International Journal of Scientific Research and Management Studies (IJSRMS)
ISSN: 2349-3771 **Volume 1 Issue 6, pg: 210-217**

ELASTO DYNAMIC RESPONSE OF A HOMOGENEOUS ISOTROPIC PIEZO-THERMO-ELASTIC PLATE

K. Kadambavanam[1], P. Ponnusamy[2], and L. Anitha[3]
[1]Department of Mathematics, Sri Vasavi College, Erode, India
[2]Department of Mathematics, Government Arts College, Coimbatore, India
[3]Department of Mathematics, Nandha Arts & Science College, Erode, India

ABSTRACT

The vibration of a homogeneous isotropic Piezo-thermo-elastic plate subjected to charge and stress-free, thermally insulated or isothermal boundary conditions has been investigated in the context of theories of thermo elasticity. Two displacement potential functions are introduced to uncouple the equations of motion. The frequency equations that include the interaction between the plate and foundation are obtained by the traction free boundary conditions using the Bessel function solutions. The numerical calculations are carried out for the material PZT-2. The dispersion curves, amplitudes of dilatation, temperature change and electric potential wave modes are presented graphically.

KEY WORDS: *Elasto-dynamic response, Piezo-thermo-elastic, Bessel functions.*

I. INTRODUCTION

Mindlin [6] first proposed a thermo-piezo-electricity theory. He also derived the governing equations of a thermo-piezo-electric plate [7]. Nowacki [8]-[10] has explored the physical law for the thermo-piezoelectric materials. Sharma and Pal[15] have proposed the propagation of waves in a transversely isotropic piezo-thermo-elastic plate by Rayleigh-Lamb method. Chandrasekharaiah [1]-[2] has generalized Mindlin's theory of thermo-piezo-electricity to account for the finite speed of propagation of thermal disturbances. Chadwick[3]-[4] have discussed the wave propagation in heat conducting materials. Thermo-elastic attenuation of surface acoustic waves was discussed by Mayer[5]. Pal [13] and Paul [14]
have studied the propagation of waves in plates, that are made of thermo-piezo-electric and pyro-electric materials. Ponnusamy [11] have studied the stress wave propagation in electro-magneto-elastic plate of arbitrary cross-sections. Wave propagation in a generalized thermo-elastic plate embedded in an elastic medium was discussed by Ponnusamy and Selvamani[12]. The piezo-thermo-elastic material response entails an iteration of three major fields, namely, mechanical, thermal and electric in the macro-physical world. One of the applications of the piezo-thermo-elastic material is to detect the responses of a structure by measuring the electric charge, sensing or to reduce excessive responses by applying additional electric forces or thermal forces, actuating.
In the present paper, an attempt has been made to investigate the propagation of waves in piezo-thermo-elastic, isotropic plate that is subjected to stress- free and charge-free, thermally insulated or isothermal boundary conditions. The dispersion curves have been obtained in the case, for symmetric mode of wave propagation in the plate. The dilatation, electric potential and temperature change are also computed. The analytical results have been verified and computed numerically for piezo-thermo-elastic (PZT-2) material plate, which are found to be in close agreement with the analytical results.

II. FORMULATION OF THE PROBLEM

Consider a finite homogeneous, isotropic, piezo-thermo-elastic plate of thickness two dimensional initially at uniform temperature T_0 and electric potential φ. The system displacement and stresses are defined in the polar co-ordinates of (r,θ) for an arbitrary point inside the plate. Let u be the displacement in the radial direction of r whereas v be the displacement in the tangential direction of θ. The in-plane vibration and displacement of the plate is obtained by assuming that there is no vibration and a displacement along the z axis (normal to the plate z=0) in the cylindrical co-ordinate system (r, θ, z).

