Abstract—Axisymmetric vibration of an infinite Pyrocomposite circular hollow cylinder made of inner and outer pyroelectric layer of 6mm-class bonded together by a Linear Elastic Material with Voids (LEMV) layer is studied. The exact frequency equation is obtained for the traction free surfaces with continuity condition at the interfaces. Numerical results in the form of data and dispersion curves for the first and second mode of the axisymmetric vibration of the cylinder BaTiO₃ / Adhesive / BaTiO₃ by taking the Adhesive layer as an existing Carbon Fibre Reinforced Polymer (CFRP) are compared with a hypothetical LEMV layer with and without voids and as well with a pyroelectric hollow cylinder. The damping is analyzed through the imaginary parts of the complex frequencies.

Keywords—Axisymmetric vibration, CFRP, hollow cylinders, LEMV, pyrocomposite

I. INTRODUCTION

CERAMIC materials and single crystals showing pyroelectric behavior are being used in many applications in electronics and optics. A huge leap in the research on smart materials came in the 1950's, leading to the widespread use of barium titanate (BaTiO₃) based ceramics in capacitor applications and pyroelectric transducer devices. Measurement of X-ray intensity in the medical diagnostic range by pyroelectric detector is analyzed by Carvalho and Alter [1]. The pyroelectric vidicon camera can be used as a medical thermograph [2]. Black et al [3] have studied that the pyroelectric thermal imaging system for use in medical diagnosis. In the Past, the propagation of wave in a pyroelectric cylinder of arbitrary cross section with a circular cylindrical cavity, a pyroelectric circular cylinder of crystal class 6 and a pyroelectric cylinder of inner and outer arbitrary shape are studied [4]-[6]. Paul and Nelson [7] have extended the study of Vasudeva and Govinda Rao [8]-[9] on the influence of distributed voids in the interfacial LEMV adhesive zones of the isotropic Sandwich plate to the axisymmetric vibration of Piezo composite hollow cylinder. A continuum theory of LEMV with distinct properties has been developed by Cowin and Nunziato [10]. In layered composites pores or voids are found in the interface region and it is known to affect the estimation of physical and mechanical properties of the composites [11]. Voorhees and Green [12] have studied the mechanical behavior of sandwich composites made of thin porous core and denser face materials. Damage detection and vibration control of a new smart board designed by mounting piezoelectric fibers with metal cores on the surface of a CFRP composite was studied by Takagikiyoshi [13].

In the present analysis axisymmetric free vibration of pyrocomposite circular hollow cylinder of crystal class 6mm with LEMV as a bonding layer is considered as in figure (1). The frequency equation for axisymmetric vibration has been derived for traction free shorted inner and outer surfaces with interface continuity conditions on both sides of the LEMV layer. Numerical work is carried out for the axisymmetric vibration of the cylinder with equal thickness of the material BaTiO₃ combined by a thin LEMV/CFRP layer. Dispersion curves have been drawn for propagation of waves along the axis of the composite cylinder with LEMV (with and without voids) is compared on replacing LEMV by CFRP and a pyroelectric hollow cylinder.

II. GOVERNING EQUATIONS

The equations governing elastic, electric and thermal behavior are given by Mindlin [14] - [15]

\[ T_{i,j} = \rho \ddot{u}_{i,j}, \]
\[ D_{i,j} = 0, \]
\[ k' \theta \gamma = \theta' \sigma', \]
where, \( T^i_{\theta} \), \( S^i_{\theta} \), \( D^i_{\theta} \), \( E^i_{\theta} \), \( \sigma^i \) and \( \theta^i \) are stresses, strains, electric displacements, electric fields, entropy and temperature. Temperature field is assumed to be uniform throughout the cylinder. Here, \( C_v \) is the specific heat capacity, \( \theta_0 \) is the reference temperature, and \( \rho^i \) is the density. Here, \( C_{ij}, C_{im}, c_{iv}, \beta_{lj} \) and \( p_{lj} \) are elastic, piezoelectric, dielectric, thermal stress coefficients and pyroelectric constants respectively. The comma followed by a dependent variable denotes partial differentiation of that coefficient with respect to that independent variable. And \( \tilde{E}^i_{\theta} = \phi^i_{\theta}, i^\dagger \). The superscript (\( i^\dagger = 1,2 \)) is to denote the constants and materials of inner and outer pyroelectric materials of hexagonal (class 6 mm).

