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A Review on Two-Temperature Thermoelasticity

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ABSTRAC: *The present paper deals with the review on the development of the theory of two-temperature thermoelasticity. The basic equations of two-temperature thermoelasticityin context of Lord and Shulman [6] theory and Green and Naghdi[15] theories of generalized thermoelasticity are reviewed. Relevant literature on two-temperature thermoelasticity is also reviewed.*

KeyWords:*Two-temperature, generalized thermoelasticity, basic equations*

1. INTRODUCTION

Thermoelasticity deals with the dynamical system whose interactions with the surrounding include not only mechanical work and external work but the exchange of heat also. Changes in temperatures causes thermal effects on materials. Some of these thermal effects include thermal stress, strain, and deformation. Thermal deformation simply means that as the "thermal" energy (and temperature) of a material increases, so does the vibration of its atoms/molecules and this increased vibration results in what can be considered a stretching of the molecular bonds - which causes the material to expand. Of course, if the thermal energy (and temperature) of a material decreases, the material will shrink or contract. Thus, thermoelasticity is based on temperature changes induced by expansion and compression of the test part. Thus, the theory of thermoelasticity is concerned with predicting the thermomechanical behaviour of elastic solids. It represents a generalization of both the theory of elasticity and theory of heat conduction in solids.The theory of thermoelasticity was founded in 1838 by Duhamel [1], who derived the equations for the strain in an elastic body with temperature gradients. Neumann [2], obtained the same results in 1841.

However, the theory was based on independence of the thermal and mechanical effects. The total strain was determined by superimposing the elastic strain and the thermal expansion caused by the temperature distribution only. The theory thus did not describe the motion associated with the thermal state, nor did it include the interaction between the strain and the temperature distributions. Hence, thermodynamic arguments were needed, and it was Thomson [3], in 1857 who first used the laws of thermodynamics to determine the stresses and strains in an elastic body in response to varying temperatures.

There are three types of thermoelasticity i.e. uncoupled, coupled and generalized thermoelasticity. The theory of classical uncoupled theory of thermoelasticity predicts two phenomena not compatible with physical observations. First, the equation of heat conduction of this theory does not contain any elastic term contrary to the fact that the elastic changes produce heat effects. Second, the heat equation is of parabolic type predicting infinite speeds of propagation for heat waves. The classical uncoupled and coupled thermoelastic theories of Biot[4] and Nowacki[5] have an inherent paradox arising from the assumption that the thermal waves propagate at infinite velocity and it is a physically unreasonable result.

Generalized thermoelasticity theories have been developed with the objective of removing the paradox of infinite speed of heat propagation inherent in the conventional coupled dynamical theory of thermoelasticity in which the parabolic type heat conduction equation is based on Fourier's law of heat conduction. This newly emerged theory which admits finite speed of heat propagation is now referred to as the hyperbolic thermoelasticity theory, since the heat equation for rigid conductor is hyperbolic-type differential equation. The first generalized theory of thermoelasticity is due to Lord and Shulman [6] who coupled elasticity with a way in which temperature can travel with a finite wave speed. The approach of Lord and Shulman [6] begins with the full nonlinear equations but they are mainly interested in developing a linear theory since they begin with "small strains and small temperature changes". The second generalization to the coupled theory is known as the generalized theory with two relaxation times. Muller[7] introduced the theory of generalized thermoelasticity with two relaxation times. A more explicit version wasthen introduced by Green and Laws [8], Green and Lindsay [9] and independently by Suhubi[10]. In this theory the temperature rates are considered among the constitutive variables. This theory also predicts finite speeds of propagation for heat and elastic waves similar to the Lord-Shulman theory. It differs from the latter in that Fourier's law of heat conduction is not violated if the body under consideration has a centre of symmetry. Dhaliwal and Sherief[11] extended the Lord and Shulman (L-S) theory for an anisotropic media. Chandrasekharaiah[12]referred to this wave-like thermal disturbance as "second sound". These writers investigate the propagation of a thermal pulse in a thermoelastic shell employing each of the linearized equations for the three thermoelastic theories, Classical, Lord-Shulman and Green-Lindsay. Their numerical results typically demonstrates that Classical theory leads to a smooth pulse while that of Lord-Shulman is less smooth showing discontinuities in derivatives. The theory of Green and Lindsay [9] leads to strong pulse behaviour displaying distinct jumps such as to the behaviour of stainless steel run tanks which holds cryogenic liquids for rocket fuel at NASA's John C. Stennis Space Centre, the strong pulse solution is definitely of interest.

