

# Thermo-poroacoustic acceleration waves in elastic materials with voids

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## Abstract

A model for coupled elasto-acoustic waves, thermal waves, and waves associated with the voids, in a porous medium is investigated. Due to the use of lighter materials in modern buildings and noise concerns in the environment such models for thermo-poroacoustic waves are of much interest to the building industry. Analysis of such waves is also of interest in acoustic microscopy where the identification of material defects is of paramount importance to industry and medicine. We present a model for acoustic wave propagation in a porous material which also allows for propagation of a thermal wave. The thermodynamics is based on an entropy inequality of A.E. Green, F.R.S. and N. Laws and is presented for a modification of the theory of elastic materials with voids due to J.W. Nunziato and S.C. Cowin. A fully nonlinear acceleration wave analysis is initiated.

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## 1. Introduction

Wave motion in an elastic material containing voids is an area with immense potential. In particular we note that Ouellette [44] draws attention to the many applications of acoustic microscopy where the presence of voids creates a major problem. She notes that “*acoustic microscopy remains a niche technology and is especially sensitive to variations in the elastic prop-*

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erties of semiconductor materials, such as air gaps, known as delaminations or voids . . .” She also observes that “acoustic microscopy is a tool for nondestructive internal inspection of plastic integrated circuit packages,” and there are many novel applications of acoustic microscopy to biology and diagnostic medicine. Ouellette [44] further observes that in this way one may “apply a special ultrasound scanner to deliver pathological assessments of skin tumours or lesions, non-invasively,” and in general in biology there is “no need to kill the specimen as is usually needed in optical microscopy.” Similar remarks are made by Diebold [13]. The website at the Office of Basic Energy Sciences [42] also emphasizes nondestructive evaluation techniques where defects such as voids may “increase the elastic nonlinearity of materials, perhaps several fold, to yield a possible nondestructive means of monitoring the information and evolution of degradation.”

Another key application area of elastic materials with voids concerns the manufacture of building materials, e.g. plasterboard, brick, concrete. Noise pollution is a major modern environmental problem which impinges much on building material design, cf. Fausti et al. [15], Sakai et al. [51]. In seismic zones buildings are constructed with much lighter porous materials and typically have thinner walls. As a consequence, there is a great need to study the acoustic properties of porous materials including the nature of the solid elastic matrix and the gas filling the pores, and the influence of temperature on these quantities. Measurements are being made of acoustic and related thermal properties of many materials, such as aluminium foams, e.g. Maysenhölder et al. [35], polyester fibre materials, e.g. Garai and Pompoli [20], and models to fit properties have been devised, e.g. Wilson [57]. We observe that in seismic zones, such as the region around Avellino, near Salerno, brick manufacturers typically attempt to increase the porosity (gas volume/total volume) to make the brick lighter. However, this usually has the effect that sound propagation through the brick is amplified and the brick itself becomes more brittle thereby making it less strong when subject to earth movement. Ciarletta et al. [8] and Ciarletta and Iovane [7] proved that, if the porosity is greater than 0.6, the stress on the fracture boundary with respect to a classical continuum increases with an exponential law. Consequently, the limit imposed on the porosity implies that we need to test bricks characterized by inclusion (in the voids) of chemical elements which when heated infuse into the brick and remain trapped in the pores in gaseous form. There is thus interest in investigating the thermo-acoustic properties associated with various gases infused this way into the brick. The last procedure may be studied in the engineering laboratories in the Salerno region, using as a basis the mathematical results obtained in the present work. We believe thermal-acoustic propagation in such materials will be a nonlinear phenomenon and so any theory which allows us to accurately predict the behaviour of a sound wave in a porous material such as an elastic material containing voids is welcome.

As may be gleaned from the applications outlined above, there is much need for accurate theoretical modelling of acoustic wave propagation in porous media. A recent simple nonlinear model has been proposed in a very interesting paper of Jordan [26]. Jordan effectively uses a classical perfect fluid model but adds a term in the momentum equation which is proportional to the velocity, a Darcy like term (cf. Nield and Bejan [38] for an account of Darcy’s law). Fellah et al. [17] indicate how transport properties in air saturated porous media may be measured and Fellah and Depollier [16] show that the equations for mass conservation and momentum in a perfect fluid, in a certain low frequency approximation lead to a linear system of equations equivalent to the Jordan–Darcy model (in a linearised form).

