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Linearly Distributed Time Harmonic Mechanical and Thermal Sources Effect at Transversely Isotropic Thermoelastic Solids with Two Temperatures and without Energy Dissipation

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Abstract

The present research is concerned with the time harmonic deformation in two dimensional homogeneous, transversely isotropic thermoelastic solids without energy dissipation and with two temperatures. Here assuming the disturbances to be harmonically time-dependent, the transformed solution is obtained in the frequency domain. The application of a time harmonic linearly distributed loads have been considered to show the utility of the solution obtained. Fourier transforms are used to solve the problem. The components of displacements, stresses and conductive temperature distribution so obtained in the physical domain are computed numerically. Effect of two temperatures and various frequencies are depicted graphically on the resulting quantities. The prepared model is useful for understanding the nature of interaction between mechanical and thermal fields since most of the structural elements of heavy industries are often subjected to mechanical and thermal stresses at an elevated temperature.

Keywords: Transversely isotropic thermoelastic, Laplace transform, Fourier transform, concentrated and distributed sources

1. INTRODUCTION

Besides the contradiction of infinite propagation speeds, the classical dynamic thermoelasticity theory offers unsatisfactory description of a solids response to a fast transient loading and at low temperatures. Such drawbacks have led many researchers to advance various generalized thermoelasticity theories and they proposed thermoelastic models with one or two relaxation times, model focused on two temperatures , models with absence of energy dissipation, a dual -phase-lag theory , even anomalous heat conduction described by fractional calculus or non local thermoelastic models.

Green and Naghdi (1992,1993) postulated a new concept in generalized thermoelasticity and proposed three models which are subsequently referred to as GN-I, II, and III models. The linearized version of model-I corresponds to classical Thermoelastic model. In model -II, the internal rate of production entropy is taken to be identically zero implying no dissipation of thermal energy . The principal feature of this theory is in contrast to classical thermoelasticity associated with Fourier's law of heat conduction, the heat flow does not involve energy dissipation. Model-III includes the previous two models as special cases and admits dissipation of energy in general. In context of Green and Naghdi model many applications have been found. Chandrasekharaiah and Srinath (2000) discussed the thermoelastic waves without energy dissipation in an unbounded body with a spherical cavity.

Youssef (2011) constructed a new theory of generalized thermoelasticity by taking into account two-temperature generalized thermoelasticity theory for a homogeneous and isotropic body without energy dissipation. Youssef (2013) also obtained variational principle of two temperature thermoelasticity without energy dissipation. Chen and Gurtin (1968), Chen et al. (1968) and (1969) have formulated a theory of heat conduction in deformable bodies which depends upon two distinct temperatures, the conductive temperature φ and the thermo dynamical temperature T. Researchers (Warren and Chen (1973), Quintanilla (2002) ,Youssef AI-Lehaibi (2007) and Youssef AI -Harby (2007), Kumar,Sharma and Lata(2016,2016), Lata, Kumar and Sharma (2016)investigated various problems on the basis of two temperature thermoelasticity.

The purpose of the present paper is to determine the expression for components of displacement, normal stress, tangential stress and conductive temperature, when the time -harmonic mechanical or thermal source is applied, by applying Integral transform techniques.

2. BASIC EQUATIONS

Following H.M. Youssef (2011) the constitutive relations and field equations are:

$$t_{ij} = C_{ijkl}e_{kl} - \beta_{ij}T \tag{1}$$

$$C_{ijkl}e_{kl,j} - \beta_{ij}T_{,j} + \rho F_i = \rho\ddot{u}_i \tag{2}$$

$$K_{ij}\varphi_{,ij} = \beta_{ij}T_0\ddot{e}_{ij} + \rho C_E\ddot{T} \tag{3}$$

where

$$T = \varphi - a_{ij}\varphi_{,ij} \quad , \quad \beta_{ij} = C_{ijkl}\alpha_{ij} \quad , e_{ij} = u_{i,j} + u_{j,i} \quad i,j = 1,2,3$$

Here
$C_{ijkl}(C_{ijkl} = C_{klij} = C_{jikl} = C_{ijlk})$ are elastic parameters, β_{ij} is the thermal tensor, T is the temperature, T_0 is the reference temperature, t_{ij} are the components of stress tensor, e_{ij} are the components of strain tensor, u_i are the displacement components, ρ is the density, C_E is the specific heat, K_{ij} is the thermal conductivity, a_{ij} are the two temperature parameters, α_{ij} is the coefficient of linear thermal expansion.