The basic governing equations for homogeneous isotropic piezo-thermo-elasticity, in the absence of change density, heat sources and body forces, are given by [15]

$$\frac{\partial}{\partial r}\sigma_{rr} + r^{-1}\frac{\partial}{\partial \theta}\sigma_{r\theta} + r^{-1}(\sigma_{rr} - \sigma_{\theta\theta}) = \rho\frac{\partial^2 u}{\partial t^2}$$

$$\frac{\partial}{\partial r}\sigma_{r\theta} + r^{-1}\frac{\partial}{\partial \theta}\sigma_{\theta\theta} + 2r^{-1}\sigma_{r\theta} = \rho\frac{\partial^2 v}{\partial t^2} \qquad (1)$$

$$(e_{15} + e_{31})\frac{\partial}{\partial r}\sigma_{r\theta} - \in_{11}\frac{\partial}{\partial \theta}\phi_{11} + P_3\frac{\partial T}{\partial r} = 0$$

$$k\left(\frac{\partial^2 T}{\partial t^2} + r^{-1}\frac{\partial T}{\partial r} + r^{-2}\frac{\partial^2 T}{\partial \theta^2}\right) - \rho C_\upsilon\frac{\partial T}{\partial t} = \beta T_o\frac{\partial}{\partial t}(e_{rr} + e_{\theta\theta}) - P_3\frac{\partial \phi}{\partial t}$$

where ρ is the mass density, C_υ is the specific heat capacity $K = \dfrac{k}{\rho C_\upsilon}$ is the diffusivity, K is the thermal conductivity, T_o is the reference temperature, e_{15} and e_{31} are the piezo-electric constants, $\in_{11}$ is the electric permittivity, P_3 is pyro-electric constants and ϕ_{11} is the electric potential.

The strain-stress displacement relations for the plate are,

$$\sigma_{rr} = \lambda(e_{rr} + e_{\theta\theta}) + 2\mu e_{rr} - \beta T + \in_P$$

$$\sigma_{\theta\theta} = \lambda(e_{rr} + e_{\theta\theta}) + 2\mu e_{\theta\theta} - \beta T + \in_P$$

$$\sigma_{r\theta} = 2\mu e_{r\theta} \qquad (2)$$

The strain displacements equations are,

$$e_{rr} = \frac{\partial u}{\partial r}$$

$$e_{\theta\theta} = r^{-1}u + r^{-1}\frac{\partial v}{\partial \theta}$$

$$e_{r\theta} = \frac{\partial v}{\partial r} - r^{-1}v + r^{-1}\frac{\partial u}{\partial \theta} \qquad (3)$$

where σ_{rr} and $\sigma_{\theta\theta}$ are the normal stress components and $\sigma_{r\theta}$ is the shear-stress component. e_{rr} and $e_{\theta\theta}$ are the normal strain components, and $e_{r\theta}$ is the shear strain component.

Substituting the equation (3) in (2) is given by,

$$\sigma_{rr} = \lambda\left(\frac{\partial u}{\partial r} + r^{-1}u + r^{-1}\frac{\partial v}{\partial \theta}\right) + 2\mu\frac{\partial u}{\partial r} - \beta T + \in_P$$

$$\sigma_{\theta\theta} = \lambda\left(\frac{\partial u}{\partial r} + r^{-1}u + r^{-1}\frac{\partial v}{\partial \theta}\right) + 2\mu\left(r^{-1}u + r^{-1}\frac{\partial v}{\partial r}\right) - \beta T + \in_P$$

$$\sigma_{r\theta} = 2\mu\left(\frac{\partial v}{\partial r} - r^{-1}v + r^{-1}\frac{\partial u}{\partial \theta}\right) \qquad (4)$$

By substituting the system of equations (4) in (1) and simplifying, it is obtained as,

$$(\lambda+2\mu)\left(\frac{\partial^2 u}{\partial r^2}+r^{-1}\frac{\partial u}{\partial r}-r^{-2}u\right)+\mu r^{-2}\frac{\partial^2 u}{\partial \theta^2}+$$

$$r^{-1}(\lambda+\mu)\frac{\partial^2 v}{\partial r\partial\theta}+\partial^{-2}(\lambda+3\mu)\frac{\partial v}{\partial\theta}-\beta\frac{\partial T}{\partial r}+\in_P=\rho\frac{\partial^2 u}{\partial t^2} \quad (5)$$

$$\mu\left(\frac{\partial^2 v}{\partial r^2}+r^{-1}\frac{\partial v}{\partial r}-r^{-2}u\right)+r^{-2}(\lambda+2\mu)\frac{\partial^2 v}{\partial\theta^2}+r^{-2}(\lambda+2\mu)\frac{\partial u}{\partial\theta}+$$

