

Variational methods for the Navier-Stokes equations (working title)

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Chapter 1

Continuum mechanics

Corpus omne perseverare in statu suo quiescendi vel movendi uniformiter in directum, nisi quatenus a viribus impressis cogitur statum suum mutare.

Mutationem motus proportionalem esse vi motrici impressae, & fieri secundum lineam rectam qua vis illa imprimitur.

Actioni contrariam semper & aequalem esse reactionem: sive corporum duorum actiones in se mutuo semper esse aequales & in partes contrarias dirigi.

Newton [1]

1.1 Newton’s laws of motion

Newton’s three laws, namely those of inertia, force, and equilibrium, have found universal success in application to mechanical systems such as the pendulum, the motion of an rigid body, the evolution of a bending beam, and, as we shall see, the motion of fluid. *Mechanics* could be thought of as the study of physical motion, but the word “physical” might be misleading. Newton’s principles are mathematical in nature, applicable to the study of motion in a general sense as some unambiguously measurable state which evolves in time.

1.1.1 Symmetry, momenta, and inertia

Mechanics as a theory of physical motion will require a definition of physical motion. A first attempt might be to posit that “physical states” are representable as points in a finite-dimensional manifold, which we call the configuration space X , which is the case for typical notions of state such as the two angles in a double pendulum, or the position and orientation of a rigid body. We might define a motion as a continuous time-parameterized curve

$$\gamma : [t_1, t_2] \rightarrow X.$$

(— motivation of $F = ma$, and momenta as fundamental quantity).

We start in the middle:

$$\text{Total force} = \text{change of momentum.} \tag{1.1}$$

In this form, Newton’s second law of motion states that a (non-explanatory) measurement of change of momentum will be called “force”.

1.2 The Euler-Lagrange equations: From $F = ma$ to $\frac{\partial \mathcal{L}}{\partial q} - \frac{d}{dt} \frac{\partial \mathcal{L}}{\partial \dot{q}} = 0$

1.2.1 A Lagrangian of a mechanical system

Force is an intensive measurement of the change in momentum. In the language of calculus,

$$\int_{s_1}^{s_2} F dt = \mathcal{P}(s_2) - \mathcal{P}(s_1) \quad (1.2)$$

for all time subintervals $[s_1, s_2] \subset [t_1, t_2]$. If we restrict F to be conservative and a function only of position q , then we may let $F = -\frac{\partial V}{\partial q}$ for some potential function V . Suppose also that $\mathcal{P} = \frac{\partial T}{\partial \dot{q}}$ for some potential function (called the “kinetic energy”) independent of position q . We then define a Lagrangian of the mechanical system to be

$$\mathcal{L}(q, \dot{q}, t) = T(\dot{q}, t) - V(q, t) = \text{kinetic} - \text{potential}.$$

By definition, we have the force equation (1.2) as

$$-\int_{s_1}^{s_2} \frac{\partial \mathcal{L}}{\partial q} dt = \frac{\partial \mathcal{L}}{\partial \dot{q}}(s_2) - \frac{\partial \mathcal{L}}{\partial \dot{q}}(s_1).$$

The step toward the calculus of variations (—)

$$\int_{s_1}^{s_2} \frac{\partial \mathcal{L}}{\partial q} h dt + \int_{s_1}^{s_2} \frac{\partial \mathcal{L}}{\partial \dot{q}} \frac{dh}{dt} dt = 0 \quad \equiv \quad \left\langle \frac{\partial \mathcal{L}}{\partial q}, h \right\rangle + \left\langle \frac{\partial \mathcal{L}}{\partial \dot{q}}, \frac{dh}{dt} \right\rangle = 0. \quad (1.3)$$

Adjointness of differential operator $\frac{d}{dt}$ to $-\frac{d}{dt}$, and integration by parts. (—) By linearity, we then get the reformulation of (1.3) as

$$\left\langle \frac{\partial \mathcal{L}}{\partial q} - \frac{d}{dt} \frac{\partial \mathcal{L}}{\partial \dot{q}}, h \right\rangle = 0$$

for all perturbation functions h .

