

Notation and Basic Concepts

This appendix is meant to introduce the reader to the notation employed throughout the book and to illustrate some basic concepts in possibly a less formal style, though with the same rigor as in the main text. Only on occasion does it serve the purpose of a repository of technical results to be invoked wherever the need arises, since we strove to make the text as self-contained as possible, preferring moderate digressions to excessive referencing.

A.1 Points, Vectors, and Tensors

In this book, we consider fluids in the three-dimensional Euclidean space \mathcal{E} . The basic elements of this space are its *points*.¹ Associated with \mathcal{E} is the linear space of *translations* \mathcal{U} that are mappings of \mathcal{E} into itself. The elements of $\mathbf{v} \in \mathcal{U}$ are called *vectors*:

$$\mathbf{v} : \mathcal{E} \rightarrow \mathcal{E}, \quad p \mapsto \mathbf{v}(p).$$

For any two points $p, q \in \mathcal{E}$ there is exactly one vector \mathbf{v} that takes p into q . We denote it by $\mathbf{v} = q - p$ and write $\mathbf{v}(p) = q$, or sometimes $q = p + \mathbf{v}$. We note that while the difference of two points is a well-defined unique vector, the sum of two points is *not* defined. If an origin $o \in \mathcal{E}$ is chosen, points can be identified by their *position vectors* relative to that origin, $\mathbf{p} = p - o$. Care needs to be taken not to confuse position vectors with ordinary vectors. A given point has different position vectors with respect to different origins. A vector $\mathbf{v} = p - q$, however, is independent of the choice of origin. By contrast, $\mathbf{p} = p - o$ and $\mathbf{p}^* = p - o^*$ are different position vectors of the same point p with respect to different origins o and o^* . We also write \mathbf{v}^2 for $\mathbf{v} \cdot \mathbf{v}$.

The *inner product* of two vectors \mathbf{u} and \mathbf{v} is denoted by $\mathbf{u} \cdot \mathbf{v}$, and the *cross product* by $\mathbf{u} \times \mathbf{v}$. The *mixed product* of three vectors \mathbf{u} , \mathbf{v} , and \mathbf{w} is the scalar

¹ For simplicity, we identify material points with their positions in Euclidean space, even though they may be richer in mechanical structure than a mere geometric point can suggest.

$$\mathbf{u} \cdot \mathbf{v} \times \mathbf{w}.$$

It is invariant under cyclic permutations of the three vectors, that is,

$$\mathbf{u} \cdot \mathbf{v} \times \mathbf{w} = \mathbf{v} \cdot \mathbf{w} \times \mathbf{u} = \mathbf{w} \cdot \mathbf{u} \times \mathbf{v} \quad \forall \mathbf{u}, \mathbf{v}, \mathbf{w} \in \mathcal{U}.$$

Two vectors \mathbf{u} and \mathbf{v} are *orthogonal* if $\mathbf{u} \cdot \mathbf{v} = 0$. The length of a vector \mathbf{v} is given by $v = |\mathbf{v}| = \sqrt{\mathbf{v} \cdot \mathbf{v}}$.

A *tensor* of rank two, usually simply called a tensor, is an element of the linear space $L(\mathcal{U})$ of all linear mappings of \mathcal{U} into itself:

$$\mathbf{T} : \mathcal{U} \rightarrow \mathcal{U}, \quad \mathbf{v} \mapsto \mathbf{T}(\mathbf{v}).$$

We write $\mathbf{T}\mathbf{v}$ for $\mathbf{T}(\mathbf{v})$. The *transpose* \mathbf{T}^\top of a tensor \mathbf{T} is defined via

$$\mathbf{u} \cdot \mathbf{T}^\top \mathbf{v} = \mathbf{v} \cdot \mathbf{T}\mathbf{u} \quad \text{for all } \mathbf{u}, \mathbf{v} \in \mathcal{U}.$$

