We derive a nonlinear theory of heat-conducting micropolar mixtures in Lagrangian description. The kinematics, balance laws, and constitutive equations are examined and utilized to develop a nonlinear theory for binary mixtures of micropolar thermoelastic solids. The initial boundary value problem is formulated. Then, the theory is linearized and a uniqueness result is established.

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1. Introduction

The importance of the study of mixtures was recognized long ago when the basic concepts of the theory have been established and the possible applications of the mathematical models have been identified. The origin of modern formulations of continuum thermo-mechanical theories of mixtures goes back to articles of Truesdell and Toupin [1], Kelly [2], Eringen and Ingram [3, 4], Green and Naghdi [5, 6], Green and Laws [7], Müller [8], and Bowen and Wiese [9]. The theoretical progress in the field is discussed in detail in review articles by Bowen [10], Atkin and Craine [11, 12], Bedford and Drumheller [13], and in the books of Samohýl [14] and Rajagopal and Tao [15].

In general, the theories of mixtures describe the interaction between fluids and gases, and the Eulerian description is used. Thus, the motion of a mixture of two continua is described by two equations, \( x = x(X, t) \) and \( y = y(Y, t) \), and the particles \( X \) and \( Y \) are assumed to occupy the same position at current time \( t \), so that \( x = y \). In contrast to mixtures of fluids, the theory on mixtures of solids is developed naturally in the Lagrangian description and it leads to different results. In this case, the motion of a binary mixture is described by the equations \( x = x(X, t) \) and \( y = y(Y, t) \), where the particles under consideration occupy the same position in the reference configuration, so that \( X = Y \).
The Lagrangian description has been used for the first time by Bedford and Stern [16, 17] in order to derive a mixture theory of binary elastic solids. In this theory, the independent constitutive variables are displacement gradients and the relative displacement. The Lagrangian description was used by Pop and Bowen [18] to establish a theory of mixtures with long-range spatial interaction, by Tiersten and Jahanmir [19] to derive a theory of composites, by Iesan [20] to elaborate on a binary mixture theory of thermoelastic solids, and by Iesan [21] to develop a theory of nonsimple elastic solids.

A special attention has been paid to include some terms in the basic formulation of the theory of mixtures in order to reflect the microstructure of the constituents. In this sense, we mention that the Eulerian approach has been used in the papers by Allen and Kline [22], Twiss and Eringen [23, 24], Dunwoody [25], Passman [26], and Eringen [27, 28]. On the other hand, Iesan [29–31] studied the mixtures of granular materials, the porous viscoelastic mixtures, and the interacting micromorphic materials in Lagrangian description.

In this work, we consider a mixture consisting of two micropolar thermoelastic solids. By using the nonlinear theory of micropolar media [32–34] and the results established in [5, 16, 17, 20, 30, 31], we derive the basic equations of a nonlinear theory in Lagrangian description. According to [32–34], each material point of such materials can independently translate and rotate, so that it has 6 degrees of freedom. The rotation is described by a proper orthogonal tensor.

We recall that in [23], the authors have derived the micromorphic and micropolar equations and entropy production inequalities for a mixture of any number of constituents in Eulerian description. The theory of mixtures for micromorphic materials is more general than the micropolar mixture theory, in that it also considers deformation of material points, requiring 12 degrees of freedom. The results have been used in [24] to construct the general form of the nonlinear, anisotropic, elastic, constitutive equations for micromorphic, and micropolar mixtures; as an illustration of a special case, the specific linear equations for an isotropic two-constituent micropolar mixture have been presented.

Concerning the mixtures of solids, it is important to have an alternative form of the theory. It is well known that for a fluid, every configuration of the body can be taken as reference configuration. So, the present configuration is taken as reference configuration and the Eulerian description is used to formulate the basic concepts. In the case of a solid, a configuration of the body is supposed to be known and this configuration is taken as reference configuration. The Lagrangian description is usually used, although the Eulerian description leads to the same theory. The situation changes in the case of mixtures; the Lagrangian description and the Eulerian description lead to different theories. For mixtures of solids, it is important to have a theory in which the motion is to be referred to the known configuration of the body in order to measure the forces and the stresses and to prescribe the boundary conditions. In this sense, Iesan [31] pointed out that “when the continuum has a reference configuration B through which it passes at time t₀, it is convenient to have an alternative form of the theory in which the generalized forces and stresses are measured with respect to this configuration. In the nonlinear theory this fact is important for specification of the boundary conditions, since the boundary of current configuration is,
in general, unknown.” In [31], Ieșan presented the basic equations of the nonlinear theory for binary mixtures of micromorphic elastic solids in Lagrangian description. Then, the initial boundary value problems were formulated and some uniqueness and continuous-dependence results were established.

In this paper, we continue the research line initiated in [31] concerning the theory of micromorphic mixtures developed in Lagrangian description. We focus our attention to the micropolar elastic mixtures, but we consider in addition the thermal effects. The intended applications of these kind of theories (see [24]) are to granular composites, to polycrystalline mixtures, or to polyatomic or polymolecular crystal lattices. The next section is devoted to a kinematical study of the motion in which we present the measures of deformation and their rates. Then, the balance laws for mass, microinertia, energy, and production of entropy are constructed. The balance equations are derived by using an idea of Green and Naghdi [5]. We assume that the two constituents have a common temperature and every thermodynamical process that takes place in mixture satisfies the Clausius-Duhem inequality. We consider the following constitutive variables: the displacement fields, displacement gradients, micromotion fields, micromotion gradients, temperature, and temperature gradient. By using the constitutive axioms, we express the dependent constitutive variables in an invariant form and then we use the Clausius-Duhem inequality to develop constitutive equations. Initial boundary value problems for the nonlinear theory are formulated. In the second part of the paper, the theory is linearized and a uniqueness result is established.

2. Kinematics

We consider a mixture of two interacting continua \( s_1 \) and \( s_2 \). The mixture is viewed as a superposition of two continua each following its own motion and at any time each place in the mixture is occupied simultaneously by different particles, one from each constituent.

We assume that at time \( t_0 \) the body occupies the region \( B \) of Euclidean three-dimensional space and is bounded by piecewise smooth surface \( \partial B \). The configuration of the body at time \( t_0 \) is taken as the reference configuration. We refer the motion of the body to the reference configuration and a fixed system of rectangular Cartesian axes. We use vector and Cartesian tensor notation with Latin indices having the values 1, 2, and 3. Greek indices are understood to range over integers (1,2) and summation convention is not used for these indices.

The position of typical particles of \( s_1 \) and \( s_2 \) at time \( t \) are \( \mathbf{x} \) and \( \mathbf{y} \), where

\[
\mathbf{x} = \mathbf{x}(\mathbf{X}, t), \quad \mathbf{y} = \mathbf{y}(\mathbf{Y}, t), \quad \mathbf{X}, \mathbf{Y} \in B, \ t \in I.
\]  

Here \( \mathbf{X} \) and \( \mathbf{Y} \) are reference positions of the particles and \( I = [t_0, t_1] \), where \( t_1 \) is some instant that may be infinity.

In this paper, we derive a theory for binary mixture of micropolar elastic solids where the particles under consideration occupy the same position in the reference configuration, so that \( \mathbf{X} = \mathbf{Y} \). The translations of the body are described by

\[
\mathbf{x} = \mathbf{x}(\mathbf{X}, t), \quad \mathbf{y} = \mathbf{y}(\mathbf{X}, t), \quad \mathbf{X} \in B, \ t \in I.
\]
We stress that in the continuum theory of mixtures, the constituents are not physically separated and in consequence a great care must be exercised to preserve the generality that the constitutive relations for a given constituent depend upon the state variables of the other. This is not the case for multiphase materials or immiscible mixtures where the constituents remain physically separate on a scale which is large in comparison with molecular dimensions and in some local sense each constituent will obey the constitutive relations for that constituent alone.

We imagine that each particle of the mixture can also independently rotate. Just as the functions $x_i(X, t)$ and $y_i(X, t)$ specify the translation of each material particle of the mixture from the reference configuration, following [32, 33], we introduce proper orthogonal tensors that specify the rotation of each material particle from reference configuration. Let a particle of the constituent $s_\alpha$ occupy the position $X$ in the reference configuration and let $\Xi^{(a)}_\alpha$ be an arbitrary vector at $X$ associated with this material particle. In the context of micropolar continua, the above vector can rigidly rotate with the particle to the vector $\xi^{(a)}_\alpha$. Then we may write $\xi^{(a)}_\alpha = \chi^{(a)}_{\alpha} \chi^{(a)}_{\alpha} = \epsilon_{LMN} \chi^{(a)}_{\alpha} \chi^{(a)}_{\alpha} \chi^{(a)}_{\alpha} = \epsilon_{lmn}$ (2.3)

and completely describes the rotation. In the above relations, $\delta_{ij}$ and $\delta_{KL}$ are Kronecker deltas and $\epsilon_{LMN}$ and $\epsilon_{lmn}$ are alternating symbols. The tensor $\chi^{(a)}_{\alpha} (X, t)$ is usually called micromotion (see [33]). Thus, the motion of a micropolar mixture is described by

$$x_i = x_i(X, t), \quad y_i = y_i(X, t), \quad \chi^{(a)}_{\alpha} = \chi^{(a)}_{\alpha}(X, t), \quad X \in B, \ t \in I, \ \alpha = 1, 2. \quad (2.4)$$

We suppose that the above functions are sufficiently smooth for the ensuing analysis to be valid.

