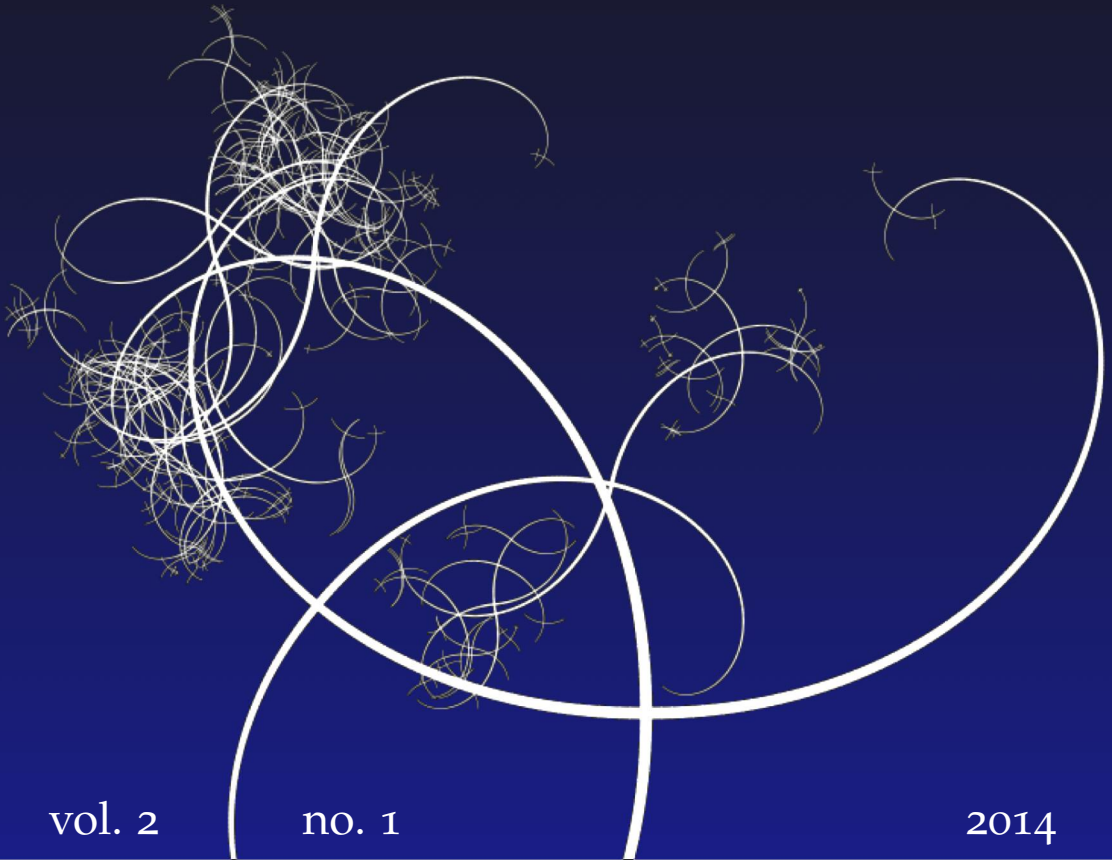


NISSUNA UMANA INVESTIGAZIONE SI PUO DIMANDARE VERA SCIENZA
S'ESSA NON PASSA PER LE MATEMATICHE DIMOSTRAZIONI
LEONARDO DA VINCI



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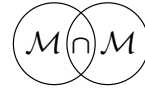
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GIANPIETRO DEL PIERO

NONCLASSICAL CONTINUA, PSEUDOBALANCE,
AND THE LAW OF ACTION AND REACTION





NONCLASSICAL CONTINUA, PSEUDOBALANCE, AND THE LAW OF ACTION AND REACTION

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Dedicated to the memory of Luiz-Carlos Martins.

The procedure followed in constructing models for generalized continua is revisited. It is shown that the microforce balance equations required for the description of generalized continua are not in fact expressions of the balance of physical quantities, but consequences of the regularity assumed for the systems of contact actions. In the proposed approach the law of action and reaction, which in classical continuum mechanics is a consequence of Euler's balance laws, recovers the status of a basic principle as held in Newtonian mechanics. Some examples of generalized continua taken from the literature are discussed.

1. Introduction

In a recent revisitation of the *method of virtual power* [Del Piero 2009], one of the conclusions was that the two terms — external power and internal power — that form the equation of virtual power should not be the object of independent assumptions. Once an expression of the external power is assumed, the internal power can be *deduced*, using some regularity properties of the system of contact actions plus the indifference of the external power.

In the present paper, the roles of regularity and indifference have been separated. Body forces and surface tractions are supposed to be *measures*, that is, vector-valued set functions additive on disjoint subsets, which we call μ and Q , respectively. The surface tractions form a system of contact actions on the interior surfaces of the body, called a *Cauchy flux* [Gurtin and Martins 1976]. The regularity assumptions are made on this system, while the indifference of power provides relations between Q and μ . This is the motivation for separating the roles of regularity and indifference.

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An appropriate set of regularity assumptions on Q , which defines what we call a *bounded Cauchy flux*, provides the general structure required for a self-consistent formulation of continuum mechanics. The first assumption is that the restriction of Q to the collection of the subsurfaces of the boundary of each fixed subbody be an absolutely continuous measure with respect to the area measure. The second is that the restriction of Q to the collection of the boundaries of all subbodies be a measure F absolutely continuous with respect to the volume measure. That is, Q has a surface density s , and F has a volume density f . Our third, and last, assumption is that Q is *skew-symmetric*. Thus, Q is defined on oriented surfaces S , and the sign of $Q(S)$ changes with the orientation of S . In mechanical terms, this corresponds to Newton's law of action and reaction.

The existence of a volume density f for F determines an integral relation between the densities f and s , which we call a *pseudobalance equation*. This equation allows us to prove the dependence of s on the normal to the surface element and the linearity of this dependence. This can be done using two basic tools of continuum mechanics: Noll's theorem on the dependence of s on the normal and Cauchy's tetrahedron theorem. We emphasize that the existence of the Cauchy stress is not deduced, as usual, from the balance law of linear momentum, but from regularity assumptions on the system of contact actions.¹

It is only at this point that indifference comes into play. It is known that the balance laws of linear and angular momentum can be deduced from the indifference of the external power [Noll 1963]. The first balance law has the same form as the pseudobalance equation, but is of a different nature: as a consequence of indifference, it is a relation between Q and the body force measure μ , and not between surface and volume densities of the same Cauchy flux Q . A comparison of the two equations leads to the identification of the volume density f of F with the volume density b of the body force. In this way the equation of virtual power is obtained, and from it a weak formulation of the equilibrium problem can be deduced.

It may look awkward to invent a complicated procedure to end up with no new conclusions. In fact, the advantages of the new procedure become evident when it is extended to more general classes of continua. Essentially, there are two ways to generalize the classical definition of a continuum:

- Relax the regularity assumed for Q and μ , by admitting the presence of singular measures.
- Consider additional external actions, represented by additional measures Q^α , μ^α .

Here we consider generalizations of the second type, which are a standard way to define continua with microstructure. Our basic assumption is that not only Q , but

¹This is indeed the main idea in [Gurtin and Martins 1976].

also all Q^α are bounded Cauchy fluxes. As a consequence, with each Q^α is associated a pseudobalance equation relating the surface density σ^α to a volume density ϕ^α . But, while Q is related to the body force measure μ by the balance law of linear momentum, no such relation is assumed to hold between the measures Q^α and μ^α .

In the literature, the role of the pseudobalance equations is played by *micro-force balance equations*, which are either postulated or deduced from an assumed expression of the internal power.² In both cases it is not clear whether or not these equations are considered as fundamental laws of mechanics, like the balance of linear momentum. If this were the case, a proliferation of postulates would take place, depending on the number and nature of the additional variables. Moreover, in most cases the new postulates would not be based on sound physical motivations.

This is the point where the pseudobalance equations play a basic role. They provide a proof of the existence of counterparts of the stress tensor for the Cauchy fluxes Q^α , without introducing extra balance laws. This makes possible the transformation of the external power into a volume integral, the *internal power*. The equality between external and internal power is the *equation of virtual power*. Note that this equation is not a relation between independent powers, as it is classically considered, but only an identity between equivalent representations of the same power. It turns out that this identity is all that is needed for the formulation of the equilibrium problem.

This paper can be divided into three parts. In the first part, Sections 2–4, some basic concepts of measure theory and geometric measure theory are recalled. The reader not interested in technical details may skip this part.³ Continuous bodies are identified with normalized sets of finite perimeter [Šilhavý 1991], and the external actions are limited to the pair (Q, μ) . A proof of Noll's theorem appropriate to this context is given in Appendix A. From it, the pseudobalance equation (4-17) is deduced.

In the second part, Sections 5 and 6, the traditional formulation of continuum mechanics and some alternative approaches are analyzed and compared with the approach based on bounded Cauchy fluxes. The final part, Sections 7 to 11, deals with continua with microstructure. For such continua, general forms of the pseudobalance equations and of the equation of virtual power are given in Section 7. The particular forms taken for specific continua depend on the *order parameters* which define the microstructure, and on the restrictions due to the indifference of

²For the first option see the book [Capriz 1989], in which a law of *balance of micromomentum* is systematically used. On the second option is based the method of virtual power developed in [Germain 1973b].

³For the reader who is interested in such details, a more general introduction can be found in [Vol'pert and Hudjaev 1985]. Basic reference books are [Evans and Gariepy 1992; Ambrosio et al. 2000] for measure theory, and [Federer 1969; Ziemer 1989] for geometric measure theory.

power, which also vary according to the nature of the continuum. We say that the order parameters define the *structural properties* of a continuum, not to be confused with the *constitutive properties*, which characterize specific classes of materials, and which are not considered in this paper.

The structural properties and the indifference requirements determine a subdivision into classes of continua, some of which are discussed in the final sections. Continua in which all measures Q^α and μ^α are indifferent to changes of observer are considered in Section 8, and *micropolar continua* and *Cosserat continua* are considered in Section 9. Section 10 deals with *second-gradient continua*. It includes some comments on the *edge forces* which show up when the contact forces are decomposed into a normal and a tangential part, as required for a correct formulation of the boundary conditions. Finally, Section 11 deals with *continua with latent microstructure*, characterized by the presence of internal constraints relating the order parameters to the macroscopic deformation.

2. Basic concepts and definitions

Let Ω be a bounded set in the N -dimensional Euclidean point space \mathcal{E}^N , and let $\wp(\Omega)$ be a collection of subsets of Ω , including Ω and the empty set \emptyset . We say that two elements Π_1 and Π_2 of $\wp(\Omega)$ are *disjoint* if

$$\Pi \in \wp(\Omega), \quad \Pi \subset \Pi_1, \quad \Pi \subset \Pi_2 \quad \Rightarrow \quad \Pi = \emptyset.$$

Assume that $\wp(\Omega)$ is equipped with a binary operation \vee , which with every pair (Π_1, Π_2) of elements of $\wp(\Omega)$ associates a set $(\Pi_1 \vee \Pi_2) \in \wp(\Omega)$, called the *join* of Π_1 and Π_2 , such that

$$\begin{aligned} \Pi_1 \subset \Pi_1 \vee \Pi_2, \quad \Pi_2 \subset \Pi_1 \vee \Pi_2, \\ \Pi_1 \subset \Pi \text{ and } \Pi_2 \subset \Pi \quad \Rightarrow \quad \Pi_1 \vee \Pi_2 \subset \Pi. \end{aligned} \tag{2-1}$$

Assume, further, that with each $\Pi \in \wp(\Omega)$ is associated a set $\Pi^c \in \wp(\Omega)$, called the *complement* of Π in Ω , such that

$$\Pi \text{ and } \Pi^c \text{ are disjoint,} \quad \Pi \vee \Pi^c = \Omega. \tag{2-2}$$

The join and the complement are unique.⁴ They define a second binary operation

$$\Pi_1 \wedge \Pi_2 = (\Pi_1^c \vee \Pi_2^c)^c, \tag{2-3}$$

called the *meet* of Π_1 and Π_2 . Two sets in $\wp(\Omega)$ are disjoint if and only if their meet is the empty set.⁵

⁴A proof of this statement and of other statements made in this section can be found in [Del Piero 2003, §5].

⁵The join and the meet are also called, respectively, the *least envelope* and the *greatest common part* of Π_1 and Π_2 ; see [Noll 1973, §8] and [Truesdell 1991, §1.2].