$$r^{-1}(\lambda+\mu)\frac{\partial^2 u}{\partial r\partial\theta}-\beta\frac{\partial T}{\partial\theta}+\in_P=\rho\frac{\partial^2 v}{\partial t^2} \quad (6)$$

$$(e_{15}+e_{31})\begin{bmatrix}2\mu\frac{\partial^2 v}{\partial r^2}-2\mu r^{-1}\frac{\partial v}{\partial r}+2\mu r^{-2}v\frac{\partial r}{\partial\theta}+\\ 2\mu r^{-1}\frac{\partial^2 u}{\partial r\theta\theta}-2\mu r^{-2}\frac{\partial u}{\partial r}\end{bmatrix}-$$

$$\in_{11}\frac{\partial\phi_{11}}{\partial\theta}+P_3\frac{\partial T}{\partial r}=0 \quad (7)$$

$$K\left(\frac{\partial^2 T}{\partial t^2}+r^{-1}\frac{\partial T}{\partial r}-r^{-2}\frac{\partial^2 T}{\partial\theta^2}\right)-\rho C_r\frac{\partial T}{\partial t}=$$

$$\beta T_o\left(\frac{\partial u}{\partial r}+r^{-1}u+r^{-1}\frac{\partial v}{\partial\theta}\right) \quad (8)$$

To complete the equations (5), (6), (7) & (8), the mechanical displacement u, v along the radial and circumferential directions given by Sharma[6] are adopted as follows

$$u=r^{-1}\frac{\partial\psi}{\partial\theta}+\frac{\partial\phi}{\partial r}$$

$$v=-\frac{\partial\psi}{\partial r}+r^{-1}\frac{\partial\phi}{\partial\theta} \quad (9) \quad (9)$$

By substituting the equation (9) in (5), (6), (7) & (8) are given by

$$\left(\lambda+2\mu\right)\left(\frac{\partial^2\phi}{\partial r^2}+r^{-1}\frac{\partial\phi}{\partial r}+r^{-2}\frac{\partial^2\phi}{\partial\theta^2}\right)- \quad \beta\frac{\partial T}{\partial r}+\in_P=\rho\frac{\partial^2 u}{\partial T^2} \quad (10)$$

$$\Omega^2=\frac{\rho\omega^2 a^2}{\mu};\quad \bar{\lambda}=\frac{\lambda}{\mu};\quad \bar{d}=\frac{\rho C_\upsilon}{\beta T_0};\quad \varepsilon_P=\frac{\omega\phi_p}{\beta T_0}$$

$$\left(\lambda+2\mu\right)\left(\nabla^2+\frac{\rho}{\mu}\omega^2\right)\psi=0 \quad (11)$$

$$\left(e_{15}+e_{31}\right)\mu\nabla^2\psi-\varepsilon_{11}\frac{\partial\phi_{11}}{\partial\theta}+P_3\frac{\partial T}{\partial r}=0 \quad (12)$$

$$\left(K\nabla^2-\rho C_\upsilon\right)T+\beta T_0\nabla^2\phi=0 \quad (13)$$

The equations (10), (11), (12) and (13) are co- partial differential equation with two displacements and heat conduct components. To uncouple these equations assume the vibration and displacements along the axial direction z to be zero. Hence the solutions of the equations (10) to (13) can be obtained as,

$$\phi\left(r,\theta,t\right)=\bar{\phi}(r)e^{i(m\theta-\omega t)}$$

$$\psi\left(r,\theta,t\right)=\bar{\psi}(r)e^{i(m\theta-\omega t)} \quad (14)$$

$$T\left(r,\theta,t\right)=\left(\frac{\lambda+2\mu}{\beta\alpha^2}\right)\bar{T}(r)e^{i(m\theta-\omega t)}$$

where $i=\sqrt{-1}$, ω is the angular frequency, m is the angular momentum , $\phi(r,\theta),\psi(r,\theta)$ and $T(r,\theta)$ are the displacement potentials.