The velocity and acceleration fields associated with constituents $s_1$ and $s_2$ are

$$v_i^{(1)} = \dot{x}_i(X, t), \quad a_i^{(1)} = \ddot{x}_i(X, t), \quad (2.5)$$

$$v_i^{(2)} = \dot{y}_i(X, t), \quad a_i^{(2)} = \ddot{y}_i(X, t), \quad (2.6)$$

respectively, where $\dot{f}$ denotes differentiation of $f$ with respect to $t$ holding $X_K$ fixed.

In view of the relation (2.3), we introduce the skew-symmetric tensor

$$v_{ij}^{(a)} (X, t) = \dot{\chi}_{ik}^{(a)} \chi_{jk}^{(a)} \ , \quad v_{ij}^{(a)} = -v_{ji}^{(a)}. \quad (2.7)$$

The corresponding angular velocity is given by

$$v_i^{(a)} = -\frac{1}{2} \epsilon_{ijk} v_{jk}^{(a)}. \quad (2.8)$$

From (2.7) and (2.8), we deduce

$$v_i^{(a)} = -\frac{1}{2} \epsilon_{ijk} \chi_{ik}^{(a)} \chi_{kl}^{(a)} \ , \quad (2.9)$$

$$\dot{\chi}_{ik}^{(a)} = \epsilon_{ijk} v_j^{(a)} \chi_{kl}^{(a)} \ . \quad (2.10)$$
We note that a rigid motion of the mixture is described by the relations

\[
x_i(X, t) = Q_{ik}(t)X_K + \tilde{c}_i(t), \quad y_i(X, t) = Q_{ik}(t)X_K + \tilde{c}_i(t),
\]

\[
\chi^{(1)}_{ik}(X, t) = Q_{ik}(t), \quad \chi^{(2)}_{ik}(X, t) = Q_{ik}(t),
\]

where \(Q\) is proper orthogonal. For rigid motions, from (2.10) and (2.11), we obtain

\[
v_i^{(1)} = \epsilon_{ijk}b_jx_k + c_i, \quad v_i^{(2)} = \epsilon_{ijk}b_jy_k + c_i, \quad y_i^{(1)} = y_i^{(2)} = b_i,
\]

where \(b_i\) is the axial vector of the skew-symmetric tensor \(Q_{ik}Q_{jk}\) and \(c_i = \tilde{c}_i - Q_{ik}Q_{jk}\tilde{c}_j\).

Later in this work, we shall need the concept of change of frame. We say that two motions of the mixture described by the functions \(x_i(X, t), y_i(X, t), \chi^{(a)}_{ik}(X, t)\), and \(\tilde{x}_i(X, t'), \tilde{y}_i(X, t'), \tilde{\chi}^{(a)}_{ik}(X, t')\), respectively, are equivalent if

\[
\tilde{x}_i(X, t') = Q_{ij}(t)x_j(X, t) + c_i(t), \quad \tilde{\chi}^{(1)}_{ik}(X, t') = Q_{ij}(t)\chi^{(1)}_{jk}(X, t),
\]

\[
\tilde{y}_i(X, t') = Q_{ij}(t)y_j(X, t) + c_i(t), \quad \tilde{\chi}^{(2)}_{ik}(X, t') = Q_{ij}(t)\chi^{(2)}_{jk}(X, t), \quad t' = t - a,
\]

where \(a\) is a constant, \(c_i\) represent a translation, and \(Q\) is an orthogonal tensor. In fact, the motions are equivalent if they differ by the reference frame and by the reference time.

Let us introduce the following measures of deformation:

\[
E_{KL} = x_iK\chi^{(1)}_{iil} - \delta_{KL}, \quad G_{KL} = y_iK\chi^{(1)}_{iil} - \delta_{KL}, \quad D_K = \chi^{(2)}_{ik}(x_i - y_j),
\]

\[
2\Gamma^{(1)}_{KL} = \epsilon_{LMN}\chi^{(1)}_{iMN} \chi^{(1)}_{iMK}, \quad 2\Gamma^{(2)}_{KL} = \epsilon_{LMN}\chi^{(2)}_{iMN} \chi^{(2)}_{iMK}, \quad \Delta_{KL} = \chi^{(2)}_{ik}\chi^{(2)}_{il} - \delta_{KL}.
\]

In the case of a single micropolar medium, the strain measures are \(E\) and \(\Gamma^{(1)}\) and their rates as well as their geometrical significance are examined in detail in [32, 33]. \(E\) and \(\Gamma^{(1)}\) are called the Cosserat deformation tensor and wryness tensor, respectively. In the context of the theory of micropolar mixtures, we introduce further the measures \(D\) and \(\Delta\) which describe relative motions of constituents (translations and rotations). Moreover, for reasons that will be obvious in the next section we use the tensor \(G_{KL}\) for the second constituent instead of the Cosserat deformation tensor \(E^{(2)}_{KL} = y_iK\chi^{(2)}_{iil} - \delta_{KL}\). As regards the kinematics, this is unimportant since \(E^{(2)}_{KL}\) can be written in terms of \(G_{KL}\) and \(\Delta_{KL}\) in the form

\[
E^{(2)}_{KL} = y_iK\delta_{ij}\chi^{(2)}_{jkl} - \delta_{KL} = y_iK\chi^{(1)}_{iim}\chi^{(1)}_{jmkl} - \delta_{KL} = G_{KM}\Delta_{ML} + G_{KL} + \Delta_{KL}.
\]

It is easy to see that two motions described by the functions \(x_i(X, t), y_i(X, t), \chi^{(a)}_{ik}(X, t)\), and \(\tilde{x}_i(X, t'), \tilde{y}_i(X, t'), \tilde{\chi}^{(a)}_{ik}(X, t')\), respectively, and related to (2.13), produce equal measures of deformations.
The time rates of $E$, $G$, $\Gamma$, $D$, and $\Delta$ computed from (2.3), (2.5), (2.9), (2.10), and (2.14) are
\begin{align}
\dot{E}_{KL} &= \chi_{il}^{(1)}(v_{i,K}^{(1)} + \epsilon_{ijk}x_{j,K}v_{k}^{(1)}), \quad \dot{G}_{KL} = \chi_{il}^{(1)}(v_{i,K}^{(2)} + \epsilon_{ijk}y_{j,K}v_{k}^{(1)}), \\
\dot{\Gamma}_{KL} &= \chi_{il}^{(1)}(v_{i,K}^{(1)}), \quad \dot{\Gamma}_{KL}^{(2)} = \chi_{il}^{(2)}v_{i,K}^{(2)}, \\
\dot{D}_{K} &= \chi_{ik}^{(1)}(v_{i}^{(1)} - v_{i}^{(2)} + \epsilon_{ijk}(x_{j} - y_{j})v_{k}^{(1)}), \quad \dot{\Delta}_{KL} = \epsilon_{ijm}\chi_{mk}^{(1)}\chi_{il}^{(2)}(v_{j}^{(1)} - v_{j}^{(2)}). \tag{2.16}
\end{align}

If these rates are zero, then the differential equations can be integrated. Following [32], we deduce that the solution is a rigid motion of the form (2.11).

By using the relation (2.3) and the properties of the alternating symbol, from (2.16) we obtain
\begin{align}
v_{i,K}^{(1)} + \epsilon_{ijk}x_{j,K}v_{k}^{(1)} &= \chi_{il}^{(1)}\dot{E}_{KL}, \quad v_{i,K}^{(2)} + \epsilon_{ijk}y_{j,K}v_{k}^{(1)} = \chi_{il}^{(1)}\dot{G}_{KL}, \\
v_{i,K}^{(1)} &= \chi_{il}^{(1)}\dot{\Gamma}_{KL}, \quad v_{i,K}^{(2)} = \chi_{il}^{(2)}\dot{\Gamma}_{KL}, \\
v_{i}^{(1)} - v_{i}^{(2)} + \epsilon_{ijk}(x_{j} - y_{j})v_{k}^{(1)} &= \chi_{ik}^{(1)}\dot{D}_{K}, \quad v_{i}^{(1)} - v_{i}^{(2)} = \epsilon_{ijm}\chi_{jk}^{(1)}\chi_{ml}^{(2)}\dot{\Delta}_{KL}. \tag{2.17}
\end{align}

### 3. Basic laws

In this section, we postulate the balance laws of micropolar mixtures and then we derive the local balance equations. We consider the following balance laws: conservation of mass for each constituent, conservation of microinertia for each constituent, conservation of energy for the mixture as a whole, and law of entropy. We suppose that the mixture is chemical inert so that we do not consider the axiom of balance of mass (or microinertia) for the mixture. The balance of momentum and balance of moment of momentum for each constituent are derived following an idea by Green and Naghdi [5]. As regards the entropy production inequality, we suppose that the constituents have a common temperature, so that the axiom involves only the statement concerning the mixture as a whole.

