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Thermoelastic Plane Waves in a Rotating Solid

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Summary

Plane waves in a homogeneous and isotropic unbounded thermoelastic solid rotating with a uniform angular velocity are discussed in the context of the generalised thermoelasticity theory of Green and Lindsay. The effects of rotation of the body on the phase velocity, energy loss and decay coefficient are discussed in some detail for waves of small and large frequencies, and for small coupling between the thermal and mechanical fields. Results of earlier works are deduced as particular cases of the more general results obtained here.

1. Introduction

The thermoelastic theory proposed by Green and Lindsay [1] has aroused much interest in recent years. Like some other thermoelasticity theories (e.g. [2], [3], [4]), this theory is a generalisation of the coupled thermoelasticity theory [5] and predicts a finite speed of propagation of thermal signals. Some problems revealing interesting phenomena which characterise this theory have been considered in [6]—[10]. Because of the experimental evidence available in favour of finiteness of heat propagation speed [11], these problems are of practical relevance too.

The purpose of the present paper is to study, in the context of the linearised theory of Green and Lindsay, the plane waves in a homogeneous and isotropic unbounded solid rotating with a uniform angular velocity. Since most of the large bodies like the earth, the moon and other planets have an angular velocity, this problem is practically more general than the corresponding problem concerned with a nonrotating body considered in [8]. In this paper we confine ourselves to the discussion of purely dilatational and purely shear waves, and our analysis is analogous to that presented in [8]. We find that if the axis of rotation of the body is not aligned with the direction of the displacement vector, the rotation causes dispersion of shear waves the speed of which, for a given frequency, is less than that of the same waves in a nonrotating body. The dilatational waves propagate in two modes and we analyse the effect of rotation of the body on the phase velocity, the decay coefficient and the specific loss of each of these two modes, by considering the cases of large and small frequencies and small coupling between the mechanical and thermal fields. In the absence of rotation of the body, our results reduce to those obtained in [8].

The counterpart of our problem in the context of the thermoelasticity theory of Lord and Shulman [2] was considered in [12]. We find that the results of [12] follow as particular cases of the corresponding results obtained in this paper. Further, because of some characteristic features of the theory of Green and Lindsay over the theory of Lord and Shulman (see, [10]), some of our results have no counterparts in [12]. Such results, as also others, are recorded at appropriate places.

It may be mentioned that the discussion of wave propagation problems in rotating elastic solids was initiated in [13]. A recent paper [14] has made use of the theory of Lord and Shulman to study magneto-thermoelastic plane waves in a rotating solid.

2. Basic Equations and Plane Wave Solution

We consider a homogeneous, isotropic and linear thermoelastic unbounded solid body rotating with a uniform angular velocity $\boldsymbol{\Omega}$. When this body undergoes dynamical deformation, the acceleration at any point with position vector $\boldsymbol{r}$($w \cdot r \cdot \boldsymbol{t} \cdot$ the origin of a system of axes rotating with the body) consists of two additional parts that do not appear in a nonrotating body: (i) the time-dependent part of the centripetal acceleration $\boldsymbol{\Omega} \times (\boldsymbol{\Omega} \times \boldsymbol{u})$, and (ii) the Coriolis acceleration $2\boldsymbol{\Omega} \times \dot{\boldsymbol{u}}$, where $\boldsymbol{u}$ is the displacement vector and $\dot{\boldsymbol{u}}$ is the velocity vector at the point. Accordingly, in the context of the linearised thermoelasticity theory of Green and Lindsay [1], the equation of motion and the equation of heat conduction for the body considered may be taken as follows:

$$\begin{aligned} v_2^2 \nabla^2 \boldsymbol{u} + (v_1^2 - v_2^2) \nabla \operatorname{div} \boldsymbol{u} - \frac{\beta}{\varrho K} \nabla(\theta + \alpha\dot{\theta}) \\ = \ddot{\boldsymbol{u}} + \boldsymbol{\Omega} \times (\boldsymbol{\Omega} \times \boldsymbol{u}) + 2\boldsymbol{\Omega} \times \dot{\boldsymbol{u}} \end{aligned} \tag{2.1}$$

$$\frac{k}{\varrho c} \nabla^2 \theta - \dot{\theta} - \alpha^* \ddot{\theta} - \frac{\beta\theta_0}{\varrho c K} \frac{\partial e_{rr}}{\partial t} = 0. \tag{2.2}$$

