IOSR Journal of Mathematics (IOSR-JM)
e-ISSN: 2278-5728, p-ISSN:2319-765X. Volume 10, Issue 1 Ver. III. (Feb. 2014), PP 63-69
www.iosrjournals.org

A problem of dynamic Response of a Thermoelastic Half-Space to a Thermal Load

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Abstract: *In this problem the distribution due to thermal source in a homogenous isotropic thermoelastic half space has been investigated by applying a combination of Laplace and Fourier transform technique in the context of Generalized theories of thermoelasticity. The inverse transform integral have been evaluated by using Cagniard method to obtain the exact closed algebraic expressions for the displacement and temperature as function of time and horizontal distances, which are valid for all epicentral distances. The displacement and temperature so obtained in the physical domain have been computed.*

I. Formulation of the Problem

We consider thermal and elastic wave motion of small amplitude in homogenous isotropic solid at uniform temperature T_0. We take z-axis of rectangular Cartesian coordinate system oxyz pointing normally in to the half space, which is suddenly applied by $z \geq 0$. The wave motion is caused by a thermal line load, which is suddenly applied at the free surface of initially undistributed elastic solid. The load is applied along the y-axis, which implies that y-component of displacement vector vanishes everywhere and remaining quantities are independent of y-coordinate. Using the fixed Cartesian coordinates system oxyz with origin at any point o of plane boundary z=0. The displacement vector $\vec{u}(x,z,t)=(u,0,w)$ and the temperature change T (x,y,t) in linear generalized thermoelasticity satisfy the governing differential equations

$$(\lambda+\mu)\nabla\left(\nabla.\vec{u}\right)+\mu\nabla^2\vec{u}-\beta\nabla(T+\delta_{2k}t_1\dot{T})=\rho\ddot{\vec{u}}, \qquad (1)$$

$$K\nabla^2T-\rho C_e(T+t_0\dot{T})=\beta_eT_0\left(\frac{\partial}{\partial t}+\delta_{1k}t_0\frac{\partial^2}{\partial t^2}\right)\nabla.\vec{u}, \qquad (2)$$

where $\beta_e=(3\lambda+2\mu)\alpha_T$. is coefficient of thermoelastic coupling, the superposed dot represent time differentiation, λ, μ the Lame's parameters, α_T is the coefficient of linear thermal expansion, ρ is the density, C_e is the specific heat at constant strain, K, is the coefficient of thermal conductivity and t_0, t_1 are thermal relaxation times. δ_{ik} is Kronecker delta and k=1 for Lord Shulman (LS) theory and k=2 for Green-Lindsay (GL) theory. The relaxation times tt_1 satisfy the inequalities $t_1 \geq t_0 \geq 0$ (3)
in case of (GL) theory only.
We consider following boundary and initial conditions
$\tau_{zz}=0,\ \tau_{xz}=0, T_{,z}=T_0\delta(x)f(t), on\, z=0$ (4) where T_0 is constant, δ (x) is Dirac Delta function, f(t) is arbitrary but sufficiently well behaved function of time. The condition at infinity requires that solution should as z becomes large. Finally; the initial conditions are such that the medium is at rest for t less than zero.

Solution of the problem:

We define the quantities

$$\delta^2=c_2{}^2/c_1{}^2,\ c_1{}^2=(\lambda+2\mu)/\rho,\quad c_2{}^2=\mu/\rho,$$

$$x'=\omega^*x/c_1,\ t'=\omega^*t,\qquad T'=T/T_0,\ \omega^*=C_e(\lambda+2\mu)/K,$$

$$\in=\frac{\beta^2T_0}{\rho C_e(\lambda+2\mu)},\ \omega'=\frac{\omega}{\omega^*},\ t_1'=\omega^*t_1,\ t_0'=\omega^*t_0,\quad \tau'=\tau_{zz}/\beta T_0, \tau'_{zx}=\tau_{xz}/\beta T_0, \quad (5)$$

Using quantities (5) in equation (1) and (2), we obtain the equation of motion and heat conduction in the dimensionless form as

$$(1-\delta^2)\nabla\nabla.\vec{u}+\delta^2\nabla^2\vec{u}-\nabla(T+\delta_{2k}\dot{T})=\ddot{\vec{u}} \qquad (6)$$

$$\nabla^2 T - (\dot{T} + t_0 \ddot{T}) = \in \nabla(\dot{\vec{u}} + \delta_{1K} T_0 \ddot{\vec{u}}) \qquad (7)$$