We say that a tensor \mathbf{T} is *symmetric* if $\mathbf{T} = \mathbf{T}^\top$ and *skew-symmetric* if $\mathbf{T} = -\mathbf{T}^\top$. All symmetric tensors constitute a linear subspace of $L(\mathcal{U})$, which we denote by $\text{Sym}(\mathcal{U})$. Likewise, all skew-symmetric tensors constitute a linear subspace of $L(\mathcal{U})$, which we denote by $\text{Skw}(\mathcal{U})$. Given any tensor \mathbf{T} , it can be uniquely written as the sum of a tensor in $\text{Sym}(\mathcal{U})$ and a tensor in $\text{Skw}(\mathcal{U})$:

$$\mathbf{T} = \frac{1}{2}(\mathbf{T} + \mathbf{T}^\top) + \frac{1}{2}(\mathbf{T} - \mathbf{T}^\top).$$

We set

$$\text{sym}(\mathbf{T}) := \frac{1}{2}(\mathbf{T} + \mathbf{T}^\top) \quad \text{and} \quad \text{skw}(\mathbf{T}) := \frac{1}{2}(\mathbf{T} - \mathbf{T}^\top),$$

and we call the former the *symmetric part* of \mathbf{T} and the latter the *skew-symmetric part* of \mathbf{T} . The identity tensor \mathbf{I} is defined by $\mathbf{I}\mathbf{v} := \mathbf{v}$ for all $\mathbf{v} \in \mathcal{U}$, and it is clearly symmetric. The trace and determinant of a tensor \mathbf{T} are denoted by $\text{tr } \mathbf{T}$ and $\det \mathbf{T}$. It is sometimes convenient to denote in a concise manner the symmetric, traceless part of a tensor \mathbf{T} ; we shall employ the following notation:

$$\overline{\mathbf{T}} := \text{sym}(\mathbf{T}) - \frac{1}{3}(\text{tr } \mathbf{T})\mathbf{I}.$$

For a tensor $\mathbf{L} \in L(\mathcal{U})$, we say that $\lambda \in \mathbb{R}$ and $\mathbf{e} \in S^2$ are an *eigenvalue* and the corresponding (normalized) *eigenvector* of \mathbf{L} if

$$\mathbf{L}\mathbf{e} = \lambda\mathbf{e}.$$

Symmetric tensors are peculiar in regard to eigenvalues and eigenvectors. The spectral theorem states that for every tensor $\mathbf{S} \in \text{Sym}(\mathcal{U})$ there is a basis $(\mathbf{e}_1, \mathbf{e}_2, \mathbf{e}_3)$ of \mathcal{U} such that

$$\mathbf{S} = \lambda_1 \mathbf{e}_1 \otimes \mathbf{e}_1 + \lambda_2 \mathbf{e}_2 \otimes \mathbf{e}_2 + \lambda_3 \mathbf{e}_3 \otimes \mathbf{e}_3.$$

Thus, clearly, \mathbf{e}_1 , \mathbf{e}_2 , and \mathbf{e}_3 are eigenvectors of \mathbf{S} , and λ_1 , λ_2 , and λ_3 are the corresponding eigenvalues. Given any skew-symmetric tensor \mathbf{W} in $\text{Skw}(\mathcal{U})$, there is precisely one vector $\mathbf{w} \in \mathcal{U}$ such that

$$\mathbf{W}\mathbf{v} = \mathbf{w} \times \mathbf{v} \quad \forall \mathbf{v} \in \mathcal{U}. \tag{A.1}$$

We say that \mathbf{w} is the *axial vector* associated with \mathbf{W} . The linear mapping established by (A.1) between the spaces $\text{Skw}(\mathcal{U})$ and \mathcal{U} is indeed invertible. The axial vector \mathbf{w} of \mathbf{W} belongs to the *null space* of \mathbf{W} , that is, it is a (nonnormalized) eigenvector of \mathbf{W} with zero eigenvalue. Actually, all (nonnormalized) eigenvectors of \mathbf{W} are parallel to \mathbf{w} , which amounts to saying that the null space of \mathbf{W} is one-dimensional. For the special skew-symmetric tensor \mathbf{W} in the form

$$\mathbf{W} = \mathbf{b} \otimes \mathbf{a} - \mathbf{a} \otimes \mathbf{b},$$

the associated axial vector \mathbf{w} is

$$\mathbf{w} = \mathbf{a} \times \mathbf{b}.$$

The *dyadic* product $\mathbf{u} \otimes \mathbf{v}$ of two vectors \mathbf{u} and \mathbf{v} is a tensor that is defined by its action on an arbitrary third vector \mathbf{w} :

$$(\mathbf{u} \otimes \mathbf{v})\mathbf{w} := (\mathbf{v} \cdot \mathbf{w})\mathbf{u} \quad \text{for all } \mathbf{w} \in \mathcal{U}.$$