The symbols and the notation in these equations are as explained in [6]. The thermal constants α and α^* appearing in these equations satisfy the inequalities

$$\alpha \geqq \alpha^* \geqq 0. \tag{2.3}$$

It is evident that if $\alpha^* > 0$ (and consequently $\alpha > 0$) the Eq. (2.2) predicts a finite speed of propagation of thermal signals and that if $\alpha = 0$ (and consequently $\alpha^* = 0$), the Eqs. (2.1) and (2.2) reduce to those of the coupled theory [5]. The case $\alpha^* = 0$ and $\alpha > 0$ is also a valid one; in this case, the Eq. (2.1) continues to be affected by the temperature--rate, while the Eq. (2.2) predicts an infinite speed for the propagation of heat.

To investigate the propagation of plane waves, we seek solutions of the Eqs. (2.1) and (2.2) in the form

$$\left.\begin{aligned} \boldsymbol{u} &= \boldsymbol{A} \exp i(\omega t - \gamma \boldsymbol{n} \cdot \boldsymbol{r}) \\ \theta &= B \exp i(\omega t - \gamma \boldsymbol{n} \cdot \boldsymbol{r}), \end{aligned}\right\} \tag{2.4}$$

where $\boldsymbol{A}$ and B are arbitrary complex constants not both zero, ω is a positive real number, γ is a complex number, $\boldsymbol{n}$ is the unit vector along the direction of propagation, and $i = \sqrt{-1}$.

If we set $\gamma = p + iq$, the exponent in the Eqs. (2.4) reduces to

$$i(\omega t - \gamma \boldsymbol{n} \cdot \boldsymbol{r}) = i\omega \left\{t - \frac{1}{V}(\boldsymbol{n} \cdot \boldsymbol{r})\right\} + q(\boldsymbol{n} \cdot \boldsymbol{r}), \tag{2.5}$$

where $V = \dfrac{\omega}{p}$ is the phase speed of the waves. Obviously, for the waves to be physically realistic, we should have $q \leqq 0$ and $p > 0$. Further, only the real parts of the Eq. (2.4) are physically relevant. The Eqs. (2.4) then correspond to waves for which $\omega/2\pi$ is the frequency and $2\pi/p$ is the wavelength.

Substituting (2.4) into (2.1) and (2.2), we obtain

$$\begin{gathered}(\omega^2 + \Omega^2 - v_2{}^2\gamma^2)\,\boldsymbol{A} - \left\{(v_1{}^2 - v_2{}^2)\,\gamma^2(\boldsymbol{A} \cdot \boldsymbol{n}) - \frac{\beta i\gamma}{\varrho K}(1 + \alpha i\omega)\,B\right\}\boldsymbol{n} \\ -\{(\boldsymbol{\Omega} \cdot \boldsymbol{A})\boldsymbol{\Omega} + 2i\omega\,(\boldsymbol{\Omega} \times \boldsymbol{A})\} = 0\end{gathered} \tag{2.6}$$

$$\left(\frac{k\gamma^2}{\varrho c} + i\omega - \alpha^*\omega^2\right)B + \frac{\beta\theta_0\omega\gamma}{\varrho c K}(\boldsymbol{A} \cdot \boldsymbol{n}) = 0. \tag{2.7}$$

For purely dilatational waves, we have $\boldsymbol{A} \cdot \boldsymbol{n} = A$, the magnitude of $\boldsymbol{A}$; and for purely shear waves, we have $\boldsymbol{A} \cdot \boldsymbol{n} = 0$. From Eq. (2.7), it is evident that the thermal field remains uncoupled with purely shear waves, as in a non-rotating Hookean solid. Taking the scalar product with $\boldsymbol{A}$ of the Eq. (2.6), we obtain the equation

$$(\omega^2 + \Omega^2 \sin^2\phi - v_1{}^2\gamma^2)\,A + \frac{\beta i\gamma}{\varrho K}(1 + \alpha i\omega)\,B = 0 \tag{2.8}$$

for dilatational waves, and the equation

$$(\omega^2 + \Omega^2 \sin^2\phi - v_2{}^2\gamma^2) = 0 \tag{2.9}$$

for shear waves.