We introduced the potential functions ϕ, ψ through the relation

$$\vec{u} = \nabla\phi + \nabla \times \vec{\psi} \qquad (8)$$

Upon using equation (8) in equation (6) and (7) we obtain

$$\nabla^2\phi - \ddot{\phi} = T + \delta_{2k} t_1 \dot{T} \qquad (9)$$

$$\nabla^2\psi - \frac{1}{\delta^2}\ddot{\psi} = 0 \qquad (10)$$

$$\nabla^2 T - (\dot{T} + t_0 \ddot{T}) = \varepsilon \nabla^2 (\dot{\phi} + t_0 \delta_{1k} \ddot{\phi}) \qquad (11)$$

where

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial z^2}$$

to solve the system of equations (9) to (11) we use Laplace transform defined by

$$L\{\phi\,(x,t)\} = \int_0^\infty \phi(x,t) e^{-pt} dt = \bar{\phi}\,(x,p) \qquad (12)$$

with respect to time t and then Fourier transform defined by

$$F\left\{\bar{\phi}(x,p)\right\} = \int_{-\infty}^{+\infty} \bar{\phi}(x,p) e^{-iqx} dx = \hat{\phi}(q,p) \qquad (13)$$

With respect to space variable x

To evaluate the inverse of Laplace transform we use Cagniard method. This method consist of recasting the integral into Laplace transform of unknown function, this allowing us to write down the inverse transform by inspection. Mathematically, this procedure is based upon rather elementary observation that

$$L^{-1}\left\{\frac{P^n}{2\pi}\int_{t_0}^{\infty} f(t) e^{-pt} f(0) - p^{n-1} f(0) \ldots\ldots f^n(0)\right\} = \frac{d^n}{dt^n} f(t) H(t - t_0) \qquad (14)$$

and that

$$L^{-1}\left\{\frac{1}{2\pi p^n}\int_{t_0}^{\infty} f(t) e^{-pt} dt\right\} = \int_1\int_2\int_3 \ldots\ldots\ldots\int_n f(t) H(\bar{t} - t_0), n = 0,1,2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots (15)$$

Where L^{-1} stands for inverse Laplace transform.

In order to apply this technique, Laplace transform parameter p is to be isolated as required by the equations (14) and (15). Due to the existence of the damping term in the temperature field equation (11), isolation of p is impossible. However this isolation of p may be achieved for small time i.e. if we assume p to be large. Hence an expansion in inverse power of p followed by change of variable q=pη leads to,

$$u = L^{-1}\left\{\bar{u}_1 + \bar{u}_2 + \bar{u}_3\right\} \qquad (16)$$

$$w = L^{-1}\left\{\bar{w}_1 + \bar{w}_2 + \bar{w}_3\right\} \qquad (17)$$

$$T = L^{-1}\left\{\bar{T}_1 + \bar{T}_2 + \bar{T}_3\right\} \qquad (18)$$

where

$$\bar{u}_k = \frac{1}{2\pi}\int_{-\infty}^{+\infty}\left(\frac{A_{1k}}{p} + \frac{B_{1k}}{p^2} + \frac{C_{1k}}{p^3}\right) e^{-p(\alpha_{k1} + i\eta x)}\, d\eta$$

$$= \frac{1}{\pi}\,\mathrm{Im}\int_0^{+\infty}\left(\frac{A_{1k}}{p} + \frac{B_{1k}}{p^2} + \frac{C_{1k}}{p^3}\right) e^{-p(\alpha_{k1} + i\eta x)}\, d\eta \qquad (19)$$

$$\bar{w}_k = \frac{1}{2\pi}\int_{-\infty}^{+\infty}\left(\frac{A_{2k}}{p}+\frac{B_{2k}}{p^2}+\frac{C_{2k}}{p^3}\right)e^{-p(\alpha_{k1}+i\eta x)}\,d\eta$$

$$=\frac{1}{\pi}\operatorname{Re}\int_{0}^{+\infty}\left(\frac{A_{2k}}{p}+\frac{B_{2k}}{p^2}+\frac{C_{3k}}{p^3}\right)e^{-p(\alpha_{k1}+i\eta x)}\,d\eta \qquad (20)$$