The existence of the join and of the complement provides $\wp(\Omega)$ with the structure of an *algebra of sets*. This structure includes the following properties:

$$\begin{aligned} \text{Associative:} \quad & \Pi \vee (\Pi_1 \vee \Pi_2) = (\Pi \vee \Pi_1) \vee \Pi_2, \\ \text{Distributive:} \quad & \Pi \vee (\Pi_1 \wedge \Pi_2) = (\Pi \vee \Pi_1) \wedge (\Pi \vee \Pi_2), \end{aligned}$$

plus the properties obtained by interchanging \vee and \wedge in the above relations. The set $\bar{\wp}(\Omega)$ of all countable joins and complements of elements of $\wp(\Omega)$ is the σ -algebra generated by $\wp(\Omega)$.

Let Y be a finite-dimensional inner-product space.⁶ A Y -valued measure on $\bar{\wp}(\Omega)$ is a map $\mu : \bar{\wp}(\Omega) \rightarrow Y$, additive on disjoint sets:

$$\Pi_1, \Pi_2 \in \bar{\wp}(\Omega), \quad \Pi_1 \wedge \Pi_2 = \emptyset \quad \Rightarrow \quad \mu(\Pi_1 \vee \Pi_2) = \mu(\Pi_1) + \mu(\Pi_2).$$

Examples of real-valued measures are the N -dimensional Lebesgue measure \mathcal{L}^N and the $(N - 1)$ -dimensional Hausdorff measure \mathcal{H}^{N-1} . For the former, $\bar{\wp}(\Omega)$ consists of all Lebesgue-measurable subsets of \mathcal{E}^N ; for the latter, it consists of all subsets of \mathcal{E}^N . For both, Y is the real line, the join and the meet are the union and the intersection of sets, and the complement of Π is the complementary set $\Omega \setminus \Pi$. For $N = 3$, the two measures are called the *volume measure* and the *area measure*, respectively. For convenience we keep these names, and use the notations V and A in place of \mathcal{L}^N and \mathcal{H}^{N-1} , for every N .

A measure $\mu : \bar{\wp}(\Omega) \rightarrow Y$ is *absolutely continuous* with respect to the volume measure (to the area measure) if $\mu(\Pi) = 0$ for all $\Pi \in \bar{\wp}(\Omega)$ for which $V(\Pi) = 0$ (for which $A(\Pi) = 0$). A measure μ is said to be *singular* with respect to the same measures if there is a $\Pi_1 \in \bar{\wp}(\Omega)$ with $V(\Pi_1) = 0$ (with $A(\Pi_1) = 0$) such that $\mu(\Pi_2) = 0$ for all $\Pi_2 \in \bar{\wp}(\Omega)$ disjoint from Π_1 . By the Lebesgue decomposition theorem, every measure μ admits a unique decomposition

$$\mu = \mu^a + \mu^s,$$

with μ^a absolutely continuous and μ^s singular with respect to the volume measure (to the area measure).

Let Π be a subset of \mathcal{E}^N , and let $B_r(x)$ be the N -dimensional ball with radius r centered at $x \in \mathcal{E}^N$. The limit

$$\rho(\Pi, x) = \lim_{r \rightarrow 0} \frac{V(B_r(x) \wedge \Pi)}{V(B_r(x))}, \tag{2-4}$$

if it exists, is a real number between 0 and 1. Then x is said to be a *point of density* for Π if $\rho(\Pi, x) = 1$, a *point of rarefaction* if $\rho(\Pi, x) = 0$, and a point of the *essential boundary* otherwise. The set of all density points, the set of all

⁶For example, the real line \mathbb{R} , the set \mathbb{R}^N of all vectors of dimension N , or the set $\mathbb{R}^{N \times N}$ of all linear transformations on \mathbb{R}^N ($N \times N$ matrices, or second-order tensors).

rarefaction points, and the essential boundary are also called the measure-theoretic interior, exterior, and boundary of Π . They will be denoted by Π^* , $\text{ext}^* \Pi$, and $\partial^* \Pi$, respectively. For the topological interior, exterior, and boundary of Π , the inclusions

$$\text{int } \Pi \subset \Pi^*, \quad \text{ext } \Pi \subset \text{ext}^* \Pi, \quad \partial \Pi \supset \partial^* \Pi, \quad (2-5)$$

hold. It is also of interest that

$$\Pi^* = (\Pi^*)^*, \quad \text{ext}^* \Pi = \text{ext}^*(\Pi^*), \quad \partial^* \Pi = \partial^*(\Pi^*). \quad (2-6)$$

Let $H(x, n)$ be the half-space through x with exterior unit normal n . Set:

$$\rho(\Pi, x, n) = \lim_{r \rightarrow 0} \frac{V(B_r(x) \wedge \Pi \wedge H(x, n))}{V(B_r(x))}.$$

We say that a unit vector n is the measure-theoretic exterior normal, in short, the *exterior normal*, to Π at x if

$$\rho(\Pi, x, n) = \frac{1}{2}, \quad \rho(\Pi, x, -n) = 0.$$

The exterior normal, if it exists, is unique. At all points x at which the exterior normal exists, one has

$$\rho(\Pi, x) = \rho(\Pi, x, n) + \rho(\Pi, x, -n) = \frac{1}{2}.$$

Therefore, all such points belong to the essential boundary of Π .

The *perimeter* of a set is the area of the essential boundary. For all *sets of finite perimeter*, the following properties hold:

- (i) The finite unions and intersections and the complementary sets of sets of finite perimeter are sets of finite perimeter,
- (ii) On the essential boundary of a set of finite perimeter the exterior normal exists A -almost everywhere,⁷
- (iii) For a set Π of finite perimeter, Π and Π^* differ by a set of zero volume.
- (iv) For a set Π of finite perimeter, the *divergence theorem*

$$\int_{\partial^* \Pi} \varphi(x) \cdot n(x) dA = \int_{\Pi} \text{div } \varphi(x) dV \quad (2-7)$$

holds for all Lipschitz continuous functions $\varphi : \mathbb{R}^N \rightarrow \mathbb{R}^N$ [De Giorgi 1954; Federer 1958; Evans and Gariepy 1992].⁸

⁷That is, except at most at a set of null area. See [Vol'pert and Hudjaev 1985, §4.5.3]. In general, the topological boundary and measure-theoretic boundary are not area-equivalent, see [Noll and Virga 1988] and [Del Piero 2003, §3].

⁸The regularity assumption on φ has been progressively relaxed, see footnote 12 below.

Note that, for

$$\varphi(x) = T^T(x)v(x),$$

with T and v sufficiently regular tensor and vector fields, respectively, (2-7) provides the *Gauss–Green formula*

$$\int_{\partial^*\Pi} T(x)n(x) \cdot v(x) dA = \int_{\Pi} (T(x) \cdot \nabla v(x) + \operatorname{div} T(x) \cdot v(x)) dV. \quad (2-8)$$

A set Π is *normalized* if $\Pi = \Pi^*$. For normalized sets, it can be proved that the rules (2-1), (2-2), and (2-3) are satisfied if and only if

$$\Pi_1 \vee \Pi_2 = (\Pi_1 \cup \Pi_2)^*, \quad \Pi^c = (\Omega \setminus \Pi)^*, \quad \Pi_1 \wedge \Pi_2 = \Pi_1 \cap \Pi_2. \quad (2-9)$$

That is, the join is the normalized union, the complement is the normalized complementary set, and the meet is the normalized intersection, which coincides with the intersection. Moreover, for normalized sets,

$$\Pi^c = \operatorname{ext}^* \Pi, \quad \operatorname{ext}^*(\Pi^c) = \Pi, \quad \partial^*(\Pi^c) = \partial^* \Pi. \quad (2-10)$$

Let Ω be a normalized set of finite perimeter, and let $\wp(\Omega)$ be the set of all normalized subsets of Ω of finite perimeter. Because the join, the meet, and the complement of normalized sets are normalized sets, and the join, the meet, and the complement of sets of finite perimeter are sets of finite perimeter, $\wp(\Omega)$ is an algebra of sets. Its elements will be called the *subbodies* of Ω . Then, $\bar{\wp}(\Omega)$ is the σ -algebra generated by the subbodies of Ω .

3. Surfaces, oriented surfaces, surface measures

The *surface* of a subbody Π is the essential boundary $\partial^*\Pi$. The *subsurfaces* of $\partial^*\Pi$ are the intersections of a surface with other subbodies

$$S_1 = \partial^*\Pi \cap \Pi_1, \quad \Pi_1 \in \wp(\Omega).$$

The relations

$$\partial^*\Pi_1 \cap \Pi_2 = \partial^*(\Pi_1 \cap \Pi_2) \cap \Pi_2 = \partial^*(\Pi_1 \vee \Pi_2^c) \cap \Pi_2 \quad (3-1)$$

hold for every pair of subbodies, and the relation

$$\partial^*\Pi_1 \cap (\Pi_1 \vee \Pi_2) = \partial^*\Pi_2 \cap (\Pi_1 \vee \Pi_2) \quad (3-2)$$

holds for every pair of disjoint subbodies. The proofs are left to the reader. The subsurface (3-2) is the *separating surface* of Π_1 and Π_2 .

Let S be a subsurface of $\partial^*\Pi$. At a point x of S , consider the limit

$$\rho(S, x) = \lim_{r \rightarrow 0} \frac{A(S \cap B_r(x))}{A_r},$$

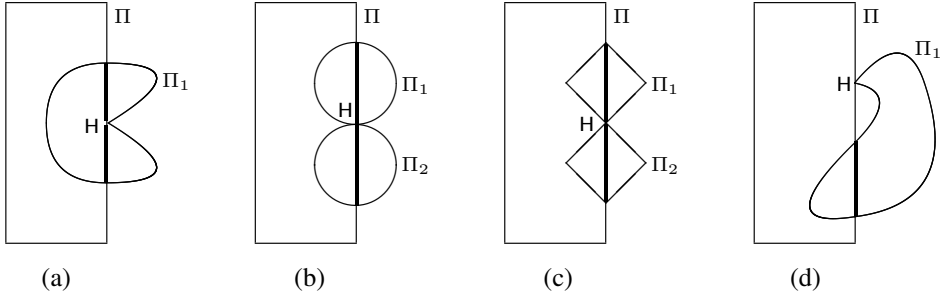


Figure 1. Two-dimensional examples. In (a), $\partial^*\Pi \cap \Pi_1$ is a non-normalized subsurface. In (b) and (c), $\partial^*\Pi \cap \Pi_1$ and $\partial^*\Pi \cap \Pi_2$ are two normalized subsurfaces, for which $\partial^*\Pi \cap (\Pi_1 \vee \Pi_2)$ is normalized in (b), but not in (c). In (d), $\partial^*\Pi \cap \Pi_1$ is a normalized subsurface for which $\partial^*\Pi \cap \Pi_1^c$ is a nonnormalized surface.

where A_r is the area of the largest circle in $B_r(x)$. For $S = \partial^*\Pi$, this limit is equal to one for A -almost every $x \in \partial^*\Pi$ [Ziemer 1983, §2]. Then for $S \subset \partial^*\Pi$ the same limit is a number between zero and one. We say that x is a *density point* for S if $\rho(S, x) = 1$. The set of all density points of S will be denoted by S^* .

A subsurface S is *normalized* if $S = S^*$. The surfaces S and S^* differ at most by a set of area zero. If Π and Π_1 are normalized sets, the subsurface $S_1 = \partial^*\Pi \cap \Pi_1$ need not be normalized. An example is given in Figure 1a, where the point H does not belong to Π_1 and, therefore, to S_1 , but belongs to S_1^* .

In a natural way, the subsurfaces of $\partial^*\Pi$ inherit the algebraic structure of $\wp(\Omega)$. For the normalized subsurfaces

$$S_1 = (\partial^*\Pi \cap \Pi_1)^*, \quad S_2 = (\partial^*\Pi \cap \Pi_2)^*, \quad (3-3)$$

the join, complement, and meet are defined by

$$\begin{aligned} S_1 \vee S_2 &= (\partial^*\Pi \cap (\Pi_1 \vee \Pi_2))^*, & S_1^\Pi &= (\partial^*\Pi \cap \Pi_1^c)^*, \\ S_1 \wedge S_2 &= (\partial^*\Pi \cap \Pi_1 \cap \Pi_2)^*, \end{aligned} \quad (3-4)$$

respectively. We say that S_1 and S_2 are disjoint if $S_1 \wedge S_2 = \emptyset$.