3. FORMULATION OF THE PROBLEM

We consider a homogeneous, transversely isotropic thermoelastic solid half-space with two temperatures. A rectangular Cartesian co-ordinate system (x_1, x_2, x_3) with x_3 axis pointing vertically downwards into the medium is introduced. we restrict our analysis in two dimensions subject to plane parallel to $x_1 - x_3$ plane. The displacement vector for two dimensional problems is taken as

$$\mathbf{u} = (u_1, 0, u_3) \tag{4}$$

Using Slaughter (2002), applying the transformation $x_1' = x_1\cos\theta + x_2\sin\theta$, $x_2' = -x_1\sin\theta + x_2\cos\theta$, $x_3' = x_3$, where θ is the angle of rotation in $x_1 - x_2$ plane basic governing equations (2) and (3) using (4) and in absence of body forces are given as

$$c_{11}u_{1,11} + c_{13}u_{3,31} + c_{44}(u_{1,33} + u_{3,13}) - \beta_1 \frac{\partial}{\partial x_1}\{\varphi - (a_1\varphi_{,11} + a_3\varphi_{,33})\} = \rho\ddot{u}_1 \tag{5}$$

$$(c_{13} + c_{44})u_{1,13} + c_{44}u_{3,11} + c_{33}u_{3,33} - \beta_3 \frac{\partial}{\partial x_3}\{\varphi - (a_1\varphi_{,11} + a_3\varphi_{,33})\} = \rho\ddot{u}_3 \tag{6}$$

$$k_1\varphi_{,11} + k_3\varphi_{,33} = T_0(\beta_1\ddot{e}_{11} + \beta_3\ddot{e}_{33}) + \rho C_E\{\ddot{\varphi} - (a_1\ddot{\varphi}_{,11} + a_3\ddot{\varphi}_{,33})\} \tag{7}$$

where $\beta_1 = (c_{11}+c_{12})\alpha_1 + c_{13}\alpha_3$, $\quad \beta_3 = 2c_{13}\alpha_1 + c_{33}\alpha_3$

In the above equations we use the contracting subscript notations $(1 \to 11, 2 \to 22, 3 \to 33, 5 \to 23, 4 \to 13, 6 \to 12)$ to relate c_{ijkl} to c_{mn}

To facilitate the solution , following dimensionless quantities are introduced:

$$x_1' = \frac{x_1}{L},\ x_3' = \frac{x_3}{L},\ u_1' = \frac{\rho c_1^2}{L\beta_1 T_0}u_1,\ u_3' = \frac{\rho c_1^2}{L\beta_1 T_0}u_3,\ T' = \frac{T}{T_0},\ t' = \frac{c_1}{L}t,\ t_{11}' = \frac{t_{11}}{\beta_1 T_0},$$

$$t_{33}' = \frac{t_{33}}{\beta_1 T_0},\ t_{31}' = \frac{t_{31}}{\beta_1 T_0},\ \varphi' = \frac{\varphi}{T_0},\ a_1' = \frac{a_1}{L},\ a_3' = \frac{a_3}{L} \tag{8}$$

where $c_1^2 = \frac{c_{11}}{\rho}$ and L is a constant of dimension of length.

Using the dimensionless quantities (8) in the set of equations(5)-(7) and suppressing the primes and applying Laplace and Fourier transforms defined by

$$\bar{f}(x_1, x_3, s) = \int_0^\infty f(x_1, x_3, t)e^{-st}dt \tag{9}$$

$$\hat{f}(\xi, x_3, s) = \int_{-\infty}^\infty \bar{f}(x_1, x_3, s)e^{i\xi x_1}dx_1 \tag{10}$$

