Wave propagation in thermoelastic saturated porous medium

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Biot's theory for wave propagation in saturated porous solid is modified to study the propagation of thermoelastic waves in poroelastic medium. Propagation of plane harmonic waves is considered in isotropic poroelastic medium. Relations are derived among the wave-induced temperature in the medium and the displacements of fluid and solid particles. Christoffel equations obtained are modified with the thermal as well as thermoelastic coupling parameters. These equations explain the existence and propagation of four waves in the medium. Three of the waves are attenuating longitudinal waves and one is a non-attenuating transverse wave. Thermal properties of the medium have no effect on the transverse wave. The velocities and attenuation of the longitudinal waves are computed for a numerical model of liquid-saturated sandstone. Their variations with thermal as well as poroelastic parameters are exhibited through numerical examples.

1. Introduction

The co-existence of porosity and thermoelasticity is a common happening in crustal and reservoir rocks in the earth. Such co-existence might be playing a crucial role in non-destructive evaluation (NDE) of composite materials and structures. The studies of fluid transport through porous media (Bear *et al* 1992; Levy *et al* 1995) considered such a co-existence and derived the fundamental equations for microscopic dynamism. Macroscopic models are obtained by the volume averaging of relevant microscopic equations. Beyond doubt, the phenomenon of wave propagation in such a medium may be an interesting and useful study.

The full-dynamic theory for wave propagation in fluid-saturated porous media was developed by Biot (1956a). Biot used Lagrange's equations to derive a set of coupled differential equations governing the motions of solid and fluid phases. Biot (1962a) extended the acoustic propagation theory in the wider context of the mechanics of porous media. Biot (1962b) developed new features of the extended theory, in more detail. During the last about two decades, the Biot's theories are verified extensively (Lakes *et al* 1983; Kelder and Smeulders 1997; Gurevich *et al* 1999) through a large number of experimental studies conducted by various researchers.

Thermoelasticity deals with the dynamical systems whose interactions with surroundings include not only mechanical work and external work but also exchange of heat. Starting with Biot (1956b), the theory of thermoelasticity has established well (Nowacki 1975) with time. Biot (1956b) explained thermoelasticity by deriving dilatation based on the thermodynamics of irreversible process and coupling it with elastic deformation. But the diffusion type heat equation used in this study predicted infinite speed for propagation of thermal signals. Lord and Shulman (1967) defined the generalised theory of thermoelasticity in which a hyperbolic equation of heat conduction with a relaxation time ensured the finite speed for thermal signals. Using two relaxation times, Green and Lindsay (1972) developed another generalized theory of thermoelasticity. A comprehensive review of the earlier research works on thermoelasticity is

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available in a study by Chandrasekhariah (1986). The wave propagation problems in thermoelastic materials are studied by many more authors (e.g., McCarthy 1972; Chadwick 1979; Dhaliwal and Sheriff 1980; Sharma and Sidhu 1986; Sharma *et al* 2000). In a recent study, the present author (Sharma 2006) derived a mathematical model for the wave propagation in generalized thermoelastic anisotropic medium.

It is a wonderful coincidence that Biot presented the theories of both thermoelasticity and poroelasticity, in the same year of 1956. Indeed Biot (1956b) was very much aware of the isomorphism between mechanics of porous media and thermoelastic continua. Another paper (Biot 1964) shows that theory of porous media applies immediately to thermoelasticity. The temperature replaces the fluid pressure and the entropy displacement is used instead of relative fluid displacement. This was an important analogy that was used by some authors to translate the results from thermoelasticity in solving the problems of poroelasticity. Some of such studies on isotropic propagation are discussed in Norris (1992). Sharma (2006) extended such a correspondence for three-dimensional wave propagation in general anisotropic media.