1.2.2 The first variation of a functional

In the calculus of variations, $\frac{\partial \mathcal{L}}{\partial q} - \frac{d}{dt} \frac{\partial \mathcal{L}}{\partial \dot{q}}$ is an instance of the *Gâteaux derivative*, also called the “first variation” of the functional

$$S[q] := \int_{t_1}^{t_2} \mathcal{L}(q, \dot{q}, t) dt.$$

The first variation measures response of the value of S , called the *action*, to perturbations of the (differentiable) input function q , and is denoted

$$\frac{\delta S}{\delta q(t)} := \frac{\partial \mathcal{L}}{\partial q} - \frac{d}{dt} \frac{\partial \mathcal{L}}{\partial \dot{q}}. \quad (1.4)$$

The first variation is linear in the perturbation function, and so another term for the Gâteaux derivative could be “functional gradient”. Setting this to zero gives the Euler-Lagrange equations, and the practice of determining trajectories of motions as stationary curves of the action is called the “principle of stationary action”.

1.2.3 From the Lagrangian to the equations of motion

In the framework of Lagrangian mechanics, $\mathcal{P} := \frac{\partial \mathcal{L}}{\partial \dot{q}}$ is the momentum. If there are d degrees of freedom in the mechanical system, and we suppose that q_1, \dots, q_d are (local) variables of state, then we say that $\mathcal{P}_i := \frac{\partial \mathcal{L}}{\partial \dot{q}_i}$ are *conjugate* to the q_i .

(—) By inducing the equations of motion by a Lagrangian, we get systems with a “physical interpretation” with “physically meaningful” force measurements.

1.2.4 Why —?

These variational ideas appear because, no matter if our configuration space is finite-dimensional, time forms a continuum, and therefore if we globally consider the calculus of the motion as a whole, it must be a “variational” calculus. (—)

(—) Physical process, conservation laws, conservative forces (hint at thermodynamics limiting the range of stress tensors?)

When we consider mechanical models of continuum processes, we will see that these same ideas appear in the spatial dimensions too. A variational understanding of a continuum mechanics model leads very easily to a class of methods called Galerkin methods for solving the corresponding (PDE) equations of motion.

1.3 Configuration spaces as function spaces

1.3.1 The state of a continuum model

(— discuss continuum modelling). Here we work with position function x and velocity u , rather than q and \dot{q} , but the principles are the same. Let U be some region of, say, \mathbb{R}^2 . We define $x : U \times [t_1, t_2] \rightarrow U$ where x is invertible to be the *displacement function*, where $x(X_0, t)$ gives the (—). The “displacement function” is just the q discussed before. Here, however, the possible states, or displacement functions, exist in an infinite-dimensional configuration space. We define the *velocity field* $u : U \times [t_1, t_2] \rightarrow \mathbb{R}^2$ to be the “differential generator” of the displacement function. This is, again, just an instance of \dot{q} as discussed before. Importantly, x and u are functions of the same domain, and therefore u is a function of the reference configuration. Further, we define $\rho : U \rightarrow \mathbb{R}^+$ to be the *mass density function*, and define our momentum to be $\mathcal{P} = \rho u$. Newton’s laws then give

$$\int_{s_1}^{s_2} F dt = \rho u(s_2) - \rho u(s_1).$$

No new mechanics has been introduced. We just have a different notion of position (a different, here infinite dimensional, configuration space X) and a relation between velocity variables and the momentum. (—body forces, surfaces forces, Lagrangian and Eulerian specifications, Reynolds transport theorem, material derivative) From $F = \frac{dp}{dt}$ to $\nabla \cdot \sigma + \rho f = \frac{D(\rho u)}{Dt}$

1.4 The kinematics of the continuum

— transport of quantity in the continuum.

1.4.1 Continuity equations and conservation laws

The integral form of a continuity equation

Consider some spatial quantity in the continuum ϕ (which could be scalar, vector or tensor-valued (—maybe specialize here to scalar)), and a flux function j which by which this quantity flows through the continuum. By definition we want this flux function to just push quantity around, and not create or destroy it: the creation and destruction of quantity is determined by some arbitrary source function s (of the same kind as ϕ). These variables are related by the continuity condition

$$\frac{d}{dt} \int_{\Omega_0} \phi dx = \int_{\partial\Omega_0} \phi j \cdot (-\hat{n}) dx + \int_{\Omega_0} s dx. \quad (1.5)$$

for arbitrary control volumes Ω_0 in the continuum. $-\hat{n}$ denotes the inward-pointing normal to the boundary of the control volume. This simply says that the change in the total quantity in the fixed control volume is accounted for exactly by that quantity pushed through the boundary by the flux function j , and the internal sources and sinks of quantity s .