If Π , Π_1 , and Π_2 are normalized, the surfaces $(\partial^*\Pi \cap (\Pi_1 \vee \Pi_2))$, $(\partial^*\Pi \cap \Pi_1^c)$, and $(\partial^*\Pi \cap \Pi_1 \cap \Pi_2)$ need not be normalized. For example, in both Figures 1b and 1c the point H is a density point for $(\partial^*\Pi \cap (\Pi_1 \vee \Pi_2))$. But in the first case it belongs to $\Pi_1 \vee \Pi_2$ and in the second it does not. In Figure 1d, H is a density point for $(\partial^*\Pi \cap \Pi_1^c)$ but does not belong to Π_1^c . Finally, for Π and Π_1 as in Figure 1a and $\Pi_2 = \Omega$, $(\partial^*\Pi \cap \Pi_1 \cap \Pi_2)$ reduces to $\partial^*\Pi \cap \Pi_1$, which is not a normalized subsurface. This proves that the meet of subsurfaces does not coincide with the intersection.

Of fundamental importance are the following properties of the partition of a subbody Π into disjoint subbodies Π_1 and Π_2 , by means of a separating surface S .

Proposition 3.1. *Let Π , Π_1 , and Π_2 be subbodies such that*

$$\Pi = \Pi_1 \vee \Pi_2, \quad \Pi_1 \cap \Pi_2 = \emptyset, \quad (3-5)$$

let S be the normalized separating surface $S = (\partial^ \Pi_1 \cap \Pi)^*$, and let*

$$S_1 = (\partial^* \Pi_1 \cap \Pi_2^c)^*, \quad S_2 = (\partial^* \Pi_2 \cap \Pi_1^c)^*. \quad (3-6)$$

Then S , S_1 , and S_2 are pairwise disjoint, and

$$S_1 \gamma S_2 = \partial^*(\Pi_1 \vee \Pi_2), \quad S \gamma S_1 = \partial^* \Pi_1, \quad S \gamma S_2 = \partial^* \Pi_2. \quad (3-7)$$

Proof. By (3-1),

$$S_1 = (\partial^* \Pi_1 \cap \Pi_2^c)^* = (\partial^* \Pi \cap \Pi_2^c)^*, \quad S_2 = (\partial^* \Pi_2 \cap \Pi_1^c)^* = (\partial^* \Pi \cap \Pi_1^c)^*.$$

Then both S_1 and S_2 are subsurfaces of $\partial^* \Pi$. By (3-4) and (2-3),

$$S_1 \wedge S_2 = (\partial^* \Pi \cap \Pi_1^c \cap \Pi_2^c)^* = (\partial^* \Pi \cap (\Pi_1 \vee \Pi_2)^c)^* = (\partial^* \Pi \cap \Pi^c)^* = \emptyset,$$

$$S_1 \gamma S_2 = (\partial^* \Pi \cap (\Pi_1^c \vee \Pi_2^c))^* = (\partial^* \Pi \cap (\Pi_1 \cap \Pi_2)^c)^* = (\partial^* \Pi)^* = \partial^* \Pi,$$

with the second to last equality due to the fact that $\Pi_1 \cap \Pi_2$ is the empty set, and therefore its complement is Ω . This proves (3-7)₁. Moreover, since both S and S_1 are subsurfaces of $\partial^* \Pi_1$, by (3-4) and by the distributive property,

$$\begin{aligned} S \wedge S_1 &= (\partial^* \Pi_1 \cap (\Pi_1 \vee \Pi_2) \cap \Pi_2^c)^* \\ &= (\partial^* \Pi_1 \cap ((\Pi_1 \cap \Pi_2^c) \vee (\Pi_2 \cap \Pi_2^c)))^* = (\partial^* \Pi_1 \cap \Pi_1 \cap \Pi_2^c)^* = \emptyset, \end{aligned}$$

because both $\Pi_2 \cap \Pi_2^c$ and $\partial^* \Pi_1 \cap \Pi_1$ are empty. Furthermore,

$$S \gamma S_1 = (\partial^* \Pi_1 \cap (\Pi_1 \vee \Pi_2 \vee \Pi_2^c))^* = (\partial^* \Pi_1)^* = \partial^* \Pi_1,$$

with the second equality due to $\Pi_2 \vee \Pi_2^c = \Omega$. To get $S \wedge S_2 = \emptyset$ and (3-7)₃ note that, by (3-2),

$$S = (\partial^* \Pi_1 \cap \Pi)^* = (\partial^* \Pi_2 \cap \Pi)^*,$$

that is, both S and S_2 are subsurfaces of $\partial^* \Pi_2$. Then it is sufficient to repeat the preceding proof, with the subscripts 1 and 2 interchanged. \square

Another remarkable consequence of the relations (3-1) is the following decomposition of the essential boundary of an intersection.⁹

⁹This proposition generalizes a relation proved in [Ziemer 1983] for nonnormalized surfaces, for which (3-8) holds only to within sets of null area.

Proposition 3.2. *For every pair Π_1, Π_2 in $\wp(\Omega)$,*

$$\partial^*(\Pi_1 \cap \Pi_2) = (\partial^*\Pi_1 \cap \Pi_2)^* \vee (\partial^*\Pi_2 \cap \Pi_1)^*. \quad (3-8)$$

Proof. By (3-1)₁,

$$\partial^*\Pi_1 \cap \Pi_2 = \partial^*(\Pi_1 \cap \Pi_2) \cap \Pi_2, \quad \partial^*\Pi_2 \cap \Pi_1 = \partial^*(\Pi_1 \cap \Pi_2) \cap \Pi_1.$$

Then, by (3-3) and (3-4)₁ with $\Pi = \Pi_1 \cap \Pi_2$,

$$(\partial^*\Pi_1 \cap \Pi_2)^* \vee (\partial^*\Pi_2 \cap \Pi_1)^* = (\partial^*(\Pi_1 \cap \Pi_2) \cap (\Pi_2 \vee \Pi_1))^*. \quad (3-9)$$

On the other hand, by (3-3) and (3-4)₂ with $\Pi = \Pi_1 \cap \Pi_2$ and with $\Pi_1 \vee \Pi_2$ in place of Π_1 ,

$$((\partial^*(\Pi_1 \cap \Pi_2) \cap (\Pi_1 \vee \Pi_2))^*)^\Pi = (\partial^*(\Pi_1 \cap \Pi_2) \cap (\Pi_1 \vee \Pi_2)^c)^*.$$

The right-hand side is the empty set, because

$$\partial^*(\Pi_1 \cap \Pi_2) \subset \partial^*\Pi_1 \cup \partial^*\Pi_2, \quad (\Pi_1 \vee \Pi_2)^c = \Pi_1^c \cap \Pi_2^c,$$

and both $\partial^*\Pi_1 \cap \Pi_1^c$ and $\partial^*\Pi_2 \cap \Pi_2^c$ are empty. If the complement of a subsurface of $\partial^*(\Pi_1 \cap \Pi_2)$ is empty, the subsurface coincides with the whole surface:

$$(\partial^*(\Pi_1 \cap \Pi_2) \cap (\Pi_1 \vee \Pi_2))^* = \partial^*(\Pi_1 \cap \Pi_2).$$

Then combining with (3-9) the desired relation (3-8) follows. \square

The surface $\partial^*\Pi$ has a natural orientation, with the interior on the side of Π and the exterior on the side of Π^c . By (2-10)₃, $\partial^*\Pi$ can also be viewed as the surface of Π^c , and in this case it has the opposite orientation. The same holds for the subsurfaces $S_1 = (\partial^*\Pi \cap \Pi_1)^*$. For a given orientation of $\partial^*\Pi$, with the symbol \vec{S} we denote the subsurface S with the same orientation, and with \overleftarrow{S} we denote the same subsurface with the opposite orientation.

By $\vec{\mathbb{S}}(\Pi)$ we denote the set of all countable joins and complements of normalized subsurfaces of $\partial^*\Pi$, oriented as $\partial^*\Pi$. This set is the σ -algebra generated by the subsurfaces of $\partial^*\Pi$. A Y -valued *surface measure* on $\partial^*\Pi$ is a function $Q : \vec{\mathbb{S}}(\Pi) \rightarrow Y$, additive on disjoint surfaces:

$$Q(S_1 \vee S_2) = Q(S_1) + Q(S_2), \quad S_1, S_2 \in \vec{\mathbb{S}}(\Pi), \quad S_1 \wedge S_2 = \emptyset. \quad (3-10)$$

4. Cauchy fluxes and pseudobalance equations

Let $\vec{\mathbb{S}}(\Omega)$ be the set of all oriented surfaces in Ω :

$$\vec{\mathbb{S}}(\Omega) = \bigcup_{\Pi \in \wp(\Omega)} \{\vec{S} : \vec{S} \in \vec{\mathbb{S}}(\Pi)\}.$$

A Y -valued Cauchy flux on Ω is a function $Q : \bar{\mathbb{S}}(\Omega) \rightarrow Y$, whose restriction to each $\bar{\mathbb{S}}(\Pi)$ is a surface measure on $\partial^*\Pi$. A Cauchy flux is *symmetric* if

$$Q(\vec{S}) = Q(\tilde{S}) \quad \text{for all } \vec{S} \in \bar{\mathbb{S}}(\Omega),$$

and is *skew-symmetric* if

$$Q(\vec{S}) = -Q(\tilde{S}) \quad \text{for all } \vec{S} \in \bar{\mathbb{S}}(\Omega).$$

An example of a real-valued symmetric Cauchy flux is the area measure. In the rest of the paper, we will be interested in skew-symmetric Cauchy fluxes. For them, the following additivity property for nondisjoint surfaces holds [Noll 1973, §8].

Proposition 4.1. *For a Cauchy flux Q , the equation*

$$Q(\partial^*(\Pi_1 \vee \Pi_2)) = Q(\partial^*\Pi_1) + Q(\partial^*\Pi_2) \quad (4-1)$$

holds for all pairs Π_1, Π_2 of disjoint subbodies, if and only if Q is skew-symmetric.

Proof. Let \vec{S} be the subsurface $(\partial^*\Pi_1 \cap (\Pi_1 \vee \Pi_2))^*$ oriented as $\partial^*\Pi_1$, and let \vec{S}_1 and \vec{S}_2 be the subsurfaces (3-6) oriented as $\partial^*\Pi_1$ and $\partial^*\Pi_2$, respectively. By Proposition 3.1 the three surfaces are pairwise disjoint, and equations (3-7), now rewritten as

$$\vec{S}_1 \vee \vec{S}_2 = \partial^*(\Pi_1 \vee \Pi_2), \quad \vec{S} \vee \vec{S}_1 = \partial^*\Pi_1, \quad \vec{S} \vee \vec{S}_2 = \partial^*\Pi_2,$$

hold. By the additivity property (3-10) on disjoint surfaces,

$$\begin{aligned} Q(\partial^*(\Pi_1 \vee \Pi_2)) &= Q(\vec{S}_1) + Q(\vec{S}_2), \\ Q(\partial^*\Pi_1) &= Q(\vec{S}) + Q(\vec{S}_1), \quad Q(\partial^*\Pi_2) = Q(\vec{S}) + Q(\vec{S}_2). \end{aligned}$$

Then (4-1) holds if and only if $Q(\vec{S}) = -Q(\tilde{S})$. □

Let Q be a Cauchy flux, and let $F : \bar{\varphi}(\Omega) \rightarrow Y$ be the function

$$F(\Pi) \doteq -Q(\partial^*\Pi). \quad (4-2)$$

We are interested in whether F is a measure. The question is answered as follows:

Proposition 4.2. *Let $Q : \bar{\mathbb{S}}(\Omega) \rightarrow Y$ be a Cauchy flux, and let F be as in (4-2). Then F is a Y -valued measure on $\bar{\varphi}(\Omega)$ if and only if Q is skew-symmetric.*

Proof. It is sufficient to prove that F is additive on disjoint subsets:

$$F(\Pi_1 \vee \Pi_2) = F(\Pi_1) + F(\Pi_2), \quad \Pi_1, \Pi_2 \in \bar{\varphi}(\Omega), \quad \Pi_1 \cap \Pi_2 = \emptyset.$$

By (4-2), this is the same as (4-1). By Proposition 4.1, (4-1) holds if and only if Q is skew-symmetric. □