For crystal class 6 mm, the material constants are

\[
C^i = \begin{bmatrix}
C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\
C_{12} & C_{11} & C_{23} & 0 & 0 & 0 \\
C_{13} & C_{23} & C_{33} & 0 & 0 & 0 \\
0 & 0 & 0 & C_{44} & 0 & 0 \\
0 & 0 & 0 & 0 & C_{44} & 0 \\
0 & 0 & 0 & 0 & 0 & C_{66}
\end{bmatrix}
\]

\[
\beta^i = \begin{bmatrix}
\beta_{11} \\
\beta_{22} \\
\beta_{33} \\
0 \\
0 \\
0
\end{bmatrix}, \quad p^i = \begin{bmatrix}
0 \\
0 \\
0 \\
0 \\
0 \\
0
\end{bmatrix}
\]

\[
e^i = \begin{bmatrix}
e_{11} & 0 & 0 \\
e_{12} & e_{15} & 0 \\
e_{23} & e_{31} & e_{33} \\
0 & e_{11} & 0 \\
0 & 0 & e_{33}
\end{bmatrix}
\]

\[
T^{i}_{rr} + T^{i}_{zz} + r^{-1}(T^{i}_{rz}) = \rho^i u^{i}_{rr},
\]

\[
T^{i}_{rzz} + T^{i}_{zrr} + r^{-1}T^{i}_{zz} = \rho^i w^{i}_{zz},
\]

where, \( k_{ij} \) is heat conduction coefficient, \( d = \frac{\rho C_v}{T_0} \). Equations for axisymmetric vibration of hexagonal symmetry when the uniform temperature field throughout the cylinder,
Using the above solution in Eqn (3) can be rewritten as

\[
C_i^{ij} \nabla^2 + A_i A_j A_j \nabla^2 + A_i A_j A_j A_j A_j \nabla^2 + A_i \nabla^2 + A_i \nabla^2 = 0
\]

where

\[
 \nabla^2 = \frac{\partial^2}{\partial x^2} + \left( \frac{1}{x} \right) \frac{\partial}{\partial x}
\]

\[
A_1 = \varepsilon^2 - (ch)^2
\]

\[
A_2 = \varepsilon (1 + C_{11})
\]

\[
A_3 = \varepsilon (C_{11} + C_{12})
\]

\[
A_4 = B_1
\]

\[
A_5 = \varepsilon^3 C_{11} - (ch)
\]

\[
A_6 = \varepsilon^2
\]

\[
A_7 = \varepsilon
\]

\[
A_8 = K_{33}^{ij} \varepsilon^2
\]

\[
A_9 = p' \varepsilon
\]

\[
A_{10} = iK_{3} \varepsilon^2 - \vec{D}
\]

and

\[
C_{ij}^{ij} = C_{11}^{ij}, \quad \varepsilon_{ij} = \varepsilon_{ij}^{ij}, \quad \vec{B} = B_3
\]

\[
\vec{T} = \rho C_{ij}^{ij} C_{ij}^{ij} \theta_0
\]

\[
\vec{K}_{ij} = \left( \frac{\rho C_{ij}^{ij} \beta_3}{\beta_3^2 h \theta_0} \right) (ch)
\]

The solutions of the Eqn (5) are taken as

\[
U^i = \sum_{j=0}^{a} \left[ A_j J_a(\alpha_j x) + B_j Y_a(\alpha_j x) \right]
\]

\[
W^i = \sum_{j=0}^{a} \left[ A_j J_a(\alpha_j x) + B_j Y_a(\alpha_j x) \right] d_j
\]

\[
\Phi^i = \sum_{j=0}^{a} \left[ A_j J_a(\alpha_j x) + B_j Y_a(\alpha_j x) \right] \Phi_j
\]

\[
T^i = \sum_{j=0}^{a} \left[ A_j J_a(\alpha_j x) + B_j Y_a(\alpha_j x) \right] \Phi_j
\]

And \((\alpha_j x)^2\) are the four roots of the Eqn (5) when replacing \(\nabla^2 = (\alpha_j x)^2\).