The work of Jordan [26] is generalised by Ciarletta and Straughan [10] who study his Jordan–Darcy model using acceleration waves, and Ciarletta and Straughan [11] extend this analysis to the important non-isothermal case. An acceleration wave is a two-dimensional singular surface in a three-dimensional body across which the acceleration suffers a finite discontinuity. The

use of acceleration waves and related analyses have proved extremely useful in recent investigations of wave motion in various dispersive and random media, in a variety of thermodynamic states, see e.g. Christov and Jordan [4], Christov et al. [5], Eremeyev [14], Fu and Scott [18,19], Gultop [22], Jordan and Christov [27], Jordan and Puri [28], Kameyama and Sugiyama [29], Ostoja-Starzewski [43], Puri and Jordan [45], Quintanilla and Straughan [48], Rai [49], Ruggeri and Sugiyama [50], Su et al. [52], Sugiyama [53], Valenti et al. [56]. Since in this paper we are able to obtain exactly the wavespeeds and wave amplitudes for the elastic, pore related and thermal waves, with no approximations, even though we deal with a completely nonlinear theory, we believe this is a main reason why acceleration waves are especially useful.

The object of this paper is in a sense to generalise the work of Ciarletta and Straughan [10,11] in that we include elastic effects of matrix material which were previously neglected and specifically include the effect of voids (pores). In fact, the theory developed herein allows, in addition to acoustic wave propagation, for the transmission of heat as a thermal wave and for the specific analysis of elastic matrix and void effects. It is increasingly being recognised that such thermal waves (second sound) have a vital role to play in the study of porous media. For example, Meyer [36] has devised an ingenious way of drying a saturated porous material via employment of second sound, Linton-Johnson et al. [31] calculate bulk properties in the porous matrix, and Vadasz et al. [55] discuss how second sound is prominent in nanofluids where many small particles are present. A recent study also shows that second sound is evidently a prominent mechanism for heat transfer in some biological tissues, such tissue also being a porous medium, cf. Mitra [37].

Various theories have been proposed to allow heat to propagate as a wave of finite speed. For example, the Maxwell–Cattaneo theory, e.g. Caviglia et al. [2], Vadasz et al. [55] and the references therein, or the time lag theory, e.g. Quintanilla and Racke [47], Vadasz [54]. However, such models have inherent difficulties when coupled to the other equations of continuum mechanics such as those for the description of fluid or elastic properties, due to the correct representation of time derivatives.

To develop a thermal poroacoustic theory which specifically allows for nonlinear elastic effects and directly accounts for the presence of voids we employ the thermodynamics of Green and Laws [21] who use a generalised temperature  $\phi$  instead of the usual temperature  $\theta$  and redevelop in this light the theory of elastic materials with voids due to Nunziato and Cowin [41], see also Nunziato and Walsh [39,40]. In fact, the basic equations have been developed by Ciarletta and Scarpetta [9], although they did not use the nonlinear theory. We here prefer to briefly reconstruct the theory referring to a reference configuration and employing a Piola–Kirchhoff stress tensor (as opposed to the symmetric tensor formulation of Ciarletta and Scarpetta [9]) for nonlinear wave propagation in a thermoelastic material, cf. Chen [3]. Since the approach of Green and Laws [21] is developed with a view to producing a rational continuum thermodynamic theory of any solid or fluid it extends naturally to the porous medium (elastic materials with voids) application we have in mind and is not subject to any criticism of objective derivatives.

The Nunziato–Cowin [41] theory has enjoyed much success in predicting various effects especially within the remit of linear theory, see e.g. Ciarletta and Iesan [6], Iesan [23], and the recent work of Quintanilla [46], Casas and Quintanilla [1], Magaña and Quintanilla [32,33], and the references therein. However, a complete theoretical description of many of the processes outlined earlier in this introduction will undoubtedly rely on a fully nonlinear theory. Recent research effort is being directed to understanding fully nonlinear processes in the theory of elastic materials with voids such as the key work of Iesan [24,25] and our goal is to continue in this vein.

In this paper we present a theory for acceleration wave propagation in an elastic material containing a distribution of voids which also allows heat to travel with a finite wavespeed. We then show that one can develop a full nonlinear analysis for our model with no approximation whatsoever. Moreover, a precise evolutionary behaviour is predicted for the amplitude of an acceleration wave.