Thus, the restriction of a skew-symmetric Cauchy flux to the surfaces $\partial^*\Pi$ of all $\Pi \in \bar{\varphi}(\Omega)$ can be identified with a measure F on $\bar{\varphi}(\Omega)$. Consider the Lebesgue decomposition of F into the sum of an absolutely continuous and a singular part with respect to the volume measure:

$$F = F^a + F^s.$$

By the Radon–Nikodým theorem (see, e.g., [Ambrosio et al. 2000]), F^a has a volume density $f \in L^1(\Omega, Y)$:

$$F^a(\Pi) = \int_{\Pi} f(x) dV \quad \text{for all } \Pi \in \bar{\varphi}(\Omega), \quad (4-3)$$

while F^s is concentrated on a subset of Π with zero volume. Moreover, the Cauchy flux Q admits the decomposition $Q = Q^a + Q^s$, with

$$Q^a(\vec{S}) = \int_S s(x, \partial^*\Pi) dA \quad \text{for all } S \in \bar{\mathbb{S}}(\Pi), \quad (4-4)$$

where $s(\cdot, \partial^*\Pi) \in L^1(\partial^*\Pi, Y)$ is the surface density associated with the restriction of Q^a to $\bar{\mathbb{S}}(\Pi)$, and Q^s is concentrated on a subset of $\partial^*\Pi$ with null area measure. Equation (4-2) then takes the form

$$\int_{\Pi} f(x) dV + F^s(\Pi) + \int_{\partial^*\Pi} s(x, \partial^*\Pi) dA + Q^s(\partial^*\Pi) = 0. \quad (4-5)$$

The measure Q is absolutely continuous with respect to the area measure if $Q^s = 0$, and F is absolutely continuous with respect to the volume measure if $F^s = 0$. A sufficient condition for the A -absolute continuity of Q is the property of *area boundedness*

$$|Q(\vec{S})| \leq K A(\vec{S}) \quad \text{for all } \vec{S} \in \bar{\mathbb{S}}(\Omega), \quad (4-6)$$

with K a positive constant and $|\cdot|$ the norm of Y . A sufficient condition for the V -absolute continuity of F is the *volume boundedness*

$$|F(\Pi)| \leq K V(\Pi) \quad \text{for all } \Pi \in \bar{\varphi}(\Omega). \quad (4-7)$$

The less restrictive condition that for every $\Pi \in \bar{\varphi}(\Omega)$ there is a nonnegative function $h^{\Pi} \in L^1(\partial^*\Pi, \mathbb{R})$ such that

$$|Q(\mathcal{S})| \leq \int_{\mathcal{S}} h^{\Pi}(x) dA \quad \text{for all } \mathcal{S} \in \bar{\mathbb{S}}(\Pi), \quad (4-8)$$

is necessary and sufficient for the A -absolute continuity of Q , and the condition that there is a nonnegative function $h \in L^1(\Omega, \mathbb{R})$ such that

$$|F(\Pi)| \leq \int_{\Pi} h(x) dV \quad \text{for all } \Pi \in \bar{\varphi}(\Omega), \quad (4-9)$$

is necessary and sufficient for the V -absolute continuity of F [Šilhavý 1985]. A flux with the properties (4-8) and (4-9) is called a *weakly balanced Cauchy flux*.¹⁰

Thus, F is a measure if and only if Q is skew-symmetric, and this measure is V -absolutely continuous if and only if Q is weakly balanced. A skew-symmetric weakly balanced Cauchy flux is called a *bounded Cauchy flux* [Šilhavý 2008]. For such fluxes, (4-2) takes the special form

$$\int_{\Pi} f(x) dV + \int_{\partial^*\Pi} s(x, \partial^*\Pi) dA = 0. \tag{4-10}$$

Equation (4-5) and its special form (4-10) will be called *pseudobalance equations*, to distinguish them from the balance equations of continuum mechanics, which have the same form but a different physical meaning.

The pseudobalance equation (4-10) has two important consequences. For almost every $x \in \Omega$,

- (i) the surface density

$$s(x, \partial^*\Pi) = \lim_{r \rightarrow 0} \frac{Q(\partial^*\Pi \cap B_r(x))}{A(\partial^*\Pi \cap B_r(x))} \tag{4-11}$$

only depends on the exterior normal n to $\partial^*\Pi$ at x ,

$$s(x, \partial^*\Pi) = s(x, n), \quad \text{a.e. } x \in \Omega, \tag{4-12}$$

and

- (ii) the dependence of s on n is linear.

The first consequence was considered a postulate by Cauchy, and was proved later by Noll [1959]. The second is the object of the celebrated *tetrahedron theorem* of Cauchy. Formally, they can be stated as follows.

Theorem 4.3. *Let Q be a bounded Cauchy flux, and let Π be a subbody. Let x be a point of $\partial^*\Pi$ at which the measure-theoretic exterior normal n exists, and let $s(x, \partial^*\Pi)$ be the limit (4-11). Then for every other subbody Π' with $x \in \partial^*\Pi'$ and with the same normal n at x ,*

$$s(x, \partial^*\Pi') = s(x, \partial^*\Pi). \tag{4-13}$$

Theorem 4.4. *Let Q and s be as above, and let the function h^P in equation (4-15) below be integrable. Then there is a mapping $T \in L^1(\Omega, \mathbb{R}^{N \times N})$ such that*

$$s(x, n) = T(x)n \tag{4-14}$$

for all $n \in Y$ and for V -almost all x in Ω .

¹⁰See [Gurtin and Martins 1976], modified in [Šilhavý 1985].

The proof of Theorem 4.3 given in Appendix A follows the lines of Noll's original proof [Noll 1959], with modifications dictated by the weaker regularity assumed for the surfaces $\partial^*\Pi$. For Theorem 4.4, the original proof based on the tetrahedron argument¹¹ is sufficient for the purposes of the present paper. It is known [Noll 1973, §8] that Cauchy's proof relies on the somehow artificial assumption of continuity of the vector field $s(\cdot, n)$. Later, the theorem was extended to integrable functions [Gurtin et al. 1968].

A sufficient condition for integrability is the following. For every fixed direction n , let \mathcal{P}_ξ^n be the plane with normal n and with signed distance ξ from a fixed point x_0 . For an absolutely continuous flux Q , the function $s(\cdot, n)$ is integrable on each \mathcal{P}_ξ^n . Then, there is a nonnegative number h^P , depending on ξ , such that

$$\int_{\mathcal{P}_\xi^n \cap \Omega} |s(x, n)| dA \leq h^P(\xi) A(P_\xi^n \cap \Omega). \quad (4-15)$$

Assume that the function $\xi \mapsto h^P(\xi)$ is integrable over the real line. If Ω is bounded, this guarantees the integrability of $s(\cdot, n)$ over Ω [Kolmogorov and Fomin 1968, §35, Problem 6].

For a bounded Cauchy flux, using (4-14) and the tensorial version of the divergence theorem (2-7)

$$\int_{\partial^*\Pi} T(x)n dA = \int_{\Pi} \operatorname{div} T(x) dV, \quad (4-16)$$

which follows from (2-8) written for a constant v , the pseudobalance equation (4-10) takes the form of a volume integral

$$\int_{\Pi} (f(x) + \operatorname{div} T(x)) dV = 0. \quad (4-17)$$

By the arbitrariness of Π , this implies the local relation

$$f(x) + \operatorname{div} T(x) = 0, \quad \text{a.e. } x \in \Omega, \quad (4-18)$$

between the divergence of T and the volume density of the measure F .¹²

5. The traditional approach to continuum mechanics

In this section we recall the traditional formulation of continuum mechanics. Some alternative formulations present in the literature are summarized in the next section.

¹¹See [Cauchy 1823]. For proofs not based on the tetrahedron argument see [Šilhavý 1985; 1990; 1991; 2008; Fosdick and Virga 1989; Marzocchi and Musesti 2003].

¹²Because f is integrable by assumption, not only T , but also its divergence is integrable. The regularity of T has been successively relaxed to L^p with divergence in L^p [Ziemer 1983; Šilhavý 1985], to L^∞ with divergence measure [Chen and Torres 2005], to L^1 with divergence measure [Degiovanni et al. 1999], and to measures with divergence measure [Chen and Frid 1999].

Let Ω be the region of \mathcal{E}^N occupied by a continuous body. The interaction of a body with the exterior is assumed to consist of two vector-valued measures, a volumic measure $\mu : \bar{\rho}(\Omega) \rightarrow \mathbb{R}^N$, called the *distance action*, and a surface measure $Q : \bar{\mathbb{S}}(\Omega) \rightarrow \mathbb{R}^N$, called the *contact action*.¹³ They are subject to two fundamental axioms, the *Euler laws of motion* and the *cut principle* of Euler and Cauchy [Truesdell 1991, §III.1].

The Euler laws are the balance laws of *linear momentum* and of *angular momentum*. They state that the total action and the total moment exerted on Ω by the exterior are zero:¹⁴

$$\int_{\Omega} d\mu + \int_{\partial^*\Omega} dQ = 0, \quad \int_{\Omega} x \times d\mu + \int_{\partial^*\Omega} x \times dQ = 0. \quad (5-1)$$

The cut principle states that the same balance laws hold for every subbody Π of Ω . This hypothesis requires, in particular, that the contact action be defined on all surfaces $\partial^*\Pi$ and not only on the boundary $\partial^*\Omega$, and that (5-1) holds with Ω replaced by Π . In other words, *the cut principle requires that Q be a Cauchy flux*.

The measures μ and Q are supposed to have a volume density b and an area density $s(\cdot, \partial^*\Pi)$, respectively. Then the balance laws take the form

$$\begin{aligned} \int_{\Omega} b(x) dV + \int_{\partial^*\Omega} s(x, \partial^*\Omega) dA &= 0, \\ \int_{\Omega} x \times b(x) dV + \int_{\partial^*\Omega} x \times s(x, \partial^*\Omega) dA &= 0. \end{aligned} \quad (5-2)$$

By the cut principle, the same laws hold for every subbody Π .¹⁵ Then, using the arbitrariness of Π , from the first balance law the dependence of $s(x, \cdot)$ on the normal, the *action-reaction law*

$$s(x, n) = -s(x, -n), \quad (5-3)$$

and the existence of a stress tensor T such that

$$s(x, n) = T(x)n \quad (5-4)$$

are deduced using Theorems 4.3 and 4.4 with f replaced by b . (For the deduction of (5-3), see [Noll 1959].) As a consequence, the balance equations (5-2) are

¹³Inertia forces are included in μ ; see [Noll 1963, §7].

¹⁴Here and in the following, we denote with the same symbol x both a point in \mathcal{E}^N and the position vector $x-o$ with respect to an origin o chosen once and for all.

¹⁵In fact, writing (5-2) with Ω replaced by Π requires some physical assumptions. Namely, using the same volume density b for Ω and for Π requires the assumption that the distance actions between parts of the body are negligible. Also, treating the contact actions at the interior surfaces of the body in the same way as the contact actions at the boundary means to exclude any special structure of the body's surface, such as, for example, the structure of the *material surfaces* studied in [Gurtin and Murdoch 1975].

reduced to the local forms

$$\operatorname{div} T(x) + b(x) = 0, \quad T(x) = T^T(x), \quad \text{a.e. } x \in \Omega. \quad (5-5)$$

These are the local equations of motion, or, in the absence of inertia forces, the *local equilibrium equations* at the internal points of Ω . After introducing a set \mathcal{V} of *virtual displacements* v , (5-5)₁ multiplied by v and integrated over Π , the Gauss–Green formula (2-8), the relation (5-4), and the symmetry condition (5-5)₂ lead to the *equation of virtual power*

$$\int_{\Pi} b(x) \cdot v(x) dV + \int_{\partial^* \Pi} s(x, n) \cdot v(x) dA = \int_{\Pi} T(x) \cdot \nabla^S v(x) dV \quad \text{for all } v \in \mathcal{V}. \quad (5-6)$$

This equation states the equality of the *external power* of the actions b and s with the *internal power*, given by the product of the *internal force* T by the *generalized deformation* $\nabla^S v$. This equation has been deduced from the equilibrium equations (5-5). Conversely, if (5-6) is assumed to hold, (5-5) follows after replacing $s(x, n)$ by $T(x)n$. Thus, (5-6) is an alternative definition of equilibrium. It can be regarded as the weak form of the definition of an *equilibrated system of actions*.

