Research Article

Effect of Rotation on Propagation of Waves in Transversely Isotropic Thermoelastic Half-Space

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The present study is concerned with the effect of rotation on the propagation of plane waves in a transversely isotropic medium in the context of thermoelasticity theory of GN theory of types II and III. After solving the governing equations, three waves propagating in the medium are obtained. The fastest among them is a quasilongitudinal wave. The slowest of them is a thermal wave. The remaining is called quasitransverse wave. The prefix “quasi” refers to their polarizations being nearly, but not exactly, parallel or perpendicular to the direction of propagation. The polarizations of these three waves are not mutually orthogonal. After imposing the appropriate boundary conditions, the amplitudes of reflection coefficients have been obtained. Numerically simulated results have been plotted graphically with respect to frequency to evince the effect of rotation and anisotropy.

1. Introduction

The study of wave propagation in anisotropic materials has been a subject of extensive investigation in the literature. It is of great importance in a variety of applications ranging from seismology to nondestructive testing of composite structures used in aircraft, spacecraft, or other engineering industries. Polymers or polymer-based matrix composites are widely used in these industrial environments. These materials possess isotropic or anisotropic properties that can strongly affect the propagation of waves. The dynamical interaction between the thermal and mechanical fields in solids also has a great number of practical applications in modern aeronautics, astronautics, nuclear reactors, and high energy particle accelerators. The generalized theory of thermoelasticity has drawn widespread attention because it removes the physically unacceptable situation of the classical theory of thermoelasticity, that is, that the thermal disturbance propagates with the infinite velocity. The Lord-Shulman theory [1] and Green-Lindsay theory [2] are two important generalized theories of thermoelasticity. Recently, Chandrasekhariah [3] and Hetnarski and Ignaczak [4] in their surveys considered the theory proposed by Green and Naghdi [5–7] as

an alternative way of formulating the propagation of heat. This theory is developed in a rational way to produce a fully consistent theory that is capable of incorporating thermal pulse transmission in a very logical manner. The development is quite general and the characterization of material response for the thermal phenomena is based on three types of constitutive functions that are labeled as type I, type II, and type III.

Some researchers in past have investigated different problem of rotating media. Chand et al. [8] presented an investigation on the distribution of deformation, stresses, and magnetic field in a uniformly rotating homogeneous isotropic, thermally, and electrically conducting elastic half-space. Many authors [9–11] studied the effect of rotation on elastic waves. References [12–14] discussed effect of rotation on different type of waves propagating in a thermoelastic medium. Othman [15] investigated plane waves in generalized thermoelasticity with two relaxation times under the effect of rotation. Othman and Song [16, 17] presented the effect of rotation in magneto-thermoelastic medium. Mahmoud [18] discussed the effect of rotation, gravity field, and initial stress on generalized magneto-thermoelastic Rayleigh waves in a granular medium.

In this paper, effect of rotation on the propagation of waves in a transversely isotropic medium in the context of thermoelasticity with GN theory of types II and III has been investigated. A cubic equation resulting in the three values of phase velocities and attenuation quality factor has been obtained. Furthermore the expressions for the amplitude ratios of the reflected wave corresponding to the three incident waves have been obtained. These expressions are then evaluated numerically and plotted graphically to manifest the effect of rotation.

2. Formulation of the Problem

In the context of thermoelasticity based on Green-Naghdi theory of type II and type III, the equation of motion for the transversely isotropic medium, taking the rotation term about y -axis as a body force, is

$$t_{ij,j} = \rho [\ddot{u}_i + (\vec{\Omega} \times \vec{\Omega} \times \vec{u})_i + (2\vec{\Omega} \times \dot{\vec{u}})_i], \quad (1)$$

where $\vec{\Omega}$ is the uniform angular velocity and ρ is the density of the medium. The generalized energy equation can be expressed as

$$K_{ij}\dot{T}_{,ij} + K_{ij}^*T_{,ij} = (T_0\beta_{ij}\ddot{u}_{i,j} + \rho c^*\ddot{T}), \quad i, j = 1, 2, 3. \quad (2)$$

The constitutive equations have the following form:

$$t_{ij} = C_{ijkl}e_{kl} - \beta_{ij}T, \quad (3)$$

where the deformation tensor is defined by $e_{ij} = (u_{i,j} + u_{j,i})/2$, t_{ij} are components of stress tensor, u_i is the mechanical displacement, e_{ij} are components of infinitesimal strain, T is the temperature change of a material particle, T_0 is the reference uniform temperature of the body, K_{ij} is the thermal conductivity, K_{ij}^* are the characteristic constants of the theory, $\beta_{ij} = C_{ijkl}\alpha_{kl}$ are the thermal elastic coupling tensor, α_{kl} are the coefficient of linear thermal expansion, c is the specific heat at constant strain, and C_{ijkl} are characteristic constants of material following the symmetry properties $C_{ijkl} = C_{klij} = C_{jikl}$, $K_{ij}^* = K_{ji}^*$, $K_{ij} = K_{ji}$, and $\beta_{ij} = \beta_{ji}$. The comma notation is used for spatial derivatives and superimposed dot represents time differentiation.