## 2. The model

We commence with the standard balance equations for an elastic material containing voids, cf. Nunziato and Cowin [41],

$$\rho \ddot{x}_i = p_{Ai,A} + \rho F_i, \quad (1)$$

$$\rho k \ddot{v} = h_{A,A} + g + \rho \ell, \quad (2)$$

$$\rho \dot{\epsilon} = -Q_{A,A} + p_{Ai} \dot{x}_{i,A} + h_A \dot{v}_{,A} - g \dot{v} + \rho r. \quad (3)$$

In these equations  $X_A$  denote reference coordinates,  $x_i$  denote spatial coordinates, a superposed dot denotes material time differentiation and  $_{,A}$  signifies  $\partial/\partial X_A$ . The variable  $\rho$  is the reference density,  $v$  is the void fraction,  $\epsilon$  is the specific internal energy,  $k$  is the inertia coefficient,  $F_i$ ,  $\ell$  and  $r$  are externally supplied body force, extrinsic equilibrated body force, and externally supplied heat. The tensor  $p_{Ai}$  is the stress per unit area of the  $X_A$ -plane in the reference configuration acting over corresponding surfaces at time  $t$  (the Piola–Kirchoff stress tensor),  $Q_A$  is the heat flux vector, while  $h_A$  and  $g$  are a vector and a scalar function arising in the conservation law for void evolution, which Nunziato and Cowin [41] refer to as the equilibrated stress and the intrinsic equilibrated body force, respectively.

To develop the theory thermodynamically we use the entropy inequality of Green and Laws [21], namely

$$\rho \dot{\eta} - \frac{\rho r}{\phi} + \left( \frac{Q_A}{\phi} \right)_{,A} \geq 0. \quad (4)$$

Here  $\eta$  is the specific entropy and  $\phi$  ( $> 0$ ) is a generalised temperature function which reduces to  $\theta$  in the equilibrium state, where  $\theta$  is the absolute temperature. To progress one introduces the Helmholtz free energy function  $\psi$  by

$$\psi = \epsilon - \eta \phi \quad (5)$$

and then (4) may be rewritten using (3) as

$$-\rho \dot{\psi} - \rho \dot{\phi} \eta + p_{Ai} \dot{x}_{i,A} - \frac{Q_A \phi_{,A}}{\phi} - g \dot{v} + h_A \dot{v}_{,A} \geq 0. \quad (6)$$

It is assumed that the constitutive functions

$$\psi, \phi, \eta, p_{Ai}, Q_A, h_A, g \quad (7)$$

depend on the variables

$$x_{i,A}, v, v_{,A}, \theta, \dot{\theta}, \theta_{,A}. \quad (8)$$

One then follows a procedure due to Coleman and Noll [12] whereby the entropy inequality (6) may be reduced and restrictions obtained on the constitutive variables. We simply present the outcome. For the generalised temperature we obtain

$$\frac{\partial \phi}{\partial x_{i,A}} = 0, \quad \frac{\partial \phi}{\partial v_{,A}} = 0, \quad \frac{\partial \phi}{\partial \theta_{,A}} = 0, \quad (9)$$

and hence

$$\phi = \phi(\theta, \dot{\theta}, v). \quad (10)$$

It is interesting to note that the generalised temperature does not depend simply on  $\theta$  and  $\dot{\theta}$ . The presence of voids must also play a role. Additionally

$$\begin{aligned} p_{Ai} &= \rho \frac{\partial \psi}{\partial x_{i,A}}, & Q_A &= -\rho \frac{\partial \psi}{\partial \theta_{,A}} \bigg/ \frac{1}{\phi} \frac{\partial \phi}{\partial \theta}, \\ h_A &= \rho \frac{\partial \psi}{\partial v_{,A}}, & g &= -\rho \left( \frac{\partial \psi}{\partial v} + \eta \frac{\partial \phi}{\partial v} \right), \end{aligned} \quad (11)$$

and

$$\eta = -\frac{\partial \psi}{\partial \dot{\theta}} \bigg/ \frac{\partial \phi}{\partial \dot{\theta}}. \quad (12)$$

The residual entropy inequality is

$$-\dot{\theta} \left( \rho \frac{\partial \psi}{\partial \theta} + \rho \eta \frac{\partial \phi}{\partial \theta} \right) - \frac{Q_A}{\phi} \left( \frac{\partial \phi}{\partial v} v_{,A} + \frac{\partial \phi}{\partial \theta} \theta_{,A} \right) \geq 0. \quad (13)$$

### 3. Acceleration waves

We are now in a position to study acceleration wave propagation using Eqs. (1)–(3). We use the notation of Chen [3] throughout and so let  $[\cdot]$  denote the jump of a function across the singular surface  $\mathcal{S}$  (acceleration wave), so that

$$[f] = f^- - f^+ \quad (14)$$

where  $f^-$  or  $f^+$  refers to the limit of  $f$  as the wave is approached from the left or right, respectively.