Applying the equations (14) in the equations (10), (11), (12) and (13), and introducing the dimensionless quantities such as

$$x=\frac{r}{a};\quad C_1=1;\quad C_2=\frac{\mu}{\rho},\quad e_1=e_{15}+e_{31};$$

The following potential differential equations with constant coefficients are of the form,

$$\left(\left(2+\bar{\lambda}\right)\nabla_1^{\,2}+\Omega^2\right)\phi-\left(2+\bar{\lambda}\right)T=0$$

$$\left(K_1\nabla_1^{\,2}-i\omega\bar{d}\,\eta_0\right)T+\beta T_0(i\omega)\nabla_1^{\,2}=0 \qquad (15)$$

$$\left(\nabla_1^{\,2}+\Omega^2\right)\psi=0$$

Here, $\nabla_1^{\,2}=\frac{\partial^2}{\partial r^2}+r^{-1}\frac{\partial}{\partial r}-mr^{-2}$ and

$\eta_0=1+i\omega$

Here ε is the thermo-elastic coupling constant, ω^* is the characteristic frequency of the medium, ε_p is piezo-thermo-elastic coupling constant.

Rewriting the equation (15) yields the following fourth order differential equation $\left(A\nabla_2^{\,4}+B\nabla_2^{\,2}+C\right)\phi=0$

Where,

$$A=(2+\bar{\lambda})K_1$$

$$B=K_1\Omega^2-i\omega(2+\bar{\lambda})\bar{d}\,\eta_0+i\omega T_0(2+\bar{\lambda})\beta$$

$$C=-i\omega\Omega^2\bar{d}\,\eta_0$$

By solving the partial differential equation (13), the solution is obtained as

$$\bar{\phi}=\sum_{i=1}^{2}[A_i J_n(\alpha_i ax)+Y_n B_i(\alpha_i ax)]\cos n\theta$$

$$\bar{\psi}=[A_3 J_n(\alpha_3 ax)+Y_n B_3(\alpha_3 ax)]\sin n\theta,$$

$$\bar{T}=\sum_{i=1}^{2}d_i[A_i J_n(\alpha_i ax)+Y_n B_i(\alpha_i ax)]\cos n\theta$$

where,

$$d_i=K_i(\alpha_i ax)^4+(2+\bar{\lambda})\beta T_0 i\omega(\alpha_i ax)^2-(2+\bar{\lambda})i\omega\bar{d}$$

$$\bar{\psi}=\begin{cases}A_2 J_n(\alpha_2 ax)+Y_n B_2(\alpha_2 ax),\alpha_2 ax>0,\\ A_2 I_n(\alpha_2 ax)+Y_n B_2(\alpha_2 ax),\alpha_2 ax<0\end{cases}$$

where J_n and Y_n are Bessel functions of the first and second kinds respectively, while I_n and K_n are modified Bessel functions of the first and second kinds respectively and $(\alpha_2 ax)^2=\Omega^2$

III. BOUNDARY CONDITIONS

In this problem, the vibration of the plate is considered. Since the boundary is irregular in shape, it is difficult to satisfy the boundary conditions of the plate directly. For the plate, the normal stress σ_{rr} and $\sigma_{r\theta}$ are equal to zero.

i.e) $\sigma_{rr}=0$; $\sigma_{r\theta}=0$

The non-dimensional insulated (or) isothermal thermal boundary condition is given by

$\frac{\partial T}{\partial r}$ + hT =0

where h is the surface heat transfer coefficient.

Here h approaches to zero corresponds to thermally insulated surface and h approaches to infinite refers to isothermal one.

Invoking the above boundary conditions in the stress equation of motion and strain displacement relations, we get the frequency equations as follows.

$\left|E_{jk}\right| = 0$ j, k = 1,2,3,4

$E_{11} = -2c_4\beta\left[\frac{k_1 I_\beta(k_1 t_1)}{t_1} - \frac{I_\beta(k_1 t_1)}{t_1^{\,2}}\right]$

$E_{12} = -2c_4\beta\left[\frac{k_1 K_\beta(k_1 t_1)}{t_1} - \frac{K_\beta(k_1 t_1)}{t_1^{\,2}}\right]$

$$E_{13} = -m_1^{\,2} I_\beta(m_1 t_1) - \frac{1-2c_4}{t_1} m_1 I_\beta(m_1 t_1) + \left[(c_3 - c_2)t_L^{\,2} a_1 + \frac{\beta_1 T_0 R\tau_1}{\lambda+\mu} b_1\right] I_\beta(m_1 t_1)$$