Experimental study of Gurevich *et al* (1999) confirms that the Biot's theory of poroelasticity is adequate to describe the behaviour of porous materials. Such a study refreshes the importance of Biot's theory in poroelasticity. In the present paper, Biot's theory is modified to show the existence of three longitudinal and one transverse waves in an isotropic thermoelastic porous solid saturated with a non-viscous fluid. Relations are derived among the temperature of the medium and the displacements of fluid and solid particles. Numerical examples are discussed to analyze the velocities and attenuation of the three longitudinal waves.

2. Basic equations

2.1 *Thermoelastic porous medium*

Consider a thermally conducting isotropic porous solid saturated with a non-viscous fluid. The stresses (τ_{ij}) in porous aggregate are obtained from the stresses in solid matrix (σ_{ij}) and fluid pressure (p_f) through the relations

$$\tau_{ij} = \sigma_{ij} + \alpha(-p_f)\delta_{ij}, \tag{1}$$

where α is Biot's parameter to represent bulk coupling between fluid and solid phases. δ_{ij} is the Kronecker symbol. In an isotropic fluid-saturated porous solid, σ_{ij} and p_f in isothermal conditions are defined as:

$$\sigma_{ij} = \lambda u_{k,k}\delta_{ij} + \mu(u_{i,j} + u_{j,i}),$$
$$-p_f = \alpha M u_{k,k} + M w_{k,k}, \tag{2}$$

where λ, μ are isothermal Lame's constants for porous solid and M is an elastic parameter for isotropic bulk coupling of fluid and solid particles. w_i, the components of the averaged fluid motion relative to solid frame, are defined as $w_i = f(U_i - u_i)$ where f is the porosity of solid. u_i and U_i are displacement components in solid and fluid phases, respectively. Indices can take the values 1, 2 and 3. Summation convention is valid for repeated indices. The comma (,) before an index represents partial space differentiation and dot over a variable represents partial time derivative.

Following Bear *et al* (1992) and Levy *et al* (1995), the constitutive relations for effective stresses in the solid and fluid parts of isotropic thermally conducting fluid-saturated porous medium are written as follows:

$$\sigma_{ij} = \lambda u_{k,k}\delta_{ij} + \mu(u_{i,j} + u_{j,i}) - \beta_s(T - T_0)\delta_{ij}, \tag{3}$$

$$-p_f = \alpha M u_{k,k} + M w_{k,k} - \beta_f(T - T_0)\delta_{ij}, \tag{4}$$

where β_s, β_f are the coefficients of thermal stress for solid and fluid, respectively. It is assumed that both the constituents of porous aggregate have the same constant temperature (T_0) in the undisturbed state.

Differential equations for thermoelastic motion in terms of stresses (τ_{ij}), fluid pressure (p_f) and temperature (T) in the deformed medium are written as:

$$\tau_{ij,j} = \rho\ddot{u}_i + \rho_f\ddot{w}_i,$$

$$(-p_f)_{,i} = \rho_f\ddot{u}_i + q\ddot{w}_i,$$

$$KT_{,jj} - \rho C_e(\dot{T} + \tau_0\ddot{T})$$
$$= T_0\beta[\tau_0(\ddot{u}_{j,j} + \ddot{w}_{j,j}) + \dot{u}_{j,j} + \dot{w}_{j,j}], \tag{5}$$

where $\beta = \beta_s + \alpha\beta_f$. ρ and ρ_f are the densities of porous aggregate and pore fluid, respectively. The parameter q represents inertial coupling between pore-fluid and solid matrix of porous aggregate.

In terms of u_i, w_i and T, the differential equations (5) are expressed as

$$(\lambda+\mu+\alpha^2 M)u_{k,ik}+\mu u_{i,kk}-\rho\ddot{u}_i$$
$$+\alpha M w_{k,ik}-\rho_f\ddot{w}_i-\beta T_{,i}=0,$$
$$\alpha M u_{k,ik}-\rho_f\ddot{u}_i+M w_{k,ik}-q\ddot{w}_i-\beta_f T_{,i}=0,$$
$$\beta T_0[(\dot{u}_{j,j}+\tau_0\ddot{u}_{j,j})+(\dot{w}_{j,j}+\tau_0\ddot{w}_{j,j})]$$
$$-[KT_{,jj}-\rho C_e(\dot{T}+\tau_0\ddot{T})]=0. \tag{6}$$