In Eqs. (2.8) and (2.9), ϕ denotes the angle between the axis of rotation of the body and the direction of the displacement vector, and $\Omega = |\boldsymbol{\Omega}|$. It is evident that if $\phi = 0$, the rotation of the body has no influence on the waves considered. We therefore assume that $\phi \neq 0$.

From Eq. (2.9), we obtain the speed of propagation of shear waves as

$$v_s = v_2\{1 + (\Omega/\omega)\sin^2\phi\}^{-1/2}. \tag{2.10}$$

We readily see that due to the presence of rotation of the body, the speed of shear waves is reduced from v_2 to v_s and that the waves are dispersive. For a given frequency, the speed is minimum when the axis of rotation of the body is perpendicular to the direction of the displacement.

For dilatational waves, the Eq. (2.7) yields

$$\frac{\beta\theta_0\omega\gamma}{\varrho cK} A + \left(\frac{k\gamma^2}{\varrho c} + i\omega - \alpha^*\omega^2\right) B = 0. \tag{2.11}$$

From Eqs. (2.8) and (2.11), it is clear that in the case of dilatational waves, the thermal field and the mechanical field are coupled together, as in a non-rotating body. The phase velocity equation of these waves is obtained, by eliminating the constants A and B from Eqs. (2.8) and (2.11), as follows:

$$(\omega^2 + \Omega^2 \sin^2\phi - v_1^2\gamma^2)\left(\frac{k\gamma^2}{\varrho c} + i\omega - \alpha^*\omega^2\right) - \frac{\beta^2\theta_0 i\omega\gamma^2}{\varrho^2K^2c}(1 + \alpha i\omega) = 0. \tag{2.12}$$

In order to analyse this equation, we introduce the quantities

$$\left.\begin{aligned} \chi &= \frac{\omega}{\omega^*}, \quad \xi = \frac{\gamma v_1}{\omega^*}, \quad \varphi = \frac{\Omega}{\omega^*}\sin\phi, \\ \delta &= \omega^*\alpha, \quad \eta = \omega^*\alpha^*, \quad \varepsilon = \frac{\beta^2\theta_0}{\varrho^2cK^2v_1^2}, \end{aligned}\right\} \tag{2.13}$$

where $\omega^* = \frac{\varrho c v_1^2}{k}$ is the characteristic frequency of the solid [5], [15].

With the aid of (2.13), the Eq. (2.12) reduces to the nondimensional form

$$[\chi^2 + \varphi^2 - \xi^2][\xi^2 + i\chi - \eta\chi^2] - \varepsilon\xi^2[i\chi - \delta\chi^2] = 0. \tag{2.14}$$

In the absence of rotation of the body this equation reduces to

$$\xi^4 - (\chi^2 + \eta\chi^2 + \varepsilon\delta\chi^2 - i\chi - i\varepsilon\chi)\,\xi^2 - i\chi^3 + \eta\chi^4 = 0, \tag{2.15}$$

which is in agreement with Eq. (2.13) of [8], apart from the notation.

The thermoelastic coupling factor ε is usually small [5]. If we neglect this factor, the Eq. (2.14) yields the following two equations:

$$\chi^2 + \varphi^2 - \xi^2 = 0; \qquad \xi^2 + i\chi - \eta\chi^2 = 0. \tag{2.16}$$

The first of these equations corresponds to a pure (nonthermal) elastic wave propagating with speed

$$v_e = v_1\{1 + (\Omega/\omega)^2 \sin^2\phi\}^{-1/2} \tag{2.17}$$

and the second equation corresponds to disturbances in the thermal field, which remain unaffected by the rotation of the body. The presence of rotation causes dispersion of the elastic wave and reduces its speed from v_1 to v_e given by (2.17). As in the case of shear waves, for a given frequency, the speed v_e is minimum when the axis of rotation is perpendicular to the displacement vector.