Assume that the external body forces b are known, that surface tractions $s(x)$ are prescribed on a portion $\partial_s^* \Omega$ of $\partial^* \Omega$, and that null displacements are prescribed on the complement $(\partial_s^* \Omega)^c$ of $\partial_s^* \Omega$. Denoting by \mathcal{V}_o the set of all virtual displacements which vanish on $(\partial_s^* \Omega)^c$, from (5-6) written for $\Pi = \Omega$ it follows that

$$\int_{\Omega} b(x) \cdot v(x) dV + \int_{\partial_s^* \Omega} s(x) \cdot v(x) dA = \int_{\Omega} T(x) \cdot \nabla^S v(x) dV \quad \text{for all } v \in \mathcal{V}_o. \quad (5-7)$$

By introducing the constitutive equation of an elastic material¹⁶

$$T = g(\nabla u), \quad (5-8)$$

the *weak form of the equilibrium problem* for an elastic body is obtained (see [Ciarlet 1988, Theorem 5.2-1]). For nonelastic bodies the formulation is more complicated, since it requires the introduction of additional variables and of the corresponding generalized forces and evolution equations (see for example, [Halphen and Nguyen 1975]). Nonelastic continua will not be considered in this paper.

6. Alternative approaches

The traditional approach to continuum mechanics illustrated in the previous section grew over the centuries, starting from the pioneering work of Newton, Euler,

¹⁶Here and in the following, the constitutive equations are relative to the current deformed configuration of the body, taken as the reference configuration. This is the reason why the kinematical variable is the gradient of the virtual displacement.

and Cauchy. Relatively recent is the realization that the balance laws (5-2) are consequences of a more fundamental physical principle, the indifference, that is, the invariance under changes of observer, of the external power [Noll 1963].¹⁷ For the external power given by the left side of (5-6)

$$P_{\text{ext}}(\Pi, v) = \int_{\Pi} b(x) \cdot v(x) dV + \int_{\partial^* \Pi} s(x, n) \cdot v(x) dA, \quad (6-1)$$

indifference is expressed by the condition

$$P_{\text{ext}}(\Pi, v) = P_{\text{ext}}(\Pi, v + a + W(\cdot)), \quad (6-2)$$

to be satisfied for all $\Pi \in \wp(\Omega)$, for all vectors a , and for all skew-symmetric tensors W .¹⁸ By the linear dependence of P_{ext} on v , this condition holds if and only if

$$P_{\text{ext}}(\Pi, a) = 0, \quad P_{\text{ext}}(\Pi, W(\cdot)) = 0, \quad (6-3)$$

for all a and for all W , and from these conditions the balance equations (5-2) easily follow.

Recently, alternative approaches have appeared in the literature. One of them consists in taking the equation of virtual power (5-6) as a postulate. In this case, the weak formulation (5-7) of the equilibrium problem follows directly from (5-6) written for $\Pi = \Omega$ and $v \in \mathcal{V}_o$, and the balance equations (5-2) follow from the same equation written for $v = a$ and $v = W(\cdot)$, respectively. This approach has been largely used to construct models of continua with microstructure [Germain 1973a; 1973b]. Some of its advantages and drawbacks will be discussed later.

Also very common is the *variational approach*, which consists in minimizing an energy functional, whose Euler equation coincides with (5-7). For an elastic continuum, the energy is

$$E(v) = \int_{\Omega} w(\nabla v(x)) dV - \int_{\Omega} b(x) \cdot v(x) dV - \int_{\partial \Omega} s(x) \cdot v(x) dA, \quad (6-4)$$

where w is the *strain energy density*, and $T = dw(\nabla v)/d\nabla v$ is the constitutive equation. Thus, in the variational approach the constitutive equation enters from the very beginning. Since it is our intention to keep the equilibrium conditions separate from the constitutive assumptions, the variational approach will not be considered here.

¹⁷In Lagrangian mechanics, the deduction of the balance of linear momentum from the translational indifference of the Lagrangian is a well-known consequence of Noether's theorem on the correspondence between the indifference properties of a functional and conservation laws; see, for example, [Lanczos 1949, p. 403].

¹⁸Here a is the rigid translation $a(x) = a$, and W is the skew-symmetric tensor $Wx = w \times x$ associated with the rotation vector w , see Appendix B.

In the approach based on the properties of bounded Cauchy fluxes introduced in Section 4, the pseudobalance equation (4-10) holds. A comparison of its local form (4-18) with (5-5)₁ leads to the identification

$$f = b. \quad (6-5)$$

That is, the volume density f of Q coincides with the body force. With this identification, the procedure leading to the equilibrium problem becomes identical to the one followed in the traditional approach.

Thus, at a first glance, the difference of the two approaches looks irrelevant. On the contrary, as pointed out in Section 1, when the external actions involve additional measures μ^α and Q^α , some problems are met in defining additional microscopic balance equations with the traditional approach. As shown in the following section, the assumption that all Q^α are bounded Cauchy fluxes provides a quite general solution to this difficulty.

7. Nonclassical continua

A *continuum with microstructure* is a continuum in which the deformations act on two length scales of different orders of magnitude, macroscopic and microscopic.¹⁹ The macrodeformation is described by the displacement vector u , and the microdeformation is described by a finite number of *order parameters* d^α , also called *internal variables* or *state variables*, defined on finite-dimensional inner product spaces Y^α . Each order parameter describes a *microstructure*, and each set of order parameters describes a *continuum with microstructure*. Here we will use the terms *nonclassical continua* and *classical continua* to denote continua with and without microstructure, respectively.

Just as the macrodeformation u is associated with a pair (μ, Q) of vector-valued measures describing the macroscopic external actions, to each d^α corresponds a pair (μ^α, Q^α) of Y^α -valued measures, describing the microscopic external actions due to the α -th microstructure. We confine our attention to the case in which all measures μ^α are absolutely continuous with respect to the volume measure, and all Q^α are absolutely continuous with respect to the area measure.²⁰ In this case

¹⁹Historically, the first example of a continuum with microstructure is the continuum with couple stresses [Cosserat and Cosserat 1909]. A short history of successive developments and a broad list of applications can be found in the book [Capriz 1989].

²⁰In general, this assumption is too restrictive. Stress concentrations corresponding to singular Cauchy fluxes appear even in some classical problems of linear elasticity. Examples of concentrated contact interactions are discussed in [Podio-Guidugli 2004], and examples of stress fields equilibrated with continuous surface tractions at the boundary and exhibiting, at the interior, stress concentrations on singular surfaces or lines are given in [Lucchesi et al. 2006; 2009]. An appropriate environment for the study of stress concentrations is provided by stress fields with divergence measure, see [Chen and Frid 1999; Degiovanni et al. 1999; Chen and Torres 2005; Šilhavý 2008].

each μ^α has a volume density, the *body microforce* β^α , each Q^α has a surface density, the *surface microtraction* σ^α , and the external power has the form

$$P_{\text{ext}}(\Pi, v, v^\alpha) = \int_{\Pi} (b \cdot v + \beta^\alpha \cdot v^\alpha) dV + \int_{\partial^* \Pi} (s \cdot v + \sigma^\alpha \cdot v^\alpha) dA, \quad (7-1)$$

where v^α are virtual variations of the order parameters d^α .²¹

We also assume that Q and all Q^α are bounded Cauchy fluxes, and we extend to continua with microstructure the approach based on bounded Cauchy fluxes, described in Section 4 for classical continua.

For a bounded Cauchy flux, the pseudobalance equation (4-10) holds for Q , and for each Q^α the pseudobalance equation

$$\int_{\Pi} \phi^\alpha dV + \int_{\partial^* \Pi} \sigma^\alpha dA = 0 \quad (7-2)$$

holds as well, with ϕ^α the volume density associated with the flux Q^α . By Theorems 4.3 and 4.4, the relations

$$s = Tn, \quad \sigma^\alpha = \Sigma^\alpha n, \quad (7-3)$$

and the local pseudobalance equations

$$\text{div } T + f = 0, \quad \text{div } \Sigma^\alpha + \phi^\alpha = 0, \quad (7-4)$$

follow, where each Σ^α is a linear map on the corresponding Y^α .²²

It is convenient to decompose the volume densities f and ϕ^α into the sums

$$f = b - z, \quad \phi^\alpha = \beta^\alpha - \zeta^\alpha, \quad (7-5)$$

where z and ζ^α measure the deviations of the external body forces b and β^α from the densities f and ϕ^α .

Using (7-4), (7-5), and the Gauss–Green formula (2-8), the external power (7-1) transforms into the *internal power*

$$P_{\text{int}}(\Pi, v, v^\alpha) = \int_{\Pi} (z \cdot v + T \cdot \nabla v + \zeta^\alpha \cdot v^\alpha + \Sigma^\alpha \cdot \nabla v^\alpha) dV. \quad (7-6)$$

This is a sum of terms, each of which is the scalar product of an *internal force* by the corresponding *generalized deformation*. Therefore, the terms z and ζ^α in (7-5) are characterized as internal forces, and v and v^α are the corresponding generalized deformations.

²¹Summation over repeated superscripts α is understood. For simplicity of notation, from here onwards the argument x is omitted.

²²For Y^α equal to \mathbb{R} , \mathbb{R}^N , and $\mathbb{R}^{N \times N}$, the values $\Sigma^\alpha(x)$ are vectors, second-order tensors, and third-order tensors, respectively.

The difference between the internal power (7-6) and the internal power (5-6) of a classical continuum is not only the presence of microstructural terms. Indeed, in (7-6) there is the extra term $(z \cdot v)$, and the generalized deformation $\nabla^S v$ is replaced by ∇v . This is due to the indifference requirements. In all examples to be discussed below, the internal power has the translational indifference property²³

$$P_{\text{int}}(\Pi, a, 0) = 0, \quad (7-7)$$

which implies

$$z = 0, \quad (7-8)$$

and, therefore, leads to the same identification $f = b$ found for the classical continuum. On the contrary, the condition of rotational indifference varies according to the physical nature of the order parameters. Therefore, the symmetry of T found for a classical continuum is not preserved, in general, in nonclassical continua. These are the reasons for the differences between (7-6) and (5-6) remarked above.

As a consequence of (7-8), z can be dropped from the list of the internal forces and, consequently, v can be dropped from the list of the generalized deformations. With this modification, the *equation of virtual power for a continuum with microstructure* takes the form

$$\begin{aligned} \int_{\Pi} (b \cdot v + \beta^\alpha \cdot v^\alpha) dV + \int_{\partial^* \Pi} (s \cdot v + \sigma^\alpha \cdot v^\alpha) dA \\ = \int_{\Pi} (T \cdot \nabla v + \zeta^\alpha \cdot v^\alpha + \Sigma^\alpha \cdot \nabla v^\alpha) dV. \end{aligned} \quad (7-9)$$

Just as (5-6) for the classical continuum, this equation defines an *equilibrated system of actions* for a continuum with microstructure.

The *constitutive equations* are relations between the internal forces and the generalized deformations

$$\begin{aligned} T = \hat{T}(\nabla v, v^\alpha, \nabla v^\alpha), \quad \zeta^\alpha = \hat{\zeta}^\alpha(\nabla v, v^\alpha, \nabla v^\alpha), \\ \Sigma^\alpha = \hat{\Sigma}^\alpha(\nabla v, v^\alpha, \nabla v^\alpha). \end{aligned} \quad (7-10)$$

Substituting into (7-9) written for $\Pi = \Omega$ and imposing boundary conditions either on the kinematical variables u and d^α or on the corresponding contact actions s and σ^α , a generalization of (5-7) is obtained. This is the *weak form of the equilibrium problem* for an elastic continuum with microstructure.

In models based on generalizations of the traditional approach, the pseudobalance equation (7-4)₁ is replaced by the balance equation of linear momentum

²³Just like (3-7) for classical continua, in the present approach the equation of virtual power is in fact an identity, which holds when all systems of contact actions are strongly balanced Cauchy fluxes. By consequence, the external power is indifferent if and only if the internal power is. In the following, we will systematically impose the indifference of the internal power.

(5-5)₁. Equations identical to (7-4)₂, called *microforce balance equations*, are either postulated,²⁴ or deduced from the equation of virtual power, assumed as a basic postulate.²⁵ In both cases, the way these equations are introduced is not completely satisfactory. In the first case, it is difficult to attribute to such equations, which are so strongly dependent on the number and physical nature of the order parameters, the same status of the balance equation of linear momentum, which is a general law of mechanics.²⁶ In the second case, it is not clear how much liberty is allowed in the choice of the internal power, once the external power has been defined. The choice cannot be completely arbitrary, because it must be compatible with the balance laws (5-2). Then there must be a tacit preselection of *admissible* forms of the internal power, in contrast with the character of a postulate attributed to the equation of virtual power.