The differential form of a continuity equation

A common technique in continuum modelling is the use of Stokes' theorem to simplify integral expressions. Equation (1.5) becomes

$$\frac{\partial \phi}{\partial t} = -\nabla \cdot (\phi j) + s \quad (1.6)$$

(—assuming ϕ is a scalar quantity, the general form requires the wedge product) assuming that ϕj is sufficiently differentiable such that the limiting integral exists. It should be noted that Stokes' theorem and its specializations are really *definitions* of (pointwise) quantities such as the divergence and curl as limits of these integral expressions for arbitrarily small regions. Continuity relations are most naturally expressed in form (1.5), while the form (1.6) may be more useful for techniques such as finite differences. For example, it is a theorem of Gauss that in Euclidean space we have

$$\nabla \cdot j = \frac{\partial j_x}{\partial x} + \frac{\partial j_y}{\partial y} + \frac{\partial j_z}{\partial z}, \quad (1.7)$$

and we get (1.6) in the form

$$\frac{\partial \phi}{\partial t} = -\nabla \phi \cdot j - \phi \left(\frac{\partial j_x}{\partial x} + \frac{\partial j_y}{\partial y} + \frac{\partial j_z}{\partial z} \right) + s, \quad (1.8)$$

by the product rule. As one equation in a system of PDEs, (1.8) is readily discretized by finite differences. For example, using forward difference in time and central differences in space, our discrete scheme is

$$\begin{aligned} \frac{\phi(t + \Delta t) - \phi(t)}{\Delta t} = & - \frac{\phi(\hat{x} + e_1 \Delta x/2) - \phi(\hat{x} - e_1 \Delta x/2)}{\Delta x} j_x \\ & - \frac{\phi(\hat{x} + e_2 \Delta y/2) - \phi(\hat{x} - e_2 \Delta y/2)}{\Delta y} j_y \\ & - \frac{\phi(\hat{x} + e_3 \Delta z/2) - \phi(\hat{x} - e_3 \Delta z/2)}{\Delta z} j_z \\ & - \frac{j_x(\hat{x} + e_1 \Delta x/2) - j_x(\hat{x} - e_1 \Delta x/2)}{\Delta x} \phi \\ & - \frac{j_y(\hat{x} + e_2 \Delta y/2) - j_y(\hat{x} - e_2 \Delta y/2)}{\Delta y} \phi \\ & - \frac{j_z(\hat{x} + e_3 \Delta z/2) - j_z(\hat{x} - e_3 \Delta z/2)}{\Delta z} \phi + s. \end{aligned} \quad (1.9)$$

Later, when we discuss numerical methods for solving continuum models, we will not take this route. The methods of interest, *Galerkin* methods, work naturally with the integral form (1.5). It will be seen later that many constructions in the presentation of Galerkin methods, such as the “weak form” of a PDE, simply undo the differentialization of the original integral form of physical PDEs. (— note: Maybe not exactly, as the integral conservation is quantified over regions, while the weak form is quantified over test functions, which still need to be sufficiently differentiable. But I think that this must express the same continuity relation.)

1.4.2 The Reynolds transport theorem

The integral form of Reynolds transport

With our integral formulation of a continuity relation (1.5), the control volume Ω_0 is fixed. We may change our perspective by considering, in addition to the flux function j (which transports quantity ϕ), another vector field \hat{u} which will transport our control volume Ω_0 . The rate of change of some time-dependent quantity γ in this *moving* control volume is expressed as

$$\frac{d}{dt} \int_{\Omega_0(t)} \gamma dx, \quad (1.10)$$

where $\Omega_0(t)$ implicitly denotes that Ω_0 is being transported under the flow of \hat{u} . Clearly, this rate of change of quantity γ is due to the motion of the control volume (— draw a picture of positive and negative contributions at the boundary), as well as internal changes of γ inside the (fixed) control volume. The formal expression of these contributions to the rate of change (1.10) is

$$\left. \frac{d}{dt} \left[\int_{\Omega_0(t)} \gamma dx \right] \right|_{t=0} = \int_{\Omega_0(0)} \frac{\partial \gamma}{\partial t} dx + \int_{\partial \Omega_0(0)} \gamma \hat{u} \cdot \hat{n} dx. \quad (1.11)$$

This result is called the *Reynolds transport theorem*, a generalization of Feynman’s popularized “differentiation under the integral sign” [10], otherwise named the Leibniz integral rule.