We consider an arbitrary material region $P_{\alpha}$ of constituent $s_{\alpha}$ at time $t$ bounded by the surface $\partial P_{\alpha}$, and we suppose that $P_{0}$ is the corresponding region at time $t_{0}$ bounded by the surface $\partial P_{0}$. The equation of balance of mass for the constituent $s_{\alpha}$ is
\begin{equation}
\frac{d}{dt}\int_{P_{\alpha}}\rho_{\alpha}dV = \int_{P_{\alpha}}m_{\alpha}dV, \tag{3.1}
\end{equation}
where $\rho_{\alpha}$ is the mass density of the constituent $s_{\alpha}$; and $m_{\alpha}$ is the rate at which mass is supplied to $s_{\alpha}$ per unit volume from the other constituent. In this paper, we assume that mass elements of each constituent are conserved so that $m_{1} = 0$ and $m_{2} = 0$. The relation (3.1) can be written in the form
\begin{equation}
\frac{d}{dt}\int_{P_{0}}J_{(\alpha)}\rho_{\alpha}dV = 0, \tag{3.2}
\end{equation}
where

\[ J_1 = \det \left( \frac{\partial x_i}{\partial X_A} \right), \quad J_2 = \det \left( \frac{\partial y_i}{\partial X_A} \right). \] (3.3)

With the usual assumptions, from (3.2) we deduce

\[ J_1 \rho_1 = \rho_0^1, \quad J_2 \rho_2 = \rho_0^2, \] (3.4)

where \( \rho_0^\alpha \) is the mass density of the constituent \( s_\alpha \) at time \( t_0 \).

Since each material particle of the micropolar mixture is envisioned as a rigid particle, we ascribe to the particle of constituent \( s_\alpha \) that occupy the position \( X \) in the reference configuration a material inertia tensor \( I_{KL}^\alpha(X) \), which is symmetric and positive definite. At time \( t \), the inertia tensor of the particle in consideration is denoted by \( i_{kl}^{(1)}(x,t) \) (if the material particle belongs to constituent \( s_1 \)) or \( i_{kl}^{(2)}(y,t) \), otherwise. Conservation of microinertia is stated as [32, 33]

\[ \frac{d}{dt} \int_{P_\alpha} \rho_\alpha^{(a)} i_{kl}^{(a)}(x,t) dV = 0, \] (3.5)

If we proceed as above, from (3.4) and (3.5), we deduce

\[ I_{KL}^{(a)} = i_{kl}^{(a)}(x,t) \chi^{(a)} kK \chi^{(a)} lL. \] (3.6)

In view of (2.10) and symmetry of \( i_{ij}^{(a)} \), the above relation leads to

\[ \frac{di_{ij}^{(a)}}{dt} = \left( \epsilon_{inn} i_{nj}^{(a)} + \epsilon_{jmn} i_{ni}^{(a)} \right) \nu^{(a)} m. \] (3.7)

Following [7, 30], we postulate an energy balance at time \( t \) in the form

\[ \frac{d}{dt} \sum_{\alpha=1}^{2} \int_{P_\alpha} \rho_\alpha \left( e + \frac{1}{2} \nu_i^{(a)} \nu_i^{(a)} + \frac{1}{2} \nu_{ij}^{(a)} \nu_i^{(a)} \nu_j^{(a)} \right) dV = \sum_{\alpha=1}^{2} \left[ \int_{P_\alpha} \rho_\alpha \left( F_i^{(a)} \nu_i^{(a)} + G_i^{(a)} \nu_i^{(a)} + r \right) dV + \int_{\partial P_\alpha} \left( t_i^{(a)} \nu_i^{(a)} + m_i^{(a)} \nu_i^{(a)} + q^{(a)} \right) da \right], \] (3.8)

where \( e \) is the internal energy of the mixture per unit mass; \( F^{(a)} \) is the body force per unit mass acting on the constituent \( s_\alpha \); \( G^{(a)} \) is the body couple per unit mass; \( r \) is the external volume supply per unit mass per unit time; \( t^{(a)} \) is the partial stress vector; \( m^{(a)} \) is the partial couple stress vector; and \( q^{(a)} \) is the heat flux per unit area per unit time associated
with the constituent $s_\alpha$. By using (3.4), we may write (3.8) in the form

$$
\frac{d}{dt} \sum_{\alpha=1}^{2} \int_{P_\alpha} \rho_\alpha^0 \left( \dot{e} + \frac{1}{2} v_{i,\alpha} (a_\alpha) v_i + \frac{1}{2} i_{ij,\alpha} \gamma_i (a_\alpha) \gamma_j (a_\alpha) \right) dV
$$

$$
= \sum_{\alpha=1}^{2} \left[ \int_{P_\alpha} \rho_\alpha^0 \left( F_{i,\alpha} (a_\alpha) v_i + G_{i,\alpha} (a_\alpha) \gamma_i + r \right) dV + \int_{\partial P_\alpha} \left( T_{i,\alpha} (a_\alpha) v_i + M_{i,\alpha} (a_\alpha) \gamma_i + Q (a_\alpha) \right) dA \right],
$$

(3.9)

where $T_{\alpha}, M_{\alpha}, Q_{\alpha}$ are the partial stress, the partial couple stress, and the heat flux, respectively, associated with the surface $\partial P_\alpha$ but measured per unit area of $\partial P_0$. From (3.9), we deduce

$$
\sum_{\alpha=1}^{2} \int_{P_\alpha} \rho_\alpha^0 \left( \dot{\epsilon} + v_{i,\alpha} (a_\alpha) a_i + i_{ij,\alpha} \gamma_i (a_\alpha) \gamma_j \right) dV
$$

$$
= \sum_{\alpha=1}^{2} \left[ \int_{P_\alpha} \rho_\alpha^0 \left( F_{i,\alpha} (a_\alpha) v_i + G_{i,\alpha} (a_\alpha) \gamma_i + r \right) dV + \int_{\partial P_\alpha} \left( T_{i,\alpha} (a_\alpha) v_i + M_{i,\alpha} (a_\alpha) \gamma_i + Q (a_\alpha) \right) dA \right].
$$

(3.10)

In (3.10), we used (3.7) to obtain $(1/2) \left( \frac{d}{dt} i_{ij,\alpha} (a_\alpha) \gamma_i (a_\alpha) \gamma_j \right) = c_{imn} \gamma_m (a_\alpha) \gamma_i (a_\alpha) \gamma_j (a_\alpha) i_{nj,\alpha} = 0$.

Let us now require that the expression given by (3.10) is invariant with respect to the rigid motion of the body (see (2.11) and (2.12)). Consider first motions of the mixture that differ from those given by (2.4) only by superposed uniform rigid body translational velocities, the continuum occupying the same position at time $t$. We assume that this motion does not lead to any changes of the quantities $\rho_\alpha^0 e, i_{ij,\alpha}, F_{i,\alpha}, G_{i,\alpha}, r, T_{i,\alpha}, M_{i,\alpha}$, and $Q_{\alpha}$. Thus the relation (3.10) is also true when $v_{i,\alpha}$ is replaced by $v_{i,\alpha} + c$, so that by substraction, we have

$$
c_i \sum_{\alpha=1}^{2} \left[ \int_{P_\alpha} \rho_\alpha^0 \left( a_{i,\alpha} - F_{i,\alpha} (a_\alpha) \right) dV - \int_{\partial P_\alpha} T_{i,\alpha} (a_\alpha) dA \right] = 0,
$$

(3.11)

for all arbitrary constants $c_i$. We deduce

$$
\sum_{\alpha=1}^{2} \left[ \int_{P_\alpha} \rho_\alpha^0 \left( a_{i,\alpha} - F_{i,\alpha} (a_\alpha) \right) dV - \int_{\partial P_\alpha} T_{i,\alpha} (a_\alpha) dA \right] = 0,
$$

(3.12)

for arbitrary region $P_0 \subset B$. From (3.12), by usual procedures, we obtain

$$
T_{i,1}^{(1)} + T_{i,2}^{(2)} = \left( T_{K_i}^{(1)} + T_{K_i}^{(2)} \right) N_K,
$$

(3.13)

where $T_{K_i}^{(\alpha)}$ is the first Piola-Kirchhoff partial stress associated with constituent $s_\alpha$, and $N_K$ are the components of the unit outward normal vector to the surface $\partial P_0$. It follows from
and that
\[ \sum_{a=1}^{2} [T_{K_i,K}^{(a)} + \rho_0^a (F_i^{(a)} - a_i^{(a)})] = 0. \]  \tag{3.14}

If we write the term \( T_i^{(1)} v_i^{(1)} + T_i^{(2)} v_i^{(2)} \) in the form
\[ T_i^{(1)} v_i^{(1)} + T_i^{(2)} v_i^{(2)} = \frac{1}{2} (T_i^{(1)} + T_i^{(2)})(v_i^{(1)} + v_i^{(2)}) + \frac{1}{2} (T_i^{(1)} - T_i^{(2)})(v_i^{(1)} - v_i^{(2)}), \]  \tag{3.15}

and use (3.13) and (3.14), then (3.10) reduces to
\[
\int_{P_0} \left[ \dot{\rho}_0 + \frac{1}{2} (\rho_0^a a_i^{(1)} - \rho_0^a a_i^{(2)}) (v_i^{(1)} - v_i^{(2)}) - \frac{1}{2} (\rho_0^0 F_i^{(1)} - \rho_0^0 F_i^{(2)}) (v_i^{(1)} - v_i^{(2)}) \right.
- \frac{1}{2} (T_{K_i}^{(1)} + T_{K_i}^{(2)})(v_i^{(1)} + v_{i,K}^{(2)}) dV + \sum_{a=1}^{2} \int_{P_0} \rho_0^a (i_{ij}^{(a)} v_i^{(a)} v_j^{(a)} - G_i^{(a)} v_i^{(a)} - r) dV
\]
\[ = \int_{\partial P_0} \left[ \frac{1}{2} (T_i^{(1)} - T_i^{(2)})(v_i^{(1)} - v_i^{(2)}) + M_i^{(1)} v_i^{(1)} + M_i^{(2)} v_i^{(2)} + Q \right] dA, \]  \tag{3.16}

where
\[
\rho_0 = \rho_1^0 + \rho_2^0, \quad Q = Q^{(1)} + Q^{(2)}. \]  \tag{3.17}