On the contrary, the approach based on bounded Cauchy fluxes provides *the most general* form of the internal power compatible with the assumed external power (7-1), that is, with the chosen order parameters. We say that this choice determines the *structural properties* of a continuum. Together with the indifference requirements, these properties define specific *classes of continua*. Within each class, the constitutive equations (7-10) define *subclasses of materials*. In many models present in the literature, the assumed form of the internal power is a special case of (7-6), resulting from a mix of structural properties and constitutive assumptions.²⁷

A bounded Cauchy flux is skew-symmetric, and this is the property from which the pseudobalance equations (4-10) and (7-2) follow. From the foundational viewpoint, I find this fact very intriguing. Indeed, the balance equations of linear and angular momentum are expressions of Newton's first two laws of motion, and the skew-symmetry of Q is an expression of the third law, the law of action and reaction. For classical continua, as seen in Section 5, the third law is a consequence of the first two. Accordingly, in classical continuum mechanics the third law is not considered as a general principle. (See, for example, [Truesdell 1991, §12].) For continua with microstructure, the third law gives a precise status to the microforce balance equations, transforming them into pseudobalance equations. In this respect, the third law recovers the role of a general principle.

²⁴See, for example, [Capriz 1989, §8]. It is interesting that the assumption that z is zero while ζ^α need not be zero, made on page 22 of the book, coincide with our conclusions deduced from the indifference of power.

²⁵This is the method proposed by Germain. Examples of models constructed in this way are given in [Gurtin 2003, Footnote 1] and in [Del Piero 2012, Chapter 2].

²⁶An alternative is to view the microforce balance equations as constitutive assumptions. To my knowledge, the nature of these equations has never been clearly specified.

²⁷In this respect, it is instructive to compare the two models for strain-gradient plasticity of [Gurtin 2003; 2004]; see [Del Piero 2012, §2.4].

8. Continua with indifferent microstructure

Here and in the following sections, we assume that the translational indifference condition (7-7) holds in general. For the rotational condition, consider first the case in which all microstructures are indifferent:

$$P_{\text{ext}}(\Pi, W(\cdot), 0) = 0. \quad (8-1)$$

Because scalars are invariant under changes of observer, this is the case of all microstructures whose order parameters are scalars. Examples are given by the scalar theories of damage, strain-gradient plasticity, and crystal plasticity. (See, for example, [Del Piero 2012, §2.2].)

The result of this condition applied to the internal power (7-6) is the symmetry of T . In this way condition (5-5)₂, which in the traditional approach was a consequence of the balance of angular momentum, is recovered. There are no restrictions on the virtual velocities ζ^α and Σ^α . In the constitutive equations (7-10), the only change is that now the values of the constitutive function \hat{T} are symmetric second-order tensors.

9. Micropolar continua

Micropolar continua are continua with microstructure whose order parameters d^α are vector fields, called *directors*. They may represent, for example, the orientations of a crystalline lattice or the directions of some crystal defects. Since the directors change their orientation with the body's deformation, the rotational indifference requires the invariance of the internal power under simultaneous rigid rotations of the body and of the directors:

$$P_{\text{int}}(\Pi, W(\cdot), Wd^\alpha(\cdot)) = 0. \quad (9-1)$$

From (7-6) with $z = 0$ it follows that

$$\begin{aligned} 0 &= \int_{\Pi} (T \cdot W + \zeta^\alpha \cdot Wd^\alpha + \Sigma^\alpha \cdot W\nabla d^\alpha) dV \\ &= W \cdot \int_{\Pi} (T + \zeta^\alpha \otimes d^\alpha + \Sigma^\alpha \nabla^T d^\alpha) dV, \end{aligned} \quad (9-2)$$

where $\nabla^T d^\alpha$ is the transpose of ∇d^α . This implies the symmetry of the integrand function. Then T is not symmetric in general, and its skew-symmetric part is

$$T^W = -(\Sigma^\alpha \nabla^T d^\alpha + \zeta^\alpha \otimes d^\alpha)^W. \quad (9-3)$$

We say that T^W is the *reactive part* of the internal force T , and that the symmetric part T^S is the *active part*. While T^W is a known function of the microstructural

internal forces ζ^α and Σ^α , T^S has to be determined by a constitutive equation. The internal power takes the form

$$\begin{aligned} & \int_{\Pi} (T^S \cdot \nabla v + \zeta^\alpha \cdot v^\alpha - (\Sigma^\alpha \nabla^T d^\alpha + \zeta^\alpha \otimes d^\alpha)^W \cdot \nabla v + \Sigma^\alpha \cdot \nabla v^\alpha) dV \\ &= \int_{\Pi} (T^S \cdot \nabla^S v + \zeta^\alpha \cdot (v^\alpha - \nabla^W v d^\alpha) + \Sigma^\alpha \cdot (\nabla v^\alpha - \nabla^W v \nabla d^\alpha)) dV. \end{aligned} \quad (9-4)$$

It shows that the generalized deformations corresponding to the internal forces T^S , ζ^α , and Σ^α are

$$\nabla^S v, \quad \psi^\alpha = v^\alpha - \nabla^W v d^\alpha, \quad \Psi^\alpha = \nabla v^\alpha - \nabla^W v \nabla d^\alpha, \quad (9-5)$$

respectively. Note that ψ^α is the relative rotation between the director d^α and the corresponding direction in the deformed body. Thus, the equation of virtual power becomes

$$\begin{aligned} & \int_{\Pi} (b \cdot v + \beta^\alpha \cdot v^\alpha) dV + \int_{\partial^* \Pi} (s \cdot v + \sigma^\alpha \cdot v^\alpha) dA \\ &= \int_{\Pi} (T^S \cdot \nabla^S v + \zeta^\alpha \cdot \psi^\alpha + \Sigma^\alpha \cdot \Psi^\alpha) dV, \end{aligned} \quad (9-6)$$

and the constitutive equations (7-10) take the form

$$\begin{aligned} T^S &= \hat{T}^S(\nabla^S v, \psi^\alpha, \Psi^\alpha), \quad \zeta^\alpha = \hat{\zeta}^\alpha(\nabla^S v, \psi^\alpha, \Psi^\alpha), \\ \Sigma^\alpha &= \hat{\Sigma}^\alpha(\nabla^S v, \psi^\alpha, \Psi^\alpha). \end{aligned} \quad (9-7)$$

Equation (9-6) defines an *equilibrated system of actions* for a micropolar continuum. When coupled with the constitutive equations (9-7), it provides the *weak formulation for the equilibrium problem* for a micropolar continuum.

Special micropolar continua are the *Cosserat continua*. In a three-dimensional body, they are characterized by three mutually orthogonal directors d^α , whose virtual velocities are

$$v^\alpha = \omega \times d^\alpha, \quad (9-8)$$

with ω a vector field. With this assumption the directors preserve length and mutual orthogonality in all infinitesimal deformations, and ω measures their common rotation. In the expression (7-1) of the external power, we have

$$\beta^\alpha \cdot v^\alpha = \beta^\alpha \cdot \omega \times d^\alpha = d^\alpha \times \beta^\alpha \cdot \omega, \quad (9-9)$$

and, similarly,

$$\sigma^\alpha \cdot v^\alpha = d^\alpha \times \sigma^\alpha \cdot \omega. \quad (9-10)$$

By setting (with α summed)

$$c = d^\alpha \times \beta^\alpha, \quad m = d^\alpha \times \sigma^\alpha, \quad (9-11)$$

the external power takes the form

$$P_{\text{ext}}(\Pi, v, \omega) = \int_{\Pi} (b \cdot v + c \cdot \omega) dV + \int_{\partial^* \Pi} (s \cdot v + m \cdot \omega) dA. \quad (9-12)$$

Here c and m are the *body couple* and the *surface couple*, respectively. Thus, due to assumption (9-8), the Cosserat continuum is a micropolar continuum with a single vectorial microstructure.

If all σ^α are the densities of bounded Cauchy fluxes, by the definition of the cross product of a vector and a tensor given in Appendix B, from (7-3) we get

$$m = d^\alpha \times \sigma^\alpha = d^\alpha \times (\Sigma^\alpha n) = (d^\alpha \times \Sigma^\alpha) n = Mn, \quad (9-13)$$

where $M = d^\alpha \times \Sigma^\alpha$ is the *couple stress*. Then using the Gauss–Green formula and setting

$$\zeta = c + \text{div } M, \quad (9-14)$$

the external power transforms into the internal power

$$P_{\text{int}}(\Pi, v, \omega) = \int_{\Pi} (T \cdot \nabla v + \zeta \cdot \omega + M \cdot \nabla \omega) dV. \quad (9-15)$$

The rotational indifference condition (9-1) now requires that

$$P_{\text{int}}(\Pi, a \times (\cdot), a) = 0, \quad (9-16)$$

for all constant vectors a . The identity $a \times x = (a \times I)x$ and the relation (B-7) in Appendix B imply

$$T(x) \cdot \nabla(a \times x) = T(x) \cdot (a \times I) = 2t(x) \cdot a, \quad (9-17)$$

with t the vector associated with the skew-symmetric part of T . Then, by (9-15) and (9-16),

$$2t + \zeta = 0. \quad (9-18)$$

This determines the skew-symmetric part of T in the case of Cosserat continua.

In the macroscopic deformation, the infinitesimal rotation is represented by the vector associated with the skew-symmetric part of ∇v . By (B-8), this vector is one half of $\text{curl } v$. Then, again from (B-7),

$$T \cdot \nabla v + \zeta \cdot \omega = T^S \cdot \nabla^S v + 2t \cdot \frac{1}{2} \text{curl } v + \zeta \cdot \omega = T^S \cdot \nabla^S v + \zeta \cdot (\omega - \frac{1}{2} \text{curl } v). \quad (9-19)$$

Then the internal power further reduces to

$$P_{\text{int}}(\Pi, v, \omega) = \int_{\Pi} (T^S \cdot \nabla^S v + \zeta \cdot (\omega - \frac{1}{2} \text{curl } v) + M \cdot \nabla \omega) dV, \quad (9-20)$$

and the constitutive equations (9-7) take the form

$$\begin{aligned} T^S &= \hat{T}^S(\nabla^S v, \omega - \frac{1}{2} \text{curl } v, \nabla \omega), & \zeta &= \hat{\zeta}(\nabla^S v, \omega - \frac{1}{2} \text{curl } v, \nabla \omega), \\ M &= \hat{M}(\nabla^S v, \omega - \frac{1}{2} \text{curl } v, \nabla \omega). \end{aligned} \quad (9-21)$$

Comparison with the constitutive equations (9-7) shows that the relative rotation $(\omega - \frac{1}{2} \text{curl } v)$ corresponds to the relative rotation ψ^α of the general micropolar continuum.

Again, the equation of virtual power obtained by equating the powers (9-12) and (9-20) defines an equilibrated system of actions for a Cosserat continuum, and this same equation coupled with the constitutive equations (9-21) provides the corresponding weak form of the equilibrium problem.

10. Second-gradient continua

A second-gradient continuum is a continuum with microstructure whose unique order parameter is the displacement gradient ∇u [Toupin 1962; Mindlin 1964; Germain 1973a]. See also [Forte and Vianello 1988; Noll and Virga 1990; Dell'Isola and Seppecher 1997; Podio-Guidugli and Vianello 2010]. The corresponding virtual velocity is ∇v , and the external power has the form

$$P_{\text{ext}}(\Pi, v) = \int_{\Pi} (b \cdot v + B \cdot \nabla v) dV + \int_{\partial^* \Pi} (s \cdot v + S \cdot \nabla v) dA. \quad (10-1)$$

If the second-order tensor field S is the surface density of a bounded Cauchy flux, the tensorial version²⁸ of Theorems 4.3 and 4.4 ensures the existence of a third-order tensor field \mathbb{T} such that

$$\begin{aligned} S &= \mathbb{T}n, & \text{div } \mathbb{T} + \Phi &= 0, \\ S_{ij} &= \mathbb{T}_{ijk}n_k, & \mathbb{T}_{ijk,k} + \Phi_{ij} &= 0, \end{aligned} \quad (10-2)$$

where Φ is the volume density associated with the Cauchy flux. The internal power, given by the right-hand side of (7-9), now has the form

$$P_{\text{int}}(\Pi, v) = \int_{\Pi} ((T + Z) \cdot \nabla v + \mathbb{T} \cdot \nabla \nabla v) dV, \quad (10-3)$$

where $Z = B - \Phi$ is the gap between the external body microforce B and Φ . The rotational indifference is expressed by condition (6-3)₂, which now implies the

²⁸See, for example, [Del Piero 2009, Appendix].

symmetry of $(T + Z)$:

$$(T + Z)^W = 0. \quad (10-4)$$

Then the generalized deformation associated with the internal force $(T + Z)$ is $\nabla^S v$ instead of ∇v . Moreover, due to the symmetry of $\nabla \nabla v$ with respect to the last two subscripts, only the part of \mathbb{T} symmetric with respect to the last two subscripts, here denoted by $\mathbb{T}^{\times S}$, contributes to the power. Therefore, for a second-gradient continuum the internal forces are the symmetric tensors $(T + Z)$ and $\mathbb{T}^{\times S}$, and $\nabla^S v$ and $\nabla \nabla v$ are the corresponding generalized deformations. For an elastic material, the constitutive equations are

$$T + Z = \hat{F}(\nabla^S v, \nabla \nabla v), \quad \mathbb{T}^{\times S} = \hat{\mathbb{T}}(\nabla^S v, \nabla \nabla v), \quad (10-5)$$

with \hat{F} symmetric, and with $\hat{\mathbb{T}}$ symmetric with respect to the last two subscripts.²⁹

The name *second-order continuum* is due to presence of $\nabla \nabla v$ among the generalized deformations. This presence causes some complication in the formulation of the boundary conditions. Indeed, the displacement gradient at the boundary has a normal and a tangential component, and the tangential component is determined by the values of v at the boundary. Then, boundary conditions of place can be prescribed only to v and to the normal component of ∇v .