To seek harmonic solution of (6) for the propagation of plane waves, we assume

$$\{u_j,w_j,T-T_0\}=\{S_j,F_j,\Gamma\}\exp\{\imath\omega(p_k x_k-t)\}, \tag{7}$$

where ω is angular frequency and (p_1,p_2,p_3) is slowness vector. In terms of the phase velocity V, slowness is written as $(p_1,p_2,p_3)=\mathbf{N}/V$. The row matrix $\mathbf{N}=(n_1,n_2,n_3)$ represents the direction of phase propagation. The vectors (S_1,S_2,S_3) and (F_1,F_2,F_3) define, respectively, the polarizations for the motions of the solid and fluid particles in the porous medium. Substituting (7) in (6), yields seven equations to be solved into two subsystems. One of them,

$$T=T_0+G(n_k u_k+n_k w_k),$$
$$G=\frac{\imath\omega T_0 V\beta\tau}{K-\rho\tau C_e V^2},$$
$$\tau=\tau_0+\frac{\imath}{\omega}, \tag{8}$$

relates the temperature (T) and particle displacements in the medium. The other subsystem is expressed as:

$$\mathbf{AS}+\mathbf{BF}=0,$$
$$\mathbf{A}=(\lambda+\mu+\alpha\alpha' M)\mathbf{N}^T\mathbf{N}+(\mu-\rho' V^2)\mathbf{I},$$
$$\mathbf{B}=\alpha' M\mathbf{N}^T\mathbf{N}-\rho_f' V^2\mathbf{I},$$
$$\mathbf{CS}+\mathbf{DF}=0,$$
$$\mathbf{C}=(\alpha M-gV^2)\mathbf{N}^T\mathbf{N}-\rho_f V^2\mathbf{I},$$
$$\mathbf{D}=(M-gV^2)\mathbf{N}^T\mathbf{N}-qV^2\mathbf{I}, \tag{9}$$

where $\alpha'=\alpha-\beta/\beta_f$, $\rho'=\rho-\rho_f(\beta/\beta_f)$, $\rho_f'=\rho_f-q(\beta/\beta_f)$, $g=T_0\tau\beta\beta_f/(K-\rho\tau C_e V^2)$. The $\mathbf{I}$ is identity matrix of order three and $\mathbf{N}^T$ denotes the transpose of row matrix $\mathbf{N}$. Assuming the matrix $\mathbf{D}$ to be non-singular, the latter system is further solved into a relation

$$\mathbf{F}=\left[\frac{\rho_f}{q}(-\mathbf{I}+\mathbf{N}^T\mathbf{N})-\frac{\alpha M-(g+\rho_f)V^2}{M-(g+q)V^2}\mathbf{N}^T\mathbf{N}\right]\mathbf{S}, \tag{10}$$

and an eigensystem

$$[a\mathbf{N}^T\mathbf{N}+b(\mathbf{I}-\mathbf{N}^T\mathbf{N})]\mathbf{S}=0, \tag{11}$$

where

$$a=(\lambda+2\mu+\alpha\alpha' M-\rho' V^2)$$
$$-(\alpha' M-\rho_f' V^2)\frac{\alpha M-(g+\rho_f)V^2}{M-(g+q)V^2},$$
$$b=\mu-\left(\frac{\rho-\rho_f^2}{q}\right)V^2. \tag{12}$$

The expression (10) relates the displacements ($\mathbf{u}$ and $\mathbf{w}$) of two constituent phases in porous aggregate. The eigensystem (11) explains the propagation phenomenon in the medium and may be called the generalized Christoffel equations for thermoelastic wave propagation in a porous solid saturated with a non-viscous fluid.

