Effects of Electric Potential on Thermo-Mechanical Behavior of Functionally Graded Piezoelectric Hollow Cylinder under Non-Axisymmetric Loads

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Abstract—The analytical solution of functionally graded piezoelectric hollow cylinder which is under radial electric potential and non-axisymmetric thermo-mechanical loads, are presented in this paper. Using complex Fourier series and estimation of power law for variations of material characterizations through the thickness, the electro thermo mechanical behavior of the FGPM cylinder is obtained. The stress and displacement distributions and the effect of electric potential field on the cylinder behavior are also presented and some applicable results are offered at the end of the paper.

Keywords—Analytical, FGM, Fourier series, Non-axisymmetric, Piezoelectric, Thermo-elasticity

I. INTRODUCTION

FUNCTIONALLY graded piezoelectric materials (FGPM) are a type of piezoelectric materials that combined of two materials which continuous transition between one material to another is in a specific gradient. The primary goal in designing such materials is to take advantage of the desirable properties. Piezoelectric materials due to their direct and inverse effects have affluence applications as sensors and actuators in many industries like aircraft and aerospace [1]. Continuous variations of material parameters are usually assumed to be in power law or exponential functions in radial direction [2]. There are many researches in symmetric conditions of FG problems but not very in asymmetric loadings. In most of them, the stress and displacement distributions and the effect of electric potential field on the cylinder behavior are also presented and some applicable results are presented at the end of paper.

II. ANALYSIS

A. Derivations

Consider a thick walled functionally graded piezoelectric cylinder with "a" and "b" as inner and outer radius, respectively. All Material properties except Poisson's ratio (\nu) which is assumed to be constant are approximated to obey the same power law through the thickness \left(X = X_0 r^p \right). These parameters are the Young's modulus (E) and the coefficients of thermal expansion (\alpha), thermal conduction (K), pyroelectric (P), dielectric (\eta), and piezoelectric (e).

To reach governing equations (Navier and Maxwell equations), it's needed at first to write equations of equilibrium and the charge equation of electrostatic (Maxwell equation). In the absence of body forces, these equations in the cylindrical coordinates are [8]:

\[
\frac{\partial \sigma_r}{\partial r} + \frac{1}{r} \frac{\partial \sigma_\theta}{\partial \theta} = 0 \\
\frac{\partial \sigma_\theta}{\partial r} + \frac{1}{r} \frac{\partial \sigma_\phi}{\partial \phi} + \frac{\sigma_r - \sigma_\phi}{r} = 0 \\
\frac{\partial D_r}{\partial r} + \frac{1}{r} \frac{\partial D_\theta}{\partial \theta} = 0
\]

(1)

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Strain-displacement and constitutive equations are also expressed as [6]

\[
\begin{align*}
\varepsilon_r &= \frac{\partial U}{\partial r} \\
\varepsilon_\theta &= \frac{U}{r} + \frac{1}{r} \frac{\partial V}{\partial \theta} \\
\varepsilon_\phi &= \frac{1}{2} \left( \frac{\partial U}{\partial r} + \frac{\partial V}{\partial \theta} \right) - \frac{V}{r}
\end{align*}
\]

(2)

\[
\begin{align*}
\sigma_r &= (\lambda + 2\mu)\varepsilon_r + \lambda\varepsilon_\theta - (3\lambda + 2\mu)\alpha T + e_r \frac{\partial \phi}{\partial r} \\
\sigma_\theta &= (\lambda + 2\mu)\varepsilon_\theta + \lambda\varepsilon_r - (3\lambda + 2\mu)\alpha T + e_\theta \frac{\partial \phi}{\partial \theta} \\
\sigma_\phi &= 2\mu e_\phi
\end{align*}
\]

(3)

Where \( U \) and \( V \) are the displacement components in radial and circumferential directions, \( \phi \) is the electric potential and \( T \) is thermal distribution in the cylinder. \( \lambda \) and \( \mu \) are Lame' coefficients and electrical displacements \( D_r \) and \( D_\theta \) are also represented as [9]

\[
\begin{align*}
D_r &= e_r e_r + e_\theta e_\theta - \eta \frac{\partial \phi}{\partial r} + p_r T \\
D_\theta &= 2e_\theta e_\theta + p_\theta T
\end{align*}
\]

(4)

Substitution (2)-(4) into (1) gives the final equations in terms of displacements and electrical potential components. All of coefficients in these three partial differential equations are described in the Appendix.

