

An assortment of theory relating to the Euler Equations on Manifolds



James Arthur
St Edmund Hall
University of Oxford

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To all the mathematicians and my parents that stood before me and
blocked me from being a Game Developer.

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Abstract

In this thesis, we discuss and present ideas surrounding fluid flow on manifolds. We model fluid flow as a Fréchet group of structure-preserving diffeomorphisms and use Euler-Poincaré reduction and Lie-Poisson reduction to derive geodesic equations. We then study the conservation quantities of these equations using (Kelvin-)Noether Theorems and Casimir Theory.

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Chapter 1

Motivation, Introduction and Background

Never reduce on the Hamiltonian and
never code your numerical methods.

Darryl D. Holm

Geometric Mechanics is based on deriving equations from symmetries baked into physical systems. In most physical systems, these symmetries are left unexploited and lead to a variety of theories and further information about our systems that is very useful. We can derive so-called conserved quantities of these physical systems. Conserved quantities give insight into how the system behaves and can help when we attempt to solve these systems numerically.

Historically, the area can be traced back to least action principles applied to mechanical systems by Maupertuis in 1744. Then optics used the ideas later, and Euler, Leibnitz and Lagrange started the boom of the least action principle. Lagrange deduced the Euler-Lagrange Equations in the 1750s,

$$\frac{\partial L}{\partial q} - \frac{d}{dt} \frac{\partial L}{\partial \dot{q}} = 0.$$

Hamilton deduced the ‘Hamilton’ least action principle in 1835,

$$\delta \int_{t_1}^{t_2} F[\mathbf{x}] \, d\mathbf{x} = 0.$$

From Hamilton’s principle, you can derive equations from a Lagrangian. Then, in 1901, Poincaré wrote down a new set of equations called the Euler-Poincaré equations,

$$\frac{d}{dt} \frac{\delta \ell}{\delta \xi} - \text{ad}_\xi^* \frac{\delta \ell}{\delta \xi} = 0.$$

While the Lagrangian framework was developing, there was a concurrent development for the Hamiltonian framework. The history here is more convoluted as the path to

understanding was rewritten several times. This framework takes a Lagrangian and then considers a Legendre transform of the Lagrangian. This involves using some Lagrange multipliers, which can be written as Clebsch variables, leading to Hamilton's Equations. The canonical Hamilton's equations using the trivial Clebsch variables,

$$\frac{\partial \mathbf{q}}{\partial t} = \frac{\partial H}{\partial \mathbf{p}} \quad \frac{\partial \mathbf{p}}{\partial t} = -\frac{\partial H}{\partial \mathbf{q}}.$$

If we consider these equations in higher generality. That is, written on some manifold. Not only do Hamilton's equations conserve the Hamiltonian, but they also conserve the canonical symplectic form.

$$\omega = dp_i \wedge dq_i$$

where p_i and q_i are local coordinates. By a quick calculation, we can verify that,

$$\frac{dF}{dt} = \frac{\partial F}{\partial q} \frac{\partial H}{\partial p} - \frac{\partial F}{\partial p} \frac{\partial H}{\partial q} := \{F, H\},$$

where H is the Hamiltonian. You can write a Hamiltonian system this way, writing the Lie-Poisson bracket on the right-hand side. This leads to the study of conserved quantities when the Lie bracket vanishes. These are Casimirs.

One of the current main figures in modern Geometric Mechanics is Professor Darryl Holm at Imperial College. Holm was inspired by work done before him by Poisson, Lie, Arnold, Marsden, Axton and Hamilton, to name a few. His idea was to move forward and use the theory before him and to apply this, conglomerate it and present a new area of mathematics—geometric Mechanics. Trained as a Physicist, Darryl presented ideas on Geometry in his work at Los Alamos labs. He was then elected as the first director of the Nonlinear Systems Institute after presenting how Geometry can be used to create new solution criteria to equations of interest.

From there, the idea spread further, with Darryl writing his infamous book, 'The Green Book' to all Geometric Mechanists. While Darryl continued to work at the coalface, new ideas were developing, and new mathematicians were starting work. The ideas of Symplectic Geometry were starting to be developed in the area by Bridges. Further, the applications of this work to Numerical Analysis were starting to form with mathematicians such as Cotter and Gay-Balmaz hearing of Geometric Mechanics and getting interested in the conservation of quantities in numerical schemes and how this relates to Geometric Mechanics.

Then, the question of industrial applications was raised with the team of Professor Tom Bridges, Dr Matt Turner and Dr Hamid Alemi Ardakani. They were interested in the application of this work in wave energy generators. They studied new variational principles similar to Hamilton's Principle, such as the Luke-Bateman principle,

$$\delta \int_{t_1}^{t_2} \int_{\mathcal{Q}} -\rho \left(\frac{\partial \Phi}{\partial t} + \frac{1}{2} \nabla \Phi \cdot \nabla \Phi - \nabla \Phi \cdot (\mathbf{v}_0 + \boldsymbol{\omega} \times \mathbf{r}) + U \right) d\mathcal{Q} dt = 0.$$

These are more general and consider more complicated fluid interactions, such as coupling and free surfaces. This is still an ongoing project and one that the author will be joining

next year under Dr Hamid Alemi Ardakani.

We can now move forward and consider this thesis. Alongside this work, Arnold wrote a lot of mathematics relating to the Ideal Fluid Euler Equations and Euler-Poincaré reduction. In this thesis, we will review that work, then use other sources and work forward to review and create a new theory for the Euler Equations on general manifolds. One of our main examples of the thesis will be to recreate the paper of Vanneste [24] regarding Geometric Mechanics. Then, we will consider the derivation of the 2D Euler Equations from the 3D Euler Equations and then consider conserved quantities. This thesis aims twofold: to understand and expose the current research in Geometric Mechanics and to fill holes in the theory by adding examples.

The motivation for using this type of mathematics is as follows. Many PDE systems can be described in a coordinate-dependent environment. The derivation of these equations is usually found by considering conservation laws and then fitting terms to that, then integrating and pulling equations out. This assumes our system already has these conserved quantities. These derivations are made quite difficult when we consider complex chemical behaviour. These conservation laws are no longer as obvious. Hence, we propose to derive these ‘standard’ equations by considering the energy. We consider the Lagrangian or the Hamiltonian,

$$L(q, \dot{q}) = K(q, \dot{q}) - V(q, \dot{q}) \quad H(q, \dot{q}) = K(q, \dot{q}) + V(q, \dot{q}).$$

Then, we can take a system, say a spherical pendulum, and derive the Hamiltonian and Lagrangian. This example is from Arthur’s ‘Lie Groups and Applications to Geometric Mechanics’ [5]. Consider a spherical pendulum as in the figure below.

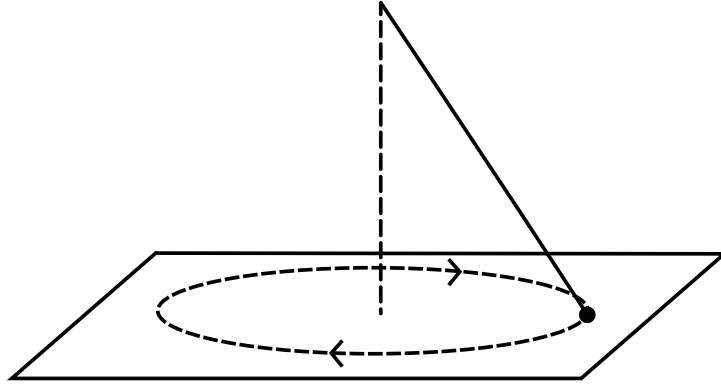


Figure 1.1: Spherical Pendulum.

Then, we can define the Lagrangian of this system as,

$$L(\mathbf{x}, \dot{\mathbf{x}}) = \frac{1}{2}m|\dot{\mathbf{x}}|^2 - mg\mathbf{x} \cdot \mathbf{e}_3.$$

We are interested in considering the motion from the spatial frame. We can use a body to space map through $\mathbf{x} \mapsto \mathbf{R}(t)X$, where $\mathbf{x}, X \in \mathbb{R}^3$ and $\mathbf{R}(t) \in \text{SO}(3)$. We can then move the Lagrangian from the body frame to the spatial frame,

$$L(\mathbf{R}, \dot{\mathbf{R}}) = \frac{1}{2}m|\dot{\mathbf{R}}(t)X|^2 - mg\mathbf{R}(t)X \cdot \mathbf{e}_3. \quad (1.1)$$

Then by manipulating the Lagrangian (1.1), we can now rewrite it again letting $\Gamma(t) = \mathbf{R}(t)\mathbf{e}_3$,

$$L(\mathbf{R}, \dot{\mathbf{R}}, \Gamma) = \frac{1}{2}m|\dot{\mathbf{R}}X|^2 - mg\Gamma \cdot X.$$

Then, we can notice that this Lagrangian concerning the symmetric part, the first term, is right symmetric and has a symmetry-breaking parameter. Therefore we take $g \mapsto g\mathbf{R}^{-1}$. So,

$$L(\mathbf{R}\mathbf{R}^{-1}, \dot{\mathbf{R}}\mathbf{R}^{-1}, \tilde{\Gamma}) := \ell(\hat{\Omega}, \tilde{\Gamma}) = \frac{1}{2}m\mathbb{I}|\hat{\Omega}|^2 - mg\tilde{\Gamma} \cdot X,$$

where $\mathbb{I} = |X|^2I - XX^T$. Then you can plug this into the Euler-Poincaré equations for right invariant systems on $\text{SO}(3)$ and get,

$$\mathbb{I}\hat{\Omega}_t = \mathbb{I}\hat{\Omega} \times \Omega + mgX \times \tilde{\Gamma}.$$

The thesis will be structured as follows,

- This first chapter will lay down the introductory material for the theory we will use later. This part of the thesis is critical for readers not well versed in Geometric Mechanics as it lays out the operators and functionals we use without definition in the rest of the thesis. This chapter covers Fundamental Differential Geometry, Exterior Calculus, Symplectic Geometry and Geometric Fluid Dynamics.
- Then, we will study the mechanics and PDEs for different fluid systems on manifolds. We will write these PDEs in the language of exterior calculus. We will learn the Lagrangian and Hamiltonian frameworks through Euler-Poincaré reduction and Lie-Poisson reduction. We will derive the associated equations and introduce the canonical Lie-Poisson bracket. We will then describe equations with advected quantities and give some motivation for the EP-Diff equations.
- Finally, to complete the theory, we will then study the conservation laws of our systems with Noether and Casimir Theory. We will prove the generalised Noether Theorem and Kelvin-Noether Theorem for the Euler-Poincaré equations on $\text{SDiff}(M)$ and then study the Casimirs and introduce the non-canonical Lie-Poisson bracket.
- To conclude the thesis, we will then study several examples relating to the theory. Such as axisymmetric fluid flow on a cylinder, derivation of 2D Eulers Equations from 3D, Fluid flow on a sphere and then the Möbius strip.

1.1 Introduction to Geometric Fluid Dynamics

We will follow Chapter 1 of Arnold and Khesin's 'Topological Methods in Hydrodynamics' [26] and, more generally, Holm, Schmah and Stoica's 'Geometric Mechanics and Symmetry' [13].

We will start with some definitions relating to Group Theory and Lie Theory. We can define a group,

Definition 1.1.1 (Group on a Manifold). *A set G of smooth transformations of a manifold M onto itself is a group if,*

1. *Given two transformations $g, h \in G$, the composition $g \circ h$ is in G ,*
2. *Given some $g \in G$, the inverse, g^{-1} , is also in G .*

We define the group like this because then the definition of the Lie Group becomes obvious. If the functions induced by the two conditions in Definition 1.1.1 are smooth, then we have a *Lie Group*. There are some pertinent examples of Lie Groups that are useful to mechanics. We use the Lie Group of length preserving rotations for rigid body dynamics, $SO(3)$. For a detailed survey of the Geometric Mechanics of $SO(3)$, see [5]. However, we are interested in the volume-preserving diffeomorphisms, $SDiff(M)$, for hydrodynamics.

Definition 1.1.2 (Diffeomorphism). *Let M and N be manifolds, then a diffeomorphism is a bijective map $\phi : M \rightarrow N$ such that both ϕ and ϕ^{-1} are differentiable. The group of diffeomorphisms are denoted $Diff(M)$.*

We can further extend this to volume-preserving diffeomorphisms,

Definition 1.1.3 (Volume Preserving Diffeomorphism). *Let $\phi : M \rightarrow N$ be a diffeomorphism and $d\mu$ be the volume element of M . Then we say ϕ is volume preserving if $\phi(d\mu)$ is the volume element of N . The group of volume preserving diffeomorphisms are denoted $SDiff(M)$.*

We say that the volume-preserving diffeomorphism describes fluid. We mean that a diffeomorphism can describe the flow of a particle. Given a terminal point, we can describe all flows of the fluid particle by a diffeomorphism; they show the path the particle takes. We can see this in Figure 2.1.

As an example, we can define the kinetic energy of a particle in a fluid as the following,

$$E = \frac{1}{2} \int_M \varphi_t^2 dx.$$

This turns out to be nicely right invariant. Let $G = SDiff(M)$. If we perform the operation, $R_h : G \rightarrow G$, defined by $R_h(g) = gh$, on the kinetic energy, we can write it as the following,

$$R_h E = \frac{1}{2} \int_M (\phi_t h)^2 dx.$$

We note that h is volume preserving, then it is just a relabelling of the fluid particles, and so $R_h E = E$.

We also note the left multiplication by h can be written as $L_h(g) = hg$.

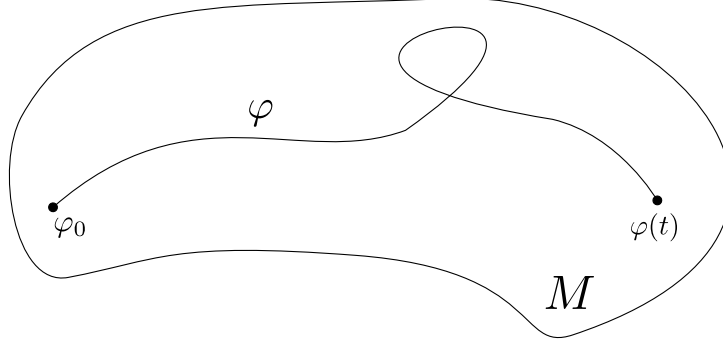


Figure 1.2: The path of a fluid particle.

1.1.1 Adjoint, Coadjoints and Group Actions

We spend the next subsection generalising and reviewing the content from [5] but for structure-preserving diffeomorphisms. We shall define the inner automorphism that quickly leads to the adjoint representation. We shall also discover the nature of the Lie Algebra of $\text{SDiff}(M)$.

We can consider the L_h and the R_h operators we defined before and define the inner automorphism.

Definition 1.1.4 (Inner Automorphism). *The inner automorphism, $A_g : G \rightarrow G$ is defined by, $A_h = L_h R_{h^{-1}}$. Given some $g \in G$, $A_h g = hgh^{-1}$ can also be written.*

This can then be used to talk about the adjoints of the group and algebra. For $\text{SDiff}(M)$, our Lie algebra will be the space of divergence-free vector fields in M . We also quickly need to note that to differentiate a map on a manifold, we denote it as follows. Given some $F : M \rightarrow M$, then the differential at a point $x \in M$ is $F_*|_x : T_x M \rightarrow T_{F(x)} M$. We can now define our Ad_g and ad_g on $\text{SDiff}(M)$ and \mathfrak{g} .