Following Slaughter [19], the appropriate transformations have been used on the set of (3) to derive equations for transversely isotropic medium. We restrict our analysis for two dimensions, in which we consider the component of the displacement vector in the following form:

$$\vec{u} = (u_1, 0, u_3). \quad (4)$$

Here we consider plane waves propagating in plane such that all particles on a line parallel to x_2 -axis are equally displaced. Therefore, all the field quantities will be independent of x_2 coordinate; that is, $\partial/\partial x_2 \equiv 0$.

Thus the field equations and constitutive relations for such a medium reduce to

$$\begin{aligned} C_{11}u_{1,11} + \frac{C_{55}}{2}u_{1,33} + \left(C_{13} + \frac{C_{55}}{2}\right)u_{3,13} - \beta_1T_{,1} \\ = \rho [\ddot{u}_1 - \Omega^2u_1 + 2\Omega\dot{u}_3], \\ \frac{C_{55}}{2}u_{3,11} + C_{33}u_{3,33} + \left(C_{13} + \frac{C_{55}}{2}\right)u_{1,13} - \beta_3T_{,3} \\ = \rho [\ddot{u}_3 - \Omega^2u_3 + 2\Omega\dot{u}_1], \\ K_1\dot{T}_{,11} + K_3\dot{T}_{,33} + K_1^*T_{,11} + K_3^*T_{,33} \\ = \rho c^*\ddot{T} + T_o(\beta_1\ddot{u}_{1,3} + \beta_3\ddot{u}_{3,1}), \end{aligned} \quad (5)$$

where $\beta_1 = C_{11}\alpha_1 + C_{13}\alpha_3$, $\beta_3 = C_{31}\alpha_1 + C_{33}\alpha_3$, and we have used the notations $11 \rightarrow 1, 13 \rightarrow 5, 33 \rightarrow 3$, for the material constants.

It is convenient to change the preceding equations into the dimensionless forms. To do this, the nondimensional parameters are introduced as follows:

$$\begin{aligned} x'_i = \frac{x_i}{L}, \quad u'_i = \frac{u_i}{L}, \quad t'_{ij} = \frac{t_{ij}}{C_{11}}, \\ t' = \frac{t}{t_o}, \quad T' = \frac{T}{T_o}, \end{aligned} \quad (6)$$

where L, t_o, T_o are parameters having dimension of length, time, and temperature, respectively.

3. Plane Wave Propagation and Reflection of Waves

Let $\vec{p} = (p_1, 0, p_3)$ denote the unit propagation vector, and c and ξ are, respectively, the phase velocity and the wave number of the plane waves propagating in $x_1 - x_3$ plane. We consider the plane wave solution of the form

$$(u_1, u_3, T) = (\bar{u}_1, \bar{u}_3, \bar{T}) e^{i\xi(p_1x_1 + p_3x_3 - ct)}. \quad (7)$$

With the help of (6) and (7) in (5), three homogeneous equations in three unknowns are obtained. Solving the resulting system of equations for nontrivial solution results in

$$Ac^6 + Bc^4 + Cc^2 + D = 0, \quad (8)$$

where

$$\begin{aligned} A &= f_{10}, \quad B = -f_5f_{10} - f_1f_{10} + f_6f_8 + f_3f_7 + f_9, \\ D &= f_1f_5f_9 - f_2f_4f_9, \\ C &= -f_5(f_9 + f_1f_{10} - f_3f_7) - f_1(f_9 - f_6f_8) \\ &\quad - f_2(f_4f_{10} + f_6f_7) + f_3f_4f_8, \end{aligned}$$