For $\varepsilon \neq 0$, the Eq. (2.14) is a quartic equation in ξ, the roots of which may be obtained as

$$\pm \frac{\sqrt{\chi}}{2}[(L - iM)^{1/2} \pm (N - iP)^{1/2}] \tag{2.18}$$

where

$$\left.\begin{aligned} L, N &= \chi(\Gamma^2 + \eta + \varepsilon\delta) \pm (2\chi)^{1/2}\,\Gamma a \\ M, P &= (1 + \varepsilon) \pm (2\chi)^{1/2}\,\Gamma b \\ a, b &= [(1 + \eta^2\chi^2)^{1/2} \pm \eta\chi]^{1/2} \end{aligned}\right\} \tag{2.19}$$

and

$$\Gamma^2 = 1 + \varphi^2/\chi^2 = 1 + (\Omega^2/\omega^2)\sin^2\phi. \tag{2.20}$$

Of the four roots for ξ given in (2.18), only two roots yield nonpositive values for the decay coefficient q. These two roots correspond to two modes of propagation; one of these modes is predominantly elastic and the other is predominantly thermal in nature. We denote the value of ξ associated with the former mode by ξ_1, and the other by ξ_2.

The general analysis of the waves on the basis of the roots given by (2.18) is quite complicated. We therefore confine ourselves to the analysis of the effect of rotation of the body on the phase velocity, the decay coefficient and the specific loss in three special cases which correspond to waves of small frequency, waves of large frequency and weak coupling between the mechanical and thermal fields. Throughout our further analysis, we assume that Γ is a constant and that [8]

$$\delta < \frac{1}{(1+\varepsilon)^2}.$$

For ready comparison with earlier works, we consider the dimensionless phase speed V^* and the dimensionless decay coefficient q^* defined through the relations

$$V^* = V/v_1 \quad \text{and} \quad q^* = qv_1/\omega^*. \tag{2.21}$$

We further note that the specific loss, which is defined as the ratio of energy dissipated per stress cycle to the total vibrational energy, is given by [8]

$$L = 4\pi q/p.$$

3. Special Cases

Case (i)

We first consider waves for which $\chi \ll 1$. Paralleling the calculations in [8], we find in this case that

$$\xi_1 \cong \frac{\Gamma\chi}{(1+\varepsilon)^{1/2}} - \frac{i}{2}\,\frac{\varepsilon + (1+\varepsilon)(\eta+\varepsilon\delta) - (1+\varepsilon)^2\eta}{(1+\varepsilon)^{5/2}}\,\Gamma^3\chi^2, \tag{3.1}$$

$$\xi_2 \cong (1-i)\left[\frac{\chi(1+\varepsilon)}{2}\right]^{1/2} + \frac{\varepsilon + (1+\varepsilon)(\eta+\varepsilon\delta)}{(1+\varepsilon)^{3/2}}\,(1+i)\,(\chi/2)^{3/2}. \tag{3.2}$$

From (3.2) it is clear that the rotation of the body does not influence the thermal mode. The non-dimensional phase speed, the specific loss and the decay coefficient associated with the elastic mode are respectively given by

$$\left.\begin{aligned} V_1^* &= (1+\varepsilon)^{1/2}/\Gamma, \\ L_1^* &= 2\pi\chi[1+(\delta-\eta)(1+\varepsilon)]\frac{\varepsilon}{(1+\varepsilon)^2}\Gamma^2, \\ q_1^* &= \frac{1}{2}\chi^2\Gamma^3\frac{\varepsilon}{(1+\varepsilon)^{5/2}}[1+(\delta-\eta)(1+\varepsilon)]. \end{aligned}\right\} \tag{3.3}$$

From these expressions, it is clear that, due to the presence of rotation of the body, the speed is reduced by a factor $1/\Gamma$, the specific loss is increased by a factor Γ^2 and the decay coefficient is increased by a factor Γ^3.

In the absence of rotation of the body, we have $\Gamma = 1$ and the expressions (3.3) reduce to the expressions (2.38)—(2.40) of [8].