Definition 1.1.5 (Group Adjoint Operator). *The differential of A_g at the unit is called the group adjoint operator, Ad_g ,*

$$\text{Ad}_g : \mathfrak{g} \rightarrow \mathfrak{g} \quad \text{Ad}_g \xi = (A_{g*}|_e) \xi \quad \xi \in \mathfrak{g} = T_e G$$

We can further define the adjoint orbit,

Definition 1.1.6 (Adjoint Orbit). *Fix $\xi \in \mathfrak{g}$. The set of $\text{Ad}_g \xi$ images of ξ under the action of Ad_g , $g \in G$, is called the adjoint orbit of ξ .*

If $g \in \text{SDiff}(M)$, then $\text{Ad}_g \xi = g\xi g^{-1}$ is the structure-preserving diffeomorphisms acting on a vector field. Now if we let $g(0) = e$ and $\dot{g}(0) = \eta$. Then we can define the adjoint representation of the Lie algebra,

Definition 1.1.7 (Adjoint Representation of the Lie algebra). *If we take the differential of Ad at the identity, we have the adjoint representation of the Lie algebra,*

$$\text{ad} : \mathfrak{g} \times \mathfrak{g} \rightarrow \mathfrak{g} \quad \text{ad}_\xi = \left. \frac{d}{dt} \right|_{t=0} \text{Ad}_{g(t)}.$$

We can now take the derivative of the group adjoint on $\text{SDiff}(M)$. We can then get that $\text{ad}_\xi \eta = -[\xi, \eta]$ for $\xi, \eta \in \mathfrak{X}(M)$ such that $\text{div } \xi = \text{div } \eta = 0$.

We can further consider the coadjoint versions of the above. These are maps to the cotangent space and the dual to the Lie algebra. The dual to the Lie algebra can be described for arbitrary dimension. Let $G = \text{SDiff}(M^n)$ the group of volume-preserving diffeomorphisms on a manifold M with boundary ∂M . The commutator of divergence-free vector fields on M is just $-\{v, w\}$. Then we have the following result,

Theorem 1.1.8 (Dual of $\text{SVect}(M)$). *The Lie Algebra, \mathfrak{g} , of the group G is naturally identified with the space of closed differential $(n-1)$ -forms on M vanishing on ∂M . A divergence-free vector field v is identified with the $(n-1)$ -form $v \lrcorner \mu$ where μ is the volume form of M . Therefore, the dual to the Lie algebra is $\mathfrak{g}^* = \Omega^1(M)/\text{d}\Omega^0(M)$.*

Proof. The proof here has two parts. Firstly we prove that the space of all $(n-1)$ -forms $v \lrcorner \mu$ is naturally identified to $\Omega^1(M)/\Omega^0(M)$. Then we can prove that $\mathfrak{g} \cong \Omega^1(M)/\Omega^0(M)$.

Recall Cartan's magic formula, $\mathcal{L}_X \alpha = X \lrcorner d\alpha + d(X \lrcorner \alpha)$. If $\alpha = \mu$ and $X = u$, some vector field, it reduces to just saying, $\mathcal{L}_u \mu = d(u \lrcorner \mu)$. We are working over the space of volume preserving diffeomorphisms. So, when we consider the Lie derivative of the volume form over an algebra element, we want it to vanish. Hence, we require $v = u \lrcorner \mu$ to be closed. Therefore, $v \in \Omega^1(M)/\Omega^0(M)$. As u was arbitrary, v is just any $(n-1)$ -form, so we have our natural identification.

Now we seek an isomorphism, $\mathfrak{g} \cong \Omega^1(M)/\Omega^0(M)$. This is more complicated and can be found in Theorem 8.3 (pg 42) of 'Topological Methods of Hydrodynamics' [26]. \square

As we are considering fluid flows on these manifolds. If M is simply connected, we can say that the dual algebra, \mathfrak{g}^* , is just the vorticities.

1.1.2 Lie-Poisson Brackets

As introduced in the introduction, we can write a Hamiltonian system as,

$$\dot{F} = \{F, H\},$$

where $F : M \rightarrow \mathbb{R}$ and H is the Hamiltonian. The right-hand side is just the Canonical Lie-Poisson bracket. We can write this as,

$$\{F, G\} := \sum_i \frac{\partial F}{\partial q_i} \frac{\partial H}{\partial p_i} - \frac{\partial F}{\partial p_i} \frac{\partial H}{\partial q_i}.$$

This is the simplest Poisson bracket, and so is called the canonical bracket. These brackets are much like the Lie Brackets reviewed in [5]. However, it feeds into the theory of conserved quantities.

Definition 1.1.9 (Poisson Structure). *A Poisson structure on a smooth manifold with a bilinear form mapping, $(f, g) \mapsto \{f, g\}$ which satisfies,*

- *The Jacobi Identity, $\{\{f, g\}, h\} + \{\{g, h\}, f\} + \{\{f, h\}, g\} = 0$,*
- *The Liebnitz Identity, $\{f, gh\} = \{f, g\}h + \{f, h\}g$.*

One of the important notions surrounding these brackets, alongside their stability detection, is Casimirs. We can define a Casimir,

Definition 1.1.10 (Casimir). *Let M be a smooth manifold, then $C : M \rightarrow \mathbb{R}$ be a function. We call C a Casimir of this system if,*

$$\{F, C\} = 0,$$

for any $F : M \rightarrow \mathbb{R}$.

There are more complicated brackets for different groups and models. For example, when we consider rigid bodies over $\text{SO}(3)$ we get,

$$\{f, h\}(\Pi) := - \left\langle \Pi, \left[\frac{\partial f}{\partial \Pi}, \frac{\partial g}{\partial \Pi} \right] \right\rangle,$$

where $\Pi = R^{-1}\dot{R} \in \mathfrak{so}(3)$, $R \in \text{SO}(3)$. This is a specific form of Nambu's \mathbb{R}^3 Poisson bracket,

$$\{f, h\} = \nabla c \cdot \nabla f \times \nabla h.$$

In ideal fluids, the bracket differs. Consider the dual of $\text{SVect}(M)$, then the bracket of this space with respect to some $\alpha \in \Omega^1/\Omega^0$ is,

$$\{F, G\}(\omega) = - \int_M \alpha \left(\left[\frac{\delta F}{\delta \omega}, \frac{\delta G}{\delta \omega} \right] \right) dV.$$

This is the Arnold bracket. In the section on conserved quantities, we will show that this bracket doesn't conserve enstrophy and provide some alternate brackets.

1.2 A short interlude into Symplectic Geometry

Hamilton's equations present an insight into the time evolution of a system. They rely on the Hamiltonian in its entirety to give information about the future. If we have M as a manifold, then Lagrangian dynamics happens on TM and Hamiltonian dynamics on T^*M . These present a very nice framework for rigid body dynamics. In fluid dynamics, it may help to consider our system's flow and the flow space. This requires some heavier-duty tools and generalising the idea of a Hamiltonian. We generalise this into the notion of a symplectic form. The symplectic form relates to the vector field for the flow, dH .

Let M be a manifold, a specific manifold we will define later, then TM be the tangent space, or phase space, and T^*M be the cotangent space, or the flow space. Then let ω be a non-degenerate section of $T^*M \otimes T^*M$. The non-degeneracy of ω means that for every dH there is some V_H such that $dH = \omega(V_H, \cdot)$. We want two properties of our system to line up with ω . Firstly, we want the Hamiltonian, H , to be constant along the flow lines. Hence,

$$dH(V_H) = \omega(V_H, V_H) = 0.$$

That is, ω is an alternating 2-form. Further, we want the Lie derivative of ω to vanish,

$$\begin{aligned} \mathcal{L}_{V_H}\omega &= d(V_H \lrcorner \omega) + V_H \lrcorner d\omega \\ &= d(dH) + d\omega(V_H) = d\omega(V_H) = 0. \end{aligned}$$

As H is arbitrary, ω must be closed. Hence, we can define this idea of a symplectic form.

Definition 1.2.1 (Symplectic Form). *A symplectic form on a smooth manifold, M , is a closed non-degenerate 2-form, ω .*

We define a symplectic manifold as a pair (M, ω) . Symplectic Manifolds are just Poisson manifolds, and the Symplectic form is usually of more interest and use. These are very useful when we get to defining symplectic leaves. These are another gateway into conserved quantities.

Definition 1.2.2 (Symplectic Leaf). *The symplectic leaf of a point on a Poisson manifold is the set of all points on the manifold that can be reached by paths starting at a given point, such that the velocity vectors of the paths are Hamiltonian at every moment.*

You can show that these leaves are just symplectic manifolds and have the same symplectic structure. That is, the flow from any point where the Hamiltonian behaves nicely is just a manifold with a nice symplectic structure, and you can use the theory we will develop on it!

Theorem 1.2.3. *The symplectic leaf of every point is a smooth, even dimensional manifold. It has natural symplectic structure defined by, $\omega(\xi, \eta) = \{f, g\}$, where ξ and η are vectors at the point x of the Hamiltonian fields with Hamiltonian functions f and g .*

We finally define a functor between symplectic manifolds that will be useful later,

Definition 1.2.4 (Symplectomorphism). *A diffeomorphism between two symplectic manifolds, $\phi : (M, \omega) \rightarrow (N, \omega')$ is a symplectomorphism if it preserves the symplectic form,*

$$\phi^*\omega' = \omega$$

Chapter 2

Reduction, Equations and Brackets

Groups will be known by their actions

Guillermo Moreno

In 1757, Euler wrote the following equation in the paper ‘Principes généraux du mouvement des fluides’.

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} = -\nabla p$$
$$\nabla \cdot \mathbf{u} = 0.$$

These are known as Euler’s equations for perfect incompressible fluid flow. In the Chapter, we will take these equations, pull them apart and put them back together. We will study a more general theory of these equations by opening the eyes of the reader to fluid dynamics on general manifolds. On \mathbb{R}^n , conserved quantity and theory can be obscured by the space’s flatness or even simplicity. We will lift these equations to curved surfaces and aim to prepare for the next chapter, where we will study conserved quantities. We first can manipulate these equations into something more amicable to generalise. We will then generalise them and prove that these are the generalised Euler equations by deriving them from the Lie-Poisson reduction of a Hamiltonian. This whole chapter draws from and builds on several sources, [26, 13, 5, 12, 27, 10, 18, 8, 22, 19, 25]

2.1 Generalisation of Eulers Equations

We can replace the $\mathbf{u} \cdot \nabla$ with a covariant derivative. We know that,

$$[\mathbf{u} \cdot \nabla]_i = u^i \frac{\partial u^i}{\partial x^i}.$$

However, this is very similar to the covariant derivative,

$$[\nabla_{\mathbf{v}} \mathbf{u}]_i = \left(v^j u^i \Gamma_{ij}^k + v^j \frac{\partial u^k}{\partial x^j} \right) \mathbf{e}_k.$$

We know that Γ_{ij}^k is the Christoffel Symbol and represents some notion of twistyness of the space, so $\Gamma_{ij}^k = 0$ for \mathbb{R}^n . Hence, for flat space,

$$\mathbf{u} \cdot \nabla = \nabla_{\mathbf{v}} \mathbf{u}.$$

Therefore, we first propose the generalisation of Euler equations by writing,

$$\begin{aligned}\frac{\partial \mathbf{u}}{\partial t} + \nabla_{\mathbf{u}} \mathbf{u} &= -\nabla p \\ \nabla \cdot \mathbf{u} &= 0.\end{aligned}\tag{2.1}$$

We can rewrite the covariant derivative with something more geometric. We want to refer to the manifold that we work on explicitly. Let M be a manifold with the Riemannian metric, and then we can prove the following theorem using the metric.

Theorem 2.1.1. *Let M be a manifold with Riemannian metric. The Lie derivative of the one-form corresponding to a vector field on a M differs from the covariant derivative along itself by a complete derivative.*

$$\mathcal{L}_v(v^\flat) = (\nabla_v v)^\flat + \frac{1}{2} d\langle v, v \rangle.$$

Proof. Assume we have v, w such that they commute. That is, $\{v, w\} = 0$. Recall the translation property of the Lie derivative and the covariant derivative,

$$\mathcal{L}_a \langle b, c \rangle = \langle \nabla_a b, c \rangle + \langle b, \nabla_a c \rangle.$$

If we specialise this formula, we can get,

$$\langle \nabla_w v, v \rangle = \frac{1}{2} d\langle v, v \rangle(w).\tag{2.2}$$

$$\mathcal{L}_v \langle w, v \rangle = \langle \nabla_v w, v \rangle + \langle w, \nabla_v v \rangle.\tag{2.3}$$

By noting that $\mathcal{L}_v f = df(v)$. As $\{v, w\} = 0$, then,

$$\langle \nabla_v w, v \rangle = \langle \nabla_w v, v \rangle.\tag{2.4}$$

Therefore, we can substitute Equations 2.2 and 2.4 into Equation 2.3. This yields,

$$\mathcal{L}_v \langle w, v \rangle = \langle \nabla_v v, w \rangle + \frac{1}{2} d\langle v, v \rangle(w).$$

It suffices to show that, $\mathcal{L}_v \langle w, v \rangle = (\mathcal{L}_v v^\flat)(w)$. This follows from the naturality rule of the Lie derivative,

$$\mathcal{L}_\xi(v^\flat(w)) = (\mathcal{L}_\xi v^\flat)(w) + v^\flat(\mathcal{L}_\xi w).$$

Then let $\xi = v$,

$$\mathcal{L}_v(v^\flat(w)) = (\mathcal{L}_v v^\flat)(w).$$

Now given that \flat is the musical isomorphism, we know $\mathcal{L}_v \langle v, w \rangle = \mathcal{L}_v(v^\flat(w))$. Therefore,

$$\mathcal{L}_v v^\flat = (\nabla_v v)^\flat + \frac{1}{2} d\langle v, v \rangle.$$

□

That is, we can write Equation 2.1, as the following,

$$\begin{aligned}\frac{\partial \mathbf{u}^\flat}{\partial t} &= -\mathcal{L}_v \mathbf{u} - df \\ d\mathbf{u}^\flat &= 0\end{aligned}\tag{2.5}$$

2.2 Euler-Poincaré Reduction

The Euler-Poincaré Equations are a set of equations that relate to a reduced Lagrangian on the Lie algebra of the manifold. We recall that a Lagrangian is a function on the tangent bundle, $L : TG \rightarrow \mathbb{R}$, then the reduced Lagrangian is $\ell : \mathfrak{g} \rightarrow \mathbb{R}$, i.e. the restriction of L to \mathfrak{g} . The following result characterises the Euler-Poincaré Equations in our current case. We note this is the first of a few very similar theorems, depending on our assumptions about our groups and system. In this section, we will consider Euler-Poincaré reduction of manifolds without boundary for a basic Lagrangian, a Lagrangian with an advective quantity, a diffusion term and then for compressible fluids. We will then recall the theory without boundary and work towards a theory for manifolds with boundary.