The composition of two tensors $\mathbf{C} = \mathbf{A}\mathbf{B}$ is defined via

$$\mathbf{C}\mathbf{v} = \mathbf{A}\mathbf{B}\mathbf{v} \quad \text{for all } \mathbf{v} \in \mathcal{U}.$$

An inner product between two tensors \mathbf{S} and \mathbf{T} is defined by

$$\mathbf{S} \cdot \mathbf{T} := \text{tr } \mathbf{S}\mathbf{T}^\top. \tag{A.2}$$

With it, we have $\text{tr } \mathbf{T} = \mathbf{T} \cdot \mathbf{I}$ for all tensors \mathbf{T} . The norm of a tensor \mathbf{T} is $|\mathbf{T}| = \sqrt{\mathbf{T} \cdot \mathbf{T}}$. In particular, $\mathbf{I} \cdot \mathbf{I} = \text{tr } \mathbf{I} = 3$.

The inner product in $L(\mathcal{U})$ defined by (A.2) enjoys the following properties:

$$\mathbf{S} \cdot \mathbf{T} = \mathbf{S}^\top \cdot \mathbf{T}^\top \quad \forall \mathbf{S}, \mathbf{T} \in L(\mathcal{U}),$$

$$\mathbf{A}\mathbf{B} \cdot \mathbf{C} = \mathbf{A} \cdot \mathbf{C}\mathbf{B}^\top = \mathbf{B} \cdot \mathbf{A}^\top\mathbf{C} \quad \forall \mathbf{A}, \mathbf{B}, \mathbf{C} \in L(\mathcal{U}).$$

Moreover, given two skew-symmetric tensors \mathbf{W}_1 and \mathbf{W}_2 with associated axial vectors \mathbf{w}_1 and \mathbf{w}_2 , respectively, the inner product of \mathbf{W}_1 and \mathbf{W}_2 is related to the inner product of \mathbf{w}_1 and \mathbf{w}_2 through the equation

$$\mathbf{W}_1 \cdot \mathbf{W}_2 = 2\mathbf{w}_1 \cdot \mathbf{w}_2.$$

The linear subspaces $\text{Sym}(\mathcal{U})$ and $\text{Skw}(\mathcal{U})$ are orthogonal complements of $L(\mathcal{U})$ with respect to the inner product in (A.2), and so any symmetric tensor is orthogonal to any skew-symmetric tensor.

The *principal invariants* $\hat{I}_i(\mathbf{T})$, $i = 1, 2, 3$, of a tensor $\mathbf{T} \in L(\mathcal{U})$ are defined as the coefficients of the following polynomial in λ :

$$\det(\mathbf{T} + \lambda \mathbf{I}) = \lambda^3 + \hat{I}_1(\mathbf{T})\lambda^2 + \hat{I}_2(\mathbf{T})\lambda + \hat{I}_3(\mathbf{T}).$$

We have that

$$\hat{I}_1(\mathbf{T}) = \text{tr } \mathbf{T}, \quad \hat{I}_2(\mathbf{T}) = \frac{1}{2} [(\text{tr } \mathbf{T})^2 - \text{tr } \mathbf{T}^2], \quad \hat{I}_3(\mathbf{T}) = \det \mathbf{T}.$$

While the principal invariant $\hat{I}_1(\mathbf{T})$ coincides with the invariant $I_1(\mathbf{T}) := \text{tr } \mathbf{T}$ introduced in (1.83), $\hat{I}_2(\mathbf{T})$ and $\hat{I}_3(\mathbf{T})$ are not the same as the corresponding invariants $I_2(\mathbf{T}) := \text{tr } \mathbf{T}^2$ and $I_3(\mathbf{T}) := \text{tr } \mathbf{T}^3$. They are related as follows:

$$\hat{I}_2 = \frac{1}{2} (I_1^2 - I_2), \quad \hat{I}_3 = \frac{1}{3} \left(I_3 - \frac{3}{2} I_1 I_2 + \frac{1}{2} I_1^3 \right).$$

