IJME

Int. J. of Applied Mechanics and Engineering, 2023, vol.28, No.1, pp.1-10
DOI: 10.59441/ijame-2023-0001

VARIABLE THERMAL CONDUCTIVITY IN MICROPOLAR THERMOELASTIC MEDIUM WITHOUT ENERGY DISSIPATION POSSESSING CUBIC SYMMETRY

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This investigation deals with the effect of variable thermal conductivity in a micropolar thermoelastic medium without energy dissipation with cubic symmetry. The normal mode technique is employed for obtaining components of physical quantities such as displacement, stress, temperature distribution and microrotation.

Keywords: variable thermal conductivity, microrotation, temperature distribution, normal mode analysis.

1. Introduction

The classical theory of thermoelasticity has been utilized in the analysis of various elastic materials for the last few decades but this theory has been inadequate to explain the behavior of polycrystalline materials, fibrous-structured materials, etc. Therefore, the micropolar theory of elasticity has been developed, which considers not only macro-deformations but micro-rotations of particles as well. This theory was formulated by Eringen and Suhubi [1], Eringen [2]. Under this theory, couple stresses can exist in addition to force stresses. Nowacki [3,4,5] included thermal effects in the micropolar theory of elasticity. The dispersion relations for transverse plane waves were studied by Eringen [6] in linear nonlocal micropolar elastic solids. Kumar and Ailawalia [7] discussed the response of a micropolar thermoelastic medium to the application of moving load. Othman *et al.* [8] demonstrated the effect of rotation and initial stress in the micropolar thermoelastic isotropic medium in the context of the three-phase-lag theory. Said *et al.* [9] proposed a general model for rotating-micropolar thermoelastic medium on the application of the magnetic field. Othman and Mondal [10] applied phase-lag models for investigating the effect of thermal loading due to laser pulse in a generalized micropolar thermoelasticity. Kalkal *et al.* [11] studied the reflection of plane waves in a nonlocal micropolar rotating thermoelastic medium. Abo Dahab *et al*. [12] applied electromagnetic field to different models of thermoelasticity for investigating fiber-reinforced micropolar thermoelastic medium. Alharbi *et al.* [13] examined a micropolar voided medium under the three-phase-lag model of thermoelasticity by applying an internal heat source. Alharbi [14] also analyzed the behavior of a micropolar thermoelastic medium on diffusion in the context of the three-phase-lag model of thermoelasticity.

In the case of cubic symmetry, four independent elastic constants are required for explaining the mechanical behavior of a cubic crystal such as iron, aluminium, nickel, silicon, magnesium, etc. Minagawa *et*

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al. [15] estimated material constants for the diamond in a cubic micropolar medium. Kumar and Ailawalia [16-17] discussed the behavior of a micropolar thermoelastic medium with cubic symmetry under the influence of time-harmonic sources with one and two relaxation times. The study of micropolar thermoelastic medium with cubic symmetry under the influence of a magnetic field and an inclined load was done by Othman *et al.* [18] by taking into account three different theories of thermoelasticity namely L-S, G-L and C-D theory. Kumar and Partap [19] worked on wave propagation in homogeneous isotropic micropolar thermoelastic plate with cubic symmetry under the L-S and G-L theory. Othman *et al.* [20] put forward a two-dimensional problem for a micropolar thermoelastic medium with cubic symmetry under the effect of rotation and inclined load. They [21] also studied the micropolar thermoelastic medium with cubic symmetry on the application of an inclined load and magnetic field in the context of GN theory.