2.2.1 Manifolds without boundary

We can introduce and prove the following theorem related to Lagrangians' basic reduction on manifolds without boundary. We consider a Lagrangian of basic form, $L = K - V$.

Theorem 2.2.1 (Basic Euler-Poincaré). *Let G be a topological group that admits a smooth manifold structure with smooth right translation, and let $L : TG \rightarrow \mathbb{R}$ be a right invariant Lagrangian. Let \mathfrak{g} denote the fiber $T_e G$, and let $\ell : \mathfrak{g} \rightarrow \mathbb{R}$, the restriction of L to \mathfrak{g} . For a curve $\eta(t) \in G$, let $\mathbf{u}(t) = TR_{\eta(t)^{-1}}\dot{\eta}(t)$. Then TFAE,*

- $\eta(t)$ satisfies the Euler-Lagrange Equations,
- $\eta(t)$ is an extremum of the action,

$$S(\eta) = \int L(\eta(t), \dot{\eta}(t)) \, dt,$$

- $u(t)$ solves the Basic Euler-Poincaré equations,

$$\frac{\partial}{\partial t} \frac{\delta \ell}{\delta u} = -\text{ad}_u^* \frac{\delta \ell}{\delta u},$$

where the coadjoint action is defined by,

$$\langle \text{ad}_u^* v, w \rangle = \langle v, [u, w] \rangle.$$

- $u(t)$ is the extremum of the reduced action,

$$s(u) = \int \ell(u(t)) \, dt,$$

for variations,

$$\delta u = \dot{w} + [w, u], \quad w = TR_{\eta^{-1}} \delta \eta.$$

Proof. This proof can be found in [13, 6, 12, 20]. We will derive the Euler-Poincaré equations from the variational principle to show where the equations come from. We denote $\ell(\xi)$ as our reduced Lagrangian, and then we write our variational principle and integrate it by parts.

$$\begin{aligned}\delta \int_{t_1}^{t_2} \ell(\xi) dt &= \int_{t_1}^{t_2} \left\langle \frac{\delta \ell}{\delta \xi}, \delta \xi \right\rangle dt \\ &= \int_{t_1}^{t_2} \left\langle \frac{\delta \ell}{\delta \xi}, \dot{\eta} - \text{ad}_\xi \eta \right\rangle dt \\ &= \int_{t_1}^{t_2} \left\langle -\frac{\partial}{\partial t} \frac{\delta \ell}{\delta \xi}, \eta \right\rangle - \left\langle \text{ad}_\xi^* \frac{\delta \ell}{\delta \xi}, \eta \right\rangle = 0.\end{aligned}$$

Therefore, the Euler-Poincaré equations are,

$$\frac{\partial}{\partial t} \frac{\delta \ell}{\delta \xi} + \text{ad}_\xi^* \frac{\delta \ell}{\delta \xi} = 0.$$

□

We note that for ideal fluids, the Lagrangian is just kinetic energy. Hence,

$$L(\eta, \dot{\eta}) = \frac{1}{2} \int_M (\dot{\eta}, \dot{\eta}) \mu \quad \eta \in \text{SDiff}(M), \dot{\eta} \in T_e \text{SDiff}(M)$$

Then, we can show that this Lagrangian is right invariant. We remember we are reducing over some group of structure-preserving diffeomorphisms, so,

$$\begin{aligned}L(\eta g, \dot{\eta} g) &= \frac{1}{2} \int_M \langle \dot{\eta} g, \dot{\eta} g \rangle \mu \\ &= \frac{1}{2} \int_M \langle \dot{\eta}, \dot{\eta} \rangle g^2 \mu \\ &= \frac{1}{2} \int_M \langle \dot{\eta}, \dot{\eta} \rangle \mu = L(\eta, \dot{\eta}).\end{aligned}$$

Hence our Lagrangian is right invariant and we can let $g = \eta^{-1}$ and hence rewrite our Lagrangian,

$$L(\eta, \dot{\eta}) = L(\eta \eta^{-1}, \dot{\eta} \eta^{-1}) = L(e, \dot{\eta} \eta^{-1}) := \ell(\xi).$$

We now note that,

$$\ell(\xi) = \frac{1}{2} \int_M \langle \xi, \xi \rangle \mu.$$

Then we can write the Euler-Poincaré equations for this system as,

$$\frac{\partial \xi}{\partial t} = \text{ad}_\xi^* \xi = \mathcal{L}_\xi \xi.$$

We note that quite nicely, we can see that this is just the Lie-Poisson Equation.

Advective Terms

In fluid mechanics, some quantities are transported by the flow. That is, the Lie Derivative transports them along vector fields. These are called advected quantities. Advection usually refers to two things: advected conserved quantities, as due to the advection term, new and more interesting conserved quantities are present, or to model substrate or substance being moved through the fluid. When we consider a Hamiltonian of these systems, we note that they have a parameter that turns from a parameter to a variable. These variables form a vector space, and our groups act on them linearly. Hence, we have a representation space. To see this more clearly, consider the following Lagrangian¹ for a spherical pendulum,

$$H(\mathbf{q}, \dot{\mathbf{q}}) = \frac{1}{2}m|\dot{\mathbf{q}}|^2 - mg\mathbf{q} \cdot \mathbf{e}_3.$$

We note that the only potential energy term variable is \mathbf{q} . Now, considering the reduced Lagrangian,

$$\ell(\hat{\Omega}, \Gamma) = \frac{1}{2}m\mathbb{I}|\hat{\Omega}|^2 - mg\Gamma \cdot X.$$

In this case, we have turned ‘created’ another variable out of the symmetry-breaking parameter. Hence a parameter has been turned into a variable and $\Gamma \in V^*$ to adjoint of the representation of $\text{SO}(3)$.

We can follow Holm, Marsden and Ratiu’s paper on Semi-direct Product Theories [12] to consider advection in our system. Let us consider a representation space, V , for our Lie Group G and let L have invariance properties for G and V .

Definition 2.2.2 (Representation). *A representation of a Lie group is a tuple (V, ρ) where V is the representation space and $\rho : G \rightarrow \text{GL}(V)$ the G -linear action on V .*

We can define a semi-direct product on a Fréchet Group and some representation groups as follows,

Definition 2.2.3 (Semidirect Product). *Let V be a vector space and G be a Fréchet Group that acts on the right by linear maps on V . The semi-direct product is the cartesian product, $G \times V$, where group multiplication is given by,*

$$(g_1, v_1)(g_2, v_2) = (g_1g_2, v_2 + v_1g_2).$$

We note that this group has identity, $(e, 0)$ and inverses, $(g, v)^{-1} = (g^{-1}, -g^{-1}v)$. Then we can consider the Lie algebra, $\mathfrak{s} = \mathfrak{g} \times V^*$, and it bestows a Lie bracket,

$$[(\xi_1, v_1), (\xi_2, v_2)] = ([\xi_1, \xi_2], v_1\xi_2 - v_2\xi_1).$$

Notation 2.2.4. *For notational purposes, we will consider the adjoint linear representation ρ^* of some vector v and $a \in V^*$ as,*

$$\rho_v^*a = v \diamond a \in \mathfrak{g}^*.$$

or,

$$\langle A \diamond a, w \rangle_{\mathfrak{g} \times \mathfrak{g}^*} = \langle A, -\mathcal{L}_w a \rangle_{V \times V^*} = - \int_{\mathcal{Q}} A \lrcorner \mathcal{L}_w a.$$

¹This is equivalent to the Hamiltonian up to Legendre transform

We consider our advected parameter to be some $a \in V^*$. Then, we can consider the semi-direct product of G and V^* , $G \ltimes V^*$. We choose the semi-direct product for flexibility, the Lie algebra of $\mathfrak{g} \ltimes V^*$.

We can define the Lagrangian as $L : G \rightarrow V^* \rightarrow \mathbb{R}$. Then we assume there is the right representation of the Lie Group on the vector space V and G acts on the right on $TG \times V^*$, $(\eta, \dot{\eta}, a)h = (\eta g, \dot{\eta} g, ag)$ for $g \in G$. Then $L : TG \times V^* \rightarrow \mathbb{R}$ is G -invariant. That is, if we define $L_{a_0}(v_g) = L(v_g, a_0)$, then L_{a_0} is right invariant under the lift and action. Finally we can now define for $\ell : \mathfrak{g} \times V^* \rightarrow \mathbb{R}$ by,

$$L(\eta\eta^{-1}, \dot{\eta}\eta^{-1}, a_0\eta^{-1}) := \ell(\xi, \alpha).$$

We now proceed with the Euler-Poincaré advection theorem.

Theorem 2.2.5 (Euler-Poincaré with advection). *Let M be a manifold and G be a Fréchet group. Then let (V, ρ) represent G . Suppose we have an advective quantity $a \in V^*$, and a Lagrangian $L : G \ltimes V^* \rightarrow \mathbb{R}$ that is right invariant under the tangent lift. Let $\eta \in G$ and $\dot{\eta} \in \mathfrak{g}$. Then the following are equivalent,*

- *Hamilton's variational principle holds, where variations vanish at endpoints,*

$$\int_{t_1}^{t_2} L_{a_0}(\eta(t), \dot{\eta}(t)) dt = 0$$

- *$\eta(t)$ satisfies the Euler-Lagrange equations for L_{a_0} ,*
- *The constrained variational principle holds for $\mathfrak{g} \times V^*$,*

$$\delta \int_{t_1}^{t_2} \ell(\xi, a) dt = 0 \quad \delta \xi = \dot{\nu} - [\xi, \nu], \quad \delta a = -a\nu$$

- *The Euler-Poincaré equations hold on $\mathfrak{g} \times V^*$,*

$$\frac{\partial}{\partial t} \frac{\delta \ell}{\delta \xi} = -\text{ad}_\xi^* \frac{\delta \ell}{\delta \xi} + \frac{\delta \ell}{\delta a} \diamond a.$$

$$\left(\frac{\partial}{\partial t} + \mathcal{L}_\xi \right) a = 0$$

Proof. The proof here is similar to 2.2.1. However, there are a few results we need to prove that are different. We first consider the time derivative of a and then the variation.

We start with a Lagrangian of the form $L(\eta, \dot{\eta}, a_0)$ and then assume that it's right invariant, that is, $L(\eta, \dot{\eta}, a_0) = L(\eta g, \dot{\eta} g, a_0 g)$. Then we can form a reduced Lagrangian, $L(\eta\eta^{-1}, \dot{\eta}\eta^{-1}, a_0 g^{-1}) := \ell(\xi, a)$ where $a := a_0 g^{-1}$. From this, we calculate,

$$\begin{aligned} \frac{\partial a}{\partial t} &= \frac{\partial}{\partial t}(a_0 g^{-1}) \\ &= -a_0 g^{-1} \frac{\partial g}{\partial t} g^{-1} = -a\xi. \end{aligned} \tag{2.6}$$

Then, similarly, we can write,

$$\begin{aligned}\delta a &= \delta(a_0 g^{-1}) \\ &= -a_0 g^{-1} \delta g g^{-1} \\ &= -a\nu,\end{aligned}$$

where $\nu := \delta g g^{-1}$. Now we can derive the equations,

$$\begin{aligned}\delta \int_{t_1}^{t_2} \ell(\xi, a) \, dt &= \int_{t_1}^{t_2} \left\langle \frac{\delta \ell}{\delta \xi}, \delta \xi \right\rangle + \left\langle \frac{\delta \ell}{\delta a}, \delta a \right\rangle \, dt \\ &= \int_{t_1}^{t_2} \left\langle \frac{\delta \ell}{\delta \xi}, \dot{\nu} - [\xi, \nu] \right\rangle + \left\langle \frac{\delta \ell}{\delta a}, -a\nu \right\rangle \, dt \\ &= \int_{t_1}^{t_2} \left\langle \frac{\delta \ell}{\delta \xi}, \dot{\nu} \right\rangle - \left\langle \frac{\delta \ell}{\delta \xi}, \text{ad}_\xi \nu \right\rangle + \left\langle \frac{\delta \ell}{\delta a}, -a\nu \right\rangle \, dt \\ &= \int_{t_1}^{t_2} \left\langle -\frac{\partial}{\partial t} \frac{\delta \ell}{\delta \xi}, \nu \right\rangle - \left\langle \text{ad}_\xi^* \frac{\delta \ell}{\delta \xi}, \nu \right\rangle + \left\langle \frac{\delta \ell}{\delta a} \diamond a, \nu \right\rangle \, dt \\ &= \int_{t_1}^{t_2} \left\langle -\frac{\partial}{\partial t} \frac{\delta \ell}{\delta \xi} - \text{ad}_\xi^* \frac{\delta \ell}{\delta \xi} + \frac{\delta \ell}{\delta a} \diamond a, \nu \right\rangle \, dt.\end{aligned}$$

Therefore, using Hamilton's principle, we have,

$$\frac{\partial}{\partial t} \frac{\delta \ell}{\delta \xi} = -\text{ad}_\xi^* \frac{\delta \ell}{\delta \xi} + \frac{\delta \ell}{\delta a} \diamond a. \quad (2.7)$$

Then considering the right concatenation using 2.6 we get,

$$\left(\frac{\partial}{\partial t} + \mathcal{L}_\xi \right) a = 0.$$

as required. \square

We can derive the Euler Equations for fluids with variable densities using this theory. Consider a Lagrangian with a fluid density advective term,

$$L(\eta, \dot{\eta}, \rho) = \int_M \frac{\rho}{2} |\dot{\eta}|^2 + p(\rho - 1)\mu.$$

This Lagrangian has a symmetry-breaking parameter [5]. Hence, we consider the symmetric part, and verifying this is right invariant is easy. Let $\eta \in \text{SDiff}(M)$ and ρ be a 0-form. Then, we can reduce this Lagrangian into,

$$L(\eta\eta^{-1}, \dot{\eta}\eta^{-1}, \rho\rho_0^{-1}) := \ell(\mathbf{u}, D) = \int_M \frac{D}{2} |\mathbf{u}|^2 + p(D - 1)\mu.$$

Then, we take functional derivatives,

$$\begin{aligned}\left\langle \frac{\delta \ell}{\delta \mathbf{u}}, \phi \right\rangle &:= \frac{d}{d\varepsilon} [\ell(u^\flat + \varepsilon \phi, D)]_{\varepsilon=0} \\ &= \langle [u^\flat] D, \phi \rangle. \\ \left\langle \frac{\delta \ell}{\delta D}, \phi \right\rangle &:= \frac{d}{d\varepsilon} [\ell(u^\flat, u^\flat + \varepsilon \phi)]_{\varepsilon=0} \\ &= \left\langle \frac{1}{2} [u^\flat]^2 + p, \phi \right\rangle.\end{aligned}$$

Then we can plug these into Equation (2.7) and get,

$$\frac{\partial[u^b]}{\partial t} + \mathcal{L}_{\mathbf{u}}[u^b] = \frac{(\frac{1}{2}[u^b]^2 + p) \diamond D}{D}.$$

Then, considering the cosets we have,

$$\frac{\partial u^b}{\partial t} + \mathcal{L}_{\mathbf{u}} u^b = F(u^b, D) := \frac{(\frac{1}{2}[u^b]^2 + p) \diamond D}{D} + df.$$

Then the advection equation is,

$$\left(\frac{\partial}{\partial t} + \mathcal{L}_{\mathbf{u}} \right) D = 0$$

2.2.2 Manifolds with Boundary

We require a manifold with some boundary to have systems with boundary conditions. This is where the theory deviates from above. We now will have three objects: the group we reduce over, G , with its associated algebra, \mathfrak{g} , and its dual \mathfrak{g}^* , the principle we use to derive the equations, usually Hamilton's principle, and the manifold we consider the flow over, M . We note that the boundary conditions will come from M and be imposed on G . Boundary conditions come in two different forms,

1. Finite conditions, so conditions along a point or a path. For example, axisymmetric flow in a cylinder.
2. Infinite conditions, limiting conditions as you approach an infinitum. For example, waves on a plane.