The latter equation in particular follows from the CAYLEY–HAMILTON theorem, which states that every tensor \mathbf{T} obeys the equation

$$\mathbf{T}^3 - \hat{I}_1 \mathbf{T}^2 + \hat{I}_2 \mathbf{T} - \hat{I}_3 \mathbf{I} = \mathbf{0}. \tag{A.3}$$

Equation (A.3) also follows from a more general identity of RIVLIN [281] valid for any triple of tensors $\mathbf{A}, \mathbf{B}, \mathbf{C}$:

$$\begin{aligned} & \mathbf{ABC} + \mathbf{ACB} + \mathbf{BCA} + \mathbf{BAC} + \mathbf{CAB} + \mathbf{CBA} \\ & - (\text{tr } \mathbf{BC} - \text{tr } \mathbf{B} \text{tr } \mathbf{C})\mathbf{A} - (\text{tr } \mathbf{CA} - \text{tr } \mathbf{C} \text{tr } \mathbf{A})\mathbf{B} - (\text{tr } \mathbf{AB} - \text{tr } \mathbf{A} \text{tr } \mathbf{B})\mathbf{C} \\ & - \text{tr } \mathbf{A}(\mathbf{BC} + \mathbf{CB}) - \text{tr } \mathbf{B}(\mathbf{CA} + \mathbf{AC}) - \text{tr } \mathbf{C}(\mathbf{AB} + \mathbf{BA}) \\ & - (\text{tr } \mathbf{A} \text{tr } \mathbf{B} \text{tr } \mathbf{C} - \text{tr } \mathbf{A} \text{tr } \mathbf{BC} - \text{tr } \mathbf{B} \text{tr } \mathbf{CA} \\ & \quad - \text{tr } \mathbf{C} \text{tr } \mathbf{AB} + \text{tr } \mathbf{ABC} + \text{tr } \mathbf{CBA})\mathbf{I} \\ & = \mathbf{0}, \end{aligned} \tag{A.4}$$

by setting $\mathbf{A} = \mathbf{B} = \mathbf{C} = \mathbf{T}$.

For an invertible tensor \mathbf{A} and every tensor \mathbf{C} ,

$$\det(\mathbf{A} + s\mathbf{C}) = (\det \mathbf{A})(1 + \hat{I}_1(\mathbf{A}^{-1}\mathbf{C})s + \hat{I}_2(\mathbf{A}^{-1}\mathbf{C})s^2 + \hat{I}_3(\mathbf{A}^{-1}\mathbf{C})s^3),$$

whence it follows that

$$\left. \frac{d}{ds} \det(\mathbf{A} + s\mathbf{C}) \right|_{s=0} = (\det \mathbf{A})\hat{I}_1(\mathbf{A}^{-1}\mathbf{C}) = \text{tr}[(\det \mathbf{A})\mathbf{A}^{-1}\mathbf{C}]. \tag{A.5}$$

A tensor of rank three is a linear mapping \mathbf{a} from the vector space \mathcal{U} into the space $L(\mathcal{U})$ of second-rank tensors:

$$\mathbf{a} : \mathcal{U} \rightarrow L(\mathcal{U}), \quad v \mapsto \mathbf{a}(v).$$

We write $\mathbf{a}v$ for the second-rank tensor $\mathbf{a}(v)$. More generally, a tensor of rank $n \geq 1$ is a linear mapping that takes a vector into a tensor of order $n - 1$. A continuous mapping from a region \mathfrak{B} of \mathfrak{E} into the space of tensors of rank n that assigns a tensor to every point $p \in \mathfrak{B}$ is called a *tensor field* of rank n .

A.2 Bases and Coordinates

An ordered set of three mutually orthogonal unit vectors $(\mathbf{e}_1, \mathbf{e}_2, \mathbf{e}_3)$ forms a *basis* for \mathcal{U} . We normally choose a *positively oriented* basis, that is, one for which $\mathbf{e}_1 \times \mathbf{e}_2 = \mathbf{e}_3$.² Every vector $\mathbf{v} \in \mathcal{U}$ can be expressed in terms of its *components* $v_i := \mathbf{v} \cdot \mathbf{e}_i$ as

$$\mathbf{v} = \sum_{i=1}^3 v_i \mathbf{e}_i.$$

To simplify notation, we apply the *summation convention*: a term with a repeated index is to be summed over all three values of that index from 1 to 3. Hence, we simply write $\mathbf{v} = v_i \mathbf{e}_i$.