Further, it was noted that there is a linear variation of thermal conductivity with respect to temperature when a thermoelastic material is exposed to high temperature. So, the concept of variable thermal conductivity became of paramount importance. A lot of research has been done by various researchers. Aouadi [22] investigated the influence of variable electrical and thermal conductivity in a thermoelastic half-space. Mondal *et al.* [23] proposed a new theory of dual-phase-lag two-temperature thermoelasticity in considerations of variable thermal conductivity. Li *et al.* [24] observed the effect of variable thermal conductivity and diffusivity on nonlinear transient responses of generalized diffusion-thermoelasticity using the finite element method. Abbas *et al.* [25] demonstrated the photo-thermo-elastic interaction in the context of variable thermal conductivity in a semi-conductor material with cylindrical cavities. Hobiny and Abbas [26] explored a semiconducting medium using the finite element method for variable thermal conductivity.

The aim of this paper is to study a micropolar thermoelastic medium with no energy dissipation having cubic symmetry under the influence of variable thermal conductivity. The physical quantities associated with the problem are obtained by using normal mode analysis.

2. Formulation of problem

A micropolar thermoelastic medium without energy dissipation with cubic symmetry is considered. A rectangular Cartesian coordinate system (x,y,z) with the y-axis pointing vertically downward is taken. If we consider the $xy-$plane, then the displacement vector in the micropolar thermoelastic medium may be taken as $\vec{u}=(u,v,0)$ where $u=u(x,y,t)$, $v=v(x,y,t)$ and the microrotation vector can be taken as $\vec{\phi}=(0,0,\phi_3)$. The field equations and constitutive relations in the absence of body forces are given [15, 27] as:

$$K^{*}\nabla^{2}T=\rho C^{*}\frac{\partial^{2}T}{\partial t^{2}}+vT_{0}\frac{\partial^{2}}{\partial t^{2}}\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right), \tag{2.1}$$

$$A_{1}\frac{\partial^{2}u}{\partial x^{2}}+\left(A_{2}+A_{4}\right)\frac{\partial^{2}v}{\partial x\partial y}+A_{3}\frac{\partial^{2}u}{\partial y^{2}}+\left(A_{3}-A_{4}\right)\frac{\partial\phi_{3}}{\partial y}-v\frac{\partial T}{\partial x}=\rho\frac{\partial^{2}u}{\partial t^{2}}, \tag{2.2}$$

$$A_{3}\frac{\partial^{2}v}{\partial x^{2}}+\left(A_{2}+A_{4}\right)\frac{\partial^{2}u}{\partial x\partial y}+A_{1}\frac{\partial^{2}v}{\partial y^{2}}-\left(A_{3}-A_{4}\right)\frac{\partial\phi_{3}}{\partial x}-v\frac{\partial T}{\partial y}=\rho\frac{\partial^{2}v}{\partial t^{2}}, \tag{2.3}$$

$$B_{3}\nabla^{2}\phi_{3}+\left(A_{3}-A_{4}\right)\left(\frac{\partial v}{\partial x}-\frac{\partial u}{\partial y}\right)-2\left(A_{3}-A_{4}\right)\phi_{3}=\rho j^{*}\frac{\partial^{2}\phi_{3}}{\partial t^{2}}, \tag{2.4}$$

$$t_{yy}=A_{2}\frac{\partial u}{\partial x}+A_{1}\frac{\partial v}{\partial y}-vT, \tag{2.5}$$

$$t_{yx} = A_4\left(\frac{\partial v}{\partial x} - \phi_3\right) + A_3\left(\frac{\partial u}{\partial y} + \phi_3\right), \tag{2.6}$$

$$m_{yz} = B_3 \frac{\partial \phi_3}{\partial y}. \tag{2.7}$$

It was observed experimentally that under high temperature, the thermal conductivity K^* varies linearly with temperature of the medium as given by the following relation [28, 29]:

$$K^*(T) = K_0^*\left(1 + K_1^* T\right). \tag{2.8}$$

Here, K_1^* is a physical parameter and K_0^* is an arbitrary constant. On applying the Kirchhoff transformation, we can get a linear form of the heat conduction equation by the following relation [30]:

$$\hat{T} = \frac{1}{K_0^*}\int_0^T K^*(\xi)\, d\xi. \tag{2.9}$$

Differentiating (2.9) with respect to time x_i using Leibnitz's rule of differentiation under integral sign, we get the following expression:

$$K_0^* \hat{T}_{,i} = K^*(T) T_{,i}\,.$$

Again differentiating above equation with respect to time x_i, we get:

$$K_0^* \hat{T}_{,ii} = \left(K^*(T) T_{,i}\right)_{,i}\,.$$

Ignoring non-linear terms in the above equation, we get:

$$K_0^* \hat{T}_{,ii} = K^*(T) T_{,ii}\,. \tag{2.10}$$

Further, differentiating (2.9) twice with respect to time t using Leibnitz's rule of differentiation under integral sign, we get the following expression:

$$K_0^* \hat{T}_{,tt} = K^*(T) T_{,tt}\,.$$

Using Eq.(2.8) in the above expression and applying the binomial theorem we can write the following equation after neglecting nonlinear terms as:

$$T_{,tt} = \frac{K_0^* \hat{T}_{,tt}}{K^*(T)} = \hat{T}_{,tt}\,. \tag{2.11}$$

Using Eqs (2.10) and (2.11) in Eqs (2.1) to (2.7), we get:

$$K_0^*\nabla^2\hat{T} = \rho C^* \frac{\partial^2\hat{T}}{\partial t^2} + \nu T_0 \frac{\partial^2}{\partial t^2}\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right), \tag{2.12}$$

$$A_1 \frac{\partial^2 u}{\partial x^2} + (A_2 + A_4)\frac{\partial^2 v}{\partial x \partial y} + A_3 \frac{\partial^2 u}{\partial y^2} + (A_3 - A_4)\frac{\partial \phi_3}{\partial y} - \nu \frac{\partial \hat{T}}{\partial x} = \rho \frac{\partial^2 u}{\partial t^2}, \tag{2.13}$$

$$A_3 \frac{\partial^2 v}{\partial x^2} + (A_2 + A_4)\frac{\partial^2 u}{\partial x \partial y} + A_1 \frac{\partial^2 v}{\partial y^2} - (A_3 - A_4)\frac{\partial \phi_3}{\partial x} - \nu \frac{\partial \hat{T}}{\partial y} = \rho \frac{\partial^2 v}{\partial t^2}, \tag{2.14}$$

$$B_3\nabla^2\phi_3 + (A_3 - A_4)\left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right) - 2(A_3 - A_4)\phi_3 = \rho j^* \frac{\partial^2 \phi_3}{\partial t^2}, \tag{2.15}$$

$$t_{yy} = A_2 \frac{\partial u}{\partial x} + A_1 \frac{\partial v}{\partial y} - \nu\hat{T}, \tag{2.16}$$

$$t_{yx} = A_4\left(\frac{\partial v}{\partial x} - \phi_3\right) + A_3\left(\frac{\partial u}{\partial y} + \phi_3\right), \tag{2.17}$$

$$m_{yz} = B_3 \frac{\partial \phi_3}{\partial y}. \tag{2.18}$$

Further, we assume the following dimensionless variables for simplifying our calculations:

$$x' = \frac{1}{C_T t^*}x, \quad y' = \frac{1}{C_T t^*}y, \quad u' = \frac{1}{C_T t^*}u, \quad v' = \frac{1}{C_T t^*}v, \quad \phi_3' = \frac{\rho C_T^{\,2}}{A_4}\phi_3,$$

$$t' = \frac{t}{t^*}, \quad t_{ij}' = \frac{t_{ij}}{A_4}, \quad m_{yz}' = \frac{1}{C_T t^* A_4}m_{yz}, \quad \hat{T}' = \frac{\nu\hat{T}}{(A_2 + 2A_4)}$$

where,

$$C_T^{\,2} = \frac{(A_2 + 2A_4)}{\rho}, \qquad t^* = \frac{K_0^{\,*}}{\rho C^* C_T^{\,2}}. \tag{2.19}$$