The first of these conditions requires manifolds with boundaries; the second is more complicated and requires a generalisation called manifolds with corners [17]. We will primarily be interested in the first case while diverting the second to subsequent work on this area. We will be using the ideas from papers by Marsden, Ratiu and Shkoller [19, 22] to develop a more general theory that we can apply to compressible Euler-Poincaré equations. We can derive Neumann, Dirichlet and Mixed conditions. We will work on two new diffeomorphism groups and mainly study the Dirichlet group that corresponds to the zero on the boundary, as that is the boundary condition seen the most in this type of fluid dynamics. We introduce the manifold of diffeomorphisms with boundary as follows.

Definition 2.2.6 (Diffeomorphism group with Boundary). *Let M be a manifold, \tilde{M} be the double of M as $H^s(M, M)$ isn't smooth and $\text{Diff}^s(M)$ be the group of C^s diffeomorphisms. Then, we define the diffeomorphism group with a boundary as,*

$$\text{Diff}^s(M) = \{\eta \in H^s(M, \tilde{M}) \cap \text{Diff}^s(M) : \eta(\partial M) = \partial M\}.$$

Then a calculation, similar to the ones done in a paper by Ebin and Marsden [8], with (E, π) being a vector bundle, leads to,

$$T_\eta \text{Diff}^s(M) = \{u \in H^s(M, TM) : \eta = \pi \circ u, g(u\eta^{-1}, n) = 0 \text{ on } \partial M, \text{div}(u\eta^{-1}) = 0\}.$$

That is,

Lemma 2.2.7. *Let M be a manifold, (E, π) be a vector bundle on M and $\xi = u\eta^{-1}$. Then the tangent space of $\text{Diff}^s(M)$ at η is,*

$$T_\eta \text{Diff}^s(M) = \{u \in \mathfrak{X}^s(M) : g(\xi, n) = 0 \text{ on } \partial M, \text{div}(\xi) = 0\},$$

with a map $\eta = \pi \circ u$ from the vector bundle to connect the group and tangent space.

Proof. See [8]. □

We now can define the structure-preserving group,

Definition 2.2.8 (Structure Preserving Diffeomorphism Group with Boundary). *Let M be a manifold, then $\text{Diff}^s(M)$ be as defined above and μ be the volume form of M . Then, the structure-preserving diffeomorphism group with boundary is,*

$$\text{SDiff}^s(M) = \{\eta \in \text{Diff}^s(M) : \eta^* \mu = \mu\}.$$

For all our groups, we note that the left action is class C^r , the right action is C^∞ and inversion, $\eta \mapsto \eta^{-1}$, is C^0 and further not Lipschitz continuous. Hence, we now work with topological groups with smooth right action.

2.2.3 Three more diffeomorphism groups

We define the following: let a diffeomorphism have a smoothness class. This smoothness class is a Hilbert H^s class. In practicality, we will assume we have diffeomorphisms that are sufficiently smooth enough to do the construction, but it is helpful to mention restrictions on this theory. We introduce a few bits of differential geometry,

Definition 2.2.9 (Weingarten map). *Let (M, g) be a Riemannian manifold, $p \in M$, n be the normal field, and v be a tangent vector. Then the Weingarten map (shape operator) is a map $S : T_p M \rightarrow T_p M$, defined by,*

$$S(n) = -\nabla_v n$$

We can introduce our three diffeomorphism groups,

Definition 2.2.10 (Neumann Group). *Let M be a manifold and N be its normal bundle. Then, the Neumann group is defined as,*

$$\text{SDiff}_N^s(M) = \{\eta \in \text{SDiff}^s(M) : T\eta \cdot n|_{\partial M} \in H^{s-3/2}(N) \text{ for all } n \in H^{s-1/2}(N)\}$$

Definition 2.2.11 (Dirichlet Group). *Let M be a manifold. Then, the Dirichlet group is defined as,*

$$\text{SDiff}_D^s(M) = \{\eta \in \text{SDiff}^s(M) : \eta|_{\partial M} = \text{Id}\}$$

Definition 2.2.12 (Mixed Group). *Let M be a manifold and N be its normal bundle. Let the boundary $\partial M = \Gamma_1 \cup \Gamma_2$ and $\overline{\Gamma_1} = M \setminus \Gamma_2$. Then, the mixed group is,*

$$\begin{aligned} \text{SDiff}_{\text{Mi}}^s(M) = \{ \eta \in \text{SDiff}^s(M) : & \eta(\Gamma_i) = \Gamma_i, T\eta \cdot n|_{\Gamma_2} \in H^{s-3/2}(N|_{\Gamma_1}) \\ & \text{for all } n \in H^{s-1/2}(N|_{\Gamma_1}), \eta|_{\Gamma_2} = \text{Id} \} \end{aligned}$$

Then their associated lie algebras

Definition 2.2.13 (Neumann Algebra). *Let M be a manifold and N be its normal bundle. Then, the Neumann algebra is defined as,*

$$T_e\text{SDiff}_N^s(M) = \{u \in T_e\text{SDiff}^s(M) : 0 = (\nabla_n u|_{\partial M})^{\text{tan}} + S_n(u) \in H^{s-3/2}(T\partial M) \text{ for all } n \in H^{s-1/2}(N)\}$$

Definition 2.2.14 (Dirichlet Algebra). *Let M be a manifold. Then, the Dirichlet algebra is defined as,*

$$T_e\text{SDiff}_D^s(M) = \{u \in T_e\text{SDiff}^s(M) : u|_{\partial M} = 0\}$$

Definition 2.2.15 (Mixed Algebra). *Let M be a manifold and N be its normal bundle. Let the boundary $\partial M = \Gamma_1 \cup \Gamma_2$ and $\overline{\Gamma_1} = M \setminus \Gamma_2$. Then, the Mixed algebra is defined as,*

$$T_e\text{SDiff}_{\text{Mi}}^s(M) = \{u \in T_e\text{SDiff}^s(M) : 0 = (\nabla_n u|_{\partial M})^{\text{tan}} + S_n(u) \in H^{s-3/2}(T\Gamma_2) \\ \text{for all } n \in H^{s-1/2}(N|_{\Gamma_2}), u|_{\Gamma_1} = 0\}$$

Now, we can prove the required theorem about how this relates to Euler-Poincaré equations.

Theorem 2.2.16 (Advection Euler-Poincare with Boundary Conditions). *Let G be a C^∞ topological group, either $\text{SDiff}_N^s(M)$, $\text{SDiff}_D^s(M)$ or $\text{SDiff}_{\text{Mi}}^s(M)$ and $\ell : \mathfrak{g} \times V^* \rightarrow \mathfrak{g}$ be a reduced Lagrangian of the form $\ell(\xi, a) = \tilde{\ell}(\xi, a) + b(\xi, a)$ where b is the tangent space boundary operator. Then the Euler-Poincaré equations for a system with advected quantities (similarly for no advected quantities) have the following form*

$$\frac{d}{dt} \frac{\delta \tilde{\ell}}{\delta \xi} - \text{ad}_\xi^* \frac{\delta \tilde{\ell}}{\delta \xi} + a \diamond \frac{\delta \tilde{\ell}}{\delta a} = 0 \\ b(\xi, a) = 0. \quad (2.8)$$

Proof. We seek to calculate the Euler-Poincaré equations for $\ell(\xi, a) = \tilde{\ell}(\xi, a) + b(\xi, a)$ via Hamilton's principle. Then, show that no extra erroneous terms appear. Then, finally, as b vanishes at the boundary, the terms on the boundary should vanish. We note that any term involving b is considered at the boundary. The calculation is standard until we reach,

$$\delta \int_{t_1}^{t_2} -\frac{\partial}{\partial t} \left(\frac{\delta \tilde{\ell}}{\delta \xi} + \frac{\delta b}{\delta \xi} \right) - \text{ad}_\xi \left(\frac{\delta \tilde{\ell}}{\delta \xi} + \frac{\delta b}{\delta \xi} \right) + a \diamond \left(\frac{\delta \tilde{\ell}}{\delta a} + \frac{\delta b}{\delta a} \right) dt = 0$$

We note that we can decouple the boundary terms,

$$\frac{\partial}{\partial t} \frac{\delta b}{\delta \xi} = -\text{ad}_\xi^* \frac{\delta b}{\delta \xi} + a \diamond \frac{\delta b}{\delta a}.$$

Then we know if $b(\xi, a) = 0$, this vanishes in the above. Hence we have,

$$\frac{d}{dt} \frac{\delta \tilde{\ell}}{\delta \xi} - \text{ad}_\xi^* \frac{\delta \tilde{\ell}}{\delta \xi} + a \diamond \frac{\delta \tilde{\ell}}{\delta a} = 0 \\ b(\xi, a) = 0.$$

□

2.3 Lie-Poisson Equation

There are two different formalisations of mechanics. Lagrangian, which we saw above, and Hamiltonian. These two formalisms come from the idea that,

$$L = K - V \quad H = K + V,$$

Furthermore, Lagrangian dynamics happen in the tangent space of the manifold and Hamiltonian dynamics happen in the cotangent space of the manifold. The Euler-Poincaré and Lie-Poisson equations relate to dynamics in the cotangent space. This implies there is some way to get between them. This is called the Legendre transform.

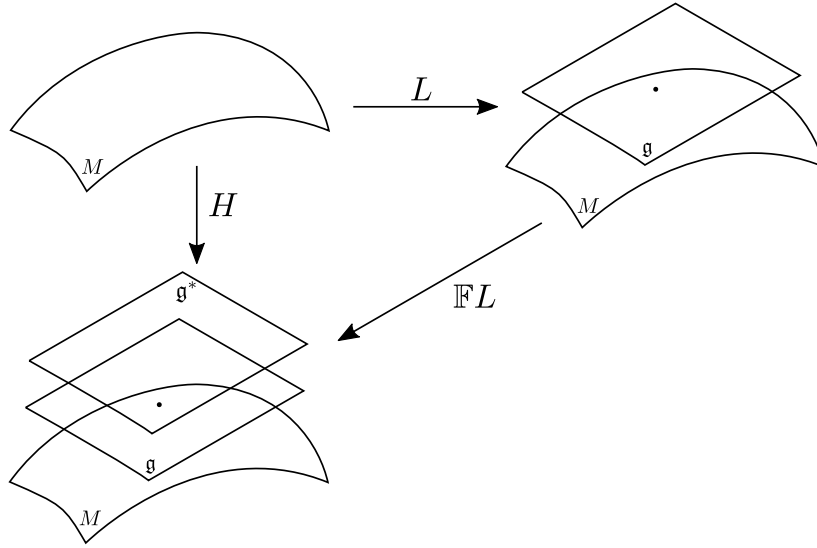


Figure 2.1: Dynamics and Legendre Transform.

In this section, we will study how to reduce Hamiltonians via Lie-Poisson reduction and then show why reducing on the Lagrangian via Euler-Poincaré reduction is usually better and then use the Legendre transform. We will see that the reduction of the Lagrangian is a lot neater and further replicates most of the modern theory. Many older Geometric Mechanics on fluids by Marsden and Arnold were mainly dedicated to Hamiltonian structures. This is because of the close connection with conserved quantities and the intuitiveness of Hamiltonians being total energy.

Several different ideas arise in this area. We will look more closely at non-canonical Lie-Poisson brackets and how to calculate them and hint at the relation to Casimirs before discussing them in greater detail in the next section.

We aim to study the way to get between Lagrangian and Hamiltonian through the Legendre transform. We include an excerpt from the author's special topic on Mechanical Mathematical Biology [4] that is relevant here.

2.3.1 Legendre Transform

Between Hamiltonians and Lagrangians, we are just working with a change of sign. A Hamiltonian is $K + V$ and a Lagrangian is $K - V$. However, if we have a Hamiltonian and want a Lagrangian, it is not necessarily obvious how to get between them. This is where the Legendre transform comes in. The Legendre transform is used in mechanics to go between a set of variables and their conjugate variables—for example, velocity and momentum. Regarding geometry, we know that Lagrangian mechanics happens on the tangent space of a manifold while Hamiltonian mechanics happens on the cotangent space of a manifold. Hence, the Legendre transform is a map between the tangent and cotangent spaces that preserves a conserved quantity, transforming from the Lagrangian to the Hamiltonian or vice versa. We will briefly show the theory and derive the Legendre transform for this problem.

Let M be a manifold and (E, π) be a vector bundle. We quickly define a vector bundle [3].

Definition 2.3.1 (Vector Bundle). *A \mathbb{k} -vector bundle over M of rank k consists of; a bundle $\pi : E \rightarrow M$ whose fibers are \mathbb{k} -vector spaces and around each point $p \in M$, there is some open $U \subset M$ and a diffeomorphism $\Phi : U \times \mathbb{k}^k \rightarrow E|_U$ such that,*

- $\pi \circ \Phi = \pi_1$ where $\pi_1 : U \times \mathbb{k}^k \rightarrow U$ is the projection of the first factor, and,
- for each $q \in U$, the map $\Phi_q : \mathbb{k}^k \rightarrow E_q$ such that $\Phi_q(\xi) := \Phi(q, \xi)$ is a \mathbb{k} -linear isomorphism.

Let $L : E \rightarrow \mathbb{R}$ be a smooth function known as the Lagrangian. The Legendre transformation is a smooth map between E and E^* , the dual of E ,

$$\mathbb{F}L : E \rightarrow E^*.$$

We define it by, $\mathbb{F}L(v) = d(L|_{E_x})$, where E_x is the fiber of E over $x \in M$. This says we take a covector and map it to the directional derivative.

This localises via a trivialisation to just saying,

$$p_i = \frac{\partial L}{\partial q_i}.$$

This is exactly how we get between conjugate and generalised variables in the derivation of Hamilton's equations. Then further, in our case, $E = TM$ and $E^* = T^*M$. This leads to the Legendre transform being an isomorphism and further a diffeomorphism. Then we reach the Legendre transform being,

$$L(v) = H(p) - p \cdot v,$$

and further, $\mathbb{F}L = (\mathbb{F}H)^{-1}$, by using the natural isomorphism $TM \cong T^*M$ [13]. More specifically, we can write,

$$\langle \mathbb{F}L(v), w \rangle := \left. \frac{d}{ds} L(v + sw) \right|_{s=0}.$$

In much the same way as Euler-Poincaré, Lie-Poisson reduction is a method to reduce equations into a more amenable form to consider conserved quantities and write numerical methods via symmetries. We will study two main things: reduced Legendre transforms and the non-canonical brackets.