The components of a second-rank tensor are defined as $T_{ij} := \mathbf{e}_i \cdot \mathbf{T} \mathbf{e}_j$. For a dyadic product this implies $(\mathbf{u} \otimes \mathbf{v})_{ij} = u_i v_j$. The components of the identity \mathbf{I} in any basis are $\mathbf{e}_i \cdot \mathbf{I} \mathbf{e}_j = \mathbf{e}_i \cdot \mathbf{e}_j = \delta_{ij}$, with

$$\delta_{ij} := \begin{cases} 1 & \text{if } i = j, \\ 0 & \text{if } i \neq j, \end{cases}$$

the KRONECKER delta. The tensor \mathbf{T} can be represented in terms of its components T_{ij} as

$$\mathbf{T} = T_{ij} \mathbf{e}_i \otimes \mathbf{e}_j.$$

Indeed,

$$\mathbf{e}_i \cdot \mathbf{T} \mathbf{e}_j = \mathbf{e}_i \cdot (T_{ab} \mathbf{e}_a \otimes \mathbf{e}_b) \mathbf{e}_j = (\mathbf{e}_i \cdot \mathbf{e}_a) T_{ab} (\mathbf{e}_b \cdot \mathbf{e}_j) = \delta_{ia} T_{ab} \delta_{bj} = T_{ij}.$$

Thus, if $(\mathbf{e}_1, \mathbf{e}_2, \mathbf{e}_3)$ is a basis of \mathcal{U} , then $(\mathbf{e}_i \otimes \mathbf{e}_j, i, j = 1, 2, 3)$ is a basis of $L(\mathcal{U})$. In general, if v_i are the components of a vector \mathbf{v} in $(\mathbf{e}_1, \mathbf{e}_2, \mathbf{e}_3)$, then $T_{ij} v_j$ are the components of $\mathbf{T} \mathbf{v}$ in the same basis. It follows immediately from the definition of the transpose tensor that $(\mathbf{T}^T)_{ij} = T_{ji}$. The trace of a tensor \mathbf{T} is given by $\text{tr } \mathbf{T} = T_{ii}$, and the components of the product $\mathbf{C} = \mathbf{A} \mathbf{B}$ of two tensors are given by $C_{ik} = A_{ij} B_{jk}$. The inner product of two tensors is thus $\text{tr } \mathbf{S} \mathbf{T}^T = S_{ij} T_{ij}$. Specifically for dyadic products, we have

$$(\mathbf{u} \otimes \mathbf{v}) \cdot \mathbf{I} = \text{tr}(\mathbf{u} \otimes \mathbf{v}) = \mathbf{v} \cdot \mathbf{u}$$

and

$$(\mathbf{s} \otimes \mathbf{t}) \cdot (\mathbf{u} \otimes \mathbf{v}) = (\mathbf{s} \cdot \mathbf{u})(\mathbf{t} \cdot \mathbf{v}).$$

For the components of a vector product we have

$$\mathbf{e}_i \cdot (\mathbf{u} \times \mathbf{v}) = \epsilon_{ijk} u_j v_k,$$

where

$$\epsilon_{ijk} := \begin{cases} 1 & \text{if } (i, j, k) \text{ is an even permutation of } (1, 2, 3), \\ -1 & \text{if } (i, j, k) \text{ is an odd permutation of } (1, 2, 3), \\ 0 & \text{in all other cases,} \end{cases}$$

is the RICCI alternator.

² A *negatively oriented* basis $(\mathbf{e}_1, \mathbf{e}_2, \mathbf{e}_3)$ is one for which $\mathbf{e}_1 \times \mathbf{e}_2 \cdot \mathbf{e}_3 = -1$. We shall always use positively oriented bases.