An acceleration wave for Eqs. (1)–(3) is a singular surface  $\mathcal{S}$  across which  $x_i$ ,  $v$  and  $\theta$  together with their first derivatives are continuous, but the second and higher derivatives suffer a finite discontinuity. We denote by  $a_i$ ,  $B$ ,  $C$  the wave amplitudes, so

$$a_i = [\ddot{x}_i], \quad B = [\ddot{v}], \quad C = [\ddot{\theta}]. \quad (15)$$

The theory of acceleration waves is now well known and lucidly described in e.g. Chen [3]. Therefore, we present only key steps. If we let  $N_A$  be the unit normal vector to  $\mathcal{S}$  in the reference configuration and  $U_N$  be the corresponding speed of  $\mathcal{S}$  at point  $(X_A, t)$  in the reference configuration then by expanding (1)–(3) with  $F_i$ ,  $\ell$  and  $r$  zero and taking the jumps of the relevant variables one derives the equations

$$\begin{aligned} \rho a_i &= \frac{\partial p_{Ai}}{\partial F_{iB}} \frac{1}{U_N^2} N_A N_B a_j + \frac{1}{U_N^2} \frac{\partial p_{Ai}}{\partial v_{,B}} N_A N_B B \\ &\quad - \frac{1}{U_N} \frac{\partial p_{Ai}}{\partial \theta} N_A C + \frac{1}{U_N^2} N_A N_B \frac{\partial p_{Ai}}{\partial \theta_{,B}} C, \end{aligned} \quad (16)$$

$$\begin{aligned} \rho k B &= \frac{\partial h_A}{\partial F_{iB}} \frac{1}{U_N^2} N_A N_B a_i + \frac{1}{U_N^2} \frac{\partial h_A}{\partial v_{,B}} N_A N_B B \\ &\quad - \frac{1}{U_N} \frac{\partial h_A}{\partial \theta} N_A C + \frac{1}{U_N^2} N_A N_B \frac{\partial h_A}{\partial \theta_{,B}} C, \end{aligned} \quad (17)$$

$$\begin{aligned}
& -\rho \frac{\partial \epsilon}{\partial F_{iA}} \frac{1}{U_N} a_i N_A - \rho \frac{\partial \epsilon}{\partial v_{,A}} \frac{1}{U_N} N_A B + \rho \frac{\partial \epsilon}{\partial \theta} C - \rho \frac{\partial \epsilon}{\partial \theta_{,A}} \frac{1}{U_N} N_A C \\
& = -\frac{\partial Q_A}{\partial F_{iB}} \frac{1}{U_N^2} N_A N_B a_i - \frac{\partial Q_A}{\partial v_{,B}} \frac{1}{U_N^2} N_A N_B B + \frac{\partial Q_A}{\partial \theta} \frac{1}{U_N} N_A C \\
& \quad - \frac{\partial Q_A}{\partial \theta_{,B}} \frac{1}{U_N^2} N_A N_B C - p_{Ai} \frac{1}{U_N} N_A a_i - h_A \frac{1}{U_N} N_A B.
\end{aligned} \tag{18}$$

One may proceed with this level of generality. However, to clearly see the novel effects associated with the current theory we now suppose the acceleration wave is advancing into an equilibrium region for which  $v^+$ ,  $\theta^+$  and  $x_i^+$  are constants, the  $+$  sign denoting the value ahead of the wave. We also suppose the body has a centre of symmetry. We believe no key loss of physics ensues by these assumptions and certainly the ensuing analysis is more transparent.