$$\bar{T}_k = \frac{1}{2\pi}\operatorname{Re}\int_{-\infty}^{+\infty}\left(\frac{A_{3k}}{p}+\frac{B_{2k}}{}+\frac{C_{3k}}{p^3}\right)e^{-p(\alpha_{k1}+i\eta x)}\,d\eta$$

$$=\frac{1}{\pi}\operatorname{Re}\int_{0}^{+\infty}\left(\frac{A_{3k}}{}\frac{B_{3k}}{p}+\frac{C_{3k}}{p^3}\right)e^{-p(\alpha_{k1}+i\eta x)}\,d\eta \qquad (21)$$

The coefficients A_{ik}, B_{ik}, C_{ik}, i=1,2,3 have their own values and here

$$\alpha^2{}_{11},\alpha^2{}_{21}=\eta^2+M^2{}_{1,2},\alpha^2{}_{31}=\eta^2+\frac{1}{\delta^2} \qquad (22)$$

$$M^2{}_{1,2}=\frac{1}{2}\left[1+t_0+\varepsilon L_k \pm\left\{1-t_0+\varepsilon L_k\right\}^2+4\varepsilon L_k t_0\right]^{\frac{1}{2}} \qquad (23)$$

$$B^2{}_{11},B^2{}_{21}=1/2\left[\varepsilon+1\pm\left\{\varepsilon+1(1+t_0+\varepsilon L_k)-2\right\}/2\left\{1-t_0+\varepsilon L_k\right\}^2+4\varepsilon L_k t_0\right]^{\frac{1}{2}} \qquad (24)$$

$$B_{31}{}^2=0\,and\,L_k=\delta_{1k}t_0+\delta_{1k}t_1 \qquad (25)$$

Here we have taken f(t)=H(t), the unit step function so that surface of the half space is subjected to step in temperature gradient and f(p)=1/p.

Singularities of Integrals:

In evaluating integrals (19) to (21) we take n as complex variables and distort the path of integration in the η-plane. When the choice of sign in α_{11}, α_{21}, α_{31} is unrestricted, the integrands are hexavalued function of η and their representation requires a six leaved Riemann surface. However, our choice that $\operatorname{Re}(m_k)\ge 0$ at all points on the path of integration, we have confined to the leaf so called upper leaf of the surface defined by $\operatorname{Re}(m_k)\ge 0$, k=1,2,3 everywhere. The possible singular points of the integrands are:

(i) **Branch Points:** The branch points are given by a_{kl}= 0, k=1,2,3 which gives us

$$\eta=\pm iM_1,\ \eta=\pm iM_2,\eta=\pm\frac{i}{8}=ic_1/c_2 \qquad (26)$$

Poles: Other singular points of the integrands are their poles which are given by

$$(2h^2+\frac{1}{d^2})^2(a_{11}^2+a_{21}^2+a_{11}a_{21}-h^2-1)=4h^2a_{11}a_{21}a_{31}(a_{11}+a_{21}) \qquad (27)$$

Because the factor $(\alpha_{21}-\alpha_{11})=0$ leads $(\alpha_{21}=\alpha_{11})$ which doesn't hold from the restriction that $\operatorname{Re}(\alpha_{kl})\ge 0,\alpha_{11}\ne\alpha_{21}$ and hence yield no singularity. We will investigate the pole given by (27) which is the Rayleigh wave frequency equation. If we set $\eta=i/V$ in equation (27), then it can be verified that for $\delta^2\langle 1$ only one value of V out of three satisfies the cubic equation (27) on the upper leaf of Riemann surface and that is the root lies in the range $\alpha V^2\langle\delta^2$. Let it be $V^2{}_R$;V_R stands corresponds to the velocity of the Rayleigh wave in generalized thermoelasticity. The under the assumptions made, the singularities of the integrands (19) to (21) which lie in the range on the upper leaf of the Riemann surface are

$$\eta=\pm ic_1/c_2,\eta=\pm iM_1,\eta=\pm iM_2,\eta=i/V_R, \qquad (27)$$

Distortion of the path of Integration:

We shall give the outline of the general approach by treating one of the integrals (19) to (21). Firs let's consider

$$\bar{u}_3=\operatorname{Im}\int_0^{\infty}\left(\frac{A_{31}}{p}+\frac{B_{31}}{p^2}+\frac{C_{31}}{p^3}\right)e^{-p(\alpha_{31}z+i\eta x)}d\eta \qquad (28)$$