By using an argument similar to that used in obtaining the relation (3.13) from (3.16), we deduce
\[
\frac{1}{2} \left[ T_i^{(1)} - T_i^{(2)} - (T_{K_i}^{(1)} - T_{K_i}^{(2)}) N_K \right] (v_i^{(1)} - v_i^{(2)}) + (M_i^{(1)} - M_{K_i}^{(1)} N_K) v_i^{(1)}
+ (M_i^{(2)} - M_{K_i}^{(2)} N_K) v_i^{(2)} + Q - Q_K N_K = 0, \]  \tag{3.18}

where \( M_{K_i}^{(a)} \) is the partial couple stress tensor associated with the constituent \( s_a \); and \( Q_K \) is the heat flux vector. Using (3.18) in (3.16) and applying the resulting equation to an arbitrary region \( P_0 \), we obtain
\[
\rho_0 \dot{\epsilon} = \sum_{a=1}^{2} (T_{K_i}^{(a)} v_i^{(a)} + M_{K_i}^{(a)} v_i^{(a)} + R_i^{(a)} v_i^{(a)}) + P_i (v_i^{(1)} - v_i^{(2)}) + Q_{K,K} + \rho_0 r, \]  \tag{3.19}

where
\[
P_i = \frac{1}{2} \left[ T_{K_i}^{(1)} + \rho_1^0 F_i^{(1)} - \rho_1^0 a_i^{(1)} - T_{K_i}^{(2)} - \rho_2^0 F_i^{(2)} + \rho_2^0 a_i^{(2)} \right], \]  \tag{3.20}
\[
R_i^{(a)} = M_{K_i}^{(a)} + \rho_0 G_i^{(a)} - \rho_0 a_{ij}^{(a)} v_j^{(a)}. \]
Assume now that the expression (3.19) is invariant with respect to a rotation of the body with a constant angular velocity \( \mathbf{b} \). Thus, by using (2.12), we suppose that

\[
\dfrac{\partial \nu_i^{(1)}}{\partial x_j} \rightarrow \dfrac{\partial \nu_i^{(1)}}{\partial x_j} + \epsilon_{ji} b_j, \quad \dfrac{\partial \nu_i^{(2)}}{\partial y_j} \rightarrow \dfrac{\partial \nu_i^{(2)}}{\partial y_j} + \epsilon_{ji} b_j,
\]

\[
\nu_i^{(1)} \rightarrow \nu_i^{(1)} + b_i, \quad \nu_i^{(2)} \rightarrow \nu_i^{(2)} + b_i, \quad \nu_i^{(1)} - \nu_i^{(2)} \rightarrow \nu_i^{(1)} - \nu_i^{(2)} + \epsilon_{ji} b_j (x_j - y_j).
\]

(3.21)

Introducing the above into (3.19) and assuming that the quantities \( \rho_0, e, T_{K_i}^{(s)}, M_{K_i}^{(a)}, P_i, R_i^{(a)}, r, \) and \( Q_{K,K} \) remain invariant, by substraction, we obtain

\[
R_s^{(1)} + R_s^{(2)} + \epsilon_{sji} [T_{K_i}^{(1)} x_{j,K} + T_{K_i}^{(2)} y_{j,K} + P_i (x_j - y_j)] = 0.
\]

(3.22)

By using the relation (3.22), we have

\[
R_s^{(1)} \nu_i^{(1)} + R_s^{(2)} \nu_i^{(2)} = (R_s^{(1)} + R_s^{(2)}) \nu_i^{(1)} - R_s^{(2)} (\nu_i^{(1)} - \nu_i^{(2)})
\]

\[
= \epsilon_{sij} [T_{K_i}^{(1)} x_{j,K} + T_{K_i}^{(2)} y_{j,K} + P_i (x_j - y_j)] \nu_i^{(1)} - R_s^{(2)} (\nu_i^{(1)} - \nu_i^{(2)}).
\]

(3.23)

From (3.23), we can write the energy equation (3.19) in the form

\[
\rho_0 \dot{e} = T_{K_i}^{(1)} (\nu_i^{(1)} + \epsilon_{ijk} x_{j,K} \nu_k^{(1)}) + T_{K_i}^{(2)} (\nu_i^{(2)} + \epsilon_{ijk} y_{j,K} \nu_k^{(1)}) + M_{K_i}^{(1)} \nu_i^{(1)} + M_{K_i}^{(2)} \nu_i^{(2)}
\]

\[+ P_i [\nu_i^{(1)} - \nu_i^{(2)} + \epsilon_{ijk} (x_j - y_j) \nu_k^{(1)}] - R_i^{(2)} (\nu_i^{(1)} - \nu_i^{(2)}) + Q_{K,K} + \rho_0 r.
\]

(3.24)

Moreover it follows from (3.14), (3.20), and (3.22) that the equations of motion are

\[
T_{K_i}^{(1)} - P_i + \rho_1^0 F_i^{(1)} = \rho_1^0 \dot{a}_i^{(1)}
\]

\[
T_{K_i}^{(2)} + P_i + \rho_2^0 F_i^{(2)} = \rho_2^0 \dot{a}_i^{(2)}
\]

\[
M_{K_i}^{(1)} + \epsilon_{ij} [T_{K_i}^{(1)} x_{j,K} + T_{K_i}^{(2)} y_{j,K} + P_i (x_j - y_j)] + R_i^{(2)} + \rho_1^0 G_i^{(1)} = \rho_1^0 \dot{a}_i^{(1)} \nu_j^{(1)},
\]

\[
M_{K_i}^{(2)} - R_i^{(2)} + \rho_2^0 G_i^{(2)} = \rho_2^0 \dot{a}_i^{(2)} \nu_j^{(2)}.
\]

(3.25)

We assume that the constituents have a common temperature and we adopt the following entropy production inequality(see [30, 35]):

\[
\sum_{a=1}^{2} \left[ \frac{d}{dt} \int_{P_a} \rho_a \eta dv - \int_{P_a} \frac{\rho_a r}{\theta} dv - \int_{\partial P_a} \frac{q^{(a)}}{\theta} da \right] \geq 0,
\]

(3.26)
where $\eta$ is the entropy per unit mass of the mixture and $\theta$ is the absolute temperature. The relations (3.4) and (3.26) yield
\[
\int P_0 \rho_0 \eta dV - \int P_0 \rho_0 \theta dV - \int Q_0 \theta dA \geq 0.
\]
(3.27)

From (3.18), we deduce
\[
Q = Q_K N_K,
\]
(3.28)

and the inequality (3.27) reduces to
\[
\rho_0 \theta \dot{\eta} - \rho_0 \theta - Q_{K,K} + \frac{1}{\theta} Q_K \theta \geq 0.
\]
(3.29)

The relation (2.16) and the second Piola-Kirchhoff quantities, defined by
\[
T_{KL}^{(1)} = T_{KL}^{(1)}, \quad T_{KL}^{(2)} = T_{KL}^{(2)}, \quad M_{KL}^{(1)} = M_{KL}^{(1)}, \quad M_{KL}^{(2)} = M_{KL}^{(2)},
\]
\[
P_i = \mathcal{P}_{KL}^{(1)}, \quad R_j = -\epsilon_{ijm} \chi_{mKL}^{(2)} \mathcal{R}_{KL},
\]
(3.30)
may be used to write the equation of energy (3.24) in the following material form:
\[
\rho_0 \dot{e} = T_{KL}^{(1)} \dot{E}_{KL} + T_{KL}^{(2)} \dot{G}_{KL} + M_{KL}^{(1)} \dot{\Gamma}_{KL} + M_{KL}^{(2)} \dot{\Gamma}_{KL} + \mathcal{P}_K \dot{D}_K + \mathcal{R}_{KL} \dot{\Delta}_{KL} + Q_{K,K} + \rho_0 r.
\]
(3.31)

Let us introduce the Helmholtz free energy $\Upsilon = e - \eta \theta$. Then the energy equation (3.31) may be written in the form
\[
\rho_0 (\dot{\Upsilon} + \dot{\theta} \eta + \theta \dot{\eta}) = T_{KL}^{(1)} \dot{E}_{KL} + T_{KL}^{(2)} \dot{G}_{KL} + M_{KL}^{(1)} \dot{\Gamma}_{KL} + M_{KL}^{(2)} \dot{\Gamma}_{KL} + \mathcal{P}_K \dot{D}_K + \mathcal{R}_{KL} \dot{\Delta}_{KL} + Q_{K,K} + \rho_0 r.
\]
(3.32)

With the help of (3.32), the inequality (3.29) becomes
\[
T_{KL}^{(1)} \dot{E}_{KL} + T_{KL}^{(2)} \dot{G}_{KL} + M_{KL}^{(1)} \dot{\Gamma}_{KL} + M_{KL}^{(2)} \dot{\Gamma}_{KL} + \mathcal{P}_K \dot{D}_K + \mathcal{R}_{KL} \dot{\Delta}_{KL} - \rho_0 \dot{\Upsilon} - \rho_0 \dot{\theta} \eta + \frac{1}{\theta} Q_K \theta \geq 0.
\]
(3.33)

The quantities $T_{KL}^{(a)}$, $M_{KL}^{(a)}$, $\mathcal{P}_K$, $\mathcal{R}_{KL}$, $\Upsilon$, $\eta$, and $Q_K$ must be prescribed by constitutive equations.