The resulting equations have non trivial solutions if the determinant of the coefficient $(\hat{u}_1, \hat{u}_3, \hat{\varphi})$ vanishes , which yield to the following characteristic equation

$$\left(P\frac{d^6}{dx_3^6} + Q\frac{d^4}{dx_3^4} + R\frac{d^2}{dx_3^2} + S\right)(\hat{u}_1, \hat{u}_3, \hat{\varphi}) = 0 \tag{11}$$

Where $P = \delta_1(\delta_4\zeta_3 a_3 s^2 - \delta_4 p_3 - \zeta_2 p_5 a_3 s^2)$

$Q = (\zeta_3 a_3 s^2 - p_3)\{(-\xi^2 + s^2)\delta_4 - \delta_1(b_1\xi^2 + s^2) + \delta_2^2\xi^2\} + \delta_1\delta_4\{\xi^2 - \zeta_3 s^2 - \xi^2\zeta_3 s^2 a_1\} + \zeta_2 s^2\{a_3 p_5(\xi^2 + s^2) + \delta_1 p_5(a_1\xi^2 + 1)\} + \xi^2 s^2\{-\delta_4 a_3(p_5\zeta_1 + \zeta_2 - \zeta_1)\}$

$R = (1 + a_1\xi^2)\{-(\xi^2 + s^2)\zeta_2 p_5 s^2 + \xi^2 s^2(p_5\zeta_1\delta_2 + \zeta_2\delta_2 - \zeta_1\delta_4)\} + (\delta_1\xi^2 + s^2)\{(\xi^2 + s^2)(s^2\zeta_3 a_3 - p_3) - \delta_1(\xi^2 - \zeta_3 s^2 - \zeta_3 s^2 a_1\xi^2) - \xi^2 a_3\zeta_1 s^2\} + (\xi^2 - \zeta_3 s^2 - \zeta_3 s^2\xi^2 a_1)\{-(\xi^2 + s^2)\delta_4 + \delta_2^2\xi^2\}$

$S = (\delta_1\xi^2 + s^2)\{(\xi^2 + s^2)(\xi^2 - \zeta_3 s^2 - \zeta_3 s^2 a_1\xi^2) + \xi^2(1 + a_1\xi^2)\xi^2\zeta_1 s^2\}$

$\delta_1 = \frac{c_{44}}{c_{11}}$, $\delta_2 = \frac{c_{13}+c_{44}}{c_{11}}$, $\delta_4 = \frac{c_{33}}{c_{11}}$, $p_5 = \frac{\beta_3}{\beta_1}$, $p_3 = \frac{k_3}{k_1}$, $\zeta_1 = \frac{T_0\beta_1^2}{k_1\rho}$, $\zeta_2 = \frac{T_0\beta_3\beta_1}{k_1\rho}$, $\zeta_3 = \frac{C_E c_{11}}{k_1}$

The roots of the equation (11) are $\pm\lambda_i$ (i = 1,2,3). Making use of the radiation condition that $\hat{u}_1, \hat{u}_3, \hat{\varphi} \to 0$ as $x_3 \to \infty$ the solution of the equation (11) may be written as

$$\hat{u}_1 = A_1 e^{-\lambda_1 x_3} + A_2 e^{-\lambda_2 x_3} + A_3 e^{-\lambda_3 x_3} \tag{12}$$

$$\hat{u}_3 = d_1 A_1 e^{-\lambda_1 x_3} + d_2 A_2 e^{-\lambda_2 x_3} + d_3 A_3 e^{-\lambda_3 x_3} \tag{13}$$

$$\hat{\varphi} = l_1 A_1 e^{-\lambda_1 x_3} + l_2 A_2 e^{-\lambda_2 x_3} + l_3 A_3 e^{-\lambda_3 x_3} \tag{14}$$

where

$d_i = \frac{-\lambda_i^3 P^* - \lambda_i Q^*}{\lambda_1^4 R^* + \lambda_1^2 S^* + T^*}$ i = 1,2,3 , $l_i = \frac{\lambda_i^2 P^{**} + Q^{**}}{\lambda_1^4 R^* + \lambda_1^2 S^* + T^*}$ i = 1,2,3