Consider the new variable of integration 't' defined by

$$t=\alpha_{31}z+i\eta x \qquad (29)$$

This represents the conformal transformation from η-plane to the t-plane. Evidently "t" has dimensions of time. The integral (28) is now given by

$$\bar{u}_3(x,z,p) = \frac{1}{\pi}\,\mathrm{Im}\int_{AB}\left(\frac{A_{31}}{p}+\frac{B_{31}}{p^2}+\frac{C_{31}}{p^3}\right)e^{-pt}\frac{d\eta}{dt}\,dt \qquad (30)$$

It is observed that from equation (29) that $\frac{d\eta}{dt}$ introduces no singularity in the form of the pole to the integrand in equation (30), but it may introduce some branch points, which may be excluded by making branch cut. This contour formed by the arc AB, with infinite arc B to the real t-axis and the real axis from ∞ to A doesn't enclose any singularity of integrand (30). The integral along infinite arc vanish since p〉0. Thus in accordance with the Cauchy's theorem, the integral (30) becomes

$$\bar{u}_3(x,z,p) = \frac{1}{\pi}\,\mathrm{Im}\int_{z/\delta}^{\infty}\left(\frac{A_{31}}{p}+\frac{B_{31}}{p^2}+\frac{C_{31}}{p^3}\right)e^{-pt}\frac{d\eta}{dt}\,dt \qquad (31)$$

Using equations (14) and (15) we get

$$u_3(x,z,t) = \mathrm{Re}\left[\int_0^t A_{31}H(\bar{t}-z/\delta)\left(\frac{\partial\eta_3}{\partial\bar{t}}\right)e^{-pt}d\bar{t} + \int_0^t \left\{\int_0^{\bar{i}} B_{31}H(\bar{t}-z/\delta)\left(\frac{\partial\eta_3}{\partial\bar{t}_1}\right)\partial t_1\right\}\partial t\int_0^t\left(\int_0^{\bar{t}}\left(\int_0^{\bar{t}} C_{31}H(t_2-z/\delta)\right.\right.\right]$$

$$\left(\frac{\partial\eta_3}{\partial\bar{t}_1}\right)\partial t_2)dt_1)dt$$

Similarly

$$u_1(x,z,t) = \mathrm{Re}\left[\int_0^t A_{11}H(\bar{t}-zM_1)\left(\frac{\partial\eta_1}{\partial\bar{t}}\right)e^{-pt}d\bar{t} + \int_0^t \left\{\int_0^{\bar{i}} B_{11}H(\bar{t}-z/\delta)\left(\frac{\partial\eta_1}{\partial\bar{t}_1}\right)\partial t_1\right\}\partial t\int_0^t\left(\int_0^{\bar{t}}\left(\int_0^{\bar{t}} C_{11}H(t_2-zM_1)\right.\right.\right]$$

$$\left(\frac{\partial\eta_1}{\partial\bar{t}_1}\right)\partial t_2)dt_1)dt$$

$$u_2(x,z,t) = \mathrm{Re}\left[\int_0^t A_{12}H(\bar{t}-zM_2)\left(\frac{\partial\eta_2}{\partial\bar{t}}\right)e^{-pt}d\bar{t} + \int_0^t \left\{\int_0^{\bar{i}} B_{12}H(\bar{t}-zM_2)\left(\frac{\partial\eta_2}{\partial\bar{t}_1}\right)\partial t_1\right\}\partial t\int_0^t\left(\int_0^{\bar{t}}\left(\int_0^{\bar{t}} C_{12}H(t_2-z/\eta_2)\right.\right.\right]$$

$$\left(\frac{\partial\eta_2}{\partial\bar{t}_{2_1}}\right)\partial t_2)dt_1)dt$$