Non-trivial solution for Christoffel equations (11) is ensured by vanishing the determinant (ba^2) of the coefficient matrix $a\mathbf{N}^T\mathbf{N}+b(\mathbf{I}-\mathbf{N}^T\mathbf{N})$. For $b=0$, we get a relation

$$V=\sqrt{\frac{\mu}{(\rho-\rho_f^2/q)}}, \tag{13}$$

with polarization $\mathbf{S}$ normal to propagation direction $\mathbf{N}$. Hence this defines the phase velocity of a non-attenuating transverse wave in the medium. It may be noted that velocity expression (13) is same as that obtained in Biot's theory. This implies that thermoelastic coupling have no effect on the propagation of transverse (say, S) waves in the porous medium. The other relation, $a = 0$, is solved into

$$
\begin{aligned}
&(\rho_f\rho_f' - \rho' q)V^4 + [(\lambda + 2\mu + \alpha\alpha' M)q \\
&\quad - (\rho_f\alpha' + \rho_f'\alpha)M + \rho' M]V^2 \\
&\quad - (\lambda + 2\mu)M - g[(\rho' - \rho_f')V^4 \\
&\quad - (\lambda + 2\mu + \alpha\alpha' M - \alpha' M)V^2] = 0. \qquad (14)
\end{aligned}
$$

In this case, the polarizations $\mathbf{S}$ become parallel to phase direction $\mathbf{N}$. This implies that above equation represents the propagation of longitudinal waves. For $\beta = 0$, we get $g = 0$, $\rho' = \rho$, $\rho_f' = \rho_f$, $\alpha' = \alpha$, then equation (14) becomes a quadratic equation in V^2 and two of its roots define the velocities of two longitudinal waves in isotropic poroelastic solid. These velocities are same as those obtained for P_f and P_s waves in Biot's theory. Then from equations (6), the thermal signal and mechanical disturbance are no longer coupled. On the other hand, for $K \neq \rho\tau C_e V^2$, the equation (14) is solved into a cubic equation in V^2. This cubic equation is written as:

$$
C_0 V^6 + C_1 V^4 + C_2 V^2 + C_3 = 0, \qquad (15)
$$

where

$$
\begin{aligned}
C_0 &= \rho C_e \tau(\rho_f\rho_f' - \rho' q), \\
C_1 &= \rho C_e \tau[(Hq - (\rho_f\alpha' + \rho_f'\alpha)M + \rho' M] \\
&\quad - K(\rho_f\rho_f' - \rho' q) + T_0\tau\beta\beta_f(\rho' - \rho_f'), \\
C_2 &= -K[Hq - (\rho_f\alpha' + \rho_f'\alpha)M + \rho' M] \\
&\quad - \rho\tau C_e(\lambda + 2\mu)M - T_0\tau\beta\beta_f(H - \alpha' M), \\
C_3 &= (\lambda + 2\mu)KM, \qquad (16)
\end{aligned}
$$

and $H = \lambda + 2\mu + \alpha\alpha' M$. Three roots of cubic equation (15) explain the existence and propagation of three longitudinal waves in thermoelastic porous solid. The relaxation time parameter τ is a frequency dependent complex number. This implies that the roots of equation (15) are complex and hence the longitudinal waves in the medium are attenuating waves.

2.2 *Special case*

Real value of inertial coupling q represents the absence of viscosity in pore fluid and hence the absence of dissipation in porous aggregate. For the presence of dissipation, q is to be replaced with $q + \imath(\gamma/\omega\chi)$. The ratio of viscosity (γ) to permeability (χ) explains the Darcy's law for fluid–solid coupling in low-frequency range that ensures Poiseuille flow in pores. For higher frequencies, a correction factor is applied to the viscosity γ (Deresiewicz and Rice 1962).