On applying the above dimensionless variables (2.19) in Eqs (2.12)-(2.15), we get:

$$E_1\nabla^2\hat{T} + E_2 \frac{\partial^2\hat{T}}{\partial t^2} + E_3 \frac{\partial^2}{\partial t^2}\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) = 0, \tag{2.20}$$

$$E_4 \frac{\partial^2 u}{\partial x^2} + E_5 \frac{\partial^2 u}{\partial y^2} + E_6 \frac{\partial^2 v}{\partial x \partial y} + E_7 \frac{\partial \phi_3}{\partial y} - \frac{\partial \hat{T}}{\partial x} = \frac{\partial^2 u}{\partial t^2}, \tag{2.21}$$

$$E_5\frac{\partial^2 v}{\partial x^2}+E_4\frac{\partial^2 v}{\partial y^2}+E_6\frac{\partial^2 u}{\partial x\partial y}-E_7\frac{\partial \phi_3}{\partial x}-\frac{\partial \hat{T}}{\partial y}=\frac{\partial^2 v}{\partial t^2}, \tag{2.22}$$

$$E_8\nabla^2\phi_3+E_9\left(\frac{\partial v}{\partial x}-\frac{\partial u}{\partial y}\right)+E_{10}\phi_3=\frac{\partial^2\phi_3}{\partial t^2}. \tag{2.23}$$

where values of $E_r\left(r=1 \text{ to } 10\right)$ are given in the appendix.

3. Normal mode analysis

Applying the normal mode technique we can get solution of the above considered physical variables as:

$$\left[u, v, \hat{T}, \phi_3\right]=\left[u^*, v^*, \hat{T}^*, \phi_3{}^*\right](y)exp\{\omega t+iax\} . \tag{3.1}$$

We observed four coupled equations in terms of $u^*, v^*, \hat{T}^*, \phi_3{}^*$ on using Eq.(3.1) in Eqs (2.20)-(2.23). After solving these coupled equations, an eighth degree equation is obtained

$$\left[X_1D^8+X_2D^6+X_3D^4+X_4D^2+X_5\right]\left(u^*,v^*,\hat{T}^*,\phi_3{}^*\right)=0 \tag{3.2}$$

where values of X_1,X_2,X_3,X_4,X_5 are given in the appendix. Using radiation conditions $u^*,v^*,\hat{T}^*,\phi_3{}^*\to 0$ as $y\to\infty$, we can write the solution of Eq.(3.2):

$$u^*=\sum_{j=1}^{4}M_j exp\left\{-k_j y\right\}, \tag{3.3}$$

$$v^*=\sum_{j=1}^{4}N_j exp\left\{-k_j y\right\}, \tag{3.4}$$

$$\hat{T}^*=\sum_{j=1}^{4}L_j exp\left\{-k_j y\right\}, \tag{3.5}$$

$$\phi_3{}^*=\sum_{j=1}^{4}O_j exp\left\{-k_j y\right\} \tag{3.6}$$

where $k_j{}^2\left(j=1,2,3,4\right)$ are roots of Eq.(3.2). Also the coupling constants M_jN_j,L_j,O_j can be expressed in terms of L_j as:

$$M_j=P_jL_j,N_j=Q_jL_j,O_j=R_jL_j. \tag{3.7}$$

where the values of P_j, Q_j, R_j are given in the appendix. Also, stress components can be expressed using above the solution as:

$$t_{yy}{}^{*} = iaA_2\sum_{j=1}^{4} M_j exp\left\{-k_j y\right\} - A_1\sum_{j=1}^{4} k_j N_j exp\left\{-k_j y\right\} - v\sum_{j=1}^{4} L_j exp\left\{-k_j y\right\}, \tag{3.8}$$

$$t_{yx}{}^{*} = iaA_4\sum_{j=1}^{4} N_j exp\left\{-k_j y\right\} - A_3\sum_{j=1}^{4} M_j exp\left\{-k_j y\right\} + \left(A_3 - A_4\right)\sum_{j=1}^{4} O_j exp\left\{-k_j y\right\}, \tag{3.9}$$

$$m_{yz}{}^{*} = -B_3\sum_{j=1}^{4} k_j O_j exp\left\{-k_j y\right\}. \tag{3.10}$$