$$\begin{aligned}
f_1 &= p_1^2 d_1 + p_3^2 d_3 - \frac{d_{13} p p_3^2}{2}, & f_2 &= p_1 p_3 d_3 - \frac{d_{13} p p_1 p_3}{2}, \\
f_3 &= i p_1 d_4, & f_4 &= p_1 p_3 d_2 - \frac{d_{13} p p_1 p_3}{2}, \\
f_5 &= p_1^2 d_3 + p_3^2 d_5 + \frac{d_{13} p p_1^2}{2}, & f_6 &= i p_3 d_6, \\
f_7 &= i p_7 d_{11}, & f_8 &= i p_3 d_{12}, \\
f_9 &= i \omega p_1^2 - d_8 p_1^2 + i \omega \bar{k} p_3^2 - d_9 p_3^2, & f_{10} &= \varepsilon_1, \\
d_1 &= \frac{C_{11} t_o^2}{\rho L^2}, & d_2 &= \frac{(C_{13} + C_{55}/2) t_o^2}{\rho L^2}, & d_3 &= \frac{C_{55} t_o^2}{2 \rho L^2}, \\
d_4 &= \frac{\beta_1 T_o t_o^2}{\rho L^2}, & d_5 &= \frac{C_{33} t_o^2}{\rho L^2}, & d_6 &= \frac{\beta_3 T_o t_o^2}{\rho L^2}, \\
\bar{k} &= d_7 = \frac{k_3}{k_1}, & d_8 &= \frac{k_1^* t_o}{k_1}, & d_9 &= \frac{k_3^* t_o}{k_1}, \\
\varepsilon_1 &= d_{10} = \frac{\rho C^* L^2}{k_1 t_o}, & d_{11} &= \frac{\beta_1 L^2}{k_1 t_o}, & d_{12} &= \frac{\beta_3 L^2}{k_1 t_o}, \\
d_{13} &= \frac{t_o^2}{\rho L^2}.
\end{aligned} \tag{9}$$

The roots of this equation give three values of c^2 . Three positive values of c will be the velocities of propagation of three possible waves. The waves with velocities c_1 , c_2 , and c_3 correspond to three types of quasiwaves. We name these waves as quasilongitudinal displacement (qLD) wave, quasithermal wave (qT), and quasitransverse displacement (qTD) wave.

4. Reflection of Waves

Consider a homogeneous transversely isotropic half-space in the context of thermoelasticity with GN theory of types II and III, rotating with angular velocity $\bar{\Omega}$ occupying the region $x_3 > 0$. Incident qLD or qT or qTD wave at the interface will generate reflected qLD, qT, and qTD waves in the half-space $x_3 > 0$. The total displacements and temperature distribution are given by

$$(u_1, u_3, T) = \sum_{j=1}^6 A_j (1, r_j, s_j) e^{i B_j}, \tag{10}$$

where

$$B_j = \begin{cases} \frac{\omega(t - x_1 \sin e_j - x_3 \cos e_j)}{c_j}, & j = 1, 2, 3, \\ \frac{\omega(t - x_1 \sin e_j + x_3 \cos e_j)}{c_j}, & j = 4, 5, 6, \end{cases} \tag{11}$$

and ω is the angular frequency. Here subscripts 1, 2, and 3, respectively, denote the quantities corresponding to incident

qLD, qT, and qTD waves whereas the subscripts 4, 5, and 6, respectively, denote the corresponding reflected waves and

$$\begin{aligned}
r_j &= \frac{\Lambda_{1j}}{\Lambda_j}, & s_j &= \frac{\Lambda_{2j}}{\Lambda_j}, \\
\Lambda_j &= \begin{vmatrix} \xi^2 (f_5 - c_j^2) & \xi f_6 \\ c_j^2 \xi^3 f_8 & \xi^2 (f_9 + f_{10} c_j^2) \end{vmatrix}, \\
\Lambda_{1j} &= \begin{vmatrix} \xi^2 f_4 & \xi f_6 \\ c_j^2 \xi^3 f_7 & \xi^2 (f_9 + f_{10} c_j^2) \end{vmatrix}, \\
\Lambda_{2j} &= \begin{vmatrix} \xi^2 f_4 & \xi^2 (f_5 - c_j^2) \\ c_j^2 \xi^3 f_7 & c_j^2 \xi^3 f_8 \end{vmatrix}.
\end{aligned} \tag{12}$$

The values of the p_1 and p_3 for 3 different waves for the cases of incidence and reflected waves are as follows:

qLD-wave: $p_1 = \sin e_1$, $p_3 = \cos e_1$,

qT-wave: $p_1 = \sin e_2$, $p_3 = \cos e_2$,

qTD-wave: $p_1 = \sin e_3$, $p_3 = \cos e_3$,

qLD-wave: $p_1 = \sin e_4$, $p_3 = \cos e_4$,

qT-wave: $p_1 = \sin e_5$, $p_3 = \cos e_5$,

qTD-wave: $p_1 = \sin e_6$, $p_3 = \cos e_6$.