2.3 *Propagation and attenuation*

We have four waves propagating in a generalized thermoelastic saturated porous solid. Three of these are attenuating longitudinal waves and one is a non-attenuating transverse wave. For real vector $\mathbf{N} = (n_1,\ n_2,\ n_3)$, even the complex value of V provides the same directions for propagation and attenuation of the longitudinal waves. Hence, all the four waves become homogeneous waves. The complex phase velocity (V) of each longitudinal wave is resolved into propagation velocity v and attenuation coefficient Q^{-1}. For a longitudinal wave with complex velocity $V = V_R + \imath V_I$, define $v(= V_R^2 + V_I^2)/V_R$ and Q^{-1} $(= -2V_I/V_R)$ as its phase velocity and attenuation coefficient, respectively. In the descending order of phase velocity v, the three longitudinal waves in thermoelastic porous medium are identified as L_1, L_2 and L_3 waves. The vector $\mathbf{N}$ with complex components will represent the propagation of inhomogeneous waves in the medium. In that case, the complex slowness vector will be specified as (Sharma 2005)

$$
\frac{\mathbf{N}}{V} = \frac{\hat{\mathbf{n}}}{v} + \imath\hat{\mathbf{a}}A, \qquad (17)
$$

for given (real) propagation direction $\hat{\mathbf{n}}$ and attenuation direction $\hat{\mathbf{a}}$.

3. Numerical examples

The velocities and attenuation of the three longitudinal waves are calculated from their complex velocities obtained as roots of cubic equation (15). This equation is not a simple one to be

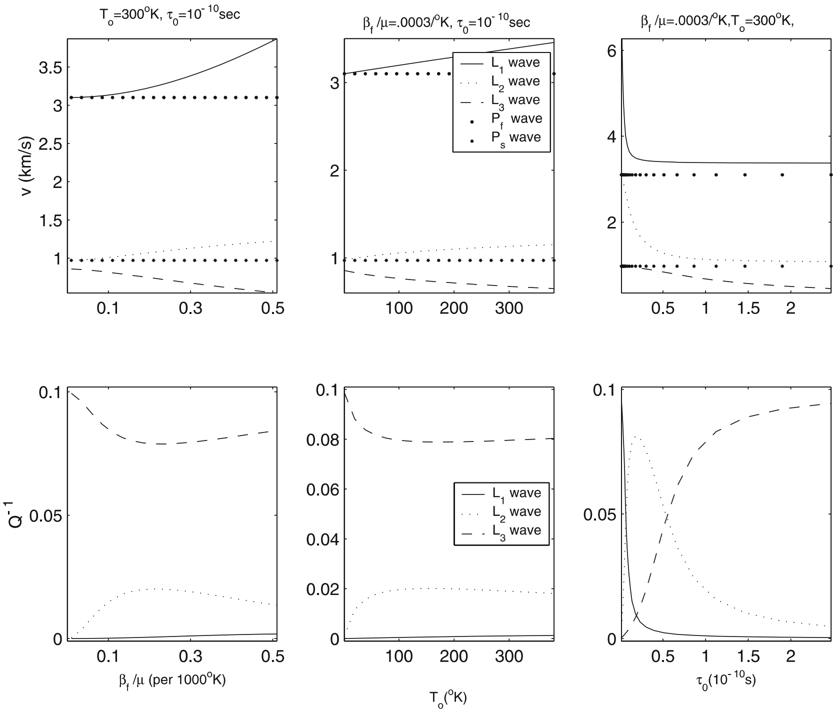

Figure 1. Variations of phase velocities and attenuation coefficients in liquid-saturated sandstone with thermal stress (β_f), initial temperature (T_0) and relaxation time (τ_0).