4. Boundary conditions

For getting values of the constants $L_j\left(j = 1,2,3,4\right)$, we can use the following boundary conditions:

1) At the free surface $\left(y = 0\right)$ a mechanical force $Fexp\left\{\omega t + iax\right\}$ is applied along the normal direction:

$$t_{yy} = -Fexp\left\{\omega t + iax\right\}. \tag{4.1}$$

2) Also we can consider the traction free surface $\left(y = 0\right)$ and use the condition written below:

$$t_{xy} = 0. \tag{4.2}$$

3) The thermal boundary condition can be expressed as:

$$\frac{\partial T}{\partial y} = 0. \tag{4.3}$$

4) For the tangential couple stress we use the boundary condition:

$$m_{yz} = 0. \tag{4.4}$$

We get the following non-homogenous system of four equations after applying the above boundary conditions.

$$Y_1 L_1 + Y_2 L_2 + Y_3 L_3 + Y_4 L_4 = F, \tag{4.5}$$

$$Z_1 L_1 + Z_2 L_2 + Z_3 L_3 + Z_4 L_4 = 0, \tag{4.6}$$

$$k_1 R_1 L_1 + k_2 R_2 L_2 + k_3 R_3 L_3 + k_4 R_4 L_4 = 0, \tag{4.7}$$

$$k_1 L_1 + k_2 L_2 + k_3 L_3 + k_4 L_4 = 0. \tag{4.8}$$

where values of $Y_j, Z_j\left(j=1,2,3,4\right)$ are given in the appendix. Cramer's rule is employed for solving the above non-homogenous system. The relation between temperature T and the operator $\hat{T}$ can be expressed as follows:

$$T=\frac{1}{K_1^*}\left[\sqrt{1+2K_1^*\hat{T}}-1\right]=\frac{1}{K_1^*}\left[\sqrt{1+2K_1^*\hat{T}^*exp\left\{\omega t+iax\right\}}-1\right]. \tag{4.9}$$

The above relation can be utilized for expressing the components of displacement, stress and temperature in the form of operator $\hat{T}$.

5. Particular cases:

Case I:

The problem reduces to a micropolar isotropic medium when

$$A_1=\lambda+2\mu+K, A_2=\lambda, A_3=\mu+K, A_4=\mu.$$

Case II:

If we take $K_1^*=0$, the problem reduces to the classical case of constant thermal conductivity.

6. Appendix

$$E_1=\frac{K_0^*}{vC^*},\quad E_2=-\frac{\left(A_2+2A_4\right)}{v},\quad E_3=-\frac{vT_0}{\rho C^*},\quad E_4=\frac{A_1}{\rho C_T^{\,2}},\quad E_5=\frac{A_3}{\rho C_T^{\,2}},\quad E_6=\frac{A_2+A_4}{\rho C_T^{\,2}},$$

$$E_7=\frac{(A_3-A_4)A_4}{\rho^2 C_T^{\,4}},\quad E_8=\frac{B_3}{\rho j^* C_T^{\,2}},\quad E_9=\frac{(A_3-A_4)C_T^{\,2}t^{*2}}{A_4 j^*},\quad E_{10}=\frac{-2(A_3-A_4)t^{*2}}{\rho j^*},$$

$$F_1=E_2\omega^2-E_1a^2,\quad F_2=-\left(E_4a^2+\omega^2\right),\quad F_3=-\left(E_5a^2+\omega^2\right),\quad F_4=E_{10}-E_8a^2-\omega^2,$$