The constants \(d_j, e_j\) and \(h_j\) can be evaluated using the following relations:

\[
(C_i^{ij} \nabla^2 + A_i - A_j d_j + A_j e_j - A_j h_j) = 0
\]

\[
(C_i^{ij} \nabla^2 + A_i - A_j d_j + A_j e_j - A_j h_j) = 0
\]

\[
(C_i^{ij} \nabla^2 + A_i - A_j d_j + A_j e_j - A_j h_j) = 0
\]

\[
(C_i^{ij} \nabla^2 + A_i - A_j d_j + A_j e_j - A_j h_j) = 0
\]

In the context of the theory of LEMV, the equations of motion and balance of equilibrated force are given by [10]

\[
\rho \ddot{u}_i = \mu u_{i,j} + (\lambda + \mu) u_{i,j} + \beta \psi u_{i,j}
\]

\[
\rho k \ddot{\psi} = \alpha \psi \omega - \omega \psi - \xi \psi - \beta u_{i,j}
\]

where \(u, \psi, \omega \) are displacements in r, 0 and z directions \(\alpha, \beta, \xi, \omega \) and \(k \) (equilibrated inertia) are material constants characterizing the core of LEMV, \(\rho \) is the density and \(\lambda, \mu \) are the Lamé’s constants and \(\psi \) is the new kinematical variable associated with a material with voids comes into contact with another material without voids. The displacement equations of motion and balance of equilibrated force for an isotropic LEMV as in [17] are

\[
(\lambda + \mu) (u_{r,r} + r^{-1} u_{r,r} - r^{-2} u_{r,r}) + \mu u_{r,r} + \beta \psi r = \rho u_{r,r}
\]

\[
(\lambda + \mu) (u_{r,z} + r^{-1} u_{r,z} + k u_{r,z}) + \mu (w_{r,z} + r^{-1} w_{r,z}) + \beta \psi z = \rho w_{r,z}
\]

\[
- \beta (u_{r,r} + r^{-1} u_{r,r}) - \beta w_{r,z} + \alpha (\psi_{r,r} + r^{-1} \psi_{r,z}) - \rho k \psi_{r,z} - \omega \psi_{r,z} - \xi \psi_{r,z} = 0
\]

The solution for Eqn. (9) is taken as

\[
u \left( r, \theta, z \right) = \left( U_r \right) \exp \left[ k (z + \rho t) \right]
\]

\[
w \left( r, \theta, z \right) = \left( \frac{W}{h} \right) \exp \left[ k (z + \rho t) \right]
\]

\[
\psi \left( r, \theta, z \right) = \left( \frac{\Phi}{h} \right) \exp \left[ k (z + \rho t) \right]
\]

Substituting Eqn. (10) in Eqn (9) and using the dimensionless variables \(x \) and \(e \), the Eqn. (10) becomes

\[
\left( \begin{array}{ccc}
(\lambda + 2 \mu) \nabla^2 + B_1 & -B_1 & B_1 \\
B_1 \nabla^2 & B_2 + B_3 & B_4 \\
-B_5 \nabla^2 & B_3 & \alpha \nabla^2 + B_6
\end{array} \right)
\left( \begin{array}{c}
U \\
W \\
\Phi
\end{array} \right) = 0
\]
where

\[
\nabla^2 = \frac{\partial^2}{\partial x^2} + \left( \frac{1}{x} \right) \frac{\partial}{\partial x}
\]

\[
B_i = \left( \frac{\rho}{\rho} \right) (c h)^2 - \pi \varepsilon^2,
\]

\[
B_i = \left( \kappa + \pi \right) \varepsilon,
\]

\[
B_i = \beta,
\]

\[
B_i = \left( \frac{\rho}{\rho} \right) (c h)^2 - (\kappa + 2 \pi) \varepsilon^2,
\]

\[
B_i = \beta \varepsilon,
\]

\[
B_i = \left( \frac{\rho}{\rho} \right) (c h)^2 - \alpha \varepsilon^2 - i\omega (c h) - \zeta,
\]

and

\[
\lambda = \frac{\kappa}{C_{44}}, \quad \mu = \frac{\mu}{C_{44}}, \quad \alpha = \frac{\alpha}{h^2 C_{44}}, \quad \beta = \frac{\beta}{C_{44}},
\]

\[
\zeta = \frac{\varepsilon}{C_{44}}, \quad \omega = \left( \frac{\omega}{(C_{44} \rho)^2} \right), \quad K = \frac{k}{h^2}
\]