solved for closed form solutions. The coefficients of this equation are large expressions involving the contribution of various thermal/elastic/pore parameters. So the effect of these parameters on the velocities and attenuation may only be analyzed in a particular model of the medium. A liquid-saturated reservoir rock (North-sea Sandstone) is chosen for the numerical model of non-dissipative porous medium. The values for the elastic and dynamical constants for the porous rock are taken from the anisotropic constants in Rasolofosaon and Zinszner (2002). These are given by, $\lambda = 3.7\,\text{GPa}$, $\mu = 7.9\,\text{GPa}$, $M = 6\,\text{GPa}$, $\alpha = 0.4$, $f = 0.16$ and $\rho = 2216\,\text{kg/m}^3$. The saturating fluid (say, liquid) is assumed with density $\rho_f = 950\,\text{kg/m}^3$ and $q = 1.05\,\rho_f/f$. Numerical values $C_e = 1040\,\text{Jkg}^{-1}/\text{K}$ and $K = 170\,\text{Wm}^{-1}/\text{K}$ define the thermoelastic character of the porous aggregate. The parameters T_0 and τ may also have their effect on the wave propagation in the medium. Define relaxation time $\tau = \tau_0(1 + \imath\eta)$, so that dimensionless parameter $\eta = (\omega\tau_0)^{-1}$ represents dissipation in thermoelastic medium. It has been noted that for $\beta = 0$, only three waves will be propagating in the medium and thermal signal decouples from mechanical disturbance. This implies that the propagation of L_3 wave in the medium is linked directly to thermal stresses β_s and β_f of the two constituents in the medium. For the present study, it is assumed that $\beta_s = 2\beta_f$.

3.1 *Velocities and attenuations*

The above numerical values are used to compute the phase velocities and attenuation of the three longitudinal waves in the medium. The lone transverse wave in the medium is unaffected by the thermal parameters and propagate with a constant velocity of 1.95 km/s. For the (isothermal) poroelastic solid with above given numerical values, the velocities of two longitudinal (P_f, P_s) waves are found to be 3.1 km/s and 0.97 km/s. These waves are non-attenuating and the horizontal lines of big dots in the velocity plots (in figures 1 and 2) represent these velocities. Figure 1 exhibits the variations in phase velocities (v) and attenuation coefficients (Q^{-1}) of the longitudinal waves with the values of β_f/μ, T_0 and τ_0. It may be observed that the velocities of L_1 and L_2 waves increase with the increase in thermal stresses (i.e., β_f, β_s) and/or initial temperature (T_0). But, the velocity of L_3 wave decreases with the increase of these thermal parameters. L_3 wave is the most attenuated wave whereas attenuation of L_1 wave is very small. Similarly, the plots of first two columns in this figure imply that changes in β_f and T_0 have nearly same effects on wave propagation in the medium considered. The velocities decrease with the increase in relaxation time τ_0. For larger values of relaxation time, thermal parameters may not affect the velocities of L_1 and L_2

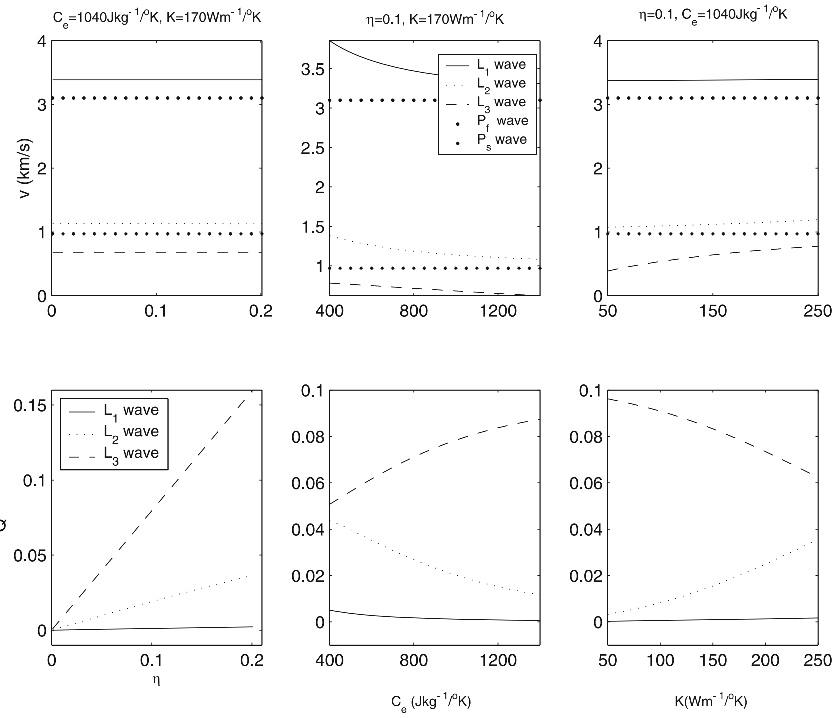

Figure 2. Variations of phase velocities and attenuation coefficients in liquid-saturated sandstone with thermal dissipation (η), specific heat (C_e) and thermal conductivity (K).