2.3.2 The Reduced Legendre Transform

The next two subsections follow Holm, Schmah and Stoica [13], but we note that we consider a right-invariant version, while Holm considers a left-invariant system. We also loosely cite Vasylykevych and Marsden's paper [25]. We first can note some more theories about the regular Legendre transform. We define a class of Lagrangians called hyperregular Lagrangians,

Definition 2.3.2 (Hyperregular). *A hyperregular Lagrangian is a Lagrangian where the Legendre transform is a diffeomorphism, and the Hessian of the Lagrangian is invertible.*

Then, we can say that any system with a hyperregular Lagrangian has a guaranteed Hamiltonian related to it. This is because we have produced a differentiable bijection that is non-degenerate. For the rest of this thesis, we will assume that our Lagrangians are hyperregular. We can now define the reduced Legendre transform,

Definition 2.3.3 (Reduced Legendre transform). *Let $L : TG \rightarrow \mathbb{R}$ be hyperregular and $\ell : \mathfrak{g} \rightarrow \mathbb{R}$ be the reduced Lagrangian defined by $\ell(\xi) = L(e, \xi)$. Then the reduced Legendre transform, $\mathbb{f}l : \mathfrak{g} \rightarrow \mathfrak{g}^*$, is defined by,*

$$\langle \mathbb{f}l(\xi), \eta \rangle := \left. \frac{d}{ds} \ell(\xi + s\eta) \right|_{s=0} = \left\langle \frac{\delta \ell}{\delta \xi}, \eta \right\rangle. \quad (2.9)$$

We want to show invariance on the Lagrangian leads to invariance in the Hamiltonian. We first define a special type of invariance,

Definition 2.3.4 (G-invariance). *Let G be a Group, then we say that a Lagrangian is G -invariant if for any $g_0 \in G$,*

$$L(qg_0, \dot{q}g_0) = L(q, \dot{q})$$

Lemma 2.3.5. *Let M be a manifold, $L : TM \rightarrow \mathbb{R}$ be G -invariant, then $\mathbb{F}L$ is G -invariant.*

Proof. Let $g_0 \in G$. We will consider the following calculation,

$$\begin{aligned} \langle \mathbb{F}L(\mathbf{q}g_0, \dot{\mathbf{q}}_1g_0), (\mathbf{q}g_0, \dot{\mathbf{q}}_2g_0) \rangle &= \left. \frac{d}{dt} L(\mathbf{q}g_0, \dot{\mathbf{q}}_1g_0 + t\dot{\mathbf{q}}_2g_0) \right|_{t=0} \\ &= \left. \frac{d}{dt} L((\mathbf{q}, \dot{\mathbf{q}}_1 + t\dot{\mathbf{q}}_2)g_0) \right|_{t=0} \\ &= \left. \frac{d}{dt} L(\mathbf{q}, \dot{\mathbf{q}}_1 + t\dot{\mathbf{q}}_2) \right|_{t=0} \\ &= \langle \mathbb{F}L(\mathbf{q}, \dot{\mathbf{q}}_1), (\mathbf{q}, \dot{\mathbf{q}}_2) \rangle \end{aligned}$$

Therefore, $\mathbb{F}L(\mathbf{q}g_0, \dot{\mathbf{q}}g_0) = \mathbb{F}L(\mathbf{q}, \dot{\mathbf{q}})$ and so $\mathbb{F}L$ is G -invariant. \square

This lemma tells us that if our Lagrangian is G -invariant, then the Legendre transform in G -invariant and as $H = E \circ (\mathbb{F}L)^{-1}$, where E is invariant from the Lagrangian, the Hamiltonian is invariant! We can now define these reduced quantities similarly to the full quantities, prove similar lemmas, and prove finally that the reduced Hamiltonian is reduced. We call the reduced energy, $\tilde{e} : \mathfrak{g} \rightarrow \mathbb{R}$, defined by

$$\tilde{e}(\xi) = \langle \mathbb{f}l(\xi), \xi \rangle - \ell(\xi),$$

and the reduced Hamiltonian, $h : \mathfrak{g}^* \rightarrow \mathbb{R}$ defined by,

$$h(\mu) = \tilde{e} \circ \mathbb{f}l^{-1}.$$

We can name $\mu = \mathbb{f}l(\xi)$ and then we get,

$$h(\mu) = \tilde{e} \circ \mathbb{f}l^{-1}(\mu) = \langle \mu, \xi(\mu) \rangle - \ell(\xi(\mu)).$$

Lemma 2.3.6. *Let M be a Fréchet Manifold, then $L : TM \rightarrow \mathbb{R}$ be a G invariant Lagrangian. If E is full energy, and \tilde{e} is reduced energy corresponding to L and $\xi = gg^{-1}$, then,*

$$\tilde{e}(\xi) = E(e, \xi) = E(g \dot{g}).$$

Suppose L is hyperregular and H is the Hamiltonian corresponding to L . If $\mu = g^{-1}\alpha$, then,

$$h(\mu) = (e, \xi) = H(g, \alpha)$$

Proof. We consider the full energy, then reduce,

$$\begin{aligned} \langle \mathbb{F}L(g, \dot{g}), (g, \dot{g}) \rangle - L(g, \dot{g}) &= \langle \mathbb{F}L(gg^{-1}, \dot{g}g^{-1}), (gg^{-1}, \dot{g}g^{-1}) \rangle - L(gg^{-1}, \dot{g}g^{-1}) \\ &= \langle \mathbb{F}L(e, \xi), (e, \xi) \rangle - L(e, \xi) \\ &= \langle \mathbb{f}l(\xi), (e, \xi) \rangle - \ell(\xi) \\ &= \langle (e, \mathbb{f}l(\xi)), (e, \xi) \rangle - \ell(\xi) \\ &= \langle \mathbb{f}l(\xi), \xi \rangle - \ell(\xi) = \tilde{e}(\xi). \end{aligned}$$

Then, the final part of the proof follows from energy and the Legendre transform being G -invariant. Then noting that $H = E \circ (\mathbb{F}L)^{-1}$ and running through a reduction procedure and noticing the reduction variable ends up being $g^{-1}\alpha$. \square

2.3.3 Derivation of Lie-Poisson

We will now move from the Euler-Poincaré equations via the reduced Legendre transform to the Lie-Poisson equations. The Legendre transform moves invariances from the Lagrangian to the Hamiltonian side. The derivation is very similar to Hamilton's equations derivation. We consider the following application of product rule and Equation 2.9,

$$\begin{aligned} \frac{\delta h}{\delta \mu} &= \left\langle \mu, \frac{\delta \xi}{\delta \mu} \right\rangle - \left\langle \frac{\delta \ell}{\delta \xi}, \frac{\delta \xi}{\delta \mu} \right\rangle + \xi(\mu) \\ &= \left\langle \mu, \frac{\delta \xi}{\delta \mu} \right\rangle - \left\langle \mu, \frac{\delta \ell}{\delta \mu} \right\rangle + \xi(\mu) \\ &= \xi(\mu). \end{aligned}$$

Given this, we can now take the basic Euler-Poincaré equations and then rewrite them as follows,

$$\dot{\mu} = -\text{ad}_{\frac{\delta h}{\delta \mu}}^* \mu.$$

This is the Lie-Poisson Equation! An equivalent derivation is from the right invariant Poisson bracket. For any two smooth functions on the manifold $F, G : M \rightarrow \mathbb{R}$, we can define the canonical Poisson bracket as,

$$\{F, G\}_{\mathfrak{g}^*}^{\text{right}} = \left\langle \mu, \left[\frac{\delta F}{\delta \mu}, \frac{\delta G}{\delta \mu} \right] \right\rangle.$$

The Lie-Poisson reduction theorem is redundant as we will reduce on the Lagrangian side. However for completeness we include it,

Theorem 2.3.7 (Lie-Poisson Reduction). *Let G be a Lie Group, then \mathfrak{g}^* be the dual Lie algebra. If $\mathcal{F}_R(\mathfrak{g}^*)$ is the set of right G -invariant functions, then the right Lie-Poisson bracket is,*

$$\{F, G\}_{\mathfrak{g}^*}^{\text{right}} = \left\langle \mu, \left[\frac{\delta F}{\delta \mu}, \frac{\delta G}{\delta \mu} \right] \right\rangle.$$

Further, this relates to the reduced bracket on T^*G/G via the isomorphism,

$$\begin{aligned} \psi : (T^* * G/G) &\mapsto \mathfrak{g}^* \\ [g, \alpha] &\mapsto g^{-1}\alpha \end{aligned}$$

Further, we have a reconstruction equation,

$$\dot{g} = g \frac{\delta h}{\delta \mu}.$$

This can be proven from momentum maps, from Appendix [INSERT APPENDIX](#)

2.3.4 Lie-Poisson Reduction for advected quantities

We note that given a Lie algebra $\mathfrak{s} = \mathfrak{g} \ltimes V^*$. Then, we can start to derive the same equations as above for semidirect products. We consider the following two actions: the adjoint and the coadjoint. We can write these as,

Proposition 2.3.8 (Adjoint Action). *The adjoint action on $\mathfrak{g} \ltimes V^*$ is,*

$$\text{Ad}_{(g,v)}(\xi, u) = (\text{Ad}_g \xi, u g^{-1} + v g^{-1} \text{Ad}_g \xi)$$

Proof. We consider the following calculation,

$$\begin{aligned} \text{Ad}_{(g,v)}(\xi, u) &= (g, v) * (\xi, u) * (g, v)^{-1} \\ &= (g\xi, u + v\xi) * (g^{-1}, -vg^{-1}) \\ &= (g\xi g^{-1}, -vg^{-1} + (u + v\xi)g^{-1}) \\ &= (g\xi g^{-1}, -vg^{-1} + ug^{-1} + v\xi g^{-1}) \\ &= (\text{Ad}_g \xi, v g^{-1} \text{Ad}_g \xi - v g^{-1}), \end{aligned}$$

as required. □

We can do something similar for the coadjoint action,

Proposition 2.3.9. *The coadjoint action on $\mathfrak{g} \ltimes V^*$ is,*

$$\text{Ad}_{(g,v)^{-1}}^*(\mu, a) = (\text{Ad}_{g^{-1}} \mu - g \diamond (v^{-1}ga), g \diamond a)$$

Proof. We consider the trace pairing of the coadjoint action and then construct the required result.

$$\begin{aligned} \langle \text{Ad}_{(g,v)^{-1}}^*(\mu, a), (\nu_1, \nu_2) \rangle &= \langle (\mu, a), \text{Ad}_{(g,v)^{-1}}(\nu_1, \nu_2) \rangle \\ &= \langle (\mu, a), (g, v)^{-1}(\nu_1, \nu_2)(g, v) \rangle \\ &= \langle (\mu, a), (g^{-1}, -vg^{-1})(\nu_1, \nu_2)(g, v) \rangle \\ &= \langle (\mu, a), (g^{-1}\nu_1, \nu_2 - vg^{-1}\nu_1)(g, v) \rangle \\ &= \langle (\mu, a), (g^{-1}\nu_1g, v + (\nu_2 - vg^{-1}\nu_1)g) \rangle \\ &= \langle (\mu, a), (g^{-1}\nu_1g, v + \nu_2g - vg^{-1}\nu_1g) \rangle \\ &= (\langle \mu, \text{Ad}_{g^{-1}} \nu_1 \rangle, \langle a, v + \nu_2g - vg^{-1}\nu_1g \rangle) \\ &= (\langle \text{Ad}_{g^{-1}}^* \mu, \nu_1 \rangle, \langle a, v \rangle + \langle a, \nu_2g \rangle - \langle a, vg^{-1}\nu_1g \rangle) \\ &= (\langle \text{Ad}_{g^{-1}}^* \mu, \nu_1 \rangle, \langle g \diamond a, \nu_2 \rangle - \langle g \diamond (v^{-1}ga), \nu_1 \rangle) \\ &= \langle (\text{Ad}_{g^{-1}} \mu - g \diamond (v^{-1}ga), g \diamond a), (\nu_1, \nu_2) \rangle. \end{aligned}$$

Therefore,

$$\text{Ad}_{(g,v)^{-1}}^*(\mu, a) = (\text{Ad}_{g^{-1}} \mu - g \diamond (v^{-1}ga), g \diamond a)$$

□

We note the following facts about the semidirect products and Lie brackets,

We now recall the definition of the Lie-Poisson bracket we gave for the basic Lie-Poisson equations and apply it to $\mathfrak{s}^* = \mathfrak{g}^* \times V^*$.

$$\{F, G\}_{\mathfrak{s}} = \left\langle (\mu, a), \left[\frac{\delta F}{\delta(\mu, a)}, \frac{\delta G}{\delta(\mu, a)} \right] \right\rangle. \quad (2.10)$$

We can now prove,

Lemma 2.3.10. *The Lie-Poisson bracket for the Lie-Poisson equations with advected quantities is,*

$$\{F, G\}_{\mathfrak{s}^*} = \left\langle \mu, \left[\frac{\delta F}{\delta \mu}, \frac{\delta G}{\delta \mu} \right] \right\rangle + \left\langle a, \frac{\delta F}{\delta \mu} \frac{\delta G}{\delta a} - \frac{\delta G}{\delta \mu} \frac{\delta F}{\delta a} \right\rangle$$

Proof. Consider Equation 2.10, and the following computation,

$$\begin{aligned} \{F, G\}_{\mathfrak{s}^*} &= \left\langle (\mu, a), \left[\frac{\delta F}{\delta(\mu, a)}, \frac{\delta G}{\delta(\mu, a)} \right] \right\rangle \\ &= \left\langle (\mu, a), \left[\left(\frac{\delta F}{\delta \mu}, \frac{\delta F}{\delta a} \right), \left(\frac{\delta G}{\delta \mu}, \frac{\delta G}{\delta a} \right) \right] \right\rangle \\ &= \left\langle (\mu, a), - \left(\left[\frac{\delta F}{\delta \mu}, \frac{\delta G}{\delta \mu} \right], \frac{\delta G}{\delta a} \frac{\delta F}{\delta \mu} - \frac{\delta F}{\delta a} \frac{\delta G}{\delta \mu} \right) \right\rangle \\ &= \left\langle \mu, \left[\frac{\delta F}{\delta \mu}, \frac{\delta G}{\delta \mu} \right] \right\rangle + \left\langle a, \frac{\delta F}{\delta \mu} \frac{\delta G}{\delta a} - \frac{\delta G}{\delta \mu} \frac{\delta F}{\delta a} \right\rangle. \end{aligned}$$

□

We can now further manipulate to prove the following,

Theorem 2.3.11 (Lie-Poisson Equations for advected parameters). *The Lie-Poisson equations for a system with advected parameters are,*

$$\begin{aligned}\frac{dh}{dt} &= -\text{ad}_{\frac{\delta h}{\delta t}}^* \mu + \frac{\delta h}{\delta a} \diamond a \\ \frac{da}{dt} &= \frac{\delta h}{\delta \mu} a\end{aligned}\tag{2.11}$$

Proof. Consider the following calculation,

$$\begin{aligned}\{F, H\}_{\mathfrak{s}} &= \left\langle \mu, \left[\frac{\delta F}{\delta \mu}, \frac{\delta G}{\delta \mu} \right] \right\rangle + \left\langle a, \frac{\delta F}{\delta \mu} \frac{\delta G}{\delta a} - \frac{\delta G}{\delta \mu} \frac{\delta F}{\delta a} \right\rangle \\ &= \left\langle \mu, -\left[\frac{\delta G}{\delta \mu}, \frac{\delta F}{\delta \mu} \right] \right\rangle + \left\langle a, \frac{\delta F}{\delta \mu} \frac{\delta G}{\delta a} \right\rangle - \left\langle a, \frac{\delta G}{\delta \mu} \frac{\delta F}{\delta a} \right\rangle \\ &= \left(\left\langle -\text{ad}_{\frac{\delta G}{\delta \mu}}^* \mu, \frac{\delta F}{\delta \mu} \right\rangle, \left\langle \frac{\delta G}{\delta a} \diamond a, \frac{\delta F}{\delta \mu} \right\rangle - \left\langle a \frac{\delta G}{\delta \mu}, \frac{\delta F}{\delta a} \right\rangle \right) \\ &= \left\langle \left(-\text{ad}_{\frac{\delta G}{\delta \mu}}^* \mu + \frac{\delta G}{\delta a} \diamond a, -\frac{\delta G}{\delta a} a \right), \left(\frac{\delta F}{\delta \mu}, \frac{\delta F}{\delta a} \right) \right\rangle\end{aligned}$$

Then, we can decompose the inner products and pairings. Let $G = h$, and we can now write,

$$\begin{aligned}\frac{dh}{dt} &= -\text{ad}_{\frac{\delta h}{\delta t}}^* \mu + \frac{\delta h}{\delta a} \diamond a \\ \frac{da}{dt} &= \frac{\delta h}{\delta \mu} a\end{aligned}\tag{2.12}$$

□

Chapter 3

Conservation

As long as algebra and geometry have been separated, their progress has been slow and their uses limited; but when these two sciences have been united, they have lent each mutual forces and have marched together towards perfection.