Thus we have

$$u(x,z,t) = \mathrm{Re}\left[\int_0^t A_{k1}H(\bar{t}-zs_k)\left(\frac{\partial\eta_k}{\partial\bar{t}}\right)d\bar{t} + \int_0^t \left\{\int_0^{\bar{i}} B_{1k}H(\bar{t}-s_kz)\left(\frac{\partial\eta_k}{\partial\bar{t}_1}\right)\partial t_1\right\}\partial t\int_0^t\left(\int_0^{\bar{t}}\left(\int_0^{\bar{t}} C_{3ik}H(t_2-s_kz)\right.\right.\right] \qquad (32)$$

$$\left(\frac{\partial\eta_k}{\partial\bar{t}_1}\right)\partial t_2)dt_1)dt$$

Where

$S_1 = M_1$, $S_2 = M_2$, $S_3 = 1/\delta$

Similarly, we can write the values for w (x, z, t) and T (x, z,t). The stresses and temperature gradient can also be computed in the similar way. The result of Lord Shulman theory and Green Lindsay theory of thermoelasticities can be obtained by taking k=1, k=2 respectively in the relevant relation.

Thermoelasticity without energy dissipation:

The basic governing equations of thermoelasticity without energy dissipation in the absence of heat sources and body forces are given by

$$\mu\nabla^2 \vec{u} + (\lambda+\mu)\nabla\nabla \vec{u} - \gamma\nabla T = \rho \ddot{\vec{u}},$$

$$K^*\nabla^2 T = \rho C_e \ddot{T} + \gamma T_0 \nabla \dddot{\vec{u}}$$

The non dimensional form of the basic governing equations of motion and heat conduction in the absence of body forces and heat sources are given as

$$c^2{}_s\nabla^2 \vec{u} + (c^2{}_p - c^2{}_s)\nabla\nabla.\vec{u} = \ddot{\vec{u}} \qquad (33)$$

$$C^2{}_T\nabla^2 T = \in^*\nabla.\ddot{\vec{u}} + \ddot{T} \qquad (34)$$

where

$$\in^* = \frac{\gamma^2 T_0}{\rho C_e(\lambda+2\mu)}, \delta^2{}_1 = \frac{c_s{}^2}{c^2{}_p} = \frac{\mu}{\lambda+2\mu} = \delta^2, \qquad (35)$$

$c^2{}_p = \dfrac{(\lambda+2\mu)}{\rho v^2}$, $c_s{}^2 = \dfrac{\mu}{\rho v^2}$, $c^2{}_T = \dfrac{K^*}{\rho C_e v^2}$, where V being standard speed.

Upon using (8), we obtain

$$c^2{}_p\nabla^2\phi - \ddot{\phi} = c^2{}_p T \qquad (36)$$

$$c^2{}_s\nabla^2\psi - \ddot{\psi} = 0 \qquad (37)$$

$$c^2{}_T\nabla^2 T - \ddot{T} = \varepsilon^*\nabla^2\ddot{\phi} \qquad (38)$$

Adopting the procedure of previous of previous sections the expression for displacement and temperature are obtained as

$$(u, w, T) = L^{-1}\left\{\sum_{k=1}^{3}(\bar{u}_k, \bar{w}_k, \bar{T}_k\right\} \qquad (39)$$

where

$$\bar{u}_k = \frac{1}{\pi}\operatorname{Im}\int_0^\infty \frac{A_{1k}{}^*}{p} e^{-p(\alpha_k z + i\eta x)} d\eta \qquad (40)$$

$$\bar{w}_k = \frac{1}{\pi}\operatorname{Re}\int_0^\infty \frac{A_{3k}{}^*}{p} e^{-p(\alpha_k z + i\eta x)} d\eta \qquad (41)$$

$$\bar{T}_k = \frac{1}{\pi}\operatorname{Re}\int_0^\infty \frac{A_{3k}{}^*}{p} e^{-p(\alpha_k z + i\eta x)} d\eta \qquad (42)$$

Where

$$A^*_{11} = i\eta T_0\left[\left(2\eta^2 + \frac{1}{c_s^2}\right)^2 - 4\eta^2\alpha_2\alpha_3\right] / \left(\alpha_2 - \alpha_1\right) D^*(\eta)$$

$$A^*_{12} = i\eta T_0\left[\left(2\eta^2 + \frac{1}{c_s^2}\right)^2 - 4\eta^2\alpha_2\alpha_3\right] / \left(\alpha_2 - \alpha_1\right) D^*(\eta)$$

$$A^*_{13} = 2i\eta T_0\alpha_3\left[\left(2\eta^2 + \frac{1}{c_s{}^2}\right)^2\right] / D^*(\eta)$$