\[
\begin{align*}
\frac{\partial^2 U}{\partial r^2} + m_1 \frac{\partial U}{\partial r} + m_2 \frac{1}{r} \frac{\partial U}{\partial \theta} + m_3 \frac{1}{r} \frac{\partial V}{\partial \theta} + m_4 \frac{1}{r} \frac{\partial \phi}{\partial r} + m_5 \frac{\partial \phi}{\partial \theta} + m_6 \frac{1}{r} \frac{\partial T}{\partial r} + m_7 \frac{1}{r} \frac{\partial T}{\partial \theta} \\
+ m_8 \frac{1}{r^2} \frac{\partial^2 V}{\partial \theta^2} + m_9 \frac{1}{r} \frac{\partial V}{\partial \theta} + m_{10} \frac{\partial V}{\partial \theta} + m_{11} \frac{1}{r} \frac{\partial \phi}{\partial \theta} + m_{12} \frac{1}{r} \frac{\partial \phi}{\partial \theta} + m_{13} \frac{\partial \phi}{\partial \theta} + m_{14} \frac{\partial \phi}{\partial \theta} + m_{15} \frac{\partial \phi}{\partial \theta} + m_{16} \frac{\partial \phi}{\partial \theta} + m_{17} \frac{\partial \phi}{\partial \theta} + m_{18} \frac{\partial \phi}{\partial \theta} \frac{\partial \phi}{\partial \theta}
\end{align*}
\]

(5-1)

\[
\begin{align*}
\frac{\partial^2 V}{\partial r^2} + m_1 \frac{\partial V}{\partial r} + m_2 \frac{1}{r} \frac{\partial V}{\partial \theta} + m_3 \frac{1}{r} \frac{\partial U}{\partial \theta} + m_4 \frac{1}{r} \frac{\partial U}{\partial \theta} + m_5 \frac{1}{r} \frac{\partial \phi}{\partial r} + m_6 \frac{\partial \phi}{\partial \theta} + m_7 \frac{1}{r} \frac{\partial T}{\partial r} + m_8 \frac{1}{r} \frac{\partial T}{\partial \theta} \\
+ m_9 \frac{1}{r^2} \frac{\partial^2 U}{\partial \theta^2} + m_{10} \frac{1}{r} \frac{\partial U}{\partial \theta} + m_{11} \frac{1}{r} \frac{\partial U}{\partial \theta} + m_{12} \frac{1}{r} \frac{\partial \phi}{\partial \theta} + m_{13} \frac{1}{r} \frac{\partial \phi}{\partial \theta} + m_{14} \frac{1}{r} \frac{\partial \phi}{\partial \theta} + m_{15} \frac{1}{r} \frac{\partial \phi}{\partial \theta} + m_{16} \frac{1}{r} \frac{\partial \phi}{\partial \theta} + m_{17} \frac{1}{r} \frac{\partial \phi}{\partial \theta} + m_{18} \frac{1}{r} \frac{\partial \phi}{\partial \theta} \frac{\partial \phi}{\partial \theta}
\end{align*}
\]

(5-2)

\[
\begin{align*}
\frac{\partial^2 \phi}{\partial r^2} + m_1 \frac{\partial \phi}{\partial r} + m_2 \frac{1}{r} \frac{\partial \phi}{\partial \theta} + m_3 \frac{1}{r} \frac{\partial U}{\partial \theta} + m_4 \frac{1}{r} \frac{\partial U}{\partial \theta} + m_5 \frac{1}{r} \frac{\partial \phi}{\partial r} + m_6 \frac{\partial \phi}{\partial \theta} + m_7 \frac{1}{r} \frac{\partial T}{\partial r} + m_8 \frac{1}{r} \frac{\partial T}{\partial \theta} \\
+ m_9 \frac{1}{r^2} \frac{\partial^2 V}{\partial \theta^2} + m_{10} \frac{1}{r} \frac{\partial V}{\partial \theta} + m_{11} \frac{1}{r} \frac{\partial V}{\partial \theta} + m_{12} \frac{1}{r} \frac{\partial \phi}{\partial \theta} + m_{13} \frac{1}{r} \frac{\partial \phi}{\partial \theta} + m_{14} \frac{1}{r} \frac{\partial \phi}{\partial \theta} + m_{15} \frac{1}{r} \frac{\partial \phi}{\partial \theta} + m_{16} \frac{1}{r} \frac{\partial \phi}{\partial \theta} + m_{17} \frac{1}{r} \frac{\partial \phi}{\partial \theta} + m_{18} \frac{1}{r} \frac{\partial \phi}{\partial \theta} \frac{\partial \phi}{\partial \theta}
\end{align*}
\]

(5-3)

To solve these equations, \( U, V \) and \( \phi \) are presumed to be in complex Fourier series form as below [6].

\[
U(r,\theta) = \sum_{n=0}^{\infty} U_n(r) e^{in\theta}
\]

\[
V(r,\theta) = \sum_{n=0}^{\infty} V_n(r) e^{in\theta}
\]

(6)

\[
\phi(r,\theta) = \sum_{n=0}^{\infty} \phi_n(r) e^{in\theta} = \phi_r(r)
\]

Where \( U_n(r) \) and \( V_n(r) \) are the coefficients of the Fourier series. Electrical field, Due to symmetry, must not be dependent to circumferential coordinate. Therefore the third equation of (6) is valid only for \( n=0 \) and the third equation of (5) will be excluded from the system of equations (5) for \( n\neq0 \).