The solutions of the Eqn. (11) are taken as

\[
\alpha, x^2 \]

are the three roots of the equation (11) when replacing \( \nabla^2 = -\left( \alpha, x^2 \right) \). The constants \( d_j \) and \( e_j \) can be evaluated using the following relations:

\[
B_i \nabla^2 + (\pi \nabla^2 + B_i) d_j + B_i e_j = 0,
\]

\[
- B_i \nabla^2 + (B_i) d_j + (\alpha \nabla^2 + B_i) e_j = 0
\]

The governing equation for CFRP core material can be deduced from Eqn. (9) by taking the void volume fraction \( \psi = 0 \), and the Lame’s constants as \( \lambda = c_{12}, \mu = \frac{c_{11} - c_{12}}{2} \)

### III. FREQUENCY EQUATIONS

The frequency equation has been derived by using the following boundary and interface conditions

(i) Since the inner and outer surfaces are traction free and coated with electrodes which are shorted, the boundary conditions becomes

\[
T_{rr}^i = T_{rr} = \phi' = T_{rr}, \quad \psi' = 0 \quad \text{at} \quad x_0 = h_0 / h \quad \text{and} \quad x_1 = h_1 / h
\]

(ii) On the interfaces (inner and middle, outer and middle), the continuity conditions are

\[
T_{rr}^i = T_{rr}^i, \quad T_{rr} = T_{rr}^i; \quad u' = \bar{u}, \quad w' = \bar{w}
\]

\[
\phi' = 0, \quad T_{rr}, \psi' = 0 \quad \text{(At non-pyroelectric core material)}
\]

\[
\psi' = 0 \quad \text{due to void volume fraction field.}
\]

The interface condition \( \psi' = 0 \) on the void volume fraction field \( \psi \) is suggested by Atkin et al. [18]. (When a material with voids comes into contact with another material without voids). The frequency equation is obtained as 22 x 22 determinantal equation, on substituting the solutions in the boundary- interface conditions. It is written in symbolic form as

\[
[E(i, j)] = 0, \quad (i, j = 1, 2, 3, \ldots, 22)
\]

The non-zero elements at \( x_0 = \frac{h_0}{h} \) by varying \( j \) from 1 to 4 are

\[
E(1, j) = 2\pi x_0 \left( \frac{\alpha_j}{x_0} \right) J_j(\alpha_j x_0)
\]

\[
- \left[ \pi_1 (\alpha_j)^2 + \pi_1 \varepsilon d_j + \pi_1 e_j + \beta h_j \right] J_0(\alpha_j x_0)
\]

\[
E(2, j) = \left( \varepsilon + d_j + \pi_1 e_j \right) \left( \frac{\alpha_j}{x_0} \right) J_1(\alpha_j x_0)
\]

\[
E(3, j) = e_j J_0(\alpha_j x_0)
\]

\[
E(4, j) = \frac{h_1}{x_0} J_0(\alpha_j x_0) - (\alpha_j) J_1(\alpha_j x_0)
\]

And the other nonzero elements \( E(1, j + 4), E(2, j + 4), E(3, j + 4) \) and \( E(4, j + 4) \) are obtained by replacing \( J_0 \) by \( J_1 \) and \( Y_0 \) by \( Y_1 \).

At \( x_1 = \frac{h_1}{h} \)

\[
E(5, j) = 2\pi x_0 \left( \frac{\alpha_j}{x_1} \right) J_j(\alpha_j x_1)
\]

\[
- \left[ \pi_1 (\alpha_j)^2 + \pi_1 \varepsilon d_j + \pi_1 e_j + \beta h_j \right] J_0(\alpha_j x_1)
\]

\[
E(5, j + 8) = - \left[ \frac{\kappa}{h} \left( \frac{\alpha_j}{x_1} \right)^2 + \beta e_j - \kappa e_j d_j \right] J_0(\alpha_j x_1)
\]

\[
E(6, j + 8) = \left( \varepsilon + d_j + \pi_1 e_j \right) \left( \frac{\alpha_j}{x_1} \right) J_1(\alpha_j x_1)
\]