where $P^* = i\xi\{(-\zeta_1 p_5 a_3 s^2 + \delta_2(\zeta_3 a_3 s^2 - p_3)\}$, $Q^* = \delta_2(\xi^2 - \zeta_3 s^2 - \zeta_3 s^2 a_1\xi^2) + p_5\zeta_1(1 + a_1\xi^2)s^2$, $R^* = -\zeta_2 p_5 a_3 s^2 + \delta_4(\zeta_3 a_3 s^2 - p_3)$, $S^* = (\xi^2 - \zeta_3 s^2 - \zeta_3 s^2 a_1\xi^2)\delta_4 - (\delta_1\xi^2 + s^2)(a_3\zeta_3 s^2 - p_3) + \zeta_2 p_5 s^2(1 + a_1\xi^2)$, $T^* = -(\delta_1\xi^2 + s^2)(\xi^2 - \zeta_3 s^2 - \zeta_3 s^2 a_1\xi^2)$, $P^{**} = (\zeta_2\delta_2 - \zeta_1\delta_4)s^2 i\xi$, $Q^{**} = \zeta_1 s^2(\delta_1\xi^2 + s^2)$.

4. APPLICATIONS

On the half-space surface($x_3 = 0$) Linearly distributed mechanical force and thermal source, which are assumed to be time harmonic, are applied. We consider boundary conditions, as follows

(1) $t_{33}(x_1, x_3, t) = -F_1\psi_1(x)e^{i\omega t}$ (2) $t_{31}(x_1, x_3, t) = 0$

(3) $\varphi(x_1, x_3, t) = F_2\psi_2(x)e^{i\omega t}$ (15)

where F_1 , F_2 is the magnitudes of the force/source applied, $\psi_1(x)$ specify the source distribution function along x_1 axis.

SUBCASE (a). **Mechanical force**

Making use of (1), (8), ,(12)-(14) in B.C. (15) and applying Laplace Transform and Fourier Transform defined by (9)-(10) ,we obtain the components of displacement, normal stress, tangential stress and conductive temperature as while $F_2 = 0$.

$$\widehat{u_3} = \frac{F_1\widehat{\psi}_1(\xi)}{\Delta}\left(-d_1M_{11}e^{-\lambda_1x_3} + d_2M_{12}e^{-\lambda_2x_3} - d_3M_{13}e^{-\lambda_3x_3}\right)e^{i\omega t} \quad (16)$$

$$\widehat{\varphi} = \frac{F_1\widehat{\psi}_1(\xi)}{\Delta}\left(-l_1M_{11}e^{-\lambda_1x_3} + l_2M_{12}e^{-\lambda_2x_3} - l_3M_{13}e^{-\lambda_3x_3}\right)e^{i\omega t} \quad (17)$$

$$\widehat{t_{33}} = \frac{F_1\widehat{\psi}_1(\xi)}{\Delta}\left(-h_1M_{11}e^{-\lambda_1x_3} + h_2M_{12}e^{-\lambda_2x_3} - h_3M_{13}e^{-\lambda_3x_3}\right)e^{i\omega t} \quad (18)$$

$$\widehat{t_{31}} = \frac{F_1\widehat{\psi}_1(\xi)}{\Delta}\left(-h'_1M_{11}e^{-\lambda_1x_3} + h'_2M_{12}e^{-\lambda_2x_3} - h'_3M_{13}e^{-\lambda_3x_3}\right)e^{i\omega t} \quad (19)$$

where

$M_{11} = \Delta_{22}\Delta_{33} - \Delta_{32}\Delta_{23}$, $M_{12} = \Delta_{21}\Delta_{33} - \Delta_{23}\Delta_{31}$, $M_{13} = \Delta_{21}\Delta_{32} - \Delta_{22}\Delta_{31}$

$M_{21} = \Delta_{12}\Delta_{33} - \Delta_{13}\Delta_{22}$, $M_{22} = \Delta_{11}\Delta_{33} - \Delta_{13}\Delta_{31}$, $M_{23} = \Delta_{11}\Delta_{32} - \Delta_{12}\Delta_{31}$

$M_{31} = \Delta_{12}\Delta_{23} - \Delta_{13}\Delta_{22}$, $M_{32} = \Delta_{11}\Delta_{23} - \Delta_{13}\Delta_{21}$, $M_{33} = \Delta_{11}\Delta_{22} - \Delta_{12}\Delta_{21}$