With the above restrictions (16)–(18) may be reduced to, recalling also  $\epsilon = \psi + \eta\phi$ ,

$$(Q_{ij} - \rho U_N^2 \delta_{ij}) a_j = U_N N_A \frac{\partial p_{Ai}}{\partial \theta} C, \tag{19}$$

$$\left( \rho k U_N^2 - N_A N_B \frac{\partial h_A}{\partial v_{,B}} \right) B = N_A N_B \frac{\partial h_A}{\partial \theta_{,B}} C, \tag{20}$$

$$\left( \rho \frac{\partial \epsilon}{\partial \theta} U_N^2 + N_A N_B \frac{\partial Q_A}{\partial \theta_{,B}} \right) C = -\frac{\partial Q_A}{\partial v_{,B}} N_A N_B B + \rho U_N N_A \phi \frac{\partial \eta}{\partial F_{iA}} a_i, \tag{21}$$

where

$$Q_{ij} = N_A N_B \frac{\partial p_{Ai}}{\partial F_{jB}}, \tag{22}$$

is the acoustic tensor.

Acceleration waves were studied by Nunziato and Cowin [41], but we observe fundamental changes when (19)–(21) are employed. In our theory the elastic wave (associated with  $a_i$ ) and the voids wave (associated with  $B$ ) do *not* decouple as they do in Nunziato and Cowin [41]. This is due to the fact that the theory of Nunziato and Cowin [41] employs the Clausius–Duhem inequality and they are forced to use a zero heat flux. Equations (19)–(21) show that the waves do not decouple with our theory and temperature effects are important. We believe the coupled theory (19)–(21) is realistic and allows us to have three interconnected waves. When the waves decouple, as in Nunziato and Cowin [41], then to have combined wave propagation one requires the artificial condition of equal wavespeeds, cf. Mariano and Sabatini [34].

From Eq. (19) we may deduce an important assertion regarding the propagation of a plane wave. This follows the analysis of Lindsay and Straughan [30] where an equivalent procedure without voids is given. Since, Chen [3], Eq. (4.10),

$$N_A = F_{iA} \frac{|\nabla_{\mathbf{x}} s|}{|\nabla_{\mathbf{x}} \mathcal{S}|} n_i$$

where  $n_i$  is the equivalent unit normal in the current configuration, we put

$$\beta_{ij} = \frac{|\nabla_{\mathbf{x}} s|}{|\nabla_{\mathbf{x}} \mathcal{S}|} \frac{\partial p_{Ai}}{\partial \theta} F_{jA}$$

and it then follows as in Lindsay and Straughan [30] that a plane wave may propagate in a direction  $\mathbf{n}^*$  where  $\beta_{ij} n_j^*$  is an eigenvector of  $Q_{ij}$ . We let  $v_i$  be the unit vector in the direction

$\beta_{ij}n_j^*$  and put  $a_i = Av_i$ . There is thus propagation of a generalised longitudinal wave in the direction  $\mathbf{n}^*$  with amplitude in the direction  $\beta_{ij}n_j^*$ .

Take the inner product of (19) with  $v_i$ . We then have a system of equations in  $A$ ,  $B$  and  $C$ , and a nonzero solution leads (together with use of (24)–(26)) to the wavespeed equation

$$(U_N^2 - U_M^2)(U_N^2 - U_P^2)(U_N^2 - U_T^2) - (U_N^2 - U_P^2)U_N^2 K_1 - (U_N^2 - U_M^2)K_2 = 0. \quad (23)$$

Here

$$U_M^2 = N_A N_B v_i v_j \frac{\partial^2 \psi}{\partial F_{iA} \partial F_{jB}}, \quad (24)$$

$$U_P^2 = \frac{N_A N_B}{k} \frac{\partial^2 \psi}{\partial v_{,A} v_{,B}}, \quad (25)$$

$$U_T^2 = \frac{N_A N_B}{\phi_\theta \eta_\theta} \frac{\partial^2 \psi}{\partial \theta_{,A} \theta_{,B}}, \quad (26)$$

$$K_1 = \frac{N_A N_K v_i v_j}{\phi_\theta \eta_\theta} \frac{\partial^2 \psi}{\partial \theta \partial F_{iA}} \frac{\partial^2 \psi}{\partial \theta \partial F_{jK}}, \quad (27)$$

$$K_2 = \frac{N_A N_B N_R N_S}{k \phi_\theta \eta_\theta} \frac{\partial^2 \psi}{\partial v_{,A} \partial \theta_{,B}} \frac{\partial^2 \psi}{\partial v_{,S} \partial \theta_{,R}}. \quad (28)$$