Joseph-Louis Lagrange

In Noether's very influential paper in 1918, named 'Invariante Variationsprobleme' [21], she stated one of the most important theorems in conservation. This was to be known as Noether's theorem. She stated, '*Every differentiable symmetry generated by local actions has a corresponding conserved current.*' This innocuous-looking theorem would lead to many years of work to find these conserved currents. The theorem said a little about how to find these quantities for the Euler-Lagrange, but there is an analogous result for Euler-Poincaré. These theorems then need to be derived for every new type of Euler-Poincaré equation. Noether's theorems apply to the Lagrangian framework. To calculate conserved quantities for the Hamiltonian framework, you go to consider Casimir's and Poisson brackets.

In this penultimate chapter, we will discuss the conservation properties of the Euler-Poincaré and Lie-Poisson equations. We will take two different routes to find the quantities depending on what framework we work under. Firstly, we will return to the Lagrangian framework and study the Noether Theorems for Euler-Poincaré theory and then consider a generalisation of these theorems called the Kelvin-Noether theorems which relate to first integrals over a path in our flow. We will then study the Hamiltonian point of view by returning to Lie-Poisson brackets, considering Casimirs and showing that certain functions that make the brackets vanish are conserved. We will also consider the relation between conserved quantities and Reeb graphs, another potential area for exploration in future work. Finally, we will attempt to show numerically that these quantities are conserved and conclude with ideas relating to extending numerical methods with the preceding theory to guarantee that the conserved quantities are conserved.

3.1 Noether Theorems

Noether Theorems can be derived from the variational principle and reduction. The process involves considering the terms we made vanish to produce the equations. We can state and prove the Noether Theorem for Euler-Poincaré equations with advected parameters.

Theorem 3.1.1 (Noether Theorem for Euler-Poincaré with advected parameters). *Each symmetry vector field of the Euler-Poincaré reduced lagrangian for the infinitesimal variations,*

$$\delta u = \dot{\nu} - \text{ad}_u \nu \quad \delta a = -\nu a,$$

corresponds to an integral of the Euler-Poincaré motion and a conserved quantity,

$$\frac{d}{dt} \int_M \left\langle \frac{\delta \ell}{\delta u}, \nu \right\rangle \mu = 0$$

Proof. We will consider the derivation of the Euler-Poincaré equations for advection parameters. Then jump to the integration by parts of the $\frac{\partial u}{\partial t}$ term.

$$\begin{aligned} 0 &= \int_{t_1}^{t_2} \int_M \left\langle \frac{\delta \ell}{\delta u}, \frac{\partial \nu}{\partial t} \right\rangle - \left\langle \text{ad}_u^* \frac{\partial \ell}{\partial u}, \nu \right\rangle + \left\langle a \diamond \frac{\delta \ell}{\delta a}, \nu \right\rangle dt \\ &= \int_{t_1}^{t_2} \int_M \left\langle -\frac{\partial}{\partial t} \frac{\delta \ell}{\delta u} - \text{ad}_u^* \frac{\partial \ell}{\partial u} + a \diamond \frac{\delta \ell}{\delta a}, \nu \right\rangle dt + \int_M \left\langle \frac{\delta \ell}{\delta u}, \nu \right\rangle \Big|_{t_1}^{t_2} \mu. \end{aligned}$$

We now note that the first pairing is just the Euler-Poincaré equations. Hence, we now can write,

$$\frac{d}{dt} \int_M \left\langle \frac{\delta \ell}{\delta u}, \nu \right\rangle \mu = 0,$$

as we use the fundamental theorem of calculus of variations. □

3.1.1 Vorticity and Helicity

We can now prove two lemmas for the specific case of the Euler Equations in barotropic fluids. The advective quantity is going to be $a = \rho dV$ and then the infinitesimal symmetry for a becomes,

$$\mathcal{L}_\eta(\rho dV) = d(\eta \lrcorner \rho dV) = 0.$$

Using rules from the appendix, this can now be written as for some vector function, Ψ ,

$$\eta \lrcorner \rho dV = d(\Psi \cdot d\mathbf{x}) = \text{curl } \Psi \cdot d\mathbf{S}. \quad (3.1)$$

Lemma 3.1.2 (Conservation of Vorticity). *In the Euler-Poincaré equations for advected quantities, the following holds and relates to vorticity being conserved,*

$$\left(\frac{d}{dt} + \mathcal{L}_u \right) \left(\text{curl } \frac{1}{\rho} \frac{\delta \ell}{\delta u} \cdot d\mathbf{S} \right) = 0. \quad (3.2)$$

Proof. We start with Noether's theorem for these equations and then perform a calculation.

$$\begin{aligned}
0 &= \frac{d}{dt} \left\langle \frac{\delta \ell}{\delta \mathbf{u}}, \eta \right\rangle \\
&= \frac{d}{dt} \int_M \frac{\delta \ell}{\delta \mathbf{u}} \cdot \eta \, dV \\
&= \frac{d}{dt} \int_M \frac{1}{\rho} \frac{\delta \ell}{\delta \mathbf{u}} \cdot d\mathbf{x} \wedge \eta \lrcorner (\rho \, dV) \\
&= \int_M \frac{\partial}{\partial t} \frac{1}{\rho} \frac{\delta \ell}{\delta \mathbf{u}} \wedge d(\Psi \cdot d\mathbf{x}) + \frac{1}{\rho} \frac{\delta \ell}{\delta \mathbf{u}} \wedge \frac{\partial}{\partial t} d(\Psi \cdot d\mathbf{x}) \\
&= - \int_M \left(\frac{\partial}{\partial t} d \left(\frac{1}{\rho} \frac{\delta \ell}{\delta \mathbf{u}} \cdot d\mathbf{x} \right) + \mathcal{L}_{\mathbf{u}} d \left(\frac{1}{\rho} \frac{\delta \ell}{\delta \mathbf{u}} \cdot d\mathbf{x} \right) \right) \wedge (\Psi \cdot d\mathbf{x}) \\
&= - \int_M \left(\left(\frac{\partial}{\partial t} + \mathcal{L}_{\mathbf{u}} \right) d \left(\frac{1}{\rho} \frac{\delta \ell}{\delta \mathbf{u}} \cdot d\mathbf{x} \right) \right) \wedge (\Psi \cdot d\mathbf{x})
\end{aligned}$$

Hence, we can say that, as we know, $\Psi \cdot d\mathbf{x} \neq 0$. Then the result appears after applying (3.1),

$$\begin{aligned}
0 &= \left(\frac{\partial}{\partial t} + \mathcal{L}_{\mathbf{u}} \right) d \left(\frac{1}{\rho} \frac{\delta \ell}{\delta \mathbf{u}} \cdot d\mathbf{x} \right) \\
&= \left(\frac{\partial}{\partial t} + \mathcal{L}_{\mathbf{u}} \right) \left(\text{curl} \frac{1}{\rho} \frac{\delta \ell}{\delta \mathbf{u}} \cdot d\mathbf{S} \right).
\end{aligned}$$

□

We now present two significant ideas in this area. We first iterated conserved quantities. Let us consider another vital theorem, called Ertel's theorem.

Theorem 3.1.3 (Ertel's Theorem). *If a quantity a satisfied the advection equation, and η satisfy $\delta\eta = \dot{\nu} + \text{ad}_{\eta}\nu$ for the labelling symmetry. Then $\mathcal{L}_{\eta}a$ is also advected.*

Proof. By a simple substitution, we find,

$$\mathcal{L}_{\eta} \left(\frac{\partial}{\partial t} + \mathcal{L}_{\mathbf{u}} \right) a = \left(\frac{\partial}{\partial t} + \mathcal{L}_{\mathbf{u}} \right) \mathcal{L}_{\eta} a = 0.$$

This is the advection equation. Hence, $\mathcal{L}_{\eta}a$ is advected by the flow. □

Consider a conserved quantity, $c(t)$; the flow carries this. Hence, we can say that $\mathcal{L}_{\mathbf{u}}c(t)$ is also conserved by the Euler-Poincaré equations. Hence, we can now consider a conserved quantity using the vorticity in (3.2). Hence, we can now set the vorticity as our conserved 2-form in (3.1).

$$d(\Psi \cdot d\mathbf{x}) = d \left(\frac{1}{\rho} \frac{\delta \ell}{\delta \mathbf{u}} \cdot d\mathbf{x} \right).$$

This will lead us to a new conserved quantity called Helicity. Helicity is a topological invariant sometimes known as the Hopf invariant. It measures the knottedness of the vortex lines and can also be used to calculate the number of linkages. As the vortex lines are baked in the Lagrangian and hence the flow, this quantity is always conserved.

Lemma 3.1.4 (Conservation of Helicity). *The Euler-Poincaré equations for advected quantities, the following holds and relates to the Helicity being conserved.*

$$\frac{d}{dt} \int_M \frac{1}{\rho} \frac{\delta \ell}{\delta \mathbf{u}} \cdot \text{curl} \left(\frac{1}{\rho} \frac{\delta \ell}{\delta \mathbf{u}} \right) dV$$

Proof. We start at the third step of the previous argument and then move forward differently,

$$\begin{aligned} 0 &= \frac{d}{dt} \int_M \left(\frac{1}{\rho} \frac{\delta \ell}{\delta \mathbf{u}} \cdot d\mathbf{x} \right) \wedge \eta \lrcorner (\rho dV) \\ &= \frac{d}{dt} \int_M \left(\frac{1}{\rho} \frac{\delta \ell}{\delta \mathbf{u}} \cdot d\mathbf{x} \right) \wedge d(\Psi \cdot d\mathbf{x}) \\ &= \frac{d}{dt} \int_M \left(\frac{1}{\rho} \frac{\delta \ell}{\delta \mathbf{u}} \cdot d\mathbf{x} \right) \wedge d \left(\frac{1}{\rho} \frac{\delta \ell}{\delta \mathbf{u}} \cdot d\mathbf{x} \right) \\ &= \frac{d}{dt} \int_M \frac{1}{\rho} \frac{\delta \ell}{\delta \mathbf{u}} \cdot \text{curl} \left(\frac{1}{\rho} \frac{\delta \ell}{\delta \mathbf{u}} \right) dV \end{aligned}$$

Therefore, we can write Helicity as,

$$\mathcal{H} := \int_M \frac{1}{\rho} \frac{\delta \ell}{\delta \mathbf{u}} \cdot \text{curl} \left(\frac{1}{\rho} \frac{\delta \ell}{\delta \mathbf{u}} \right) dV$$

□

3.1.2 Kelvin-Noether Theorem

We can now find other conservation quantities using similar ideas to the above. Consider the following change of variables,

$$\oint_{\gamma_t} \frac{1}{\rho_t} \frac{\delta \ell}{\delta \mathbf{u}} = \oint_{\gamma_0} \eta^* \left[\frac{1}{\rho_0} \frac{\delta \ell}{\delta \mathbf{u}} \right] = \oint_{\gamma_0} \frac{1}{\rho_0} \eta^* \left[\frac{\delta \ell}{\delta \mathbf{u}} \right].$$

Now, we can use the definition of the Lie derivative to write,

$$\frac{d}{dt}(\eta^* \alpha) = \eta^* \left(\frac{\partial}{\partial t} \alpha + \mathcal{L}_{\mathbf{u}} \alpha \right).$$

Hence, we can write,

$$\begin{aligned} \frac{d}{dt} \oint_{\gamma_t} \frac{1}{\rho_t} \frac{\delta \ell}{\delta \mathbf{u}} &= \oint_{\gamma_0} \frac{1}{\rho_0} \eta^* \left(\frac{\partial}{\partial t} \alpha + \mathcal{L}_{\mathbf{u}} \alpha \right) \\ &= \oint_{\gamma_t} \frac{1}{\rho_t} \left(\frac{\partial}{\partial t} \alpha + \mathcal{L}_{\mathbf{u}} \alpha \right) \\ &= \oint_{\gamma_t} \frac{1}{\rho_t} \frac{\delta \ell}{\delta a} \diamond a. \end{aligned}$$

The last step is from just considering the Euler-Poincaré equations for advected parameters. From this, we present the Kelvin-Noether theorem for advected Euler-Poincaré,

Theorem 3.1.5 (Kelvin-Noether Theorem for Euler Poincaré Equations). *For the Euler-Poincaré equation with advected quantities, we can write the following,*

$$\frac{d}{dt} \oint_{\gamma_t} \frac{1}{\rho_t} \frac{\delta \ell}{\delta \mathbf{u}} = \oint_{\gamma_t} \frac{1}{\rho_t} \frac{\delta \ell}{\delta a} \diamond a.$$

We have two remarks,

Remark 3.1.6. *For basic Euler-Poincaré equations, the following is a conserved quantity,*

$$\oint_{\gamma} \frac{1}{\rho} \frac{\delta \ell}{\delta \mathbf{u}}.$$

Remark 3.1.7. *We can write the Euler-Poincaré equations in Kelvin-Noether form,*

$$\left(\frac{\partial}{\partial t} + \mathcal{L}_{\mathbf{u}} \right) \frac{\delta \ell}{\delta \mathbf{u}} = \frac{\delta \ell}{\delta a} \diamond a.$$

3.2 Casimirs

First, we will consider the Hamiltonian formalism to find conserved quantities with the idea of Casimir's. Then, we will briefly examine the ideas surrounding Reeb graphs and their application to this area. We cite Kolev's paper [18] as a good overview of this area.