$\Delta_{1i} = \frac{c_{31}}{\rho c_1^2} i\xi - \frac{c_{33}}{\rho c_1^2} d_i\lambda_i - \frac{\beta_3}{\beta_1} l_i + \frac{\beta_3}{\beta_1 T_0} l_i\lambda_i^2 \quad i = 1,2,3$,$\Delta_{2i} = -\frac{c_{44}}{\rho c_1^2}\lambda_i + \frac{c_{44}}{\rho c_1^2} i\xi d_i \quad i = 1,2,3$

$\Delta_{3i} = l_i \quad i = 1,2,3$, $\Delta = \Delta_{11}M_{11} - \Delta_{12}M_{12} + \Delta_{13}M_{13}$,$h_i = \frac{c_{31}}{\rho c_1^2} i\xi - \frac{c_{33}}{\rho c_1^2} d_i\lambda_i - \frac{\beta_3}{\beta_1} l_i + \frac{\beta_3}{\beta_1 T_0} l_i\lambda_i^2 \quad i = 1,2,3$ $h_i' = -\frac{c_{44}}{\rho c_1^2}\lambda_i + \frac{c_{44}}{\rho c_1^2} i\xi d_i \quad i = 1,2,3$

SUBCASE (b). **Thermal source on the surface of half-space**

Making use of (1), (8), ,(12)-(14) in B.C. (15) and applying Laplace Transform and Fourier Transform defined by (9)-(10) and taking $F_1 = 0$,we obtain the components of displacement, normal stress, tangential stress and conductive temperature are as given by equations (16)-(19) with M_{11}, M_{12} and M_{13} replaced by M_{31}, M_{32} and M_{33} respectively and F_1 replaced by F_2.

5. LINEARLY DISTRIBUTED FORCE:

The solution due to linearly distributed force applied on the half space is obtained by setting

$$\{\psi_1(x), \psi_2(x)\} = \begin{cases} 1 - \dfrac{|x|}{a} & \text{if } |x| \le a \\ 0 & \text{if } |x| > a \end{cases}$$

in equation (15). Here 2a is the width of the strip load , using (8) and applying the transform defined by (9)-(10) ,

we obtain $\{\widehat{\psi}_1(\xi),\ \widehat{\psi}_2(\xi)\} = \left[2\{1-\cos(\xi a)\Big/\xi^2 a\right]\ \xi \neq 0$ (20)

using (20) and (16)-(19) , we can obtain components of displacement, stress and conductive temperature**.**

6. PARTICULAR CASE:

In case of isotropic thermoelastic solid, we have

$$c_{11} = \lambda + 2\mu = c_{33},\ c_{12} = c_{13} = \lambda,\ c_{44} = \mu$$

7. INVERSION OF THE TRANSFORMATION

To obtain the solution of the problem in physical domain, we must invert the transforms in equations (16)-(19) . Here the displacement components , normal and tangential stresses and conductive temperature are functions of x_3 , the parameters of Laplace and Fourier transforms s and ξ respectively and hence are of the form f (ξ, x_3 , s). To obtain the function $f(x_1, x_3, t)$ in the physical domain, we first invert the Fourier transform using

$$\bar{f}(x_1, x_3, s)=\frac{1}{2\pi}\int_{-\infty}^{\infty} e^{-i\xi x_1}\,\hat{f}(\xi, x_3, s)d\xi = \frac{1}{2\pi}\int_{-\infty}^{\infty}|\cos(\xi x_1)\, f_e - i\sin(\xi x_1) f_o|\, d\xi$$

Where f_e andf_o are respectively the odd and even parts of $\hat{f}\,(\xi, x_3, s)$. Thus the above expression gives the Laplace transform $\bar{f}(x_1, x_3, s)$ of the function $f(x_1, x_3, t)$. Following Honig and Hirdes (1984) , the Laplace transform function $\bar{f}(x_1, x_3, s)$ can be inverted to $f(x_1, x_3, t)$.