It is of interest to note that  $U_M$  is the wavespeed of an elastic wave in the absence of other effects, Chen [3],  $U_P$  is the wavespeed of a wave associated with the void fraction, Nunziato and Cowin [41], whereas  $U_T$  is the wavespeed of a thermal wave, Lindsay and Straughan [30]. The terms  $K_1$  and  $K_2$  represent cross derivative effects whose magnitude depends on the form of functional relationship for  $\psi$ . If these terms are zero then (23) allows propagation of three distinct waves with different speeds  $U_M$ ,  $U_P$ ,  $U_T$  (together with three waves moving in the opposite direction). Thus, if  $K_1$  and  $K_2$  are not too large we may use a continuity argument to conclude (23) has three distinct real solutions  $U_N^2$  and three distinct waves continue to propagate. Physically we expect this to happen and the values found together with experimental results should suggest what functional form of  $\psi$  will be useful in theoretical modelling of thermoacoustic wave propagation in elastic materials with voids.

One may progress well beyond this. We may, in fact, determine exactly the amplitudes  $A$ ,  $B$ ,  $C$  as functions of time. To do this one differentiates (1)–(3), with  $F_i$ ,  $\ell$ ,  $r$  zero, with respect to say time and then takes the jumps of the respective equations. By combining the resulting equations in such a way that (in one space dimension) terms like  $[\dot{F}_X]$ ,  $[\ddot{\theta}_X]$ ,  $[\dot{v}_X]$ ,  $[\dot{\theta}_{XX}]$ , and  $[\dot{F}]$  disappear one may arrive at an equation of form

$$\frac{\delta C}{\delta t} + bC + aC^2 = 0.$$

This equation has explicit solution, cf. expression (3.12) of Ciarletta and Straughan [11]. One may then deduce the evolutionary behaviour of  $C$  which may blow-up in a finite time, behaviour thought to be associated with shock wave formation. However, unlike Ciarletta and Straughan [11] where  $a$ ,  $b$  have acceptable forms from which we may interpret physical behaviour, the expressions we here find for  $a$  and  $b$  are very complicated and we have not been able to simplify them sufficiently to obtain useful physics.