Here $e_1 = e_4$, $e_2 = e_5$, and $e_3 = e_6$; that is, the angle of incidence is equal to the angle of reflection in for generalized thermoelastic transversely isotropic half-space, so that the velocities of reflected waves are equal to their corresponding incident waves; that is, $c_1 = c_4$, $c_2 = c_5$, and $c_3 = c_6$.

5. Boundary Conditions

The boundary conditions at the thermally insulated surface $x_3 = 0$ are given by

$$t_{33} = 0, \quad t_{31} = 0, \quad \frac{\partial T}{\partial x_3} = 0, \tag{13}$$

where

$$\begin{aligned}
t_{33} &= C_{13} \frac{\partial u_1}{\partial x_1} + C_{33} \frac{\partial u_3}{\partial x_3} - \beta_3 T, \\
t_{31} &= \frac{C_{55}}{2} \left(\frac{\partial u_1}{\partial x_3} + \frac{\partial u_3}{\partial x_1} \right).
\end{aligned} \tag{14}$$

The wave numbers ξ_j , $j = 1, 2, \dots, 6$ and the apparent velocity c_j , $j = 1, 2, \dots, 6$ are connected by the relation

$$c_1 \xi_1 = c_2 \xi_2 = \dots = c_6 \xi_6 = \omega, \tag{15}$$

at the surface $x_3 = 0$. Relation (15) may also be written in order to satisfy the boundary conditions (13) as follows:

$$\frac{\sin e_1}{c_1} = \frac{\sin e_2}{c_2} = \dots = \frac{\sin e_6}{c_6} = \frac{1}{c}. \tag{16}$$

Making use of (6), (10), (14), and (15) into thermally insulated boundary conditions (13), we obtain

$$\sum_{j=1}^6 A_{ij} A_j = 0, \quad i = 1, 2, 3, \quad (17)$$

where

$$A_{1j} = \begin{cases} a_j^1 + r_j a_j^2 - t_j a_j^3, & j = 1, 2, 3, \\ a_j^1 - r_j a_j^2 - t_j a_j^3, & j = 4, 5, 6, \end{cases}$$

$$A_{2j} = \begin{cases} b_j^1 + r_j b_j^2, & j = 1, 2, 3, \\ -b_j^1 + r_j b_j^2, & j = 4, 5, 6, \end{cases} \quad (18)$$

$$A_{3j} = \begin{cases} t_j c_j^1, & j = 1, 2, 3, \\ -t_j c_j^1, & j = 4, 5, 6, \end{cases}$$

and

$$a_j^1 = -\frac{i\omega C_{13}}{C_{11}} \frac{\sin e_j}{c_j}, \quad a_j^2 = \frac{i\omega C_{33}}{C_{11}} \frac{\cos e_j}{c_j},$$

$$a_j^3 = \frac{i\beta_3 T_0 s_j}{C_{11}}, \quad b_j^1 = \frac{i\omega C_{55}}{2C_{11} c_j} \frac{\cos e_j}{c_j}, \quad (19)$$

$$b_j^2 = \frac{i\omega C_{55}}{2C_{11} c_j} \frac{\sin e_j}{c_j}, \quad c_j^1 = \frac{\omega \cos e_j}{c_j}.$$

5.1. Incident qLD-Wave. In case of incident qLD-wave, $A_2 = A_3 = 0$. Dividing set of (17) throughout by A_1 , we obtain a system of three nonhomogeneous equations in three unknowns which can be solved by Gauss elimination method and we have

$$Z_i = \frac{A_{i+3}}{A_1} = \frac{\Delta_i^1}{\Delta}, \quad i = 1, 2, 3. \quad (20)$$

5.2. Incident qT-Wave. In case of incident qT-wave, $A_1 = A_2 = 0$ and thus we have

$$Z_i = \frac{A_{i+3}}{A_2} = \frac{\Delta_i^2}{\Delta}, \quad i = 1, 2, 3. \quad (21)$$

5.3. Incident qTD-Wave. In case of incident qTD-wave, $A_1 = A_2 = 0$ and thus we have

$$Z_i = \frac{A_{i+3}}{A_3} = \frac{\Delta_i^3}{\Delta}, \quad i = 1, 2, 3, \quad (22)$$

where $\Delta = |A_{ii+3}|_{3 \times 3}$ and Δ_i^p ($i = 1, 2, 3, p = 1, 2, 3$) can be obtained by replacing, respectively, the 1st, 2nd, and 3rd columns of Δ by $[-A_{1p} - A_{2p} - A_{3p}]^T$.