The boundary conditions are a part of the strong formulation of the equilibrium problem. For a three-dimensional body Ω , at the boundary $\partial^* \Omega$ take an orthonormal local reference frame (e^α, e^n) , where e^α , $\alpha \in \{1, 2\}$, are tangent vectors, and e^n is the exterior normal n . After decomposing the product $S \cdot \nabla v$ into a sum of normal and tangential parts, the Gauss–Green formula applied to $\partial^* \Omega$ yields

$$\begin{aligned} \int_{\partial^* \Omega} S \cdot \nabla v \, dA &= \int_{\partial^* \Omega} (S_{in} v_{i,n} + S_{i\alpha} v_{i,\alpha}) \, dA \\ &= \int_{\partial^* \Omega} (S_{in} v_{i,n} - S_{i\alpha, \alpha} v_i) \, dA = \int_{\partial^* \Omega} (Sn \cdot \nabla_n v - \operatorname{div}_\alpha S \cdot v) \, dA. \end{aligned} \quad (10-6)$$

In a similar way, a double application of the Gauss–Green formula provides a well-known transformation of the second-gradient term [Toupin 1962; Mindlin 1964]:

$$\begin{aligned} \int_{\Omega} \mathbb{T} \cdot \nabla \nabla v \, dV &= \int_{\Omega} \mathbb{T}_{ijk}^{\times S} v_{i,jk} \, dV = - \int_{\Omega} \mathbb{T}_{ijk,k}^{\times S} v_{i,j} \, dV + \int_{\partial^* \Omega} \mathbb{T}_{ijn}^{\times S} v_{i,j} \, dA \\ &= \int_{\Omega} \mathbb{T}_{ijk,kj}^{\times S} v_i \, dV + \int_{\partial^* \Omega} (\mathbb{T}_{inn}^{\times S} v_{i,n} + \mathbb{T}_{i\alpha k}^{\times S} n_k v_{i,\alpha}) - \mathbb{T}_{ink,k}^{\times S} v_i \, dA \\ &= \int_{\Omega} \mathbb{T}_{ijk,kj}^{\times S} v_i \, dV + \int_{\partial^* \Omega} (\mathbb{T}_{inn}^{\times S} v_{i,n} - (\mathbb{T}_{i\alpha n, \alpha}^{\times S} + \mathbb{T}_{ink,k}^{\times S}) v_i) \, dA. \end{aligned} \quad (10-7)$$

²⁹In particular, the constitutive equations are independent of $\nabla^W v$. See [Grioli 1960, Equation 19], and [Toupin 1962, Equations 5.1–5.3].

By the symmetry of $\mathbb{T}^{\times S}$,

$$\begin{aligned}\mathbb{T}_{i\alpha n, \alpha}^{\times S} &= \mathbb{T}_{i n \alpha, \alpha}^{\times S} = (\operatorname{div}_\alpha(\mathbb{T}^{\times S} n))_i, \\ \mathbb{T}_{i n k, k}^{\times S} &= \mathbb{T}_{i n \alpha, \alpha}^{\times S} + \mathbb{T}_{i n n, n}^{\times S} = (\operatorname{div}_\alpha(\mathbb{T}^{\times S} n))_i + (\nabla_n(\mathbb{T}^{\times S} n n))_i.\end{aligned}$$

Therefore,

$$\begin{aligned}\int_{\Omega} \mathbb{T} \cdot \nabla \nabla v \, dV &= \int_{\Omega} \operatorname{div} \operatorname{div} \mathbb{T}^{\times S} \cdot v \, dV + \int_{\partial^* \Omega} \mathbb{T}^{\times S} n n \cdot \nabla_n v \, dA \\ &\quad - \int_{\partial^* \Omega} (2 \operatorname{div}_\alpha(\mathbb{T}^{\times S} n) + \nabla_n(\mathbb{T}^{\times S} n n)) \cdot v \, dA.\end{aligned}\quad (10-8)$$

After the transformation

$$\int_{\Omega} B \cdot \nabla v \, dV = - \int_{\Omega} \operatorname{div} B \cdot v \, dV + \int_{\partial^* \Omega} B n \cdot v \, dA, \quad (10-9)$$

and a similar transformation for $(T + Z)$, the equation of virtual power eventually takes the form

$$\begin{aligned}\int_{\Omega} (b - \operatorname{div} B) \cdot v \, dV &+ \int_{\partial^* \Omega} (S n \cdot \nabla_n v + (B n + s - \operatorname{div}_\alpha S) \cdot v) \, dA \\ &= \int_{\Omega} (\operatorname{div} \operatorname{div} \mathbb{T}^{\times S} - \operatorname{div}(T + Z)) \cdot v \, dV + \int_{\partial^* \Omega} \mathbb{T}^{\times S} n n \cdot \nabla_n v \, dA \\ &\quad + \int_{\partial^* \Omega} ((T + Z) n - 2 \operatorname{div}_\alpha(\mathbb{T}^{\times S} n) - \nabla_n(\mathbb{T}^{\times S} n n)) \cdot v \, dA.\end{aligned}\quad (10-10)$$

From the arbitrariness of v , the equilibrium equation

$$\operatorname{div} \operatorname{div} \mathbb{T}^{\times S} - \operatorname{div}(T + Z) = b - \operatorname{div} B, \quad (10-11)$$

at the interior points, and the conditions

$$\begin{aligned}(\mathbb{T}^{\times S} n) n - S n &\cdot \nabla_n v = 0, \\ ((T + Z) n - 2 \operatorname{div}_\alpha(\mathbb{T}^{\times S} n) - \nabla_n((\mathbb{T}^{\times S} n) n) - B n - s + \operatorname{div}_\alpha S) \cdot v &= 0,\end{aligned}\quad (10-12)$$

at the boundary, are deduced. The latter provide the desired forms of the boundary conditions of traction

$$\begin{aligned}(\mathbb{T}^{\times S} n) n &= S n, \\ (T + Z) n - 2 \operatorname{div}_\alpha(\mathbb{T}^{\times S} n) - \nabla_n((\mathbb{T}^{\times S} n) n) &= B n + s - \operatorname{div}_\alpha S,\end{aligned}\quad (10-13)$$

on the portion of the boundary on which the values of the contact actions S and s are prescribed.³⁰

³⁰These are the equations in [Mindlin 1964], in the improved version of [Bleustein 1967], plus the simplification (10-8) due to the symmetry of $\mathbb{T}^{\times S}$. An interesting interpretation of the boundary conditions in terms of *orthofibers* is given in [Froio et al. 2010].

The operator $(\operatorname{div}_\alpha)$, obtained in (10-6) and (10-7) when applying the Gauss–Green formula to $\partial^*\Omega$, must be interpreted in the distributional sense. Then, if the boundary $\partial^*\Omega$ has an *edge line*, that is, a line at which the normal is discontinuous, the terms $\operatorname{div}_\alpha S$ in (10-6) and $\operatorname{div}_\alpha(\mathbb{T}^{\times S}n)$ in (10-8) include singularities, called *edge forces*, represented by forces per unit length applied to the edge line.³¹

In (10-6), the power of the *hypertractions* S is represented as the sum of the powers of two ordinary tractions, (Sn) and $(\operatorname{div}_\alpha S)$, and the latter has singularities at points at which the normal is discontinuous. Some authors believe that the presence of singularities requires a reformulation of Theorems 4.3 and 4.4. This does not seem to be the case, as long as the field S itself is not singular, that is, as long as the Cauchy flux Q^α is absolutely continuous with respect to the area measure. Indeed, in this case the tensorial versions of Theorems 4.3 and 4.4 apply. The singularities are merely apparent, because they originate from the representation of the power in a discontinuous local basis.³²

On the contrary, more regular regions and generalized versions of Noll’s and Cauchy’s theorems become necessary when the external actions involve singular measures. In spite of some valuable progress,³³ the construction of a comprehensive, self-consistent theory of higher-order continua in the presence of singular measures is still an open problem.

11. Continua with latent microstructure

A continuum with latent microstructure is a continuum subject to internal constraints relating the order parameters to the macroscopic deformation [Capriz 1985; 1989]. By effect of the constraint, the internal forces decompose into the sum of an *active part* and a *reactive part*. The latter does not appear in the constitutive equations or in the equilibrium equations.

³¹ Similarly, in a third-gradient continuum, concentrated forces, called *wedge forces*, appear at vertices, and higher-order terms appear in higher-gradient continua. See [Noll and Virga 1988; Di Carlo and Tatone 2001; Podio-Guidugli and Vianello 2010; Dell’Isola et al. 2011]. A characterization of the power of a n -th gradient continuum based on the concept of *diffused subbody* was proposed in [Degiovanni et al. 2007].

³² As stated in [Noll and Virga 1990], “edge interactions should not be confused with external actions concentrated along curves”. The problems caused by writing the power equation in terms of tangential and normal components have a long history. They were perhaps met for the first time in the theory of the bending of plates. The determination of the boundary conditions for this problem kept scientists of the caliber of Poisson, Lagrange, Kirchhoff, and Kelvin busy for a good part of the nineteenth century. For a history of the problem see [Timoshenko 1953].

³³ The problem of the regularity of regions was posed in [Noll and Virga 1990]. *Sets with curvature measure* have been introduced by [Degiovanni et al. 2006]. For extensions of Theorems 4.3 and 4.4 in the presence of singular measures see [Dell’Isola and Seppecher 1997; Marzocchi and Musesti 2003; Degiovanni et al. 2006; Dell’Isola et al. 2011].

An example is the second-gradient continuum described in the preceding section. It has a single tensorial order parameter, whose virtual velocity V^α is subject to the constraint

$$V^\alpha = \nabla v. \quad (11-1)$$

By (10-3), the internal forces are $(T + Z)$ and \mathbb{T} , and the active parts are $(T + Z)^S$ and $\mathbb{T}^{\times S}$.

A second example is given by the *Cauchy–Born hypothesis*, by which the orientations of the directors d^α are forced to follow the macroscopic deformation. That is, their variations v^α must satisfy the internal constraint³⁴

$$v^\alpha = \nabla v d^\alpha. \quad (11-2)$$

In this case, the external power (7-1) takes the form (with α summed)

$$P_{\text{ext}}(\Pi, v) = \int_{\Pi} (b \cdot v + (\beta^\alpha \otimes d^\alpha) \cdot \nabla v) dV + \int_{\partial^* \Pi} (s \cdot v + (\sigma^\alpha \otimes d^\alpha) \cdot \nabla v) dA.$$

This is a special case of (10-1), with

$$B = \beta^\alpha \otimes d^\alpha, \quad S = \sigma^\alpha \otimes d^\alpha. \quad (11-3)$$

The internal power is

$$P_{\text{int}}(\Pi, v) = \int_{\Pi} ((T + \Sigma^\alpha \nabla^T d^\alpha + \zeta^\alpha \otimes d^\alpha) \cdot \nabla v + (\Sigma^\alpha \otimes d^\alpha) \cdot \nabla \nabla v) dV, \quad (11-4)$$

with ζ^α as in (7-5)₂. This is a special case of (10-3), with

$$Z = \Sigma^\alpha \nabla^T d^\alpha + \zeta^\alpha \otimes d^\alpha, \quad \mathbb{T} = \Sigma^\alpha \otimes d^\alpha. \quad (11-5)$$

Thus, a micropolar continuum obeying the Cauchy–Born hypothesis is a second-gradient continuum with particular forms for B , S , Z , and \mathbb{T} .