Green and Naghdi[13-15] proposed three new thermoelastic theories based on entropyequality than the usual entropy inequality. The constitutive assumption for the heat flux vector are different in each theory. Thus they obtained three theories which are called thermoelasticity of type I, thermoelasticity of type II and thermoelasticity of type III. Green and Naghdi[15] postulated a new concept ingeneralizedthermoelasticity which is called the thermoelasticity without energy dissipation. The principal feature of this theory is that in contrast to the classical thermoelasticity, the heat flow does not involve energy dissipation. Also, the samepotential function which is defined to derive the stress tensor is used to determine the constitutive equation for the entropy flux vector. In addition, the theory permits the transmission of heat as thermal waves at finite speeds. Dhaliwal and Wang [16] formulated the heat-flux dependent thermoelasticity theory for an elastic material with voids. This theory includes the heat-flux among the constitutive variables and assumes an evolution equation for the heat-flux. Hetnarski and Ignaczack[17] examined five generalizations to the coupled theory and obtained a number of important analytical results. Literature on generalized thermoelasticity is available in the books like "Thermoelastic Solids" by Suhubi[10], "Thermoelastic Deformations" by lesan and Scalia[18], "Thermoelastic Models of Continua" by Iesan [19], "Thermoelasticity with Finite Wave Speeds" by Ignaczak and Ostoja-Starzewski [20] etc.

II.LITERATURE SURVEY

Chen and Gurtin[21] and Chen et al. [22-23] have formulated a theory of heat conduction in deformable bodies, which depends on two distinct temperatures, the conductive temperature Φ and the thermodynamic temperature T. The two-temperature theory involves a material parameter $a^* > 0$. The limit $a^* \rightarrow 0$ implies that $\Phi \rightarrow T$ and hence classical theory can be recovered from two-temperature theory. The two-temperature model has been widely used to predict the electron and phonon temperature distributions in ultrashort laser processing of metals. For time-independent situations, the difference between these two temperatures is proportional to the heat supply, and in the absence of any heat supply, the two temperatures are identical. For time-dependent problems, however, and for wave propagation problems in particular, the two temperatures are in general different, regardless of the presence of a heat supply. The two temperatures T and Φand the strain are found to have representations in the form of a travelling wave plus a response, which occurs instantaneously throughout the body. Warren and Chen [24] investigated the wave propagation in the two-temperature theory of thermoelasticity. Following Boley and Tolins, [25], they studied the wave propagation in the two-temperature theory of coupled thermoelasticity.

Youssef [26] developed a new theory of generalized thermoelasticity by taking into account the theory of heat conduction in deformable bodies, which depends on two distinct temperatures, the conductive temperature and the thermodynamic temperature where the difference between these two temperatures is proportional to the heat supply. Youssef and Al-Harby[27] studied the state-space approach of two-temperature generalized thermoelasticity of infinite body with a spherical cavity subjected to different types of thermal loading . Youssef and Al-Lehaibi[28]applied the state space techniques of two-temperature generalized thermoelasticityto one-dimensional problemof half-space subjected to thermal shock and traction free. Youssef [29] studied two-dimensional problem of a two-temperature generalized thermoelastic half-space subjected to ramp type heating. Youssef andBassiouny[30]used the theory of two-temperature generalized thermoelasticity, based on the theory of Youssef to solve boundary value problems of one-dimensional finite piezoelectric rod with loading on its boundary with different types of heating.Abbas and Youssef [31]analysed a finite element model of two-temperature generalized magneto-thermoelasticity.Ezzat et.al.[32] studied the two-temperature theory in generalized magneto-thermo-viscoelasticity. Mukhopadhyay and Kumar[33] studiedthermoelastic interactions on two-temperature generalized thermoelasticity in an infinite medium with a cylindrical cavity.Youssef[34] constructed a model of two-temperature generalized thermoelasticity for an elastic half-space with constant elastic parameters. Ezzat and Awad[35] derived the equations of motion and the constitutive relations for the theory of micropolar generalized two-temperature thermoelasticity. Kaushal et al. [36]solved the boundary-value problem in frequency domain in the context of two generalized theories of thermoelasticity (Lord and Shulman, Green and Lindsay) by employing the Hankel transform. Kumar et.al.[37]established a variational principle of convolutional type and a reciprocal principle in the context of linear theory of two-temperature generalized thermoelasticity, for a homogeneous and isotropic body. Kumar and Mukhopadhyay[38] investigated the propagation of harmonic plane waves in elastic media in the context of the linear theory of two-temperature-generalized thermoelasticity. Youssef [39] solved a problem of thermoelastic interactions in an elastic infinite medium with cylindrical cavity thermally shocked at its bounding surface and subjected to moving heat source with constant velocity. Youssef and El-Bary[40]studied two-temperature generalized thermoelasticity with variable thermal conductivity.Awad[41] write a note on the spatial decay estimates in non-classical linear thermoelastic semi-cylindrical bounded domains. El-Karamany[42] presented two-temperature theory in linear micropolarthermoviscoelastic anisotropic solid.El-Karamany and Ezzat [43] introduced the two general models of fractional heat conduction law for non-homogeneous anisotropic elastic solid, obtained the constitutive equations for the two-temperature fractional thermoelasticity theory, proved uniqueness and reciprocal theorems and established the convolutional variational principle.El-Karamany and Ezzat[44] gave the constitutive laws for two-temperature Green–Naghdi theories and proved that the two-temperature thermoelasticity theory admits dissipation of energy and the theory of elasticity without energy dissipation is valid only when the two-temperatures coincide.Ezzat and El-Karamany[45] studied the two-temperature theory in generalized magneto-thermoelasticity with two relaxation times. Ezzat and El-Karamany[46] constructed fractional order heat conduction law in magneto-thermoelasticity involving two temperatures.Miglani and Kaushal [47] studied theaxi-symmetric deformation in generalized thermoelasticity with two temperatures.Mukhopadhyayet. al.[48] presented the theory of two-temperature thermoelasticity with two phase-lags. Singh and Bijarnia[49] studied the propagation of plane waves in anisotropic two-temperature generalized thermoelasticity.Youssef [50] presented a theory of two-temperature thermoelasticity without energy dissipation. Banik and Kanoria [51] studied the effects of three-phase-lag on two-temperature generalized thermoelasticity for infinite medium with spherical cavity.Bijarnia and Singh [52] studied the propagation of plane waves in an anisotropic generalized thermoelastic solid with diffusion. Ezzat et al. [53] introduced both modified Ohm's and Fourier's laws to the equations of the linear theory of magneto-thermo-viscoelasticity involving two-temperature theory, allowing the second sound effects obtained the exact formulas of temperature, displacements, stresses, electric field, magnetic field and current density.Singh and Bala[54] studied the reflection of P and SV waves from the free surface of a two-temperature thermoelastic solid half-space.