8. NUMERICAL RESULTS AND DISCUSSION

Copper material is chosen for the purpose of numerical calculation whose numerical data is

$c_{11} = 18.78 \times 10^{10}\ Kgm^{-1}s^{-2},\ c_{12} = 8.76 \times 10^{10}\ Kgm^{-1}s^{-2}$, $c_{13} = 8.0 \times 10^{10}\ Kgm^{-1}s^{-2}$ $c_{33} = 17.2 \times 10^{10}\ Kgm^{-1}s^{-2}$, $c_{44} = 5.06 \times 10^{10}\ Kgm^{-1}s^{-2}$,

$C_E = 0.6331 \times 10^3 JKg^{-1}K^{-1}$ $\alpha_1 = 2.98 \times 10^{-5}K^{-1}$, $\alpha_3 = 2.4 \times 10^{-5}K^{-1}$,

$a = 2.4 \times 10^4 m^2s^{-2}, b = 13 \times 10^5 m^5s^{-2}Kg^{-1}$ $\rho = 8.954 \times 10^3 Kgm^{-3}$,

$K_1 = 0.433 \times 10^3 Wm^{-1}K^{-1}$, $K_3 = 0.450 \times 10^3 Wm^{-1}K^{-1}$

A comparison of values of normal displacement u_3, normal force stress t_{33} , tangential stress t_{31} for a transversely isotropic thermoelastic solid with distance x are presented graphically for non dimensional two temperature parameters a=0.02 and a=0.08 for the non-dimensional frequencies ω=.25, ω=.5 and ω=.75

1). The solid line, long dashed line, small dashed line respectively corresponds to a=0.02 with non-dimensional frequencies ω=.25, ω=.5 and ω=.75 respectively.

2). The solid line with centre symbol circle , the long dashed line with centre symbol triangle , the small dashed line with centre symbol diamond respectively corresponds to a =0.08 and ω=.25, ω=.5 and ω=.75 respectively.

Figs.1-3 present the variations due to mechanical force. Figs 3-6 present variations due to thermal source. In the figures1-3,behaviour of deformation is similar oscillatory in the two temperature case and with different temperatures, oscillatory pattern is different. With different frequencies, amplitude of oscillation changes. In the figures 4-6, pattern of oscillation is different for two temperature case, whereas change in frequency changes the amplitude of oscillation.

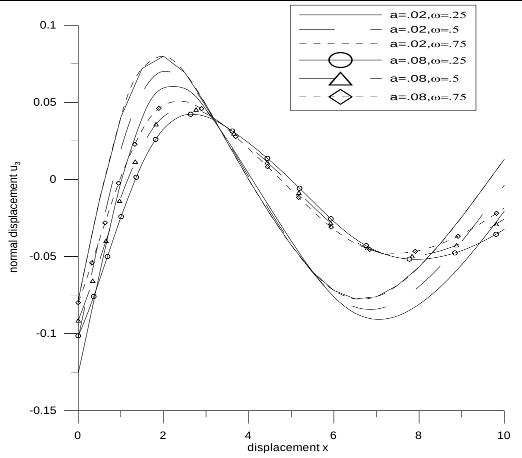

Fig.1. Variation of normal displacement u_3 with distance x (Mechanical force)

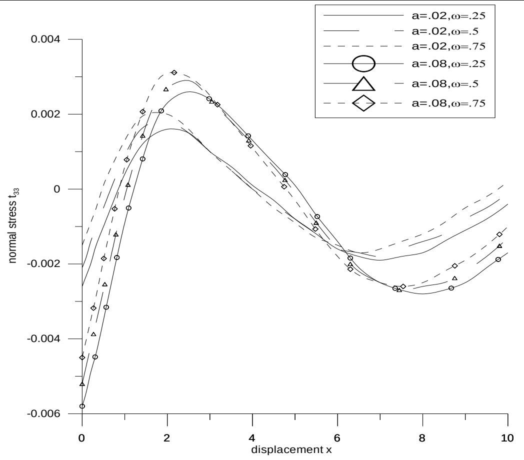

Fig.2 Variation of normal stress t_{33} with distance x (Mechanical force)