Another special case is the *Cosserat continuum with constrained rotation* [Toupin 1964]. For this continuum, the virtual velocities v^α are subject to the internal constraint

$$v^\alpha = \nabla^W v d^\alpha. \quad (11-6)$$

By (B-4) and (B-8), this constraint can be put in the equivalent form $v^\alpha = \frac{1}{2} \text{curl } v \times d^\alpha$. Comparing with (9-8), we see that the internal constraint reduces to

$$\omega = \frac{1}{2} \text{curl } v. \quad (11-7)$$

³⁴If the directors d^α form a basis for the underlying space and if d_α is the dual basis, this is a special case of (11-1), with $V^\alpha = v^\alpha \otimes d_\alpha$.

That is, the rotations ω of all directors coincide with the rotation $\frac{1}{2} \operatorname{curl} v$ in the macroscopic deformation. The external power (9-12) reduces to

$$P_{\text{ext}}(\Pi, v) = \int_{\Pi} (b \cdot v + \frac{1}{2} c \cdot \operatorname{curl} v) dV + \int_{\partial^* \Pi} (s \cdot v + \frac{1}{2} m \cdot \operatorname{curl} v) dA, \quad (11-8)$$

and the internal power (9-20) reduces to

$$P_{\text{int}}(\Pi, v) = \int_{\Pi} (T^S \cdot \nabla^S v + \frac{1}{2} M \cdot \nabla \operatorname{curl} v) dV. \quad (11-9)$$

Therefore, the generalized deformations corresponding to the internal forces T^S and M are $\nabla^S v$ and $\frac{1}{2} \nabla \operatorname{curl} v$, respectively. The constitutive equations (9-21) become

$$T^S = \hat{T}^S(\nabla^S v, \frac{1}{2} \nabla \operatorname{curl} v), \quad M = \hat{M}(\nabla^S v, \frac{1}{2} \nabla \operatorname{curl} v). \quad (11-10)$$

This is still a second-order continuum. Indeed, by (B-8),

$$\frac{1}{2} M \cdot \operatorname{curl} v = \frac{1}{2} M_{ij} e_{ihk} v_{k,hj} = \mathbb{T} \cdot \nabla \nabla v, \quad (11-11)$$

with \mathbb{T} the third-order tensor

$$\mathbb{T}_{khj} = \frac{1}{2} M_{ij} e_{ihk}. \quad (11-12)$$

Note that \mathbb{T} is skew-symmetric with respect to the first two subscripts. Thus \mathbb{T} has nine independent components, as many as the couple stress tensor M . For the internal forces T , ζ , and M in (9-15), the active parts are T^S , 0, and M , and the reactive parts are T^W , ζ , and 0, respectively. The latter do not appear in (11-9) and (11-10).

Appendix A: Proof of Theorem 4.3

The proof is divided into four steps.

Step 1. For simplicity, write B_r in place of $B_r(x)$. Consider the definition (4-2) for the set $\Pi \cap B_r$:

$$F(\Pi \cap B_r) + Q(\partial^*(\Pi \cap B_r)) = 0.$$

By Proposition 3.2, the set $\partial^*(\Pi \cap B_r)$ admits the decomposition (3-8):

$$\partial^*(\Pi \cap B_r) = (\Pi \cap \partial^* B_r)^* \curlywedge (\partial^* \Pi \cap B_r)^*.$$

Then, by the additivity property (3-10),

$$Q(\partial^*(\Pi \cap B_r)) = Q((\Pi \cap \partial^* B_r)^*) + Q((\partial^* \Pi \cap B_r)^*),$$

and the pseudobalance equation reduces to

$$F(\Pi \cap B_r) + Q((\Pi \cap \partial^* B_r)^*) + Q((\partial^* \Pi \cap B_r)^*) = 0. \quad (\text{A-1})$$

Step 2. Let us prove that

$$\lim_{r \rightarrow 0} \frac{F(\Pi \cap B_r)}{A(\partial^* B_r)} = 0. \quad (\text{A-2})$$

By the property (4-9) of the bounded Cauchy fluxes, there is a positive function $h \in L^1(\Omega, \mathbb{R})$ such that

$$|F(\Pi \cap B_r)| = |Q(\partial^*(\Pi \cap B_r))| \leq \int_{\Pi \cap B_r} h(x) dV.$$

Therefore,

$$\lim_{r \rightarrow 0} \left| \frac{F(\Pi \cap B_r)}{A(\partial^* B_r)} \right| \leq \lim_{r \rightarrow 0} \frac{\int_{\Pi \cap B_r} h(x) dV}{V(\Pi \cap B_r)} \frac{V(\Pi \cap B_r)}{A(\partial^* B_r)}.$$

The first term on the right converges to a finite value V -almost everywhere, by the Lebesgue–Besicovitch differentiation theorem (see, e.g., [Evans and Gariepy 1992]), and the second term converges to zero, because the volume of B_r goes to zero faster than the area. Then, (A-2) follows.

Step 3. Let us prove that

$$\lim_{r \rightarrow 0} \frac{Q((\partial^* B_r \cap \Pi)^*)}{A(\partial^* B_r)} = \lim_{r \rightarrow 0} \frac{Q((\partial^* B_r \cap H)^*)}{A(\partial^* B_r)}, \quad (\text{A-3})$$

where $H = H(x, n)$ is the half-space with x as a boundary point and with exterior normal n . From the identity

$$\Pi = (\Pi \cap H) \vee (\Pi \cap H^c)$$

it follows that

$$\begin{aligned} (\partial^* B_r \cap \Pi)^* &= (\partial^* B_r \cap (\Pi \cap H))^* \vee (\partial^* B_r \cap (\Pi \cap H^c))^*, \\ (\partial^* B_r \cap H)^* &= (\partial^* B_r \cap (H \cap \Pi))^* \vee (\partial^* B_r \cap (H \cap \Pi^c))^*. \end{aligned}$$

Then it is sufficient to prove that

$$\lim_{r \rightarrow 0} \frac{Q((\partial^* B_r \cap \Pi \cap H^c)^*)}{A(\partial^* B_r)} = 0, \quad \lim_{r \rightarrow 0} \frac{Q((\partial^* B_r \cap H \cap \Pi^c)^*)}{A(\partial^* B_r)} = 0. \quad (\text{A-4})$$

Since $H^c = H(x, -n)$, from the definition of the measure-theoretic normal we have

$$\lim_{r \rightarrow 0} \frac{V(B_r \cap \Pi \cap H^c)}{V(B_r)} = 0. \quad (\text{A-5})$$

On the other hand, by the coarea formula [Ziemer 1983, Equation (8)]

$$V(B_r \cap \Pi \cap H^c) = \int_0^r A(\partial^* B_\eta \cap \Pi \cap H^c) d\eta,$$

that is, the map $r \mapsto V(B_r \cap \Pi \cap H^c)$ is differentiable, and

$$\frac{d}{dr} V(B_r \cap \Pi \cap H^c) = A(\partial^* B_r \cap \Pi \cap H^c) \quad (\text{A-6})$$

for almost every r , again by the Lebesgue–Besicovitch theorem. (The same holds for the identity next to (A-7) below.) Since $V(B_r) = O(r^N)$, from (A-5) it follows that $V(B_r \cap \Pi \cap H^c) = o(r^N)$, and from (A-6) it follows that $A(\partial^* B_r \cap \Pi \cap H^c) = o(r^{N-1})$. Because $A(\partial^* B_r) = O(r^{N-1})$, we conclude that

$$\lim_{r \rightarrow 0} \frac{A(\partial^* B_r \cap \Pi \cap H^c)}{A(\partial^* B_r)} = 0. \quad (\text{A-7})$$

In the identity

$$\lim_{r \rightarrow 0} \frac{Q((\partial^* B_r \cap \Pi \cap H^c)^*)}{A(\partial^* B_r)} = \lim_{r \rightarrow 0} \frac{Q((\partial^* B_r \cap \Pi \cap H^c)^*)}{A((\partial^* B_r \cap \Pi \cap H^c)^*)} \lim_{r \rightarrow 0} \frac{A((\partial^* B_r \cap \Pi \cap H^c)^*)}{A(\partial^* B_r)},$$

by the absolute continuity of Q , the first limit on the right exists and is finite for A -almost every x in Ω . The second limit is zero by (A-7), because a subsurface differs from the corresponding normalized surface at most by a set of area zero. Then (A-4)₁ follows. Equation (A-4)₂ is proved in the same way.

Step 4. From (A-1), (A-2), and (A-3) it follows that

$$\lim_{r \rightarrow 0} \frac{Q((\partial^* \Pi \cap B_r)^*)}{A(\partial^* B_r)} = \lim_{r \rightarrow 0} \frac{Q((\partial^* H \cap B_r)^*)}{A(\partial^* B_r)}. \quad (\text{A-8})$$

If the first limit exists for some Π , it also exists for H and, by consequence, it exists for any other Π' with normal n at x . On the other hand,

$$\lim_{r \rightarrow 0} \frac{Q((\partial^* \Pi \cap B_r)^*)}{A(\partial^* B_r)} = \lim_{r \rightarrow 0} \frac{Q((\partial^* \Pi \cap B_r)^*)}{A((\partial^* \Pi \cap B_r)^*)} \lim_{r \rightarrow 0} \frac{A((\partial^* \Pi \cap B_r)^*)}{A(\partial^* B_r)}.$$

At A -almost every x on $\partial^* \Pi$, the first limit on the right is equal to $s(x, \partial^* \Pi)$, and the second limit is equal to one [Ziemer 1983, Equation (5)]. By (A-8), the same conclusion holds with Π replaced by H . This proves that

$$s(x, \partial^* \Pi) = s(x, \partial^* H) \quad (\text{A-9})$$

at all points $x \in \partial^* \Pi$ at which the limit $s(x, \partial^* \Pi)$ exists, that is, A -almost everywhere on $\partial^* \Pi$.

If x is one of such points and if Π' is another surface such that $x \in \partial^* \Pi'$ and n is the normal at x , in the same way as above it can be proved that

$$s(x, \partial^* \Pi') = s(x, \partial^* H). \quad (\text{A-10})$$

Then it is possible to denote by $s(x, n)$ the common value of all $s(x, \partial^* \Pi')$, and (4-13) follows from (A-9) and (A-10). \square

Appendix B: The cross product of a vector by a tensor

The cross product of a vector w by a second-order tensor A is the second-order tensor $(w \times A)$ such that³⁵

$$(w \times A)v = w \times (Av) \quad (\text{B-1})$$

for all vectors v . In components,

$$(w \times A)_{ij} = e_{ihk} w_h A_{kj}. \quad (\text{B-2})$$

In particular, $w \times I$ is the second-order tensor such that

$$(w \times I)v = w \times v \quad (\text{B-3})$$

for all v . By definition, $(w \times I)$ is the skew-symmetric tensor associated with w . In components, for $W = w \times I$ the relations

$$W_{ij} = e_{ikj} w_k, \quad w_i = \frac{1}{2} e_{jik} W_{jk}, \quad (\text{B-4})$$

hold. In particular, let V and W be the skew-symmetric tensors associated with v and w , respectively. Then, by (B-1),

$$2w \cdot v = e_{jik} W_{jk} v_i = -(v \times W)_{ii} = -I \cdot (v \times W), \quad (\text{B-5})$$

and, by (B-1) and (B-3),

$$v \times W = (v \times I)W = VW. \quad (\text{B-6})$$

Then, by the skew-symmetry of V and W ,

$$2w \cdot v = -I \cdot VW = V \cdot W. \quad (\text{B-7})$$

Finally, consider the curl of a vector field v

$$(\text{curl } v)_h = e_{hsr} v_{r,s}.$$

By (B-2),

$$(\text{curl } v \times I)_{ij} = e_{ihk} e_{hsr} v_{r,s} \delta_{kj} = v_{i,j} - v_{j,i} = 2(\nabla^W v)_{ij}, \quad (\text{B-8})$$

that is, $2\nabla^W v$ is the skew-symmetric tensor associated with $\text{curl } v$.

³⁵This definition is modified from [Antman and Osborn 1979].

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GIANPIETRO DEL PIERO: dlpgpt@unife.it

Dipartimento di Ingegneria, Università di Ferrara, via Saragat 1, 44100 Ferrara, Italy