$$A^*_{21} = -\alpha_1 T_0 \left[\left(2\eta^2 + \frac{1}{c_s^{\,2}}\right)^2 - 4\eta \ \alpha_2\alpha_3\right] / (\alpha_2 - \alpha_1)(\eta)$$

$$A^*_{22} = -\alpha_1 T_0 \left[\left(2\eta^2 + \frac{1}{c_s^{\,2}}\right)^2 - 4\eta \ \alpha_1\alpha_3\right] / (\alpha_2 - \alpha_1) D^*(\eta)$$

$$A^*_{23} = -2\eta^2 T_0 \left[\left(2\eta^2 + \frac{1}{c_s^2}\right)^2\right] / D^*(\eta)$$

$$A^*_{32} = T_0\left(\alpha_1^{\,2} - \eta^2 - \frac{1}{c^2{}_p}\right) \ \left[\left(2\eta^2 + \frac{1}{c_s^{\,2}}\right)^2 - 4\eta\alpha_2\alpha_3\right] / (\alpha_2 - \alpha_1) D^*(\eta)$$

$$A^*_{33} = 0$$

$$D^*(\eta) = \left(2\eta^2 + \frac{1}{c^2}\right)^2 \left[\alpha_1^{\,2} + \alpha_2^{\,2} + \alpha_1\alpha_2 - \eta^2 - \frac{1}{c^2{}_s}\right] - 4\eta^2\alpha_1\alpha_2\alpha_3(\alpha_1 + \alpha_2)$$

$$\alpha_1 = (\eta^2 + \alpha^2{}_{1,2})^2, \ i = 1, 2$$

$$\alpha_1 = \left(\eta^2 + \frac{1}{c^2{}_s}\right)^2$$

$$\alpha_1^{\,2}, \alpha^2{}_2 = \frac{1}{2}\left[\frac{1}{c^2 p} + \frac{\varepsilon^* - 1}{c^2{}_1} \pm \left\{\left(\frac{1}{c^2{}_p} + \frac{\varepsilon^* - 1}{c^2{}_1}\right)^2 + \frac{4\varepsilon^*}{c_T{}^4}\right\}\right]$$

The singularities of the given integrand and which lies on the upper surface of the Riemann surface in this case are given by

(a) Branch Points: $\eta = \pm i a_1, \pm i a_2, \pm i / c_s$

(b) Poles: $\eta \pm i / V_R$

Where V_R is the Rayleigh wave speed. On distorting the path of integration as in previous section we obtain the expressions for displacement and temperature as under:

$$u(x,z,t) = \sum_{k=1}^{3} \mathrm{Im}\left[\left\{\int_0^t A_{1k}{}^* H(t_1 - s_k z)\left(\frac{\partial \eta_k}{\partial t_1}\right) dt_1\right\}\right] \quad (43)$$

$$w(x,z,t) = \sum_{k=1}^{3} \mathrm{Re}\left[\left\{\int_0^t A_{2k}{}^* H(t_1 - s_k z)\left(\frac{\partial \eta_k}{\partial t_1}\right) dt_1\right\}\right]$$

$$T(x,z,t) = \sum_{k=1}^{3} \mathrm{Re}\left[\left\{\int_0^t A_{3k}{}^* H(t_1 - s_k z)\left(\frac{\partial \eta_k}{\partial t_1}\right) dt_1\right\}\right], \qquad \eta_k = 1,2,3$$

can be determined from

$$t = \alpha_k z + i\eta_k x$$

and

$$s_1 = a_1, s_2 = a_2, s_3 = \frac{1}{c_s}$$

If there is no coupling between the thermal and mechanical fields, then the temperature path is observed to vanish. The stresses can also be computed in the similar way. The results for lord Shulman and Green Lindsay theories of thermoelasticities can be obtained by putting k=1, k=2 respectively in the relevant relations. The results for the coupled theory can be obtained by setting the thermal relaxation times equal to zero.

II. Conclusion:

In this chapter the distribution due to thermal source in a homogenous isotropic thermostatic half space has been investigated by applying a combination of Laplace and Fourier transform technique in the context of Generalized theories of thermoelasticity. The inverse transform integral have been evaluated by using Cagniard method to obtain the exact closed algebraic expressions for the displacement and temperature as function of time and horizontal distances, which are valid for all epicentral distances. The displacement and temperature so obtained in the physical domain have been computed.

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