$$E_{15} = -m_2^{\,2} I_\beta(m_2 t_1) - \frac{1-2c_4}{t_1} m_2 I_\beta(m_2 t_1) + \left[(c_3 - c_2)t_L^{\,2} a_2 + \frac{\beta_1 T_0 R\tau_1}{\lambda+\mu} b_2\right] I_\beta(m_2 t_1)$$

$$E_{17} = -m_3^{\,2} I_\beta(m_3 t_1) - \frac{1-2c_4}{t_1} m_3 I_\beta(m_3 t_1) + \left[(c_3 - c_2)t_L^{\,2} a_3 + \frac{\beta_1 T_0 R\tau_1}{\lambda+\mu} b_3\right] I_\beta(m_3 t_1)$$

$E_{21} = \frac{\beta}{t_1} I_\beta(k_1 t_1)$

$E_{23} = I_\beta(m_1 t_1) - a_1 m_1 I_\beta(m_1 t_1)$

$E_{25} = I_\beta(m_2 t_1) - a_2 m_2 I_\beta(m_2 t_1)$

$E_{27} = I_\beta(m_3 t_1) - a_3 m_3 I_\beta(m_3 t_1)$

$$E_{31} = -k_1 I_\beta(k_1 t_1) + \frac{k_1}{t_1} I_\beta(k_1 t_1) - \frac{\beta^2}{t_1^{\,2}} I_\beta(k_1 t_1)$$

$E_{33} = -\frac{2\beta m_1}{t_1} I_\beta(m_1 t_1) + \frac{2\beta}{t_1^{\,2}} I_\beta(m_1 t_1)$

$E_{35} = -\frac{2\beta m_2}{t_1} I_\beta(m_2 t_1) + \frac{2\beta}{t_1^{\,2}} I_\beta(m_2 t_1)$

$E_{37} = -\frac{2\beta m_3}{t_1} I_\beta(m_3 t_1) + \frac{2\beta}{t_1^{\,2}} I_\beta(m_3 t_1)$

$E_{41} = 0$

$E_{43} = b_1 m_1 I_\beta(m_1 t_1)$

$E_{45} = b_2 m_2 I_\beta(m_2 t_1)$

$E_{47} = b_3 m_3 I_\beta(m_3 t_1)$

Table 1: Lowest frequency parameter $\omega^{*}= \omega a\sqrt{\rho_{max/}c_{max}}$ of the piezo-thermo-elastic plate.

Or der	*Symmetric mode*		*Anti-Symmetric mode*	
	1st	**2nd**	**1st**	**2nd**
1	2.30033	2.10902	1.97472	1.54009
2	2.80145	2.81507	2.33726	2025432
3	3.93927	3.96097	3.18631	3.21210
4	5.31985	4.38852	4.23897	3.78466
5	6.79683	5050595	5.37695	4.52726

Table 2: Lowest dimensionless frequencies Ω of a Piezo-thermo-elastic plate for two laminate models

P	***Class***	***Frequency Order***				
		1	**2**	**3**	**4**	
29	**1st**	**1.04277**	**3.36482**	**6.47999**	**9.64833**	**12.8308**
	2nd	**0.431788**	**1.83818**	**3.79365**	**6.35670**	**8.02087**
30	**1st**	**1.04277**	**3.36482**	**6.47999**	**9.64833**	**12.8308**
	2nd	**0.431785**	**1.83818**	**3.79364**	**6.35670**	**8.02088**

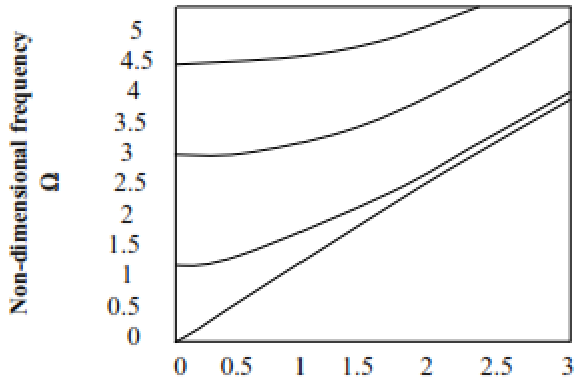

Figure.1 Aspect ratio ($\frac{a}{b}$)