## References

- [1] P.S. Casas, R. Quintanilla, Exponential decay in one-dimensional porous thermoelasticity, *Mech. Res. Comm.* 32 (2005) 652–658.
- [2] G. Caviglia, A. Morro, B. Straughan, Thermoelasticity at cryogenic temperatures, *Internat. J. Non-Linear Mech.* 27 (1992) 251–263.
- [3] P.J. Chen, Growth and decay of waves in solids, in: S. Flügge, C. Truesdell (Eds.), *Handbuch der Physik*, vol. VIa/3, Springer, Berlin, 1973, pp. 303–402.
- [4] C.I. Christov, P.M. Jordan, Heat conduction paradox involving second sound propagation in moving media, *Phys. Rev. Lett.* 94 (2005) 154301-1–154301-4.
- [5] I. Christov, P.M. Jordan, C.I. Christov, Nonlinear acoustic propagation in homentropic perfect gases: A numerical study, *Phys. Lett. A* 353 (2006) 273–280.
- [6] M. Ciarletta, D. Iesan, *Non-Classical Elastic Solids*, Longman, New York, 1993.
- [7] M. Ciarletta, G. Iovane, Hypersingular integral equations and applications to porous materials with periodic cracks, in: *Proc. XVII Cong. U.M.I.*, vol. 8-B, 2005, pp. 415–420.
- [8] M. Ciarletta, G. Iovane, M.A. Sumbatyan, On stress analysis for cracks in elastic materials with voids, *Internat. J. Engrg. Sci.* 41 (2003) 2447–2461.
- [9] M. Ciarletta, E. Scarpetta, Some results in a generalised thermodynamic theory for elastic materials with voids, *Rev. Roumaine Sci. Tech. Mec. Appl.* 34 (1989) 113–119.
- [10] M. Ciarletta, B. Straughan, Poroacoustic acceleration waves, *Proc. R. Soc. Lond. Ser. A* (2006), in press.
- [11] M. Ciarletta, B. Straughan, Poroacoustic acceleration waves with second sound, 2006, manuscript.
- [12] B.D. Coleman, W. Noll, The thermodynamics of elastic materials with heat conduction and viscosity, *Arch. Ration. Mech. Anal.* 13 (1963) 167–178.
- [13] A.C. Diebold, Subsurface imaging with scanning ultrasound holography, *Science* 310 (2005) 61–62. Also see website: <http://www.sciencemag.org/cgi/content/full/310/5745/61>.
- [14] V.A. Eremeyev, Acceleration waves in incompressible elastic media, *Dokl. Phys.* 50 (2005) 204–206.
- [15] P. Fausti, R. Pompoli, R.S. Smith, An intercomparison of laboratory measurements of airborne sound insulation of lightweight plasterboard walls, *Building Acoustics* 6 (1999) 127–140.
- [16] Z.E.A. Fellah, C. Depollier, Transient acoustic wave propagation in rigid porous media: A time-domain approach, *J. Acoust. Soc. Am.* 107 (2000) 683–688.
- [17] Z.E.A. Fellah, C. Depollier, S. Berger, W. Lauriks, P. Trompette, J.Y. Chapelon, Determination of transport parameters in air-saturated porous materials via reflected ultrasonic waves, *J. Acoust. Soc. Am.* 114 (2003) 2561–2569.
- [18] Y.B. Fu, N.H. Scott, Acceleration wave propagation in an inhomogeneous heat conducting elastic rod of slowly varying cross section, *J. Thermal Stresses* 15 (1988) 253–264.
- [19] Y.B. Fu, N.H. Scott, The transition from acceleration wave to shock wave, *Internat. J. Engrg. Sci.* 29 (1991) 617–624.
- [20] M. Garai, F. Pompoli, A simple empirical model of polyester fibre materials for acoustical applications, *Appl. Acoustics* 66 (2005) 1383–1398.
- [21] A.E. Green, N. Laws, On the entropy production inequality, *Arch. Ration. Mech. Anal.* 45 (1972) 47–53.
- [22] T. Gultop, On the propagation of acceleration waves in incompressible hyperelastic solids, *J. Sound Vibration* 462 (2006) 409–418.
- [23] D. Iesan, *Thermoelastic Models of Continua*, Kluwer, 2004.
- [24] D. Iesan, Second-order effects in the torsion of elastic materials with voids, *ZAMM Z. Angew. Math. Mech.* 85 (2005) 351–365.
- [25] D. Iesan, Nonlinear plane strain of elastic materials with voids, *Math. Mech. Solids* (2005), in press, doi:10.1177/1081286505044134.
- [26] P.M. Jordan, Growth and decay of acoustic acceleration waves in Darcy-type porous media, *Proc. R. Soc. Lond. Ser. A* 461 (2005) 2749–2766.
- [27] P.M. Jordan, C.I. Christov, A simple finite difference scheme for modelling the finite-time blow-up of acoustic acceleration waves, *J. Sound Vibration* 281 (2005) 1207–1216.
- [28] P.M. Jordan, A. Puri, Growth/decay of transverse acceleration waves in nonlinear elastic media, *Phys. Lett. A* 341 (2005) 427–434.
- [29] N. Kameyama, M. Sugiyama, Analysis of acceleration waves in crystalline solids based on a continuum model incorporating microscopic thermal vibration, *Contin. Mech. Thermodyn.* 8 (1996) 351–359.
- [30] K.A. Lindsay, B. Straughan, Propagation of mechanical and temperature acceleration waves in thermoelastic materials, *Z. Angew. Math. Phys.* 30 (1979) 477–490.