3.2.1 The Arnold Bracket

As stated by Arnold in Topological Methods in Hydrodynamics [26], we can find a Hamiltonian system description through a Poisson bracket. That is,

$$\dot{F} = \{F, H\}.$$

To be able to use these brackets, we have to show that on a space of smooth functions, \mathcal{F} , they create a Hamiltonian structure,

Definition 3.2.1 (Hamiltonian Structure). *A Hamiltonian structure is a bilinear operation, $\{\cdot, \cdot\}$ on the space of smooth functionals, \mathcal{F} , that satisfies the following, for any $F, G \in \mathcal{F}$,*

1. $\{F, G\} \in \mathcal{F}$,
2. $\{F, G\} = -\{G, F\}$,
3. $\{\{F, G\}, H\} + \{\{G, H\}, F\} + \{\{H, F\}, G\} = 0$.

Remark 3.2.2. *The well-trained eye will notice that $\{\cdot, \cdot\}$ isn't technically a Poisson bracket as it doesn't have a Liebnitz rule. This is because local functionals don't necessarily have this property.*

Our first bracket is the Arnold bracket. For functionals with L^2 gradients on the Lie algebra, it is defined as,

$$\{F, G\}(\omega) = \int_M \omega \left(\frac{\delta F}{\delta \omega}, \frac{\delta G}{\delta \omega} \right)$$

Proving this provides a Hamiltonian structure is a quick calculation of inner products. Further, this bracket is the Hamiltonian structure that relates to the incompressible Euler Equations. Recall we can write curl as follows,

$$\mu \lrcorner \text{curl } u = du^\flat,$$

and we know that the curl of a vector field relates to an exact 2-form. Hence, we can write an inertia operator $A : \text{SVect}(M) \rightarrow \text{SVect}^*(M)$ defined by $u \mapsto \text{curl } u$. Then we can say that $u = A^{-1}\omega$ is the unique solution of the Euler Equations subject to,

$$\text{curl } u = \omega \quad \text{div } u = 0 \quad u \cdot n = 0 \text{ on } \partial M.$$

Our Hamiltonian is going to be,

$$H(\omega) = \int_M |\mathbf{u}|^2 \mu,$$

and $dH = u = A^{-1}\omega$. Now we consider the L^2 gradient of \mathbf{u} , and we can derive,

$$\begin{aligned}\int_M \partial_t \mathbf{u} \cdot \delta F &= \int_M \partial_t (A^{-1}\omega) \cdot \delta F \\ &= \int_M \omega \cdot (\delta F \times \mathbf{u}) \\ &= \int_M \delta F \cdot (\mathbf{u} \times \omega).\end{aligned}$$

Therefore, our bracket provides the Hamiltonian system modulo a 1-form,

$$\partial_t \mathbf{u} = \mathbf{u} \times \omega.$$

This is the vorticity form of the Euler Equations. We can consider the pullback of this functional to get something more amicable to work with,

$$\{F, G\}(\omega) = \int_M \text{curl } \mathbf{u} \cdot \left(\frac{\delta F}{\delta \mathbf{u}} \times \frac{\delta G}{\delta \mathbf{u}} \right). \quad (3.3)$$

We can show that Helicity is conserved by finding the Casimir. We define a Casimir as,

Definition 3.2.3 (Casimir). *We define the Casimir as a smooth function $C : M \rightarrow \mathbb{R}$,*

$$\{C, H\} = 0.$$

Now we find the Casimirs of the bracket (3.3). We consider the following argument,

$$\begin{aligned}0 &= \int_M \text{curl } \mathbf{u} \cdot \left(\frac{\delta C}{\delta \mathbf{u}} \times \frac{\delta H}{\delta \mathbf{u}} \right) \mu \\ &= \int_M \text{curl } \mathbf{u} \cdot \left(\frac{\delta C}{\delta \mathbf{u}} \times \mathbf{u} \right) \mu \\ 0 &= - \int_M \frac{\delta C}{\delta \mathbf{u}} \cdot (\text{curl } \mathbf{u} \times \mathbf{u}) \mu \\ &= - \int_M \frac{\delta C}{\delta \mathbf{u}} \cdot \left((u \cdot \nabla)u - \frac{1}{2} \nabla(u^2) \right) \mu \\ &= \int_M -\frac{\delta C}{\delta \mathbf{u}} \cdot (u \cdot \nabla)u + \frac{1}{2} \frac{\delta C}{\delta \mathbf{u}} \cdot \nabla(u^2) \mu \\ &= \int_M \left(\frac{\delta C}{\delta \mathbf{u}} \cdot \partial_t \mathbf{u} + \frac{1}{2} \nabla \frac{\delta C}{\delta \mathbf{u}} \cdot \mathbf{u}^2 \right) \mu + \int_{\partial M} \frac{1}{2} \frac{\delta C}{\delta \mathbf{u}} \cdot (u^2 \cdot n) \mu_{\partial} \\ &= \int_M \left(\partial_t \frac{\delta C}{\delta \mathbf{u}} \cdot \mathbf{u} + \frac{1}{2} \nabla \frac{\delta C}{\delta \mathbf{u}} \cdot \mathbf{u}^2 \right) \mu + \left[\int_M \frac{1}{2} \frac{\delta C}{\delta \mathbf{u}} \cdot \mathbf{u} \mu \right]_{t_1}^{t_2} \\ &= \int_M \left(\partial_t \frac{\delta C}{\delta \mathbf{u}} + \frac{1}{2} \nabla \frac{\delta C}{\delta \mathbf{u}} \cdot \mathbf{u} \right) \cdot \mathbf{u} \mu + \left[\int_M \frac{1}{2} \frac{\delta C}{\delta \mathbf{u}} \cdot \mathbf{u} \mu \right]_{t_1}^{t_2}.\end{aligned}$$

Hence, we require,

$$\frac{\partial}{\partial t} \frac{\delta C}{\delta \mathbf{u}} + \frac{1}{2} \nabla \frac{\delta C}{\delta \mathbf{u}} \cdot \mathbf{u} = 0 \quad \frac{\delta C}{\delta \mathbf{u}} = 0 \text{ on } \partial M. \quad (3.4)$$

We note that when we let the Casimir be Helicity, the equation (3.4) turns into,

$$\int_M (\mathbf{u}_t + (\mathbf{u} \cdot \nabla) \mathbf{u}) \cdot (1 + \mathbf{u} \times \omega) + ((\omega_t + \mathbf{u} \cdot \nabla \omega) \times \mathbf{u}) \cdot \mathbf{u} = 0.$$

Hence, we have proven that Helicity is a Casimir. This bracket seems to be conserving what we want to conserve. Let us now look to enstrophy for a 2D system. We consider generalised enstrophy,

$$C(\omega) = \int_M \phi(\omega) dx \wedge dy.$$

We can take the Fréchet derivative,

$$DC(\omega) = \int_M \text{curl}(\phi'(\omega) \hat{\mathbf{k}}) d\alpha + \oint_{\partial M} \phi'(\omega) d\alpha.$$

Using the Arnold bracket requires the function's derivative to be an L^2 gradient. This isn't as it has boundary terms. Hence, the Arnold bracket doesn't conserve enstrophy. Further, if we set $\phi'(\omega) = 0$, we would fall back to enstrophy, which is covered by the conservation of Helicity. Hence, we need a stronger bracket.

In Zakharov's 1968 paper [28], he presented the following Hamiltonian system for irrotational waves,

$$H = \frac{1}{2} \iiint (\text{grad } \phi)^2 dV + \frac{1}{2} \lambda \iint \zeta^2 dS.$$

This was then generalised to include vorticity, and the bracket was found for a free boundary Σ and a velocity field v such that,

1. δv is a divergence-free vector field on some domain D_Σ . Further, we have a divergence-free vector field $\frac{\delta F}{\delta v}$ defined on some domain D_Σ such that,

$$D_v F(v, \Sigma) = \int_{D_\Sigma} \frac{\delta F}{\delta v} \cdot \delta v,$$

where D_v is the derivative with respect to v with Σ fixed.

2. Similarly, there's a $\delta \Sigma$ that's normal to Σ and some smooth function $\frac{\delta F}{\delta \Sigma}$ such that,

$$D_\Sigma F(v, \Sigma) = \int_{D_\Sigma} \frac{\delta F}{\delta \Sigma} \cdot \delta \Sigma.$$

Then the bracket is,

$$\{F, G\} = \int_{D_\Sigma} \omega \cdot \left(\frac{\delta F}{\delta v} \times \frac{\delta G}{\delta v} \right) + \int_\Sigma \left(\frac{\delta F}{\delta \Sigma} \frac{\delta G}{\delta \phi} - \frac{\delta G}{\delta \Sigma} \frac{\delta F}{\delta \phi} \right),$$

where $\omega = \text{curl } u$ and,

$$\frac{\delta F}{\delta \phi} = \frac{\delta F}{\delta v} \Big|_\Sigma \cdot n.$$

This proof of conservation here is more involved and will be covered in my PhD thesis.

3.2.2 Reeb Graphs

Another interesting way to derive the conserved quantities of a Hamiltonian system and derive all of the Casimir's of the system is to consider Reeb graphs of the manifold you work over. In this section, we will review and expose the work of Izosimov and Khesin [26, 16]. We will return to the problem we left in the previous section of proving in 2D that Enstrophy is conserved in the Hamiltonian form of the Euler Equations. There are two main theorems we are interested in, which give the following correspondences,

$$\text{Reeb Graphs} \longleftrightarrow \text{Morse Functions} \longleftarrow \text{Casimirs}$$

The two theorems that relate to this diagram are,

Theorem 3.2.4 (Reeb Graphs give Morse Functions). *The mapping assigning the measured Reeb graph Γ_F to a simple Morse function F provides a one-to-one correspondence between simple Morse functions on M up to symplectomorphism and measured Reeb graphs compatible with M .*

Theorem 3.2.5 (Casimirs are moments of the Morse functions). *A complete set of Casimirs to the 2D Euler Equation in a neighbourhood of a Morse-type coadjoint orbit is given by the momenta,*

$$I_{i,e} = \int_{M_e} F^i \omega, \quad i \in \mathbb{N},$$

for each $e \in \Gamma$ and all circulations of the velocity v over cycles in the singular levels of the vorticity function F on M .

We will now define Morse functions and measures reeb graphs and then give proof of Enstrophy being conserved in the 2D Euler Equations.

Definition 3.2.6 (Morse Function). *Let M be a closed connected space, then a morse function $F : M \rightarrow \mathbb{R}$ is called simple if any level set of F contains at most one critical point.*

Now, we can associate a graph with a morse function. To do this, we take each critical point of F and place a critical point of the graph there, as shown in Figure 3.1. We can

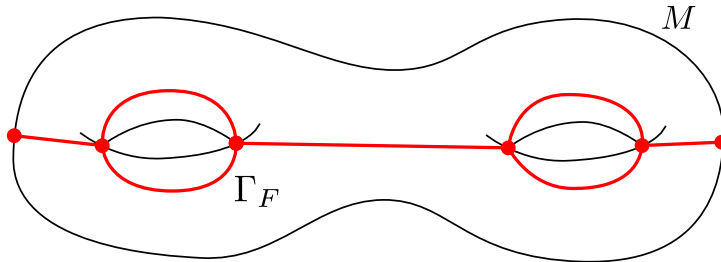


Figure 3.1: The Reeb Graph of a manifold.

now define a Reeb graph as follows,

Definition 3.2.7 (Reeb Graph). *A Reeb graph, (Γ, f) is an oriented smooth connected finite graph Γ with a continuous function $f : \Gamma \rightarrow \mathbb{R}$ which satisfy the following,*

1. All vertices of Γ are either 1-valent or 3-valent,
2. For each 3-valent vertex, there are either two incoming and two outgoing or vice versa,
3. The function f is strictly monotonous on each edge, and the edges of Γ are oriented towards the direction of increasing f .

It is a standard result in Morse theory that a graph Γ_F associated with a simple Morse function $F : M \rightarrow \mathbb{R}$ on an orientable connected surface is a Reeb graph. Further, if this surface is endowed with an area or symplectic form ω , then we can take the pullback of that form and define a measured reeb graph.

Definition 3.2.8 (Measured Reeb Graph). *Let (Γ, f) be a Reeb graph associated with a surface with symplectic form ω . Then we can define a measure $\mu = f^*\omega$. Then, a measured Reeb graph is a Reeb graph with a measure, (Γ, f, μ) .*

We can say that the simple Morse functions are the same as the measured Reeb graphs up to symplectomorphism under the following compatibility conditions.

Definition 3.2.9 (Compatible). *We say that a closed compact surface endowed with a symplectic form, (M, ω) , is compatible with a measured reeb graph, (Γ, f, μ) if the following are satisfied,*

1. The dimension of the first homology group [11], $H_1(\Gamma, \mathbb{R})$ is equal to the genus of M ,
2. The volume of Γ with respect to μ is the same as the volume of M ,

$$\int_{\Gamma} d\mu = \int_M \omega.$$

Then from this Theorem 3.2.4 follows.

Classifying coadjoint orbits

We note that the coadjoint action of $\text{SDiff}(M)$ on $\mathfrak{vect}(M)$ is just a symplectomorphism, a volume preserving map,

$$\text{Ad}_{\Phi}^*[\alpha] = [\Phi^*\alpha].$$

The orbits of this action can be described by $\mathbf{curl} : \Omega^1(M)/d\Omega^0(M) \rightarrow C^\infty(M)$ given by vorticity,

$$\mathbf{curl}[\alpha] := \frac{d\alpha}{\omega}.$$

This mapping is equivariant, which means that if two maps differ by a symplectomorphism, they are in the same coadjoint orbit as each other. Hence, all the simple Morse functions are in one coadjoint orbit.

Definition 3.2.10 (Morse-Type forms). *We say that a coset of 1-forms, $[\alpha] \in \mathfrak{vect}^*(M)$, is morse type if $\mathbf{curl}[\alpha]$ is a simple morse function. A coadjoint orbit is Morse-type if any coset is Morse-type.*

For the remainder, let $[\alpha] \in \mathbf{svect}^*(M)$ be morse-type and $F := \mathbf{curl}[\alpha]$. Then Γ_F is invariant under the coadjoint action! However, if M is not simply connected, our theory fails as the graph branches and causes issues. Hence, we use a circulation function to deal with branches. Let $\pi : M \rightarrow \Gamma_F$ be the natural projection. Take any point x in the interior of some edge $e \in \Gamma_F$. Then $\pi^{-1}(x)$ is a circle. It is naturally oriented, and the integral does not depend on α . Hence we have a function $\mathbf{c} : \Gamma_F \setminus V(\Gamma_F) \rightarrow \mathbb{R}$ defined by,

$$\mathbf{c}(x) := \int_{\pi^{-1}(x)} \alpha.$$

We now define yet another graph,

Definition 3.2.11 (Circulation Measured Reeb Graph). *A circulation measured Reeb graph, $(\Gamma, f, \mu, \mathbf{c})$, is a measured Reeb graph endowed with a circulation function $\mathbf{c} : \Gamma_F \setminus V(\Gamma_F) \rightarrow \mathbb{R}$ defined by,*

$$\mathbf{c}(x) := \int_{\pi^{-1}(x)} \alpha.$$

We note that non-circulation graphs work for us because Fluid Dynamics problems only have ‘pants decompositions’ and ‘Dehn half twists’. These more complicated ideas don’t arise in this example but should be considered for more complex phenomena. We can now prove that the following momenta,

$$m_{i,e}(F) = \int_{M_e} F^i \omega$$

form a complete set of invariants for the 2D Euler Equations.