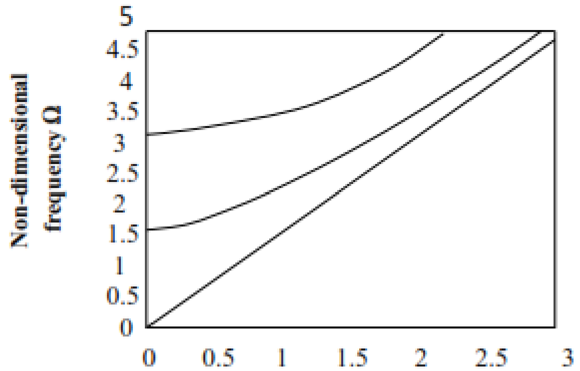

Figure.2 Aspect ratio ($\frac{a}{b}$)

In figure.1, the dispersion of frequencies with the wave number is studied for both the thermally insulated and isothermal boundaries of the piezo-thermo-elastic plate in different modes of vibration. In figure.2, it is observed that the frequency increases exponentially with increasing wave number for thermally insulated modes of vibration. But smaller dispersion exists in the frequency in the current range of wave numbers in figure.2 for the isothermal mode due to the combined effect of damping and insulation.

The solution for a doubly connected plate, when aspect ratio $\frac{a}{b}$ reduces to zero, does not coincide with the solid plate. The fundamental frequency should be little lower in the case of solid plate, because the rigidity of the plate has decreased. This behavior is observed in all the graphs of longitudinal and flexural anti-symmetric modes of vibrations. The graphs (1)-(2) reveals the fact that at first the frequency decreases and then it starts to increase with when the plate has a hole. The effect of frequencies of the inner boundary with clamped or simply supported is large compared with $\frac{a}{b}$ that of free edge boundary conditions.
The non-dimensional frequency of a ring-shaped piezo-thermo-elastic plate is obtained for various combinations of the outer and inner boundary conditions. To clarify the effect of the hole, the dispersion curves are drawn between the aspect ratio versus the frequency . The solution for a doubly connected plate when aspect ratio reduces to zero does not coincide with the solid plate. The fundamental frequency should be little lower than in the case of solid plate. Because the rigidity of the plate has decreased. This behavior is depicited in the figure (1)-(2) of longitudinal and flexural anti-symmetric modes of vibrations.
From all the figures, it can be noted that at first the frequency decreases and then it starts to increase with when the plate has a hole. The effect of frequencies of the inner boundary with clamped or simply supported is large compared with that of free edge boundary conditions.
Figures are drawn for boundary conditions for Lord Shulman (LS) theory of thermo elasticity between the non-dimensional aspect ratio versus dimensionless frequency for longitudinal modes of triangular plates respectively and are shown in figures (1) and (2). Further it is observed that the non-dimensional frequency increases with respect to its aspect ratio. It is noted that the frequency for $\frac{a}{b}$.
The frequencies increase for higher modes of vibrations, and the cross over points in the trend line indicates the transfer of heat energy among the modes of vibrations. The transfer of heat energy is higher in the lower modes of vibrations as compared to the higher modes. The same physical behavior of a plate is obtained for longitudinal modes of square which is shown in Figure 2 for Green Lindsay (GL) theory of piezo-thermo-elasticity.

IV. CONCLUSION

In this paper, the Elasto dynamic response of a homogeneous isotropic piezo-thermo-elastic plate analyzed by considering the boundary conditions using the Bessel function solutions. Numerically, the frequency equations are analyzed for the material Piezo-thermo-elastic PZT-2. The computed non-dimensional frequencies are plotted in graphs.

REFERENCES

[1]. D.S. Chandrasekharaiah, A temperature rate dependent theory of piezoelectricity, Journal of Thermal Stresses 7 (1984) 293-306.
[2]. D.S. Chandrasekharaiah, A generalized linear thermo-elasticity theory in piezoelectric media, Acta Mechanica 71 (1988) 39-49.
[3]. P.Chadwick, L.T.C. Seet, Wave propagation in transversely isotropic heat conducting elastic materials, Mathematica 17 (1970) 255-274.
[4]. P.Chadwick, Basic Properties of plane harmonic waves in pre-stressed heat conducting elastic material, Journal of Thermal Stresses 2 (1979) 193-214.
[5]. Lord, H.W. and Shulman, V. (1967), “A generalized dynamical theory of thermo- elasticity”, J. Mech. Phys.Solids, 15(5), pg.no.299-309.
[6]. A.P.Mayer, Thermo-elastic attenuation of surface acoustic waves, International Journal of Engineering Sciences 28 (1990) 1073-1082.