- [31] D. Linton-Johnson, T.J. Plona, H. Kajima, Probing porous media with first and second sound Acoustic properties of water saturated porous media, *J. Appl. Phys.* 76 (1994) 115–125.
- [32] A. Magaña, R. Quintanilla, On the time decay of solutions in one-dimensional theories of porous materials, *Internat. J. Solids Structures* 43 (2006) 3414–3427.
- [33] A. Magaña, R. Quintanilla, On the spatial behaviour of solutions for porous elastic solids with quasi-static microvoids, *Math. Comput. Modelling* (2006), in press.
- [34] P.M. Mariano, L. Sabatini, Homothermal acceleration waves in multifield theories of continua, *Internat. J. Non-Linear Mech.* 35 (2000) 963–977.
- [35] W. Maysenhölder, A. Berg, P. Leistner, Acoustic properties of aluminium foams—measurements and modelling, in: CFA/DAGA'04, Strasbourg, 22–25/03/2004. See also: <http://www.ibp.fhg.de/ba/forschung/aluschaum/aluschaum.pdf>, 2004.
- [36] R.J. Meyer, Ultrasonic drying of saturated porous solids via second sound, <http://www.freepatentsonline.com/6376145.html>, 2006.
- [37] K. Mitra, S. Kumar, A. Vedavarz, M.K. Moallemi, Experimental evidence of hyperbolic heat conduction in processed meat, *Trans. ASME J. Heat Transfer* 117 (1995) 568–573.
- [38] D. Nield, A. Bejan, *Convection in Porous Media*, second ed., Springer, New York, 1999.
- [39] J.W. Nunziato, E.K. Walsh, On the influence of void compaction and material non-uniformity on the propagation of one-dimensional acceleration waves in granular materials, *Arch. Ration. Mech. Anal.* 64 (1977) 299–316.
- [40] J.W. Nunziato, E.K. Walsh, Addendum “On the influence of void compaction and material non-uniformity on the propagation of one-dimensional acceleration waves in granular materials”, *Arch. Ration. Mech. Anal.* 67 (1978) 395–398.
- [41] J.W. Nunziato, S.C. Cowin, A nonlinear theory of elastic materials with voids, *Arch. Ration. Mech. Anal.* 72 (1979) 175–201.
- [42] Office of Basic Energy Sciences, Metals and Ceramics Division, Acoustic harmonic generation by microstructures, <http://mfnl.xjtu.edu.cn/gov-doe-ornl/bes/bes/welcome.htm#top%20of%20page>, 2006.
- [43] M. Ostoj-Starzewski, J. Trebicki, On the growth and decay of acceleration waves in random media, *Proc. R. Soc. Lond. Ser. A* 455 (1999) 2577–2614.
- [44] J. Ouellette, Seeing with sound. Acoustic microscopy advances beyond failure analysis. American Institute of Physics Website, <http://www.aip.org/tip/INPHFA/vol-10/iss-3/p14.html>, 2004.
- [45] P. Puri, P.M. Jordan, On the propagation of plane waves in type-III thermoelastic media, *Proc. R. Soc. Lond. Ser. A* 460 (2004) 3203–3221.
- [46] R. Quintanilla, On uniqueness and continuous dependence in the nonlinear theory of mixtures of elastic solids with voids, *Math. Mech. Solids* 6 (2001) 281–298.
- [47] R. Quintanilla, R. Racke, A note on stability in dual-phase-lag heat conduction, *Int. J. Heat Mass Transfer* 49 (2006) 1209–1213.
- [48] R. Quintanilla, B. Straughan, Discontinuity waves in type III thermoelasticity, *Proc. R. Soc. Lond. Ser. A* 460 (2004) 1169–1175.
- [49] A. Rai, Breakdown of acceleration waves in radiative magnetic fluids, *Defence Sci. J.* 53 (2003) 425–430.
- [50] T. Ruggeri, M. Sugiyama, Hyperbolicity, convexity and shock waves in one-dimensional crystalline solids, *J. Phys.* A 38 (2005) 4337–4347.
- [51] H. Sakai, S. Sato, R. Pompoli, N. Prodi, Measurement of regional environmental noise by use of a PC-based system: An application to the noise near the airport ‘G Marconi’ in Bologna, *J. Sound Vibration* 241 (2001) 57–68.
- [52] S. Su, W. Dai, P.M. Jordan, R.E. Mickens, Comparison of the solutions of a phase-lagging heat transport equation and damped wave equation, *Int. J. Heat Mass Transfer* 48 (2005) 2233–2241.
- [53] M. Sugiyama, Statistical mechanical study of wave propagation in crystalline solids at finite temperatures, *Current Topics in Acoustics Research* 1 (1994) 139–158.
- [54] P. Vadasz, Lack of oscillations in dual-phase-lagging heat conduction for a porous slab subject to imposed heat flux and temperature, *Int. J. Heat Mass Transfer* 48 (2005) 2822–2828.
- [55] J.J. Vadasz, S. Govender, P. Vadasz, Heat transfer enhancement in nano-fluids suspensions: Possible mechanisms and explanations, *Int. J. Heat Mass Transfer* 48 (2005) 2673–2683.
- [56] G. Valentini, C. Curro, M. Sugiyama, Acceleration waves analysed by a new continuum model of solids incorporating microscopic thermal vibrations, *Contin. Mech. Thermodyn.* 16 (2004) 185–198.
- [57] D.K. Wilson, Simple, relaxational models for the acoustic properties of porous media, *Appl. Acoustics* 50 (1997) 171–188.