The steady state heat conduction problem is already solved by Jabbari et al. [6] and is in the form of complex Fourier series too.

\[
T(r,\theta) = \sum_{n=0}^{\infty} T_n(r) e^{in\theta}
\]

\[
T_n(r) = D_r e^{\gamma r \theta} + D_\theta e^{\gamma \theta r}
\]

(7)

\[
\gamma_{r,\theta} = \frac{-\beta}{2} \pm \sqrt{\frac{\beta^2}{4} + \mu_i}
\]

Replacement of (6) and (7) into Navier Equations (5) yield the system of equations which must be solved in homogenous and particular solution considering the boundary conditions. It is obvious that to get the complete answers, the solution for \( n=0 \) must be also done.

B. Boundary Conditions

To have non-axisymmetric loadings, the hollow cylinder is supposed to be under harmonic internal pressure and temperature as \( \sigma_r(a,\theta) = 40\cos^2 \theta \) and \( T(a,\theta) = 40\cos^2 \theta \) respectively. There is no shear force in inner surface and the outer surface of cylinder is traction free and is constrained to have no radial and circumferential displacements. The electric potential in both inner and outer surfaces are also zero and the cylinder in its outside surface undergoes constant zero temperature.

III. RESULTS AND DISCUSSION

Fig.1 and 2 represent the radial and circumferential displacement in the thick walled cylinder. Both of these quantities have zero value at outer surface of cylinder due of imposed boundary conditions. Whereas a fluctuation behavior is clear in each parameter at inside surface. As depicted in Fig.3 unlike radial displacement, the circumferential distribution has less variation and is almost constant.
As can be seen in Fig. 4, the radial stress has a harmonic behavior which is in correspondence with the mechanical boundary conditions and is nearly uniform in each angular position (θ) along the radial direction. However, the circumferential distribution shows different behavior and its variations along the radial direction cannot be considered uniform (Fig. 5). It must be remembered that unlike the radial stress, there are not any imposed conditions for circumferential stress in both sides. Shear stress nearly has a behavior like circumferential distribution of stress, but as showed by Fig. 6 its maximum value is about 17.5 MPa in outside surface compared with 15.5 MPa of circumferential one.

Electric potential field causes a part of radial and circumferential displacement due of piezoelectricity nature of the material. Fig. 7 represents this part of total displacement in radial direction.
IV. CONCLUSION

An analytical solution using complex Fourier series is used to obtain electro thermo mechanical behavior of a functionally graded piezoelectric hollow cylinder which is under non-axisymmetric loads. Boundary conditions are assumed to be in harmonic form and the material parameters are considered to vary through the thickness based on the power law functions. Piezoelectricity nature of the material when is excited by electric potential field, increases the displacement components of cylinder. Therefore,Knowing the displacement and stress distributions in such parts, make one capable to apply these materials better in different industries as sensors and actuators. At the end, it should be noted that this solution method does not have any mathematical limitations to exert different boundary conditions.

APPENDIX

\[ m_i = \beta + 1, m_2 = \beta \nu - 1, m_3 = \frac{2\alpha(\beta + 1) - 1}{2(1 - \nu)}, m_4 = \frac{1 - 2\nu}{2(1 - 2\nu)(1 - \nu)} \]

\[ m_5 = \frac{1 - 2\nu}{2(1 - \nu)}, m_6 = \frac{\varepsilon_{\text{ext}}(\beta + 1) - \varepsilon_{\text{ext}}(1 + \nu)(1 - 2\nu)}{(1 - \nu)\varepsilon_0}, m_7 = \frac{2\beta\alpha(1 + \nu)}{(1 - \nu)}, m_8 = \frac{\alpha(1 + \nu)}{(1 - \nu)}, m_{10} = \beta + 1 \]

\[ m_{11} = \frac{2(1 - \nu)(1 + \nu)}{(1 - 2\nu)}, m_{12} = \frac{2\alpha(1 + \nu)}{(1 - 2\nu)}, m_{13} = \frac{1}{(1 - \nu)}, m_{14} = \frac{2(1 - \nu)}{(1 - 2\nu)} \]

\[ m_{15} = \frac{2\varepsilon_{\text{ext}}(1 + \nu)}{E_0}, m_{16} = \frac{2\alpha(1 + \nu)}{(1 - 2\nu)}, m_{17} = \beta + 1, m_{18} = \frac{-\varepsilon_{\text{ext}}}{\eta_0} \]

\[ m_{19} = \frac{-\varepsilon_{\text{ext}}}{\eta_0}, m_{20} = \frac{-\varepsilon_{\text{ext}}(1 + \beta) - \varepsilon_{\text{ext}}}{\eta_0}, m_{21} = \frac{-\varepsilon_{\text{ext}}(1 + \beta) - \varepsilon_{\text{ext}}}{\eta_0}, m_{22} = \frac{-\varepsilon_{\text{ext}} - \varepsilon_{\text{ext}}}{\eta_0} \]

\[ m_{23} = \frac{-\varepsilon_{\text{ext}}(1 + \beta) - \varepsilon_{\text{ext}}}{\eta_0}, m_{24} = \frac{\rho\varepsilon_{\text{ext}}(1 + 2\beta)}{E_0}, m_{25} = \frac{\rho\varepsilon_{\text{ext}}}{\eta_0}, m_{26} = \frac{\rho\varepsilon_{\text{ext}}}{\eta_0} \]

REFERENCES