$$F_5=ia\left(E_5+E_6\right),\quad F_6=F_3-a^2E_6,\quad F_7=iaE_6E_8,\quad F_8=ia(E_6F_4-E_7E_9),\quad F_9=E_4E_8,$$

$$F_{10}=F_3E_8+F_4E_4,\quad F_{11}=F_3F_4-a^2E_7E_9,\quad G_1=E_1E_4,\quad G_2=F_1E_4+E_1F_6+\omega^2F_3,$$

$$G_3=F_1F_6-a^2\omega^2E_3,\quad G_4=ia\omega^2E_3E_4-\omega^2E_3F_5,\quad G_5=ia\omega^2\left(E_3F_6-E_3F_2\right),$$

$$H_1=E_1F_9,\quad H_2=F_1F_9+E_1F_{10}+\omega^2E_3E_8,\quad H_3=F_1F_{10}+E_1F_{11}+\omega^2E_3F_4,\quad H_4=F_1F_{11},$$

$$H_5=\omega^2E_3\left(iaF_9-F_7\right),\quad H_6=\omega^2E_3\left(iaF_{10}-F_8\right),\quad H_7=ia\omega^2E_3F_{11},$$

$$H_8 = -E_1 G_4 + ia\omega^2 E_3 G_1, \quad H_9 = -F_1 G_4 - E_1 G_5 + ia\omega^2 E_3 G_2, \quad H_{10} = ia\omega^2 E_3 G_3 - F_1 G_5,$$

$$H_{11} = -\omega^2 E_3 E_9 G_1, \quad H_{12} = -\omega^2 E_3 E_9 G_2 - iaH_8 E_9, \quad H_{13} = -\omega^2 E_3 E_9 G_3 - iaH_9 E_9,$$

$$H_{14} = -iaH_{10} E_9, X_1 = G_1 H_5 - H_1 G_4, X_2 = G_1 H_6 + G_2 H_5 - H_2 G_4,$$

$$X_3 = G_1 H_7 + G_2 H_6 + G_3 H_5 - H_3 G_4, X_4 = G_2 H_7 + G_3 H_6 - H_3 G_5 - H_4 G_4,$$

$$X_5 = G_3 H_7 - G_5 H_4, \quad P_j = -\frac{G_1 k_j^4 + G_2 k_j^2 + G_3}{G_4 k_j^2 + G_5}, \quad Q_j = \frac{H_8 k_j^4 + H_9 k_j^2 + H_{10}}{\omega^2 E_3 \left(G_4 k_j^3 + G_5 k_j \right)},$$

$$R_j = \frac{H_{11} k_j^6 + H_{12} k_j^4 + H_{13} k_j^2 + H_{14}}{\omega^2 E_3 \left(G_4 k_j^3 + G_5 k_j \right)\left(E_8 k_j^2 + F_4 \right)}, \quad Y_j = A_1 k_j Q_j + v - iaA_2 P_j,$$

$$Z_j = iaA_4 Q_j - A_3 k_j P_j + \left(A_3 - A_4 \right) R_j, \quad \left(j = 1,2,3,4 \right).$$

Acknowledgement

The present work was done at MMDU, Mullana and Chandigarh University under the supervision of Dr. Praveen Ailawalia. I would like to extend my thanks to my supervisor for his guidance.

Nomenclature

a	– wave number in the x-direction
A_1	– $= A_2 + A_3, + A_4$
A_1, A_2, A_3, A_4, B_3	– physical constants which characterize the material
C^*	– specific heat at constant strain
j^*	– micro inertia
K^*	– $= \frac{C^*\left(A_2 + A_4 \right)}{4}$
m_{yz}	– components of tangential couple stress
t_{yx}	– components of tangential force stress
t_{yy}	– components of normal force stress
β_T	– coefficient of linear expansion
v	– $= \left(A_1 + 2A_2 \right)\beta_T$
ρ	– density
ω	– complex time constant

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Received: July 2, 2022
Revised: December 14, 2022