The differential form of Reynolds transport

In the limit, with the routine application of Stokes’ theorem, we can differentialize (1.11) to get

$$\frac{d_{\hat{u}} \gamma}{d_{\hat{u}} t} = \frac{\partial \gamma}{\partial t} + \nabla \cdot (\gamma \hat{u}), \quad (1.12)$$

where $\frac{d_{\hat{u}}}{d_{\hat{u}} t}$ denotes a “convective derivative” with respect to \hat{u} , which measures the change in volume of a quantity when a small control volume around the point of evaluation is moved, expanded or contracted by the flow field \hat{u} . (— notation and terminology? This is not a material derivative, since the divergence of the flow field is considered to expand/contract the small control volume).

Reynolds transport applied to a continuity equation

Letting our quantity γ in (1.11) be the quantity ϕ transported by flux function j (described in continuity equation (1.5)), we can get a specialized form of the Reynolds transport theorem for continuity equations. Term $\frac{\partial \gamma}{\partial t}$ in (1.11) becomes $\frac{\partial \phi}{\partial t}$ in the differential form of the continuity equation (1.6), giving

$$\begin{aligned} \left. \frac{d}{dt} \left[\int_{\Omega_0(t)} \phi dx \right] \right|_{t=0} &= \int_{\Omega_0(0)} -\nabla \cdot (\phi j) + s dx + \int_{\partial \Omega_0(0)} \phi \hat{u} \cdot \hat{n} dx \\ &= \int_{\Omega_0(0)} s dx + \int_{\partial \Omega_0(0)} \phi (\hat{u} - j) \cdot \hat{n} dx. \end{aligned} \quad (1.13)$$

This has a clear interpretation. The $\hat{u} - j$ term is due to us wanting to measure the contributions to the total ϕ due to the moving boundary of Ω_0 , where the motion that matters is *relative* to the flux of the quantity j . Specifically, if we move the control volume by the same flux function j (letting $\hat{u} = j$), we get

$$\left. \frac{d}{dt} \left[\int_{\Omega_0(t)} \phi dx \right] \right|_{t=0} = \int_{\Omega_0(0)} s dx. \quad (1.14)$$

In fact, (1.14) is just another form for the conservation law (1.5), where the “frame of reference” for measurement of ϕ follows the transport of ϕ . This simply means that as we follow some volume of quantity original situated in Ω_0 , a conservation law posits that the only change detected is due to the source function s . In differential form (1.14) becomes

$$\frac{d_j \phi}{d_j t} = s, \quad (1.15)$$

a succinct equivalent to (1.6). This idea, of following the flow while making measurements, is called the *Lagrangian* perspective, in contrast to the *Eulerian* (fixed) perspective. Before describing these notions of flow, we first investigate the property of incompressibility.

1.4.3 Incompressible and compressible transport

While the continuity equation (1.5) gives us a general conservation law, transporting some quantity through our continuum (—without loss of generality, assume some domain $U \subset \mathbb{R}^2$), this is simply analogous to how general vector fields on the configuration space describe the evolution of a state in a finite-dimensional mechanical system (— note that the “vector field” in consideration for the continuum case is really a “vector field of vector fields” on X , since a vector in the tangent space of X here would be the vector field giving transport. Need to clearly distinguish these notions and use clear terminology, as it could be confusing). Analogous to the constraints on the motion of a finite mechanical system, (— section on Lagrangian mechanics should have an example of constraints of motion for a pendulum) we can constrain possible movement of our continuous quantity to *incompressible transport*. Much like how, in the framework of Lagrangian mechanics, constraints on motion are implicitly enforced by strong “virtual forces”, constraining transport to be incompressible will lead to the notion of *pressure*, when we later consider the dynamics of the continuum.

1.5 The dynamics of the continuum

1.6 The continuum hypothesis and constitutive relations

1.7 Lagrangians of Cauchy momentum equations

— Require conservative body forces and “thermodynamic conditions” on surface forces, such that there exists a Lagrangian.

Chapter 2

The Navier-Stokes equations

Chapter 3

The finite element method

3.1 Discretizing variational principles

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