In the special case when $\eta = \delta$, the expressions (3.3) reduce to

$$\left.\begin{aligned} L_1^* &= [2\pi\chi\varepsilon/(1+\varepsilon)^2]\,\Gamma^2, \\ V_1^* &= (1+\varepsilon)^{1/2}/\Gamma, \\ q_1^* &= \frac{1}{2}\frac{\varepsilon}{(1+\varepsilon)^{5/2}}\chi^2\Gamma^3. \end{aligned}\right\} \tag{3.4}$$

It is interesting to note that the expressions (3.4) are identical with the corresponding expressions obtained in the context of the theory of Lord and Shulman, (see, [12], Eq. (17)]. The expressions (3.4) are also valid in the coupled theory which corresponds to the case $\eta = \delta = 0$.

Comparing the expressions (3.3) and (3.4), we see that, while the phase speed is the same in all the three theories, the energy loss and the decay coefficient in the theory of Green and Lindsay differ from those in the other two theories. In fact, in the Green and Lindsay theory, the specific loss and the decay coefficient are increased by

$$2\pi\chi\Gamma^2\varepsilon(\delta-\eta)/(1+\varepsilon) \quad \text{and} \quad \chi^2\Gamma^3\varepsilon(\delta-\eta)/2\,(1+\varepsilon)^{3/2}$$

respectively.

Thus, the behaviour of small frequency elastic mode in the theory of Green and Lindsay differs from that in the theory of Lord and Shulman and the coupled theory.

Case (ii)

We now consider waves for which $\frac{1}{\chi} \ll 1$. Paralleling the calculations in [8], we find in this case that

$$\left.\begin{aligned} \xi_1 &= \frac{1}{2}\chi[R+S] - \frac{i}{4}\frac{1}{\sqrt{\eta}}[X-Y] \\ \xi_2 &= \frac{1}{2}\chi[R-S] - \frac{i}{4}\frac{1}{\sqrt{\eta}}[X+Y] \end{aligned}\right\} \tag{3.5}$$

where

$$\left.\begin{aligned} R, S &= \left(\Gamma^2 \pm 2\Gamma\sqrt{\eta} + \eta + \varepsilon\delta\right)^{1/2} \\ X, Y &= \frac{\Gamma \pm (1+\varepsilon)\sqrt{\eta}}{(\Gamma^2 \pm 2\Gamma\sqrt{\eta} + \eta + \varepsilon\delta)^{1/2}}. \end{aligned}\right\} \tag{3.6}$$

It is clear that, unlike in the case (i), the rotation of the body influences both the modes. The phase speed, the specific loss and the decay coefficients corresponding to these modes are given by

$$\left.\begin{aligned} V_1^* &= \frac{1}{\Gamma}\left(1 - \frac{1}{2}\frac{\varepsilon\delta}{\Gamma^2}\right); \quad L_1 = \frac{2\pi\varepsilon}{\chi\Gamma^2}\left(1 + \frac{\delta+\eta}{\Gamma^2}\right) \\ q_1^* &= \frac{\varepsilon}{2\Gamma}\left(1 + \frac{\delta+\eta}{\Gamma^2}\right) \end{aligned}\right\} \tag{3.7}$$

$$\left.\begin{aligned} V_2^* &= \frac{1}{\sqrt{\eta}}\left(1 + \frac{1}{2}\frac{\varepsilon\delta}{\Gamma^2}\right); \quad L_2 = \frac{2\pi}{\chi\eta}\left(1 - \frac{\varepsilon\eta}{\Gamma^2}\right) \\ q_2^* &= \frac{1}{2\sqrt{\eta}}\left[1 - \frac{\varepsilon}{\Gamma^2}\left(\eta + \frac{1}{2}\delta\right)\right]. \end{aligned}\right\} \tag{3.8}$$

In the absence of rotation of the body, the expressions (3.7) and (3.8) reduce to the expressions (2.51)—(2.53) and (2.57)—(2.59) of [8].

