

Vector calculus

In Section A.9 of Appendix A we review the algebra of vectors, and in Chapter 1 we considered how to transform one vector into another using a linear operator. In this chapter and the next we discuss the calculus of vectors, i.e. the differentiation and integration both of vectors describing particular bodies, such as the velocity of a particle, and of vector fields, in which a vector is defined as a function of the coordinates throughout some volume (one-, two- or three-dimensional). Since the aim of this chapter is to develop methods for handling multi-dimensional physical situations, we will assume throughout that the functions with which we have to deal have sufficiently amenable mathematical properties, in particular that they are continuous and differentiable.

2.1 Differentiation of vectors

Let us consider a vector $\mathbf{a}$ that is a function of a scalar variable u . By this we mean that with each value of u we associate a vector $\mathbf{a}(u)$. For example, in Cartesian coordinates $\mathbf{a}(u) = a_x(u)\mathbf{i} + a_y(u)\mathbf{j} + a_z(u)\mathbf{k}$, where $a_x(u)$, $a_y(u)$ and $a_z(u)$ are scalar functions of u and are the components of the vector $\mathbf{a}(u)$ in the x -, y - and z -directions respectively. We note that if $\mathbf{a}(u)$ is continuous at some point $u = u_0$ then this implies that each of the Cartesian components $a_x(u)$, $a_y(u)$ and $a_z(u)$ is also continuous there.

Let us consider the derivative of the vector function $\mathbf{a}(u)$ with respect to u . The derivative of a vector function is defined in a similar manner to the ordinary derivative of a scalar function $f(x)$. The small change in the vector $\mathbf{a}(u)$ resulting from a small change δu in the value of u is given by $\delta \mathbf{a} = \mathbf{a}(u + \delta u) - \mathbf{a}(u)$ (see Figure 2.1). The derivative of $\mathbf{a}(u)$ with respect to u is defined to be

$$\frac{d\mathbf{a}}{du} = \lim_{\delta u \rightarrow 0} \frac{\mathbf{a}(u + \delta u) - \mathbf{a}(u)}{\delta u} \quad (2.1)$$

assuming that the limit exists, in which case $\mathbf{a}(u)$ is said to be differentiable at that point. Note that $d\mathbf{a}/du$ is also a vector, which is not, in general, parallel to $\mathbf{a}(u)$. In Cartesian coordinates, the derivative of the vector $\mathbf{a}(u) = a_x\mathbf{i} + a_y\mathbf{j} + a_z\mathbf{k}$ is given by

$$\frac{d\mathbf{a}}{du} = \frac{da_x}{du}\mathbf{i} + \frac{da_y}{du}\mathbf{j} + \frac{da_z}{du}\mathbf{k}.$$

Perhaps the simplest application of the above is to finding the velocity and acceleration of a particle in classical mechanics. If the time-dependent position vector of the particle with respect to the origin in Cartesian coordinates is given by $\mathbf{r}(t) = x(t)\mathbf{i} + y(t)\mathbf{j} + z(t)\mathbf{k}$

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without understanding why it behaves as it does We can also operate machines that rely on fluid behavior drive a car for exam 15 behavior mathematical analysis ple without understanding the fluid dynamics of the engine and we can even repair and maintain engines piping networks and other complex systems without having studied the mathematics of flow What is the purpose then of learning to mathematically describe fluid The answer to this question is quite practical knowing the patterns fluids form and why they are formed and knowing the stresses fluids generate and why they are generated is essential to designing and optimizing modern systems and devices While the ancients designed wells and irrigation systems without calculations we can avoid the wastefulness and tediousness of the trial and error process by using mathematical models

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