4. Constitutive equations

In this section, we will state the constitutive equations that serve to classify the particular types of mixtures to be studied throughout the remainder of the paper. To be concrete,
we assume that the mixture is consisting of two simple thermoelastic solids. According to basic postulates, the independent constitutive variables are

\[ \mathcal{A} = (x_i, x_{i,K}, y_i, y_{i,K}, \chi_{iK}, \chi_{iK,L}, \chi_{iKL}, \theta, \theta_K; X_K). \]  

(4.1)

So that, the constitutive equations are

\[ T_{KL}^{(a)} = T_{KL}^{(a)}(\mathcal{A}), \quad M_{KL}^{(a)} = M_{KL}^{(a)}(\mathcal{A}), \quad P_K = P_K(\mathcal{A}), \quad R_{KL} = R_{KL}(\mathcal{A}), \]

\[ Y = Y(\mathcal{A}), \quad \eta = \eta(\mathcal{A}), \quad Q_K = Q_K(\mathcal{A}), \]  

(4.2)

where the constitutive functionals are assumed to be sufficiently smooth. For homogeneous continua, the response functionals do not depend on \( X_K \) explicitly.

Let us now consider the restrictions imposed by the axiom of material frame-indifference. Following this principle, the constitutive functionals are form-invariant under the rigid body motions of the spatial frame of reference (see (2.13)). So that, by considering a translational motion of the frame of reference described by the vector \( c_i(t) = y_i(X_K,t) \), then we conclude that the constitutive functionals depend on \( x_i \) and \( y_i \) only through the relative displacement \( x_i - y_i \). Moreover, if we consider a rotation of the form \( Q = [\chi^{(1)}]^T \), where \([\chi^{(1)}]^T\) denotes the transpose of \( \chi^{(1)} \), and take into account the fact that

\[ \chi_{iM}^{(1)} \chi_{iK,L}^{(2)} = \chi_{iM}^{(1)} \delta_{ij} \chi_{jK,L}^{(2)} = \chi_{iM}^{(1)} \chi_{iN}^{(2)} \chi_{jN}^{(2)} \chi_{jK,L}^{(2)} = f(\Delta_{KL}, \Gamma_{KL}^{(2)}), \]  

(4.3)

then, in view of (2.14), it follows that \( T_{KL}^{(a)}(x_i, x_{i,K}) \), \( M_{KL}^{(a)}(x_i, y_i) \), \( P_K \), \( R_{KL} \), \( Y \), \( \eta \), and \( Q_K \) must be expressible in the following invariant form:

\[ T_{KL}^{(a)} = T_{KL}^{(a)}(E_{MN}, G_{MN}, \Gamma_{MN}^{(1)}, \Gamma_{MN}^{(2)}, D_M, \Delta_{MN}, \theta, \theta_M; X_M), \]

\[ M_{KL}^{(a)} = M_{KL}^{(a)}(E_{MN}, G_{MN}, \Gamma_{MN}^{(1)}, \Gamma_{MN}^{(2)}, D_M, \Delta_{MN}, \theta, \theta_M; X_M), \]

\[ P_K^{(a)} = P_K^{(a)}(E_{MN}, G_{MN}, \Gamma_{MN}^{(1)}, \Gamma_{MN}^{(2)}, D_M, \Delta_{MN}, \theta, \theta_M; X_M), \]

\[ R_{KL}^{(a)} = R_{KL}^{(a)}(E_{MN}, G_{MN}, \Gamma_{MN}^{(1)}, \Gamma_{MN}^{(2)}, D_M, \Delta_{MN}, \theta, \theta_M; X_M), \]

\[ Y = Y(E_{MN}, G_{MN}, \Gamma_{MN}^{(1)}, \Gamma_{MN}^{(2)}, D_M, \Delta_{MN}, \theta, \theta_M; X_M), \]

\[ \eta = \eta(E_{MN}, G_{MN}, \Gamma_{MN}^{(1)}, \Gamma_{MN}^{(2)}, D_M, \Delta_{MN}, \theta, \theta_M; X_M), \]

\[ Q_K = Q_K(E_{MN}, G_{MN}, \Gamma_{MN}^{(1)}, \Gamma_{MN}^{(2)}, D_M, \Delta_{MN}, \theta, \theta_M; X_M). \]  

(4.4)
With the help of (4.4), inequality (3.33) becomes

\[
\begin{align*}
\left( T_{KL}^{(1)} - \frac{\partial \sigma}{\partial E_{KL}} \right) \dot{E}_{KL} + \left( T_{KL}^{(2)} - \frac{\partial \sigma}{\partial G_{KL}} \right) \dot{G}_{KL} + \left( M_{KL}^{(1)} - \frac{\partial \sigma}{\partial \Gamma_{KL}^{(1)}} \right) \dot{\Gamma}_{KL}^{(1)} \\
+ \left( M_{KL}^{(2)} - \frac{\partial \sigma}{\partial \Gamma_{KL}^{(2)}} \right) \dot{\Gamma}_{KL}^{(2)} + \left( \mathcal{P}_{K} - \frac{\partial \sigma}{\partial D_{K}} \right) \dot{D}_{K} + \left( \mathcal{R}_{KL} - \frac{\partial \sigma}{\partial \Delta_{KL}} \right) \dot{\Delta}_{KL}
\end{align*}
\]

(4.5)

where \( \sigma = \rho_0 \gamma \).

From (4.5), we deduce

\[
\sigma = \sigma (E_{MN}, G_{MN}, \Gamma_{MN}^{(1)}, \Gamma_{MN}^{(2)}, D_{M}, \Delta_{MN}, \theta, X_{M}),
\]

(4.6)

\[
T_{KL}^{(1)} = \frac{\partial \sigma}{\partial E_{KL}}, \quad T_{KL}^{(2)} = \frac{\partial \sigma}{\partial G_{KL}}, \quad M_{KL} = \frac{\partial \sigma}{\partial \Gamma_{KL}},
\]

(4.7)

\[
\mathcal{P}_{K} = \frac{\partial \sigma}{\partial D_{K}}, \quad \mathcal{R}_{KL} = \frac{\partial \sigma}{\partial \Delta_{KL}}, \quad \rho_0 \eta = -\frac{\partial \sigma}{\partial \theta},
\]

(4.8)

The inequality (4.8) implies

\[
Q_{K} (E_{MN}, G_{MN}, \Gamma_{MN}^{(1)}, \Gamma_{MN}^{(2)}, D_{M}, \Delta_{MN}, \theta, X_{M}) = 0.
\]

(4.9)

From (3.30) and (4.7), we obtain

\[
T_{Ki}^{(1)} = \chi_{il}^{(1)} \frac{\partial \sigma}{\partial E_{KL}}, \quad T_{Ki}^{(2)} = \chi_{il}^{(2)} \frac{\partial \sigma}{\partial G_{KL}}, \quad M_{Ki}^{(1)} = \chi_{il}^{(1)} \frac{\partial \sigma}{\partial \Gamma_{KL}^{(1)}}, \quad M_{Ki}^{(2)} = \chi_{il}^{(2)} \frac{\partial \sigma}{\partial \Gamma_{KL}^{(2)}},
\]

\[
P_{i} = \chi_{ik}^{(2)} \frac{\partial \sigma}{\partial D_{K}}, \quad R_{ij}^{(2)} = -\epsilon_{ijm} \chi_{mk}^{(1)} \chi_{il}^{(2)} \frac{\partial \sigma}{\partial \Delta_{KL}}, \quad \rho_0 \eta = -\frac{\partial \sigma}{\partial \theta}.
\]

(4.10)

In conclusion, the constitutive equations are (4.6), (4.10), and the equation

\[
Q_{K} (E_{MN}, G_{MN}, \Gamma_{MN}^{(1)}, \Gamma_{MN}^{(2)}, D_{M}, \Delta_{MN}, \theta, X_{M}) = 0.
\]

(4.11)

We note that by using the relations (4.6) and (4.7), the energy balance (3.32) reduces to

\[
\rho_0 \theta \dot{\eta} = Q_{K,K} + \rho_0 \dot{r}.
\]

(4.12)

The complete system of field equations of nonlinear theory consist of the equations of conservation of microinertia (3.6), equations of motion (3.25), energy equation (4.12), constitutive equations (4.6), (4.10), (4.11), and the geometric equations (2.14). To these
equations, we adjoin boundary conditions and initial conditions. In the case of first boundary value problem, the boundary conditions are

\[ x_i = \tilde{x}_i, \quad y_i = \tilde{y}_i, \quad \chi_{ik}^{(1)} = \tilde{\chi}_{ik}^{(1)}, \quad \chi_{ik}^{(2)} = \tilde{\chi}_{ik}^{(2)}, \quad \theta = \tilde{\theta}, \quad \text{on } \partial B \times I, \]  

(4.13)

where \( \tilde{x}_i, \tilde{y}_i, \tilde{\chi}_{ik}^{(1)}, \tilde{\chi}_{ik}^{(2)}, \) and \( \tilde{\theta} \) are prescribed functions. In the second boundary value problem, the boundary conditions are

\[ (T_{ki}^{(1)} + T_{ki}^{(2)}) N_K = \tilde{T}_i, \quad x_i - y_i = \tilde{d}_i, \quad (M_{ki}^{(1)} + M_{ki}^{(2)}) N_K = \tilde{M}_i, \]

\[ \chi_{ik}^{(1)} \chi_{il}^{(2)} = \tilde{\Delta}_{KL}, \quad Q_K N_K = \tilde{Q}, \quad \text{on } \partial B \times I, \]  

(4.14)

where \( \tilde{T}_i, \tilde{d}_i, \tilde{M}_i, \tilde{\Delta}_{KL}, \) and \( \tilde{Q} \) are given and \( \tilde{\Delta}_{KL} \) is proper orthogonal.