A.3 Rotations

An *orthogonal transformation* is a linear transformation that preserves the length of all vectors and their relative angles. Hence, it takes a set of basis vectors $(\mathbf{e}_1, \mathbf{e}_2, \mathbf{e}_3)$ into a new set of basis vectors, say $(\mathbf{e}_1^*, \mathbf{e}_2^*, \mathbf{e}_3^*)$. More generally, given any two vectors \mathbf{u} and \mathbf{v} in \mathcal{U} ,

$$\mathbf{R}\mathbf{u} \cdot \mathbf{R}\mathbf{v} = \mathbf{u} \cdot \mathbf{v},$$

whence it follows that

$$(\mathbf{R}^T \mathbf{R} - \mathbf{I})\mathbf{u} \cdot \mathbf{v} = 0 \quad \forall \mathbf{u}, \mathbf{v} \in \mathcal{U}.$$

This means that $\mathbf{R}^T \mathbf{R} = \mathbf{I}$. It follows that $1 = \det \mathbf{I} = \det(\mathbf{R}^T \mathbf{R}) = (\det \mathbf{R})^2$, and so $\det \mathbf{R} = \pm 1$. Two consecutive orthogonal transformations $\mathbf{R}_1 \mathbf{R}_2$ result in a new orthogonal transformation $\mathbf{R} = \mathbf{R}_1 \mathbf{R}_2$. The set of orthogonal transformations in three-dimensional Euclidean space forms the group $O(3)$.

For any two vectors \mathbf{u} and \mathbf{v} , an orthogonal tensor \mathbf{R} is such that

$$\mathbf{R}\mathbf{u} \times \mathbf{R}\mathbf{v} = (\det \mathbf{R})\mathbf{R}(\mathbf{u} \times \mathbf{v}).$$

A *rotation* is an orthogonal transformation that transforms a positively oriented basis into a positively oriented basis.³ It is an orthogonal transformation $\mathbf{R} \in O(3)$ with $\det \mathbf{R} = +1$. Rotations form the group of *special* orthogonal transformations $SO(3)$.

Both $SO(3)$ and $O(3)$ are proper subgroups of the *unimodular* group $U(3)$ defined by

$$U(3) := \{\mathbf{U} \in L(\mathcal{U}) \mid |\det \mathbf{U}| = 1\}.$$

As proved by BRAUER and NOLL [35, 239], $O(3)$ is the maximal subgroup of $U(3)$, meaning that no subgroup of $U(3)$ exists that is not included in $O(3)$.

A.4 Time Derivatives

The position of a point p in motion is a function of time $p(t)$. The *velocity* \mathbf{v} of the point p is defined as

$$\mathbf{v}(p, t) = \dot{p} = \frac{dp}{dt} = \lim_{\epsilon \rightarrow 0} \frac{p(t + \epsilon) - p(t)}{\epsilon}. \quad (\text{A.6})$$

The field $\mathbf{v}(p, t)$ thus gives the velocity of the point that at time t occupies the position p .

For a scalar quantity $\phi(p, t)$ that depends on time and position we write $\frac{\partial \phi}{\partial t}$ for the *local* time derivative. It is the rate of change of ϕ at the fixed position that p attains at time t . The dependence of ϕ at fixed time on position is given by the gradient $\nabla \phi = \frac{\partial \phi}{\partial p}$. The *material* time derivative is the rate of change of ϕ at the moving

³ Actually, it also transforms a negatively oriented basis into a negatively oriented one.

material point p . We denote it by $\dot{\phi}$, and it is the total time derivative of $\phi(p(t), t)$, $\dot{\phi} = \frac{d\phi}{dt} = \frac{\partial\phi}{\partial p} \frac{dp}{dt} + \frac{\partial\phi}{\partial t}$. With (A.6), we obtain

$$\dot{\phi} = \frac{\partial\phi}{\partial t} + \nabla\phi \cdot \mathbf{v}.$$

Time derivatives of vectors and tensors are defined similarly. We use the convention that

$$(\nabla\mathbf{v})_{ij} = v_{i,j}.$$

For example, the acceleration of a point p is $\mathbf{a} = \dot{\mathbf{v}} = \ddot{\mathbf{p}}$, and we have

$$\dot{\mathbf{v}} = \frac{\partial\mathbf{v}}{\partial t} + (\nabla\mathbf{v})\mathbf{v}.$$

Elaborating on these basic kinematic concepts, in Section 2.1.2 we define the motion of a continuous body.