\[
E(6, j + 8) = - \pi (\varepsilon + d_j) \left( \frac{\alpha_j}{x_1} \right) J_1(\alpha_j x_1)
\]
and the other nonzero element at the interfaces \( x = x_1 \) can be obtained on replacing \( J_0 \) by \( J_1 \) and \( Y_0 \) by \( Y_1 \) in the above elements. They are

\[
E(i, j + 4), E(i, j + 8), E(i, j + 11), E(i, j + 14), (i = 5, 6, 7, 8)
\]

and

\[
E(9, j + 4), E(10, j + 4), E(11, j + 4).
\]

At the interface \( x = x_2 \), nonzero elements along the following rows \( E(i, j), (i = 12, 13, \ldots, 18 \text{ and } j = 8, 9, \ldots, 20) \) are obtained on replacing \( x_1 \) by \( x_2 \) and superscript 1 by 2 in order.

Similarly, at the outer surface \( x = x_3 \), the nonzero elements \( E(i, j), (i = 19, 20, 21, 22 \text{ and } j = 14, 15, \ldots, 22) \) can be had from the nonzero elements of first four rows by assigning \( x_3 \) for \( x_0 \) and superscript 2 for 1.

In the case of without voids in the interface region, the frequency equation is obtained by taking \( \psi = 0 \) in Eqn. (9) which reduces to a 20 x 20 determinantal equation. The frequency equations derived above are valid for different inner and outer materials of 6mm class and arbitrary thickness of layers.

IV. NUMERICAL RESULTS

Zeros of the frequency equations are evaluated using Muller’s method [19]. The elastic, piezoelectric, dielectric and pyroelectric constants for BaTiO3 are taken from Ref. [20]-[21]. The material constants of LEMV bonding layer are taken as the hypothetical material no.2, in Table III of Puri and Cowin [16]. The value of dimensionless number \( N \), which is void volume measure factor, defined in eq. (3.4) of Ref [16], and the value of \( N \) is found to be \( 0 \leq N \leq 0.66 \). The material constants of CFRP bonding layer are taken from [22]. The frequencies are calculated by fixing real wave numbers for the thin core of thickness 0.002m and the inner and outer shell of thickness 0.03m. The complex frequencies for the axisymmetric waves in the first and second modes are given in Tables (1) and (2). The imaginary parts of the frequencies of the axisymmetric vibration of pyrocomposite LEMV cylinder are compared with pyrocomposite CFRP and pyroelectric cylinders. Due to the thermal effect of the pyroelectric shells when combined with porous nature of the interfacial layers LEMV/CFRP shows a poor variation in the attenuation of the complex frequencies when compared to Piezocomposite hollow cylinder [7]. The dispersion curves of the Pyrocomposite hollow cylinder in the first and second axial modes are plotted in figs. (2) and (3) respectively. In both the figs (2) and (3), the bold, dotted, continuous and discontinuous lines indicates the Pyrocomposite with interfacial layers LEMV with \( N=0 \), \( N=0.33 \), CFRP and a single layered pyroelectric cylinder respectively. The limitations of Higher-order Mindlin Plate Theory are discussed by Ji Wang [23].

### Table I Dimensionless Complex Frequencies for Different Values of Real Wave Numbers in the First Axial Mode

<table>
<thead>
<tr>
<th>Wave number (( \epsilon ))</th>
<th>Pyrocomposites ( \epsilon )</th>
<th>LEMV ( \epsilon = 0 )</th>
<th>LEMV ( \epsilon = 0.33 )</th>
<th>CFRP ( \epsilon )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>0.1999E+01</td>
<td>0.1999E+01</td>
<td>0.2000E+01</td>
<td>1.9935E+03</td>
</tr>
<tr>
<td>0.12</td>
<td>0.1999E+00</td>
<td>0.1999E+00</td>
<td>0.2137E+00</td>
<td>0.1426E+04</td>
</tr>
<tr>
<td>0.6</td>
<td>0.6000E+00</td>
<td>0.6000E+00</td>
<td>0.6000E+00</td>
<td>0.6000E+00</td>
</tr>
<tr>
<td>1.2</td>
<td>0.1200E+01</td>
<td>0.1200E+01</td>
<td>0.1200E+01</td>
<td>0.1200E+01</td>
</tr>
<tr>
<td>1.8</td>
<td>0.1800E+01</td>
<td>0.1800E+01</td>
<td>0.1800E+01</td>
<td>0.1800E+01</td>
</tr>
<tr>
<td>2.4</td>
<td>0.2400E+01</td>
<td>0.2400E+01</td>
<td>0.2400E+01</td>
<td>0.2400E+01</td>
</tr>
<tr>
<td>3.0</td>
<td>0.3000E+01</td>
<td>0.3000E+01</td>
<td>0.3000E+01</td>
<td>0.3000E+01</td>
</tr>
</tbody>
</table>