The initial conditions are

\[ x_i(X, 0) = x^0_i(X), \quad y_i(X, 0) = y^0_i(X), \quad \chi_{ik}^{(a)}(X, 0) = \chi_{ik}^{(a)0}(X), \]

\[ 0 \]

\[ \dot{x}_i(X, 0) = v_{i(1)}^{(0)}(X), \quad \dot{y}_i(X, 0) = v_{i(2)}^{(0)}(X), \quad v_{i(a)}(X, 0) = v_{i(a)0}(X), \]

\[ \eta(X, 0) = \eta^0(X), \quad X \in B, \]  

(4.15)

where \( x^0_i, y^0_i, \chi_{ik}^{(a)0}, v_{i(a)0}, \eta^0 \) are prescribed functions.

5. The linear theory

In the following, we linearize the above equations. We use the notations

\[ X_i = \delta_{ik} X_K, \quad \chi_{ij}^{(a)} = \delta_{jk} \chi_{ik}^{(a)}, \quad \frac{\partial f}{\partial X_i} = f_j, \]  

(5.1)

where \( \delta_{ik} \) is the Kronecker delta. We have

\[ x_i = X_i + u_i, \quad y_i = X_i + w_i, \]  

(5.2)

where \( u_i \) and \( w_i \) are the displacements vectors associated with \( s_1 \) and \( s_2 \), respectively. We denote

\[ T = \theta - T_0, \]  

(5.3)

where \( T_0 \) is the constant absolute temperature of the mixture in the reference configuration. Being concerned with first-order approximations, following [33] (see (1.2.19) and (1.6.6)), we take

\[ \chi_{ij}^{(a)} = \delta_{ij} - \epsilon_{ij}^{(a)} \phi_s^{(a)}, \]  

(5.4)

where \( \phi_s^{(a)} \) is the microrotation vector associated with the constituent \( s_{\alpha} \). We suppose that

\[ u_i = \epsilon \tilde{u}_i, \quad w_i = \epsilon \tilde{w}_i, \quad T = \epsilon \tilde{T}, \quad \phi_i^{(a)} = \epsilon \tilde{\phi}_i^{(a)}, \quad \alpha = 1, 2, \]  

(5.5)
where \( \epsilon \) is a constant small enough for squares and higher powers to be neglected and \( \tilde{u}_i, \tilde{w}_i, \tilde{T}, \) and \( \tilde{\varphi}_i^{(a)} \) are independent of \( \epsilon. \) It follows from (2.10), (5.4), and (5.5) that

\[
\tilde{\varphi}_i^{(a)} = \gamma_i^{(a)}.  \tag{5.6}
\]

Moreover, the strain measures \( E_{KL}, G_{KL}, D_K, \Gamma_{KL}^{(a)}, \Delta_{KL} \) defined by (2.14) reduce to

\[
e_{ij} = u_{i,j} + \epsilon_{sij}\varphi_i^{(1)}, \quad g_{ij} = w_{i,j} + \epsilon_{sij}\varphi_i^{(1)}, \quad d_i = u_i - w_i, \tag{5.7}
\]

and the microinertia tensor \( i_{ij}^{(a)} \) is given by

\[
i_{ij}^{(a)} = I_{ij}^{(a)}.  \tag{5.8}
\]

If we introduce the notations

\[
t_{ji} = \delta_{jk}T_{Ki}^{(1)}, \quad s_{ji} = \delta_{jk}T_{Ki}^{(2)}, \quad m_{ij}^{(a)} = \delta_{jk}M_{Ki}^{(a)}, \tag{5.9}
\]

\[
p_i = P_i, \quad \breve{R}_i = -R_i^{(2)}, \quad q_i = \delta_{ik}Q_K,
\]

then the equations of motion (3.25) and the energy equation (4.12) can be written in the form

\[
t_{ji,j} - p_i + \rho_0T_{ij}^{(1)} = \rho_0\tilde{u}_i, \tag{5.10}
\]

\[
s_{ji,j} + p_i + \rho_0T_{ij}^{(2)} = \rho_0\tilde{w}_i,
\]

\[
m_{ij}^{(1)} + \epsilon_{ijk}[t_{jk} + s_{jk}] - \breve{R}_i + \rho_0G_i^{(1)} = \rho_0G_i^{(1)}\varphi_j^{(1)},
\]

\[
m_{ij}^{(2)} + \breve{R}_i + \rho_0G_i^{(2)} = \rho_0G_i^{(2)}\varphi_j^{(2)}, \tag{5.11}
\]

\[
\rho_0T\dot{\eta} = q_{ij} + \rho_0r. \tag{5.12}
\]

Since \( \Delta_{ij} \) is skew-symmetric, we may consider that \( \sigma \) depends on the following variables:

\[
\sigma = \sigma(e_{ij}, g_{ij}, \gamma_{ij}^{(1)}, \gamma_{ij}^{(2)}, d_i, \pi_i, T; X_i),  \tag{5.13}
\]

where

\[
\pi_i = \varphi_i^{(1)} - \varphi_i^{(2)}.  \tag{5.14}
\]

Collecting (4.10), (5.4), (5.5), (5.7), (5.9), (5.13), and (5.14), we deduce

\[
t_{ij} = \frac{\partial \sigma}{\partial e_{ij}}, \quad s_{ij} = \frac{\partial \sigma}{\partial g_{ij}}, \quad m_{ij}^{(a)} = \frac{\partial \sigma}{\partial \gamma_{ij}^{(a)}},
\]

\[
p_i = \frac{\partial \sigma}{\partial d_i}, \quad \rho_0\dot{\eta} = -\frac{\partial \sigma}{\partial \theta}, \quad \breve{R}_i = \epsilon_{ijk}\frac{\partial \sigma}{\partial \pi_s}\frac{\partial \pi_s}{\partial \pi_t}\frac{\partial \pi_t}{\partial \pi_i} = \frac{\partial \sigma}{\partial \pi_i}. \tag{5.15}
\]
Assuming that the initial body is free from stress and couple stress, in the context of linear theory, we have

\[
\sigma = \frac{1}{2} A_{ijrs} e_{ij} e_{rs} + B_{ijrs} e_{ij} g_{rs} + \frac{1}{2} C_{ijrs} g_{ij} g_{rs} \\
+ \sum_{a=1}^{2} \left( \frac{1}{2} D_{ijrs}^{(a)} y_{ij}^{(a)} y_{rs}^{(a)} + F_{ijrs} e_{ij} y_{rs}^{(a)} + H_{ijrs} g_{ij} y_{rs}^{(a)} \right) \\
+ D_{ijrs}^{(3)} y_{ij}^{(1)} y_{rs}^{(2)} + \frac{1}{2} a_{ij} d_i d_j + \frac{1}{2} b_{ij} \pi_i \pi_j + c_{ij} d_i \pi_j + a_{ijk} e_{ij} d_k \\
+ b_{ijk} e_{ij} \pi_k + c_{ijk} g_{ij} d_k + d_{ijk} g_{ij} \pi_k + \alpha^{(1)}_{ijk} y_{ij}^{(1)} d_k + \beta^{(1)}_{ijk} y_{ij}^{(1)} \pi_k + \alpha^{(2)}_{ijk} y_{ij}^{(2)} d_k \\
+ \beta^{(2)}_{ijk} y_{ij}^{(2)} \pi_k - \frac{1}{2} a^* T^2 - (\alpha^*_{ij} e_{ij} + \beta^*_{ij} g_{ij} + \nu^*_{ij} y_{ij}^{(1)} + \mu^*_{ij} y_{ij}^{(1)} + \tau^* d_i + \sigma^* \pi_i) T, \\
q_i = k_{ij} T_{ij},
\]

where the constitutive coefficients have the following symmetries:

\[
A_{ijrs} = A_{rsij}, \quad C_{ijrs} = C_{rsij}, \quad D_{ijrs}^{(a)} = D_{rsij}^{(a)},
\]

\[
a_{ij} = a_{ji}, \quad b_{ij} = b_{ji}.
\]

From (5.13), (5.15), and (5.16), we obtain the following constitutive equations:

\[
t_{ij} = A_{ijrs} e_{ij} e_{rs} + B_{ijrs} g_{ij} g_{rs} + F_{ijrs} e_{ij} y_{rs}^{(1)} + D_{ijrs} y_{ij}^{(1)} y_{rs}^{(2)} + a_{ijk} d_k + b_{ijk} \pi_k - \alpha_{ij}^* T, \\
s_{ij} = B_{rsij} e_{ij} g_{rs} + C_{ijrs} g_{ij} g_{rs} + H_{ijrs} e_{ij} y_{rs}^{(1)} + D_{ijrs} y_{ij}^{(1)} y_{rs}^{(2)} + c_{ijk} d_k + d_{ijk} \pi_k - \beta_{ij}^* T, \\
m_{ij}^{(1)} = F_{rsij} e_{rs} + H_{rsij} g_{rs} + D_{ijrs} y_{ij}^{(1)} y_{rs}^{(2)} + a_{ijk} d_k + b_{ijk} \pi_k - \alpha_{ij}^* T, \\
m_{ij}^{(2)} = F_{rsij} e_{rs} + H_{rsij} g_{rs} + D_{ijrs} y_{ij}^{(1)} y_{rs}^{(2)} + a_{ijk} d_k + b_{ijk} \pi_k - \beta_{ij}^* T, \\
\rho_i = a_{ij} d_j + c_{ij} \pi_j + a_{jki} e_{jk} + e_{jki} g_{jk} + \alpha^{(1)}_{jki} y_{jk}^{(1)} + \alpha^{(2)}_{jki} y_{jk}^{(2)} - \tau_i^* T, \\
\rho^0 \eta = a^* T + \alpha_{ij}^* e_{ij} + \beta_{ij}^* g_{ij} + \nu_{ij} y_{ij}^{(1)} + \mu_{ij} y_{ij}^{(2)} + \tau_i^* d_i + \sigma_i^* \pi_i, \\
q_i = k_{ij} T_{ij}.
\]

