}}{A_{22}} N_i$$

$$\tilde{M}_i = M_i - \frac{B_{12}}{A_{22}} N_{i, x} \quad (23)$$

3.3. Governing equation

The governing equation of the ATR blade for the active twisting actuation is derived using the principle of the minimum potential energy.

$$\delta U - \delta W_{ext} = 0. \quad (24)$$

In this paper, only the problem for the active twisting actuation under a static state is considered. Therefore, the variation of the external work $\delta W_{ext}$ is zero.

On the other hand, the variation of the internal strain energy $\delta U$ can be represented as

$$\delta U = \int_{R} \int_{\Gamma_d} \left( \begin{bmatrix} N_i \\ N_{i, x} \end{bmatrix} \delta e^n_{i, x} + N_i \delta \gamma_{i, y} + M_i \delta \kappa_n \right) \, dx \, ds$$

$$= \int_{R} \int_{\Gamma_d} \left[ \begin{bmatrix} \delta e^n_{i, x} \\ \delta \gamma_{i, y} \\ \delta \kappa_n \end{bmatrix} \right] \times \left( \begin{bmatrix} L_{11} & L_{12} & L_{13} \\ L_{12} & L_{22} & L_{23} \\ L_{13} & L_{23} & L_{33} \end{bmatrix} \begin{bmatrix} e_{i, x} \\ \gamma_{i, y} \\ \kappa_n \end{bmatrix} - \begin{bmatrix} \tilde{N}_i \\ \tilde{N}_{i, x} \\ \tilde{M}_i \end{bmatrix} \right) \, dx \, ds$$

$$= \int_{R} \int_{\Gamma_d} \delta \mathbf{e}^T \mathbf{Le} \, dx \, ds - \int_{R} \int_{\Gamma_d} \delta \mathbf{e}^T \mathbf{F}^u \, dx \, ds = 0 \quad (25)$$

where $R$ is the length of the span of the ATR blade.
Table 3. Material properties of standard and single crystal MFC.

<table>
<thead>
<tr>
<th>Material properties</th>
<th>Standard MFC [22]</th>
<th>Standard MFC (present)</th>
<th>Single crystal MFC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_1$ (GPa)</td>
<td>30.3</td>
<td>31.20</td>
<td>6.23</td>
</tr>
<tr>
<td>$E_2$ (GPa)</td>
<td>15.9</td>
<td>17.05</td>
<td>11.08</td>
</tr>
<tr>
<td>$G_{12}$ (GPa)</td>
<td>5.52</td>
<td>5.12</td>
<td>2.01</td>
</tr>
<tr>
<td>$v_{12}$</td>
<td>0.31</td>
<td>0.303</td>
<td>0.229</td>
</tr>
<tr>
<td>$d_{11}$ ($\times 10^{-12}$ m V$^{-1}$)</td>
<td>460 ($</td>
<td>E</td>
<td>&lt; 1$ kV mm$^{-1}$)</td>
</tr>
<tr>
<td></td>
<td>460 ($</td>
<td>E</td>
<td>&gt; 1$ kV mm$^{-1}$)</td>
</tr>
<tr>
<td>$d_{12}$ ($\times 10^{-12}$ m V$^{-1}$)</td>
<td>-170 ($</td>
<td>E</td>
<td>&lt; 1$ kV mm$^{-1}$)</td>
</tr>
<tr>
<td></td>
<td>-210 ($</td>
<td>E</td>
<td>&gt; 1$ kV mm$^{-1}$)</td>
</tr>
<tr>
<td>$\rho$ (kg m$^{-3}$)</td>
<td>N/A</td>
<td>5115.9</td>
<td>5338.3</td>
</tr>
</tbody>
</table>

Figure 5. Elastic and shear modulus of standard MFC with variation of the PZT fiber angle.

Figure 6. Elastic and shear modulus of single crystal MFC with variation of the PMN-PT fiber angle.

Figure 7. Effective piezoelectric strain constants of standard MFC with variation of the volume fraction of PZT fiber.
piezoelectric strain constants of single crystal MFC are much higher than those of standard MFC for all volume fractions of PMN-PT.

4.2. ATR blades using single crystal MFC

In this section, the active twisting performance of the ATR blade using single crystal MFC is presented, and compared with the results for AFC and standard MFC.

4.2.1. Code verification. To verify the code in this study, the active twisting actuation of the ATR blade using AFC is investigated and compared with the previous result [2]. Figure 9 shows the variation of the blade tip twist as a function of applied voltage to the AFC. The present result has good agreement with the previous numerical and experimental results. Both previous and present numerical results are slightly higher than the experimental result, because the form core used in the experimental model is not considered in the analytical model.

4.2.2. Active twisting performance of ATR blades. In this section, the active twisting performance of the ATR blade using single crystal MFC is studied and compared with the results of AFC and standard MFC. The model of the ATR blade with a NACA0012 airfoil for the analysis is shown in figure 10. The span length \( R \) is 0.483 m, and the chord length \( C \) is 0.05 m. The non-active region without single crystal MFC consists of two layers of E-glass at 0\(^\circ\) to the blade axis. The material properties of the E-glass are:

\[
E_1 = 14.8 \text{ GPa} \quad E_2 = 13.6 \text{ GPa} \\
G_{12} = 1.9 \text{ GPa} \quad \nu_{12} = 0.19 \\
\rho = 1800 \text{ kg m}^{-3} \quad \text{Thickness: } 2.032 \times 10^{-4} \text{ m}.
\]

In addition, the active region with single crystal MFC consists of two layers of E-glass at 0\(^\circ\) and one layer of single crystal MFC: [E-glass/MFC/E-glass]. In each single crystal MFC actuator, the PMN-PT fibers are aligned at +45\(^\circ\) at the top and −45\(^\circ\) at the bottom of the ATR blade to maximize the twisting actuation.

Figure 11 shows the active twisting performance of the ATR blade using AFC [3], standard MFC [22] and single crystal MFC. For all cases, the tip twist of the ATR blade is increased linearly with the increase of the applied voltage to the actuators. For the active twisting actuation performance of the ATR blade, single crystal MFC outperforms AFC and standard MFC. When the applied voltage to the actuators is 500 V, single crystal MFC produces 2.87 and 8.63 times the tip twist angles of the ATR blades with standard MFC and AFC, respectively.

The twisting distribution along the spanwise coordinate for a constant applied voltage of 400 V is shown in figure 12.
The twist angle of the ATR blade with single crystal MFC is higher than that using AFC and standard MFC along the whole span of the ATR blade.

5. Conclusions

The material properties of single crystal MFC are predicted by the analytical method. For single crystal MFC, the mechanical properties are calculated by the classical lamination theory, and the piezoelectric strain constants are predicted by the UFM. The predicted material properties of single crystal MFC are compared with those of standard MFC. Single crystal MFC is more flexible, and has much higher piezoelectric strain constants. In addition, the active twisting performance of the ATR blade using single crystal MFC is studied. As compared with the ATR blade using AFC and standard MFC, the ATR blade with single crystal MFC has an excellent twisting actuation performance. However, the density of single crystal MFC is slightly higher than that of AFC and standard MFC; therefore, the optimal design for single crystal MFC should be investigated to actuate the structure efficiently.

Acknowledgment

This work was supported by Korea Research Foundation Grant (KRF-2004-041-D00039).

References

[1] Bent A A 1997 Active fiber composites for structural actuation PhD Dissertation Department of Aeronautics and Astronautics, Massachusetts Institute of Technology