Gradients of tensors of rank two and higher are defined in a similar way, for example,

$$(\nabla\mathbf{T})_{ijk} = T_{ij,k},$$

so that

$$\dot{\mathbf{T}} = \frac{\partial\mathbf{T}}{\partial t} + (\nabla\mathbf{T})\mathbf{v}.$$

The divergence of a vector field \mathbf{v} is defined by

$$\operatorname{div} \mathbf{v} := \operatorname{tr}(\nabla\mathbf{v}) = v_{i,i}.$$

We define the divergence of a tensor field \mathbf{T} to be the vector $\operatorname{div} \mathbf{T}$ such that

$$\mathbf{a} \cdot \operatorname{div} \mathbf{T} = \operatorname{div}(\mathbf{T}^T \mathbf{a}) \quad \text{for all } \mathbf{a} \in \mathcal{U}.$$

To find an expression for the components of $\operatorname{div} \mathbf{T}$ we first compute

$$\mathbf{T}^T \mathbf{e}_i = T_{ba}(\mathbf{e}_a \otimes \mathbf{e}_b) \mathbf{e}_i = T_{ba}(\mathbf{e}_i \cdot \mathbf{e}_b) \mathbf{e}_a = T_{ba} \delta_{ib} \mathbf{e}_a = T_{ia} \mathbf{e}_a.$$

Now

$$\operatorname{div}(T_{ia} \mathbf{e}_a) = \nabla(T_{ia}) \cdot \mathbf{e}_a = T_{ia,j} \mathbf{e}_j \cdot \mathbf{e}_a = T_{ia,j} \delta_{ja} = T_{ij,j},$$

and so

$$\mathbf{e}_i \cdot \operatorname{div} \mathbf{T} = T_{ij,j}.$$

The divergence of a higher-rank tensor is defined similarly as the contraction of the gradient of that tensor over its last two indices.

A.5 Divergence Theorems

For a smooth vector field $\mathbf{v} : \mathcal{P} \rightarrow \mathcal{U}$ on a fit region⁴ $\mathcal{P} \subset \mathcal{E}$, the divergence theorem states that

$$\int_{\mathcal{P}} \operatorname{div} \mathbf{v} \, dV = \int_{\partial^* \mathcal{P}} \mathbf{v} \cdot \boldsymbol{\nu} \, dA,$$

where $\partial^* \mathcal{P}$ is the *reduced* boundary of \mathcal{P} , and $\boldsymbol{\nu}$ is its outer unit normal.

An immediate consequence of the divergence theorem is the integral-gradient theorem. By applying the divergence theorem to a vector field $\mathbf{v}(p) = f(p)\mathbf{a}$ that is the product of a scalar function $f(p)$ and an arbitrary vector \mathbf{a} uniform in space, one finds that

$$\int_{\mathcal{P}} \nabla f \, dV = \int_{\partial^* \mathcal{P}} f \boldsymbol{\nu} \, dA.$$

Considering the divergence theorem for the vector field $\mathbf{T}^T \mathbf{a}$, where \mathbf{a} is again an arbitrary uniform vector, leads us to the following identities:

$$\int_{\mathcal{P}} \operatorname{div}(\mathbf{T}^T \mathbf{a}) \, dV = \int_{\partial^* \mathcal{P}} \mathbf{T}^T \mathbf{a} \cdot \boldsymbol{\nu} \, dA = \mathbf{a} \cdot \int_{\partial^* \mathcal{P}} \mathbf{T} \boldsymbol{\nu} \, dA =: \mathbf{a} \cdot \int_{\mathcal{P}} \operatorname{div} \mathbf{T} \, dV,$$

the last of which actually defines $\operatorname{div} \mathbf{T}$ in such a way that the divergence theorem holds in the form

$$\int_{\mathcal{P}} \operatorname{div} \mathbf{T} \, dV = \int_{\partial^* \mathcal{P}} \mathbf{T} \boldsymbol{\nu} \, dA.$$

Analogous theorems hold for higher-rank tensors.

⁴ The definition of a *fit region* is given in Section 2.1.1, where also the use of these regions to describe the shapes of a body in continuum mechanics is justified.

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