6. Numerical Results and Discussion

To illustrate the theoretical problem numerical results are presented. The Cobalt material was chosen for the purpose

FIGURE 1: Variations of the amplitude ratios $|Z_1|$ with frequency for incident qLD wave.

of numerical computation, whose physical data is given in Dhaliwal and Singh [20]:

$$C_{11} = 3.071 \times 10^{11} \text{ Nm}^{-2}, \quad C_{12} = 1.650 \times 10^{11} \text{ Nm}^{-2},$$

$$C_{13} = 1.027 \times 10^{11} \text{ Nm}^{-2}, \quad C_{33} = 3.581 \times 10^{11} \text{ Nm}^{-2},$$

$$C_{55} = 1.51 \times 10^{11} \text{ Nm}^{-2}, \quad \beta_1 = 7.04 \times 10^6 \text{ Nm}^{-2} \text{ K},$$

$$\beta_1 = 6.98 \times 10^6 \text{ Nm}^{-2} \text{ K}, \quad \rho = 8.836 \times 10^3 \text{ Kg m}^{-3},$$

$$K_1 = 6.90 \times 10^2 \text{ W m}^{-1} \text{ K}, \quad K_3 = 7.01 \times 10^2 \text{ W m}^{-1} \text{ K},$$

$$K_1^* = 1.313 \times 10^2 \text{ W sec}, \quad K_3^* = 1.54 \times 10^2 \text{ W sec},$$

$$c^* = 4.27 \times 10^2 \text{ J Kg K}, \quad T = 298 \text{ K}. \quad (23)$$

The physical quantities displacement, temperature, and amplitude ratios depend not only on time “ t ” and space coordinates but also on the characteristic parameter of the Green-Naghdi theory of type II and type III. Here, all variables are taken in nondimensional form. Figures 1, 2, 3, 4, 5, 6, 7, 8, and 9 exhibit the variations of amplitude ratio of reflected qLD, qTD, and qT waves, for incident qLD, qTD, and qT waves for transversely isotropic medium under GN type II and type III (TISO) and isotropic thermoelastic (ISO) medium at three different values of rotation $\Omega = 0, 2, 4$. In Figures 1–3, the graphical representation is given for the variation of amplitude ratios $|Z_1|$, $|Z_2|$, and $|Z_3|$ for incident

FIGURE 2: Variations of the amplitude ratios $|Z_2|$ with frequency for incident qLD wave.

FIGURE 3: Variations of the amplitude ratios $|Z_3|$ with frequency for incident qLD wave.

qLD wave. Figures 4–6 and 7–9, respectively, represent the similar situation, when qTD and qT waves are incident. In these figures the solid curves lines correspond to the case of TISO, while broken curves correspond to the case of ISO. The curves without center symbol represent the case without

FIGURE 4: Variations of the amplitude ratios $|Z_1|$ with frequency for incident qTD wave.

rotation (i.e., $\Omega = 0$), curves with center symbol ($-o-o-$) represent the variation corresponding to $\Omega = 2$, and curves with center symbol ($-\times-\times-$) represent the variation corresponding to $\Omega = 4$.

Incident qLD-Wave. Figures 1–3 illustrate the variation of amplitude ratios of $|Z_i|$, $i = 1, 2, 3$, with frequency for incident qLD-wave.

Incident qTD-Wave. Figures 4–6 illustrate the variation of amplitude ratios of $|Z_i|$, $i = 1, 2, 3$, with frequency for incident qT-wave.

Incident qT-Wave. Figures 7–9 illustrate the variation of amplitude ratios of $|Z_i|$, $i = 1, 2, 3$, with frequency for incident qTD-wave.

7. Conclusion

Effect of rotation on the reflection of waves from the free surface of transversely isotropic medium in the context of thermoelasticity with GN theory of types II and III has been discussed. It is depicted from the graphical results that anisotropy and rotation play an important role in amplitude ratios of reflected waves. It can be concluded from the graphs that the value of amplitude ratios increased for the cases of incident qTD and qT waves. However a reverse effect is depicted in the case of incident qLD wave. Also, the values of amplitude ratios get increased due to effect of anisotropy for all the cases.

FIGURE 5: Variations of the amplitude ratios $|Z_2|$ with frequency for incident qTD wave.

FIGURE 7: Variations of the amplitude ratios $|Z_1|$ with frequency for incident qT wave.

FIGURE 6: Variations of the amplitude ratios $|Z_3|$ with frequency for incident qTD wave.

FIGURE 8: Variations of the amplitude ratios $|Z_2|$ with frequency for incident qT wave.

FIGURE 9: Variations of the amplitude ratios $|Z_3|$ with frequency for incident qT wave.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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