For isotropic solids, odd-order constitutive tensors vanish and even-order tensors can be constituted by the products of \( \delta_{ij} \). We also note that \( e_{ij}, g_{ij}, d_i, \theta, t_{ij}, s_{ij}, p_i \) and \( \eta \) are polar tensors, while \( y_{ij}^{(a)}, \pi_i, m_{ij}^{(a)} \), and \( R_i \) are axial tensors. By examining (5.18), we find
that the only surviving isotropic material constants are

\[ A_{ijrs} = \lambda_1 \delta_{ij} \delta_{rs} + (\mu_1 + \kappa_1) \delta_{ir} \delta_{js} + \mu_1 \delta_{is} \delta_{jr}, \]

\[ C_{ijrs} = \lambda_2 \delta_{ij} \delta_{rs} + (\mu_2 + \kappa_2) \delta_{ir} \delta_{js} + \mu_2 \delta_{is} \delta_{jr}, \]

\[ D_{ijrs}^{(1)} = \alpha_1 \delta_{ij} \delta_{rs} + \gamma_1 \delta_{ir} \delta_{js} + \beta_1 \delta_{is} \delta_{jr}, \]

\[ D_{ijrs}^{(2)} = \alpha_2 \delta_{ij} \delta_{rs} + \gamma_2 \delta_{ir} \delta_{js} + \beta_2 \delta_{is} \delta_{jr}, \]

\[ B_{ijrs} = \nu \delta_{ij} \delta_{rs} + \xi \delta_{ir} \delta_{js} + \zeta \delta_{is} \delta_{jr}, \]

\[ \lambda_{ij} = \lambda_{ij}, \quad b_{ij} = b_{ij}, \quad b_{ijk} = b^0 \epsilon_{ijk}, \quad d_{ijk} = d^0 \epsilon_{ijk}, \]

\[ a_{ij} = a^0 \epsilon_{ij}, \quad a_{ij}^{(1)} = a^0 \epsilon_{ij}, \quad a_{ij}^{(2)} = b^0 \epsilon_{ij}, \quad \alpha_{ij} = \alpha^* \delta_{ij}, \quad \beta_{ij} = \beta^* \delta_{ij}. \]

Hence

\[ \sigma = \frac{1}{2} \lambda_1 \epsilon_{ij} \epsilon_{jj} + \frac{1}{2} (\mu_1 + \kappa_1) \epsilon_{ij} \epsilon_{ij} + \frac{1}{2} \mu_1 \epsilon_{ij} \epsilon_{ij} + \nu \epsilon_{ij} \epsilon_{jj} + \xi \epsilon_{ij} \epsilon_{ij} + \zeta \epsilon_{ij} \epsilon_{ij} \]

\[ + \frac{1}{2} \alpha_1 \epsilon_{ii}^{(1)} \epsilon_{jj}^{(1)} + \frac{1}{2} \gamma_1 \epsilon_{ij}^{(1)} \epsilon_{ij}^{(1)} + \frac{1}{2} \beta_1 \epsilon_{ij}^{(1)} \epsilon_{ij}^{(1)} + \alpha_3 \epsilon_{ii}^{(2)} \epsilon_{jj}^{(2)} \]

\[ + \gamma_3 \epsilon_{ij}^{(1)} \epsilon_{ij}^{(2)} + \beta_3 \epsilon_{ij}^{(1)} \epsilon_{ij}^{(2)} + \frac{1}{2} \alpha_2 \epsilon_{ii}^{(2)} \epsilon_{jj}^{(2)} + \frac{1}{2} \gamma_2 \epsilon_{ij}^{(2)} \epsilon_{ij}^{(2)} + \frac{1}{2} \beta_2 \epsilon_{ij}^{(2)} \epsilon_{ij}^{(2)} \]

\[ + \frac{1}{2} a_d d_i + \frac{1}{2} b \pi_i \pi_i + b^0 \epsilon_{ijk} \epsilon_{ij} \pi_k + d^0 \epsilon_{ijk} \epsilon_{ij} \pi_k \]

\[ + a^0 \epsilon_{ijk} \epsilon_{ij}^{(1)} d_k + b^0 \epsilon_{ijk} \epsilon_{ij}^{(2)} d_k - \frac{1}{2} a^* T^2 - (\alpha^* \epsilon_{ii} + b^* \epsilon_{ii}) T. \]

The constitutive equations reduce to

\[ t_{ij} = \lambda_1 \epsilon_{rr} \delta_{ij} + (\mu_1 + \kappa_1) \epsilon_{ij} + \mu_1 \epsilon_{ij} + \nu \epsilon_{rr} \delta_{ij} + \xi \epsilon_{ij} + \zeta \epsilon_{ij} + b^0 \epsilon_{ijk} \pi_k - \alpha^* T \delta_{ij}, \]

\[ s_{ij} = \nu \epsilon_{rr} \delta_{ij} + \xi \epsilon_{ij} + \zeta \epsilon_{ij} + \lambda_2 \epsilon_{rr} \delta_{ij} + (\mu_2 + \kappa_2) \epsilon_{ij} + \mu_2 \epsilon_{ij} + d^0 \epsilon_{ijk} \pi_k - \beta^* T \delta_{ij}, \]

\[ m_{ij}^{(1)} = \alpha_1 \epsilon_{rr}^{(1)} \delta_{ij} + \gamma_1 \epsilon_{ij}^{(1)} + \beta_1 \epsilon_{ij}^{(1)} + \alpha_3 \epsilon_{rr}^{(2)} \delta_{ij} + \gamma_3 \epsilon_{ij}^{(2)} + \beta_3 \epsilon_{ij}^{(2)} + a^0 \epsilon_{ijk} d_k, \]

\[ m_{ij}^{(2)} = \alpha_3 \epsilon_{rr}^{(1)} \delta_{ij} + \gamma_3 \epsilon_{ij}^{(1)} + \beta_3 \epsilon_{ij}^{(1)} + \alpha_2 \epsilon_{rr}^{(2)} \delta_{ij} + \gamma_2 \epsilon_{ij}^{(2)} + \beta_2 \epsilon_{ij}^{(2)} + b^0 \epsilon_{ijk} d_k, \]

\[ p_i = a d_i + a^0 \epsilon_{jk} \epsilon_{jk}^{(1)} + b^0 \epsilon_{jk} \epsilon_{jk}^{(2)} + \rho^* \epsilon_{ij}^{(1)}, \]

\[ R_i = b \pi_i + b^0 \epsilon_{jk} \epsilon_{jk} + d^0 \epsilon_{ijk} g_{jk}, \]

\[ \rho_0 \eta = a^* T + a^* \epsilon_{ii} + b^* \epsilon_{ii}, \]

\[ q_i = k T_i. \]
From (4.8), we deduce

\[ k \geq 0. \quad (5.22) \]

Thus, the basic equations in the linear theory are the equations of motions (5.10) and (5.11), the energy equation (5.12), the constitutive equations (5.18), and the geometric equations (5.7) and (5.14). In the case of first boundary value problem, the boundary conditions are

\[ u_i = \tilde{u}_i, \quad w_i = \tilde{w}_i, \quad \varphi_i = \tilde{\varphi}_i^{(a)}, \quad T = \tilde{T}, \quad \text{on } \partial B \times I, \quad (5.23) \]

where \( \tilde{u}_i, \tilde{w}_i, \tilde{\varphi}_i^{(a)} \), and \( \tilde{T} \) are prescribed functions. In the second boundary value problem, the boundary conditions are

\[ (t_{ji} + s_{ji}) n_j = \tilde{t}_i, \quad (m_{ji}^{(a)} + m_{ji}^{(a)}) n_j = \tilde{m}_i, \]

\[ d_i = \tilde{d}_i, \quad \pi_i = \tilde{\pi}_i, \quad q_i n_i = \tilde{q}, \quad \text{on } \partial B \times I, \quad (5.24) \]

where \( \tilde{t}_i, \tilde{m}_i, \tilde{d}_i, \tilde{\pi}_i \) and \( \tilde{q} \) are given. The initial conditions are

\[ u_i(X,0) = \hat{a}_i(X), \quad w_i(X,0) = \hat{b}_i(X), \quad \dot{u}_i(X,0) = \hat{c}_i(X), \quad \dot{w}_i(X,0) = \hat{f}_i(X), \]

\[ \varphi_i^{(a)}(X,0) = \hat{\varphi}_i^{(a)}(X), \quad \dot{\varphi}_i^{(a)}(X,0) = \hat{\omega}_i^{(a)}(X), \quad T(X,0) = \hat{T}(X), \quad X \in B, \quad (5.25) \]

where the functions \( \hat{a}_i, \hat{b}_i, \hat{c}_i, \hat{f}_i, \hat{\varphi}_i^{(a)}, \hat{\omega}_i^{(a)} \), and \( \hat{T} \) are prescribed.