In the special case when $\eta = \delta = m$, say, the expression (3.7) and (3.8) reduce respectively, to

$$\left.\begin{aligned} V_1^* &= \frac{1}{\Gamma}\left(1 - \frac{1}{2}\frac{\varepsilon m}{\Gamma^2}\right), \quad L_1 = \frac{2\pi\varepsilon}{\chi\Gamma^2}\left(1 + \frac{2m}{\Gamma^2}\right) \\ q_1^* &= \frac{\varepsilon}{2\Gamma}\left(1 + \frac{2m}{\Gamma^2}\right) \end{aligned}\right\} \tag{3.9}$$

$$\left.\begin{aligned} V_2^* &= \frac{1}{\sqrt{m}}\left(1 + \frac{1}{2}\frac{\varepsilon m}{\Gamma^2}\right), \quad L_2 = \frac{2\pi}{\chi m}\left(1 - \frac{\varepsilon m}{\Gamma^2}\right) \\ q_2^* &= \frac{1}{2\sqrt{m}}\left(1 - \frac{3\varepsilon m}{2\Gamma^2}\right). \end{aligned}\right\} \tag{3.10}$$

As $m \to 0$, we find from Eqs. (3.10) that $V_2^*, L_2, q_2^* \to \infty$. This is in agreement with the prediction of the coupled theory that the thermal disturbances propagate with infinite speed. The expressions (3.9), which correspond to the elastic mode, reduce, as $m \to 0$, to

$$V_1^* = \frac{1}{\Gamma}, \quad L_1 = \frac{2\pi\varepsilon}{\chi\Gamma^2}, \quad q_1^* = \frac{\varepsilon}{2\Gamma} \tag{3.11}$$

which are valid in the context of the coupled theory.

We readily verify that the expressions in (3.9) and (3.10) are in agreement with the expressions (21)—(23) and (24)—(26) obtained in [12]. Comparing the expressions (3.7) and (3.8) with (3.9) and (3.10), we find that the qualitative behaviour of the elastic mode in the coupled as well as in the theories of Lord and Shulman and of Green and Lindsay is one and the same. In all the three theories, the phase speed, the specific loss and the decay coefficients of this mode are reduced due to the rotation of the body. The effect of rotation on the thermal mode in the theories of Lord and Shulman and Green and Lindsay is to reduce the phase speed and to increase the specific loss and the decay coefficient.

Comparing the expressions (3.7) with (3.11), we find that in the theory of Green and Lindsay, the phase speed is decreased by $\frac{1}{2}\,\varepsilon\delta/\Gamma^3$ and the specific loss and the decay coefficient are increased by

$$2\pi\varepsilon(\delta + \eta)/\chi\Gamma^4 \quad \text{and} \quad \varepsilon(\delta + \eta)/2\Gamma^3$$

respectively.

Case (iii)

If we assume that ε, δ, $\eta \ll 1$ with no restriction on χ, we find, by carrying out calculations similar to those in [8], that for the elastic mode the specific loss has a local maximum when

$$\chi = \frac{1}{\Gamma^2}\,(1 + \varepsilon + \eta/\Gamma^2). \tag{3.12}$$

This result is valid in the context of the theory of Lord and Shulman also, as noted in [12]. Further, for the thermal mode, the specific loss has no extremum value in the cases: (i) $\varepsilon = 0$, (ii) $\varepsilon = \eta = 0$, and (iii) $\delta = \eta$. In the case when $\eta = 0$, $\delta \neq 0$ and $\varepsilon \neq 0$, the specific loss for the thermal mode *does* have a local minimum at

$$\chi = (1 + \varepsilon)/\Gamma^2. \tag{3.13}$$

It has been noted in [12] that the specific loss for the thermal mode has *no* local extremum; this result is in agreement with our observation made above for the case $\delta = \eta$.

Thus, unlike in the uncoupled and generalised (Lord and Shulman) thermoelasticity theories, there can occur, in the theory of Green and Lindsay, a local minimum for the specific loss for the thermal mode.

In the absence of rotation of the body, the expression (3.13) reduces to

$$\chi = 1 + \varepsilon, \tag{3.14}$$

which is referred to as the "critical frequency" in [8] and [16]. A comparison of the expressions (3.13) and (3.14) shows that the rotation of the body reduces the critical frequency by a factor $1/\Gamma^2$.

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