[7]. R.D.Mindlin, on the equations of motion of piezoelectric crystals, problem of continuum, in: N.I.Muskelishvili (Ed.), Mechanics, 70th Birthday Volume, SIAM, Philadelphia, 1961, pp. 282-290.
[8]. R.D. Mindlin, Equations of High Frequency Vibrations of Thermo-piezoelectric, Crystal Plates, Interactions in Elastic Solids, Springer, Wein, 1979.
[9]. W.Nowacki, Some general theorems of thermo-piezoelectricity, Journal of Thermal Stresses 1 (1978), 171-182.
[10]. W.Nowacki, Foundations of linear piezoelectricity, in: H.Parkus (Ed.), Electromagnetic Interactions in Elastic solids, Springer, Wein, 1979 (Chapter 1).
[11]. W.Nowacki, New problems in mechanics of continua, Mathematical Models of Phenomenological Piezoelectricity, University of Waterloo Press, Ontario, 1983, pp. 29-49.
[12]. P.Ponnusamy, Stress wave propagation in electro-magneto-elastic plate of arbitrary cross-sections, IJSER, Vol.3, (2012) 1-25.
[13]. P.Ponnusamy and R.Selvamani, Wave propagation in a generalized thermo elastic plate embedded in an elastic medium, Interaction and Multi scale Mechanics, Vol. 5, No. 1 (2012) 13-26.
[14]. A.K. Pal, Surface waves in a thermo-piezoelectric medium of monoclinic symmetry, Czechoslovak Journal of Physics 29 (1979) 1271-1281
[15]. H.S.Paul, K.Ranganatham, Free vibrations of a pyro-electric layer of hexagonal (6mm) class, Journal of the Acoustical Society of America 78 (1985) 395-397.
[16]. J.N.Sharma and Mohinder Pal, Propagation of Lamb waves in a transversely isotropic piezo-thermo-elastic plate, Journal of Sound and Vibration 270 (2004) 587-610.

AUTHORS BIOGRAPHY

K. Kadambavanam was born in Palani, Tamilnadu, India, in1956. He did his post-graduate studies at Annamalai University in 1979. He completed his M.Phil, degree in Annamalai University in 1981. He obtained his Ph.D., degree from Bharathiar University, Coimbatore. His area of research is Fuzzy Queueing Models and Fuzzy Inventory Models. His research interests include Solid mechanics, Random Polynomials and Fuzzy Clustering. He has 33 years of teaching experience in both U.G and P.G level and 18 years of research experience. He is a Chairman of Board of Studies (P.G) in Mathematics and Ex-Officio Member in Board of Studies (U.G) in Mathematics in Bharathiar University, Coimbatore. He is a member in : Panel of Resource Persons, Annamalai University, Annamalai Nagar, Doctoral Committee for Ph.D., program, Gandhigram Rural University, Gandhigram.

P.Ponnusamy was born in Tiruchy, Tamil Nadu, India. He completed his Ph.D., degree at Anna University in 2006. He has 15 years of teaching experience in both U.G and P.G level and 8 years of research experience. He is a Board of Studies member (P.G&U.G) in Mathematics in Bharathiar University, Coimbatore. He published more than 20 International journals. He attended more than 15 Conferences/Workshops/Seminars. His research areas are Mechanical vibration in cylinder, plates, shells and panels. He is the syndicate member in Madras University. He is the Question paper Setter and Examiner of the various Universities and Autonomous Colleges'.

L.Anitha was born in Erode, Tamil Nadu, India, in 1978. She did her post-graduate studies at Madurai Kamaraj University in 2000. She completed her M.Phil., degree in Bharathiar University. She is doing her Ph.D., degree in Sri Vasavi College, Erode which is affiliated to the Bharathiar University, Coimbatore. Her area of research is Vibrations in Solid Mechanics. She has 11 years of teaching experience in both U.G and P.G level and 5 years of research experience through guiding the M.Phil., Students. She is the Question paper Setter and Examiner of the various Universities and Autonomous Colleges.