III. THE BASIC EQUATIONS OF TWO-TEMPERATURE GENERALIZED THERMOELASTICITY

Following Youssef [26], the basic equations of two-temperature anisotropic thermoelasticity in context of Lord and Shulman [6] theory are

The stress-strain temperature relations :

$\sigma_{ij} = c_{ijkl}\, e_{kl} - \gamma_{ij}\, (T - \Phi_0)$ (1)

The displacement-strain relation :

$e_{ij} = 1/2(u_{i,j} + u_{j,i})$ (2)

The equation of motion:

$\rho\, \ddot{u}_i = \sigma_{ji,j} + \rho F i$(3)

The energy equation :

$-q_{i,i} = \rho T_0 \dot{S}$ (4)

The modified Fourier's law :

$-K_{ij}\Phi_{,j} = q_i + \tau_0\, \dot{q}_i$ (5)

The equations (1) to (5) gives the basic equations of isotropic two-temperature thermoelasticity in context of Lord and Shulman theory as :

$K\Phi_{,ii} = \rho c_E(\dot{\theta} + \tau_0 \ddot{\theta}) + \gamma T_0(\dot{e}_{kk} + \tau_0 \ddot{e}_{kk})$ (6)

$\rho\ddot{u}_i = (\lambda + \mu)u_{j,ij} + \mu u_{i,jj} - \gamma\theta{,i} + \rho F i$(7)

$\sigma_{ij} = 2\mu\, e_{ij} + (\lambda\, e_{kk} - \gamma\theta)\delta ij$ (8)

Following Youssef [50], the basic equations for isotropic two-temperature thermoelasticity in context of Green and Naghdi[15] theory are :

The heat equations :

$T_0\gamma\, \delta_{ij}\, \ddot{e}_i + \rho c_E \ddot{T} = K^*\Phi_{,ii}$ (9)

The constitutive equation :

$\sigma_{ij} = 2\mu\, e_{ij} + (\lambda\, e_{kk} - \gamma\theta)\delta_{ij}$ (10)

The equations of motion :

$\rho\ddot{u}_i = (\lambda + \mu)u_{j,ij} + \mu u_{i,jj} - \gamma T{,i} + \rho F i$(11)

Here, T is the mechanical temperature, $\Phi_0 = T_0$, is the reference temperature, where $\theta = |T - T_0|$ and $\frac{\theta}{T_0} << 1$, σ_{ij} is the stress tensor, e_{kl} is the strain tensor, c_{ijkl} is tensor of elastic constants, γ_{ij} is stress-temperature tensor, F_i is the external forces per unit mass, ρ is the mass density, q_i is the heat conduction vector, K_{ij} is the thermal conductivity tensor, c_E is the specific heat at constant strain, $u_i$are the components of the displacement vector, S is the entropy per unit mass, τ_0 is the thermal relaxation time (which will ensure that the heat conduction equation will predict finite speeds of heat propagation), $\gamma = (3\lambda + 2\mu)\alpha_t$, and α_t is the thermal expansion coefficient, λ and μ are called Lame's elastic constants, δij is the Kronecker delta symbol,$\Phi$is the conductive temperature and satisfying the relation$\Phi - T = a^*\,\Phi_{,ii}$, where $a^* > 0$, is the two-temperature parameter and K, K^* are material characterstic constants.

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