6. Uniqueness theorem

In this section, we will establish a uniqueness result in the linear theory. It is indifferent which instant \( t_0 \) is selected as the initial one and hence we choose \( t_0 = 0 \). Let us introduce the following notations:

\[ U = \frac{1}{2} A_{ijrs} e_{ij}e_{rs} + B_{ijrs} e_{ij}g_{rs} + \frac{1}{2} C_{ijrs} g_{ij}g_{rs} \]

\[ + \sum_{a=1}^{2} \left( \frac{1}{2} D_{ijrs}^{(a)} \varphi_{ij}^{(a)} \varphi_{rs}^{(a)} + F_{ijrs}^{(a)} e_{ij} \varphi_{rs}^{(a)} + H_{ijrs}^{(a)} g_{ij} \varphi_{rs}^{(a)} + D_{ijrs}^{(3)} \varphi_{ij}^{(1)} \varphi_{rs}^{(2)} \right) + D_{ijrs}^{(3)} \varphi_{ij}^{(1)} \varphi_{rs}^{(2)} \]

\[ + \frac{1}{2} a_{ij} d_{ij} + \frac{1}{2} b_{ij} \pi_i \pi_j + c_{ij} d_i \pi_j + a_{ijk} e_{ij} d_k + b_{ijk} e_{ij} \pi_k + c_{ijk} g_{ij} d_k \]

\[ + d_{ijk} g_{ij} \pi_k + \alpha_{ijk}^{(1)} \varphi_{ij}^{(1)} d_k + \beta_{ijk}^{(1)} \varphi_{ij}^{(1)} \pi_k + \alpha_{ijk}^{(2)} \varphi_{ij}^{(2)} d_k + \beta_{ijk}^{(2)} \varphi_{ij}^{(2)} \pi_k, \]

\[ E = \frac{1}{2} \int_B \left( \rho_0^0 u_i \dot{u}_i + \rho_0^0 w_i \dot{w}_i + \rho_1^0 \dot{\varphi}_i \varphi_j^{(1)} + \rho_2^0 \dot{\varphi}_i \varphi_j^{(2)} + a^* T^2 + 2U \right) dv. \]

Theorem 6.1. Assume the following:

(i) \( \rho_0^0 \) and \( a^* \) are strictly positive and \( I_{ij}^{(a)} \) is positive definite;
(ii) the constitutive coefficients satisfy symmetry relations (5.17) and the inequality
\[ k_{ij} T_i T_j \geq 0; \]  

(6.3)

(iii) \( U \) is a positive semidefinite form.

Then the initial boundary value problem defined by the equations of motion (5.10) and (5.11), the energy equation (5.12), the constitutive equations (5.18), the geometrical equations (5.7) and (5.14), the boundary conditions (5.23) (or (5.24)), and the initial conditions (5.25) has at most one solution.

**Proof.** In view of the (5.17), (5.18), and (6.1) we deduce
\[ t_i \dot{e}_{ij} + s_{ij} \dot{g}_{ij} + m_{ij}^{(1)} \ddot{y}_{ij} + m_{ij}^{(2)} \dot{y}_{ij} + p_i \dot{d}_i + R_i \pi_i + \rho_0 \dot{\eta} T = \frac{\partial}{\partial t} \left( \frac{1}{2} a^* T^2 + U \right). \]  

(6.4)

On the other hand, in view of (5.10), (5.11), (5.12), (5.7), and (5.14), we obtain
\[ t_i \dot{e}_{ij} + s_{ij} \dot{g}_{ij} + m_{ij}^{(1)} \ddot{y}_{ij} + m_{ij}^{(2)} \dot{y}_{ij} + p_i \dot{d}_i + R_i \pi_i + \rho_0 \dot{\eta} T \]
\[ = (t_{ji} \dot{u}_i + s_{ji} \dot{w}_i + m_{ji}^{(1)} \ddot{\varphi}_i + m_{ji}^{(2)} \dot{\varphi}_i + \frac{1}{T_0} q_i \dot{T})_j + \rho_1^0 \dot{F}_i^{(1)} \dot{u}_i + \rho_2^0 \dot{F}_i^{(2)} \dot{w}_i + \rho_1^0 G_i^{(1)} \dot{\varphi}_i^{(1)} + \rho_2^0 G_i^{(2)} \dot{\varphi}_i^{(2)} \]
\[ + \frac{1}{T_0} \rho_0 r T - \frac{1}{2} \frac{\partial}{\partial t} \left( \rho_1^0 \dot{u}_i \dot{u}_i + \rho_2^0 \dot{w}_i \dot{w}_i + \rho_1^0 F_i^{(1)} \dot{\varphi}_i^{(1)} + \rho_2^0 F_i^{(2)} \dot{\varphi}_i^{(2)} \right) \]
\[ - \frac{1}{T_0} k_{ij} T_i T_j. \]  

(6.5)

Then (6.4) and (6.5) imply
\[ \frac{1}{2} \frac{\partial}{\partial t} \left( \rho_1^0 \dot{u}_i \dot{u}_i + \rho_2^0 \dot{w}_i \dot{w}_i + \rho_1^0 F_i^{(1)} \dot{\varphi}_i^{(1)} + \rho_2^0 F_i^{(2)} \dot{\varphi}_i^{(2)} + \frac{1}{T_0} \rho_0 r T + 2U \right) \]
\[ + \frac{1}{T_0} k_{ij} T_i T_j = \rho_1^0 F_i^{(1)} \dot{u}_i + \rho_2^0 F_i^{(2)} \dot{w}_i + \rho_1^0 G_i^{(1)} \dot{\varphi}_i^{(1)} + \rho_2^0 G_i^{(2)} \dot{\varphi}_i^{(2)} + \frac{1}{T_0} \rho_0 r T \]
\[ + \frac{1}{2} \left[ (t_{ji} + s_{ji}) (\dot{u}_i + \dot{w}_i) + (t_{ji} - s_{ji}) (\ddot{u}_i - \dot{w}_i) \right. \]
\[ + (m_{ij}^{(1)} + m_{ij}^{(2)}) (\ddot{\varphi}_i^{(1)} + \dot{\varphi}_i^{(1)}) + (m_{ij}^{(1)} - m_{ij}^{(2)}) (\ddot{\varphi}_i^{(1)} - \dot{\varphi}_i^{(2)}) \]
\[ + \frac{2}{T_0} q_j \dot{T} \right]_j. \]  

(6.6)

By an integration of the above relation over \( B \) and by using the divergence theorem and (6.2), we obtain
\[ E + \int_B \frac{1}{T_0} k_{ij} T_i T_j dV = \int_B \left( \rho_1^0 F_i^{(1)} \dot{u}_i + \rho_2^0 F_i^{(2)} \dot{w}_i + \rho_1^0 G_i^{(1)} \dot{\varphi}_i^{(1)} + \rho_2^0 G_i^{(2)} \dot{\varphi}_i^{(2)} + \frac{1}{T_0} \rho_0 r T \right) dV \]
\[ + \frac{1}{2} \int_{\partial B} \left[ (t_{ji} + s_{ji}) (\dot{u}_i + \dot{w}_i) + (t_{ji} - s_{ji}) \dot{d}_i + (m_{ij}^{(1)} + m_{ij}^{(2)}) \right. \]
\[ \times (\ddot{\varphi}_i^{(1)} + \dot{\varphi}_i^{(1)}) + (m_{ij}^{(1)} - m_{ij}^{(2)}) \dot{\pi}_i + \frac{2}{T_0} q_j \dot{T} \right] n_i dA. \]  

(6.7)
Let us suppose that there are two solutions \( \{ \bar{u}_i, \bar{w}_i, \bar{\varphi}_i^{(1)}, \bar{T}_i \} \) and \( \{ \tilde{u}_i, \tilde{w}_i, \tilde{\varphi}_i^{(1)}, \tilde{T}_i \} \). Because of the linearity of the considered initial boundary value problem, their difference \( \mathcal{P} = \{ \bar{u}_i, \bar{w}_i, \bar{\varphi}_i^{(1)}, \bar{T}_i \} \) corresponds to the null data. It follows from (5.23), (5.24), and (6.7) that

\[
\dot{E} + \int_B \frac{1}{T_0} k_{ij} \bar{T}_{,i}^{,j} dV = 0,
\]

where \( E \) is the function defined by (6.2) associated with the process \( \mathcal{P} \). In view of the inequality (6.3), we deduce \( \dot{E} \leq 0 \) on \([0, t_1)\), so that \( \dot{E}(t) \leq \dot{E}(0), t \in [0, t_1) \). From the initial conditions, we find \( \dot{E}(t) = 0 \) and therefore \( \dot{E}(0) = 0, t \in [0, t_1) \). The hypotheses (i) and (iii) imply \( \bar{u} = 0, \bar{w} = 0, \bar{\varphi}^{(1)} = 0, \bar{\varphi}^{(2)} = 0, \bar{T} = 0 \) on \( B \times [0, t_1) \). Since \( \bar{u}, \bar{w}, \bar{\varphi}^{(1)}, \bar{\varphi}^{(2)} \) vanish initially, we conclude that \( \bar{u} = 0, \bar{w} = 0, \bar{\varphi}^{(1)} = 0, \bar{\varphi}^{(2)} = 0, \bar{T} = 0 \) on \( B \times [0, t_1) \) and the proof is complete. \( \square \)

References


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