A

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* $\mathcal{V}$ that are mappings of $\mathcal{E}$ into itself. The elements of $\boldsymbol{v} \in \mathcal{V}$ are called *vectors*:

$$\boldsymbol{v} : \mathcal{E} \to \mathcal{E}, \quad p \mapsto \boldsymbol{v}(p).$$

For any two points $p, q \in \mathcal{E}$ there is exactly one vector $\boldsymbol{v}$ that takes p into q. We denote it by $\boldsymbol{v} = q - p$ and write $\boldsymbol{v}(p) = q$, or sometimes $q = p + \boldsymbol{v}$. 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, $\boldsymbol{p} = p - o$. 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 $\boldsymbol{v} = p - q$, however, is independent of the choice of origin. By contrast, $\boldsymbol{p} = p - o$ and $\boldsymbol{p}^* = p - o^*$ are different position vectors of the same point p with respect to different origins o and o^*. We also write $\boldsymbol{v}^2$ for $\boldsymbol{v} \cdot \boldsymbol{v}$.

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

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

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

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

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

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

$$\mathbf{T} : \mathcal{V} \to \mathcal{V}, \quad \boldsymbol{v} \mapsto \mathbf{T}(\boldsymbol{v}).$$

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

$$\boldsymbol{u} \cdot \mathbf{T}^{\mathsf{T}}\boldsymbol{v} = \boldsymbol{v} \cdot \mathbf{T}\boldsymbol{u} \quad \text{for all } \boldsymbol{u}, \boldsymbol{v} \in \mathcal{V}.$$

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

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

We set

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

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 $\mathbf{I}\boldsymbol{v} := \boldsymbol{v}$ for all $\boldsymbol{v} \in \mathcal{V}$, and it is clearly symmetric. The trace and determinant of a tensor $\mathbf{T}$ are denoted by $\operatorname{tr}\mathbf{T}$ 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:

$$\overset{\sqcap}{\mathbf{T}} := \operatorname{sym}(\mathbf{T}) - \frac{1}{3}(\operatorname{tr}\mathbf{T})\mathbf{I}.$$

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

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

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

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

Thus, clearly, $\boldsymbol{e}_1$, $\boldsymbol{e}_2$, and $\boldsymbol{e}_3$ 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 $\mathsf{Skw}(\mathcal{V})$, there is precisely one vector $\boldsymbol{w} \in \mathcal{V}$ such that

$$\mathbf{W}\boldsymbol{v} = \boldsymbol{w} \times \boldsymbol{v} \qquad \forall\, \boldsymbol{v} \in \mathcal{V}. \tag{A.1}$$

We say that $\boldsymbol{w}$ is the *axial vector* associated with $\mathbf{W}$. The linear mapping established by (A.1) between the spaces $\mathsf{Skw}(\mathcal{V})$ and $\mathcal{V}$ is indeed invertible. The axial vector $\boldsymbol{w}$ of $\mathbf{W}$ belongs 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 $\boldsymbol{w}$, 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

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

the associated axial vector $\boldsymbol{w}$ is

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

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

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

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

$$\mathbf{C}\boldsymbol{v} = \mathbf{AB}\boldsymbol{v} \quad \text{for all } \boldsymbol{v} \in \mathcal{V}.$$

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

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

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

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

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

$$\mathbf{AB} \cdot \mathbf{C} = \mathbf{A} \cdot \mathbf{C}\mathbf{B}^{\mathsf{T}} = \mathbf{B} \cdot \mathbf{A}^{\mathsf{T}}\mathbf{C} \quad \forall\, \mathbf{A}, \mathbf{B}, \mathbf{C} \in \mathsf{L}(\mathcal{V}).$$

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

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

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

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

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

We have that

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

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

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

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

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

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

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

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

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

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

whence it follows that

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

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

$$\mathsf{a} : \mathcal{V} \to \mathsf{L}(\mathcal{V}), \quad \boldsymbol{v} \mapsto \mathsf{a}(\boldsymbol{v}).$$

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

A.2 Bases and Coordinates

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

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

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 $\boldsymbol{v} = v_i \boldsymbol{e}_i$.

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

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

Indeed,

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

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

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

and

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

For the components of a vector product we have

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

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 $(\boldsymbol{e}_1, \boldsymbol{e}_2, \boldsymbol{e}_3)$ is one for which $\boldsymbol{e}_1 \times \boldsymbol{e}_2 \cdot \boldsymbol{e}_3 = -1$. 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 $(\boldsymbol{e}_1, \boldsymbol{e}_2, \boldsymbol{e}_3)$ into a new set of basis vectors, say $(\boldsymbol{e}_1^*, \boldsymbol{e}_2^*, \boldsymbol{e}_3^*)$. More generally, given any two vectors $\boldsymbol{u}$ and $\boldsymbol{v}$ in $\mathcal{V}$,

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

whence it follows that

$$(\mathbf{R}^{\mathsf{T}}\mathbf{R} - \mathbf{I})\boldsymbol{u} \cdot \boldsymbol{v} = 0 \qquad \forall\, \boldsymbol{u},\, \boldsymbol{v}\, \in \mathcal{V}.$$

This means that $\mathbf{R}^{\mathsf{T}}\mathbf{R} = \mathbf{I}$. It follows that $1 = \det\mathbf{I} = \det(\mathbf{R}^{\mathsf{T}}\mathbf{R}) = (\det\mathbf{R})^2$, 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 $\mathsf{O}(3)$.

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

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

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

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

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

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

A.4 Time Derivatives

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

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

The field $\boldsymbol{v}(p,t)$ 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 $\frac{\partial p}{\partial t}$ 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

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

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

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

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

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

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

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

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

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

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

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

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

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

Now

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

and so

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

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 $\boldsymbol{v} : \mathcal{P} \to \mathcal{V}$ on a fit region[4] $\mathcal{P} \subset \mathcal{E}$, the divergence theorem states that

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

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 $\boldsymbol{v}(p) = f(p)\boldsymbol{a}$ that is the product of a scalar function $f(p)$ and an arbitrary vector $\boldsymbol{a}$ 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 $\mathbf{T}^{\mathsf{T}}\boldsymbol{a}$, where $\boldsymbol{a}$ is again an arbitrary uniform vector, leads us to the following identities:

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

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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