Fig. 2 Comparison of dispersion curves of composite hollow cylinder BaTiO3 / CFRP / BaTiO3 (Thin line), hollow cylinder BaTiO3 / LEMV (\( N=0 \)) / BaTiO3 (bold line), hollow cylinder BaTiO3 / LEMV (\( N=0.33 \)) / BaTiO3 (dotted line) and Pyroelectric cylinder (discontinuous line) in the first axial Mode.
TABLE II  Dimensionless Complex Frequencies for different values of Real Wave Numbers in the Second Axial Mode

<table>
<thead>
<tr>
<th>Wave no. (n)</th>
<th>Pyro. Material</th>
<th>Composite with core</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LEMV (N=0)</td>
<td>LEMV (N=0.33)</td>
</tr>
<tr>
<td>0.01</td>
<td>0.1052E+00 +i</td>
<td>0.3040E-01 +i</td>
</tr>
<tr>
<td></td>
<td>0.2325E-01</td>
<td>0.2269E-16</td>
</tr>
<tr>
<td>0.2</td>
<td>0.2000E+00 +i</td>
<td>0.2000E+00 +i</td>
</tr>
<tr>
<td></td>
<td>0.0030E+00</td>
<td>0.2693E-30</td>
</tr>
<tr>
<td>0.6</td>
<td>0.6000E+00 +i</td>
<td>0.6000E+00 +i</td>
</tr>
<tr>
<td></td>
<td>0.4693E-31</td>
<td>0.9198E-19</td>
</tr>
<tr>
<td>1.2</td>
<td>0.1200E+01 +i</td>
<td>0.1200E+01 +i</td>
</tr>
<tr>
<td></td>
<td>0.1423E-29</td>
<td>0.1423E-29</td>
</tr>
<tr>
<td>1.8</td>
<td>0.1800E+01 +i</td>
<td>0.1800E+01 +i</td>
</tr>
<tr>
<td></td>
<td>0.7103E-23</td>
<td>0.6346E-25</td>
</tr>
<tr>
<td>2.4</td>
<td>0.2400E+01 +i</td>
<td>0.2400E+01 +i</td>
</tr>
<tr>
<td></td>
<td>0.1119E-29</td>
<td>0.9378E-24</td>
</tr>
<tr>
<td>3.0</td>
<td>0.3000E+01 +i</td>
<td>0.3000E+01 +i</td>
</tr>
<tr>
<td></td>
<td>0.2098E-22</td>
<td>0.2068E-22</td>
</tr>
</tbody>
</table>

Fig. 3 Comparison of dispersion curves of composite hollow cylinder BaTiO3 / CFRP / BaTiO3 (Thin line), hollow cylinder BaTiO3 / LEMV (N=0) / BaTiO3 (bold line), hollow cylinder BaTiO3 / LEMV (N=0.33) / BaTiO3 (dotted line) and Pyroelectric cylinder (discontinuous line) in the second axial Mode

V. CONCLUSION

The frequency equation for free axisymmetric vibration of pyrocomposite hollow cylinder with LEMV as core material is derived. Dispersion curves in the first and second axial modes of the pyrocomposite hollow cylinders with a hypothetical LEMV core and an existing CFRP core are compared with a single layered pyroelectric cylinder. The damping observed is not significant due to the thermal effect of the pyroelectric layers and the presence of voids in the interfacial LEMV/CFRP layers. However an increase in damping often results in corresponding decrease in mechanical property. The present model with CFRP core may be modified suitably to have a similar practical application discussed in [24]-[25].

REFERENCES