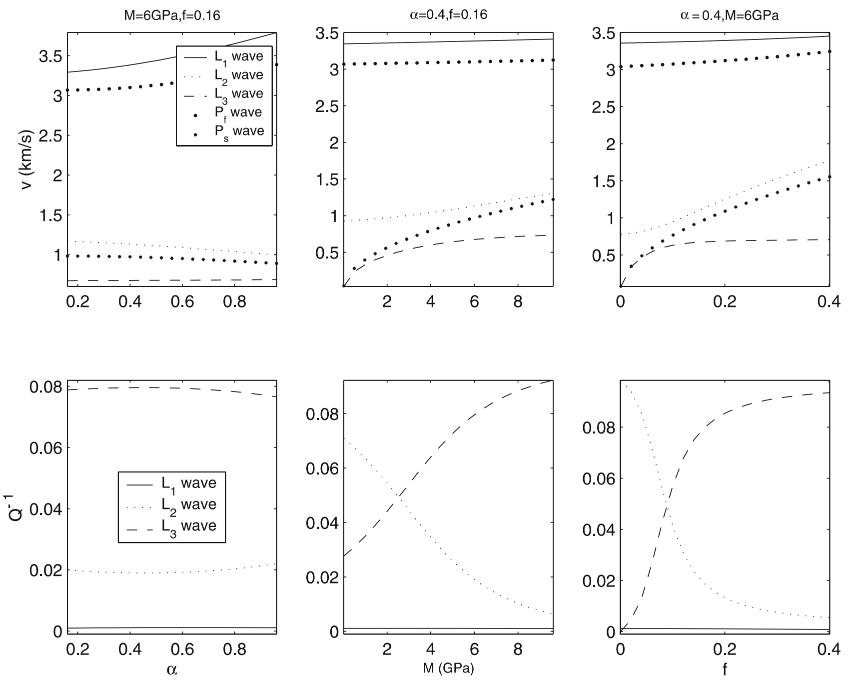

Figure 3. Variations of phase velocities and attenuation coefficients in liquid-saturated sandstone with poroelastic parameters (α, M, f).

waves. These two waves may have larger attenuation for smaller relaxation time. The attenuation of L_3 waves increases sharply with the increase of τ_0.

In another numerical example, the fixed values $\beta_f/\mu = 0.3 \times 10^{-3}$/K, $T_0 = 300$ K and $\tau_0 = 10^{-10}$ s are used to compute the effects of η, C_e and K on velocities and attenuation. Figure 2 shows the variations in velocities and attenuation of longitudinal waves with the variations in these three parameters. As expected, the first column plots show that a change in η has no effect on the velocities. Though L_1 wave is nearly an unattenuated wave, attenuation of all the three waves do increase with the increase in η. The increase in specific heat C_e decreases the velocities of all the three waves. With the increase in C_e, the attenuation of L_2 wave decreases but that of L_3 wave increases. The increase in thermal conductivity K have nearly no effect on the propagation of L_1 wave but it causes a little increase in the velocity and attenuation of L_2 wave. With the increase of thermal conductivity K, velocity of L_3 wave increases but its attenuation decreases. The effects of changes in thermal parameters C_e and K on the propagation of L_2 and L_3 waves are nearly reverse to each other.