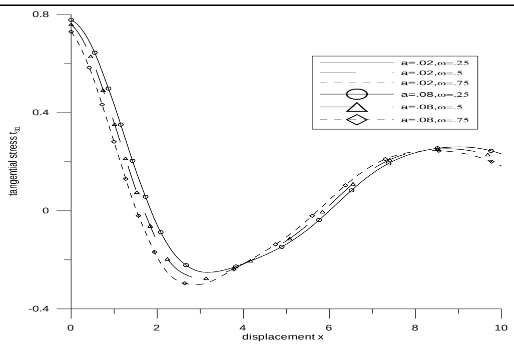

Fig.3. Variation of tangential stress t_{31} with distance x (Mechanical force)

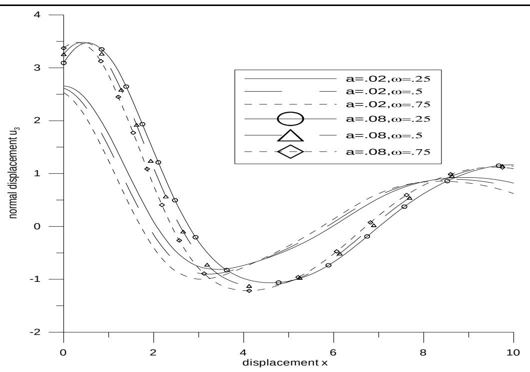

Fig.4 Variation of normal displacement u_3 with distance x (Thermal source)

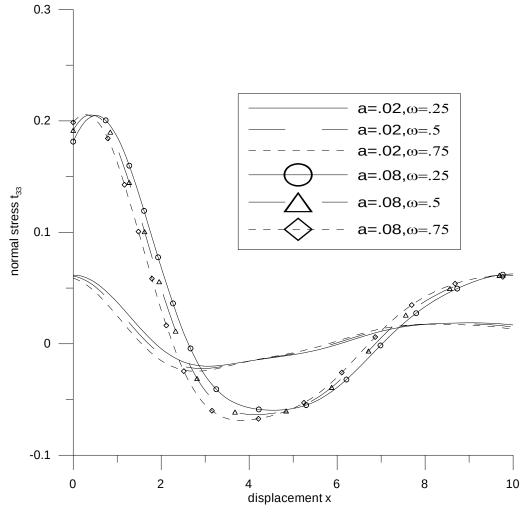

Fig.5 Variation of normal stress t_{33} with distance x (Thermal source)

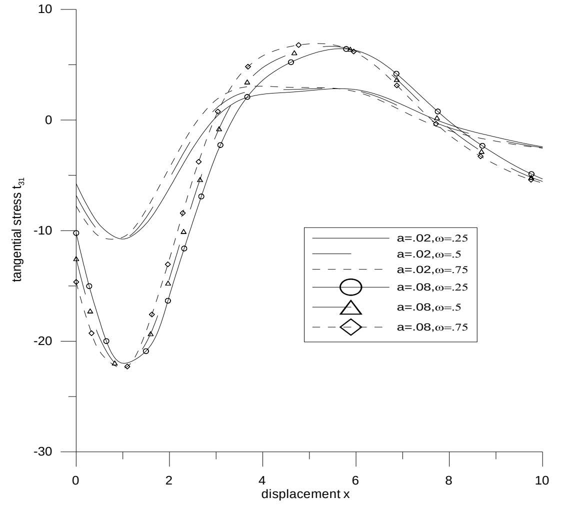

Fig.6. Variation of tangential stress t_{31} with distance x (Thermal source)

9. CONCLUSION

The properties of a body depend largely on the direction of symmetry. Frequency plays an important role in the study of deformation of the body. The effect of two temperature has significant impact on components of normal displacement , normal stress, tangential stress and conductive temperature. It is observed from the figures that the trends in the variations of the characteristics mentioned are similar with difference in their magnitude when the mechanical forces are applied , where as the trends are different when thermal sources are applied. But the variations of the normal stress, tangential stress and normal displacement quantities are smoother when the body is deformed on the application thermal source where as variation in the conductive temperature is not smooth . As disturbance travels through the constituents of the medium, it suffers sudden changes resulting in an inconsistent / non uniform pattern of graphs.

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