In third numerical example, thermal properties are defined with their fixed values used in figures 1 and 2. Variations in the porous character of the medium is represented with the variable values for α, M and porosity f. The resulting effects on velocities and attenuation of longitudinal waves are presented in figure 3. Again, the big-dot plots represent the velocities of P_f and P_s waves in isothermal poroelastic medium. As expected, a change in the value of α does not have any effect on attenuation of all the waves. Similarly, the velocity of L_3 wave is unaffected with the change in α. Also, the thermal effects on velocities are unchanged with the change in α. But, the same is not true for changes in M and f. Thermal effect on velocities of L_1 and L_2 may decrease with the increase of M and/or f. Velocity of L_3 wave may increase with the increase in M and/or f. The attenuation of two slower (L_2, L_3) waves are very much affected with the changes in M and f. The changes in M and f have nearly similar effects on velocities and attenuation of the longitudinal waves.

4. Conclusions

The presented work is an effort to construct a mathematical model for the propagation of thermoelastic waves in a saturated porous solid. For isothermal propagation, the derived mathematical model is reducible to Biot's theory (1962a, b). The thermal properties do not affect the propagation of transverse waves in porous medium. The analogy between thermoelastic and poroelastic propagations may indicate the convergence/superposition of both the diffusive (L_2 and L_3) waves into one. But, no such possibility is observed and three different longitudinal waves propagate in the medium. The thermal effect on the wave propagation may vary with the changes in the pore characteristics of the porous medium. The thermal effects on the wave propagation may be independent of the fluid–solid coupling in porous aggregate when the thermal conductivities of both the constituents are nearly same. Researchers in this field may use the analytical expressions derived in this work in their simulation studies. These expressions may provide a base for further modifications to get more realistic models for thermoelastic propagation in rocks and composites. The propagation theory proposed along with relevant sets of boundary conditions, may be able to provide more accurate solutions to the NDE problems involving wave propagation in thermoelastic porous solids. When supported with a real/synthetic data, the derived model can be used for a variety of geophysical problems. Few of them may be explained as follows:

- The advancement in knowing the structure of the earth consists of more accurate determination of seismic velocities and attenuation. This is particularly true in exploration industry and in the investigation of tectonic stress and failure where small scale fracturing and flow of fluid into the fractures are important. For example, the decrease of seismic velocities with temperature is used through time-lapse survey to trace the flow path taken by the injected steam in a reservoir (Paulsson *et al* 1994).
- Fluid-saturated rocks exhibit attenuation and velocity dispersion that is not observed in dry rocks. These effects are ascribed to the complex nature of crack/pore structure of rocks and to the schemes of fluid occupying and flowing within the pore structure. Along with the viscosity of pore-fluid, the thermal dissipation may also be one of the main causes of attenuation of elastic waves in reservoir rocks and other porous materials.
- The characterization of residual stresses in the reservoirs, earth masses and composite materials could be possible through analyzing the velocity variations in them. Otherwise, the stress is difficult to measure, *in-situ*, even in the most accessible parts of the crust. The prediction of these residual stresses always require a more realistic approach for seismic velocity analysis appropriate for rock physics applications (Dutta 2002). A thermoelastic propagation relating the rock (elastic/thermal/pore) properties of subsurface formations to the seismic velocities may be a much effective approach for this purpose.
- Seismic data from sedimentary regions often exhibit more intrinsic attenuation that cannot be explained using existing theoretical models (Pride *et al* 2004). This requires more realistic models to explain the attenuation loss as determined from seismograms. It is expected

that thermoelastic propagation models may be able to explain the increased attenuation in such regions.

This wave propagation study is an attempt to explore the role of subsurface features (porosity, pore pressure, fluid-solid coupling, thermal parameters) in the propagation of seismic waves. Oceans cover more than two-third of earth's crust and water-saturated porous medium can be a much realistic seismic model for oceanic bed. At the ocean bottom, lithosphere is formed by upwelling of hot material at ridges which spreads around and cools with time. Seismological observations provide evidences for thermal-mechanical processes that control the formation and evolution of thermoelastic lithosphere below oceans. Hence, the ultimate applications of this study are geophysical whether for the exploration of the oceanic crust, structural engineering or to hydrocarbon/geothermal processes.

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