Theorem 3.2.12. *Let (M, ω) be a closed connected symplectic surface, and let F and G be simple morse functions on M . Then let $\phi : \Gamma_F \rightarrow \Gamma_G$ be an isomorphism of abstract directed graphs which preserve moments on all edges. Then Γ_F and Γ_G are isomorphic as measured in Reeb graphs, and there is a symplectomorphism $\Phi : M \rightarrow M$ such that $\Phi_* F = G$*

Proof. We first construct two intervals of the two Reeb graphs. Let $[v, w] \in \Gamma_F$. Then we push forward by the measure using a homomorphism $f : e \rightarrow [v, w]$ we get a measure μ_f on an interval, $I_f = [f(v), f(w)]$ and similarly $I_g = [g(\phi(v)), g(\phi(w))]$ for $g : e \rightarrow [g(v), g(w)]$, we get a measure μ_g . These intervals have the same moments. We aim to prove that $\mu_f = \mu_g$. This follows from the Hausdorff moment problem. Consider an interval I that contains both I_f and I_g ; then the measures are measures of I supported on their respective intervals. Then, by the Hausdorff moment problem, $\mu_f = \mu_g$. \square

The above proves that if we take F as a Morse vorticity function for an ideal flow v on a closed surface M associated with a Reeb graph Γ . Then the moments of that graph $m_{i,e}(F)$ are just the generalised enstrophies,

$$m_{i,e}(F) = \int_{M_i} F^i \omega = \int_{M_i} \phi(\omega) dx \wedge dy,$$

in two dimensions. Then, you can single each conserved quantity out by Theorem 3.2.5, and we also have these conserved quantities of the 2D Euler Equations.

3.3 Numerics

Proving quantities are conserved is a great way of theoretically verifying our results are correct. However in practicality the reason that numerical analysts are interested in this area of mathematics is to create more precise numerical schemes. We shall now show that normal numerical schemes sometimes provide non-realistic solutions and show how we can produce more realistic results.

We shall take the standard Euler equations as a simplistic example to show our point. Consider the following Euler equation.

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} = 0.$$

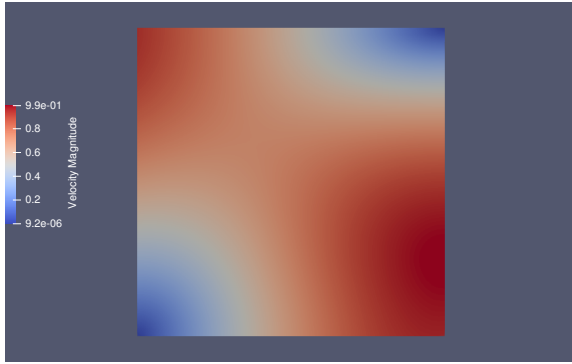
We can run a Crank-Nicholson scheme on this. It is well known that Crank-Nicholson is symplectic, that is it preserves the symplectic form. Further, this means that it conserves energy. These schemes can be adapted to conserve other quantities. To motivate these we consider a finite element scheme with a cubed 50×50 grid with order 2 Lagrange elements. We set an initial condition of,

$$u_0(x, y) = \left(-\cos\left(\frac{\pi x}{2}\right) \sin\left(\frac{\pi x}{2}\right), \sin\left(\frac{\pi x}{2}\right) \cos\left(\frac{\pi y}{2}\right) \right),$$

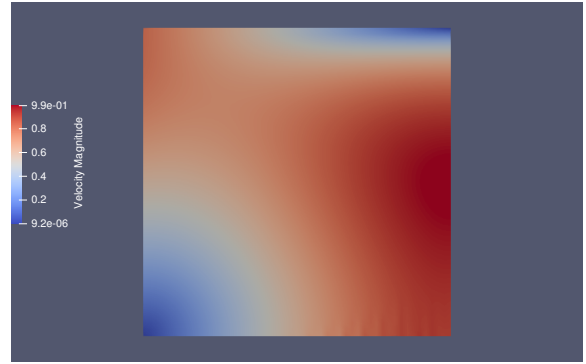
and Neumann boundary conditions. The finite element scheme solves for the spatial steps and we use a Crank-Nicholson for the temporal steps. Hence our scheme is,

$$\frac{\mathbf{u}^{n+1} - \mathbf{u}^n}{\Delta t} = \frac{1}{2} \left((\mathbf{u}^{n+1} \cdot \nabla) \mathbf{u}^{n+1} + (\mathbf{u}^n \cdot \nabla) \mathbf{u}^n \right).$$

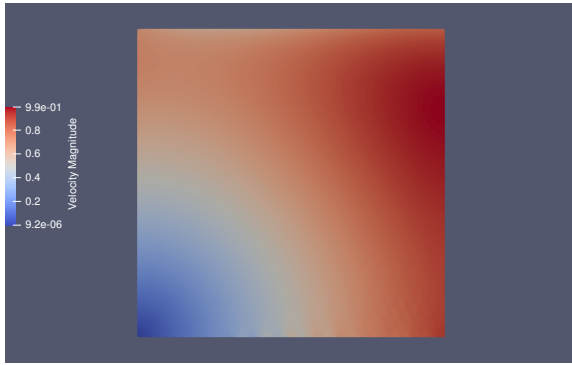
This produces the following simulation,



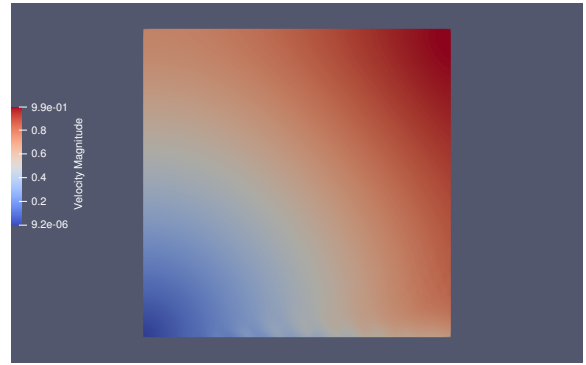
(a) Network 1



(b) Network 2



(c) Network 3



(d) Network 4

Figure 3.2: The average and standard deviation of critical parameters: Region R4

Chapter 4

Examples

All mathematics is divided into three parts: cryptography (paid for by CIA, KGB and the like), hydrodynamics (supported by manufacturers of atomic submarines) and celestial mechanics (financed by military and by other institutions dealing with missiles, such as NASA.).

V. I. Arnold

In this final chapter, we will spend some time producing some examples to give the reader some idea of the scope of this theory. It has many applications, from Geophysical Fluid Dynamics [15] to computer graphics and image processing [13] to liquid crystals [14]. In this section, we will focus on Geophysical Fluid Dynamics and study some examples that will culminate in the Euler-Boussinesq equations for a rotating stratified fluid and a recreation of the very popular paper by Vannaste on fluid flow on a Mobius strip [24] from a classical Geometric Mechanics point of view.

4.1 Axisymmetric Flow on a Cylinder

We start this examples section with a classical and simple example relating to axisymmetric flow on a cylinder. We will use much of the theory in subsection 2.2.2. Recall that we need three objects: a group to reduce over, a manifold to act as a space for dynamics to happen and a Lagrangian. Here, we let the manifold be the cylinder,

$$M = \overline{D}(0, 1) \times [0, 1].$$

The group is $\text{SDiff}(M)$ with Dirichlet boundary conditions. We also make a modelling assumption that all the particles can be traced back to a plane, as seen in Figure 4.1. This doesn't impede the dynamics as it imposes the axisymmetric assumption but makes it easier to model. These assumptions give,

$$G = \{\eta \in \text{SDiff}(M) : \eta(0) \in [0, 1] \times [0, 1] \text{ and } \eta = \text{Id on } D(0, 1) \times [0, 1]\}.$$

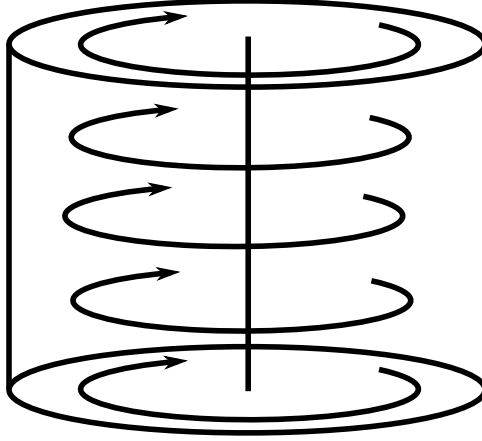


Figure 4.1: Axisymmetric Flow on a cylinder.

The Lagrangian is defined as,

$$L(\eta, \dot{\eta}) = \int_M (\dot{\eta}, \dot{\eta}) \mu.$$

We can show that the Lagrangian is right invariant by letting $g \in \text{SDiff}(M)$ then considering,

$$\begin{aligned} L(\eta g, \dot{\eta} g) &= \int_M (\dot{\eta} g, \dot{\eta} g) \mu \\ &= \int_M (\dot{\eta}, \dot{\eta}) g^2 \mu \\ &= \int_M (\dot{\eta}, \dot{\eta}) \mu = L(\eta, \dot{\eta}). \end{aligned}$$

The second step comes from noting that g is volume preserving. Hence we let $g = \eta^{-1}$ and $\mathbf{u} = \dot{\eta} \eta^{-1}$ and we get that,

$$\ell(\mathbf{u}) = \int_M |\mathbf{u}|^2 \mu.$$

Then, we find the variational derivative of the Lagrangian and plug it into the Euler-Poincaré equation. Then we get,

$$\frac{\partial[\mathbf{u}^b]}{\partial t} = \text{ad}_{\mathbf{u}}[\mathbf{u}^b].$$

We note that we have transferred from the algebra to the dual when we took the functional derivative. We now need to impose boundary conditions. We get Dirichlet boundary conditions by using the group and considering the tangent space. Hence, our equations are,

$$\begin{aligned} \frac{\partial \mathbf{u}^b}{\partial t} &= \text{ad}_{\mathbf{u}} \mathbf{u}^b + \text{d}f = \mathcal{L}_{\mathbf{u}} \mathbf{u}^b + \text{d}f \\ \mathbf{u}^b &= 0 \text{ on } \partial M \end{aligned} \tag{4.1}$$

where f is a 0-form.

4.2 Möbius Strip

The Möbius strip brings a new level of complexity to this theory. The Möbius strip is a non-orientable surface. This means that if you send a vortex around the strip spinning clockwise, it returns anticlockwise rotation. This obviously can cause issues for the Euler Equations and the theory surrounding them. In a paper by Vanneste on this area, he produces some numerical simulations and equations for the Möbius strip [24]. We will first show the group that relates to this problem and then argue why this group is Fréchet Group. Then, we will discuss conserved quantities of this system.

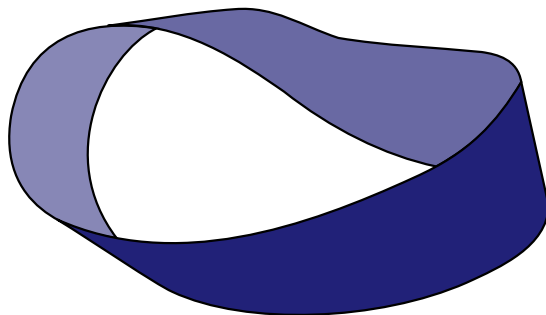


Figure 4.2: Möbius Strip.

We first note the Möbius strip diagram above and consider the following question.

Question 4.2.1. *How do we define the Möbius strip amicably?*

The answer to this is quite simple. Consider the following diagram.

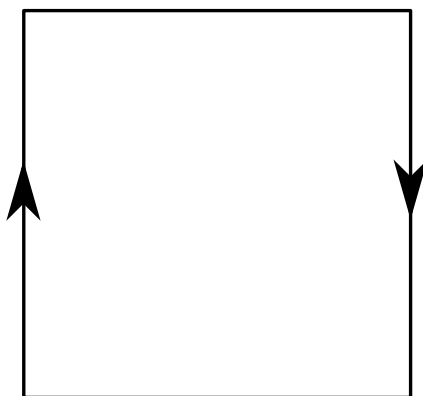


Figure 4.3: Plane representation of a Möbius Strip.

This is a Möbius strip. We note that we can connect the two arrowed sides by performing a half twist and glueing. This gives rise to the following definition of a Möbius Strip. Without loss of generality, imagine we are working on the square, $[-1, 1] \times [-1, 1]$. This holds as we can nondimensionalise in the x and y directions and get a unit square. Then, we can define our manifold as,

$$M = \{(x, y) \in [-1, 1] \times [-1, 1] : -x \sim x \text{ when } y = 1\}.$$

We can turn our manifold into boundary conditions on our diffeomorphism group. There has been much contention about what happens on the boundary of the Möbius strip when we consider the tangent space. There are a few ways to deal with this; the easiest is to set the vector fields to vanish at the boundary. Hence, our diffeomorphism group is,

$$G = \{\eta \in \text{SDiff}(M) : \eta(-1, y) = \eta(1, -y), \eta(x, -1) = \eta(x, 1) = \text{Id}\}.$$

Now we can find the tangent space and say the Lie algebra is isomorphic to,

$$\mathfrak{g} \cong \{\xi \in \mathfrak{X}(M) : \xi(0, y) = \xi(1, -y), \xi(x, -1) = \xi(x, 1) = 0\}.$$

Then, this is a Lie algebra because it doesn't introduce discontinuities into the system and performs a smooth genus-changing deformation between the square and the strip.

Now, we use the theory of subsection 2.2.2. This produces similar equations to the above, just with different boundary conditions. This produces,

$$\begin{aligned} \frac{\partial \mathbf{u}^b}{\partial t} &= \mathcal{L}_{\mathbf{u}} \mathbf{u}^b + \text{d}f & \mathbf{u} \in \mathfrak{X}([-1, 1]^2) \\ \mathbf{u}(-1, y) &= \mathbf{u}(1, -y) \\ \mathbf{u}(x, -1) &= \mathbf{u}(x, 1) = 0 \end{aligned} \tag{4.2}$$

where f is a 0-form.

As we have a continuous manifold with just a boundary condition that vanishes. Our Casimir functions will be equivalent to Vannaste's, the generalised enstrophies. However, the non-orientability of the Möbius strip produces the new constraint only for even functions in the enstrophy. This is because of the well-known fact that we can't integrate over non-orientable surfaces. Hence, we turn to the theory of pseudo-forms. The theory can be found in Frankel's Geometry of Physics [9]. This leads to the idea that we need even functions, f , to assert the following are conserved,

$$C_f(\omega) = \int_M f(\omega) \mu.$$

4.3 Rotating Stratified Fluid

We finally aim to derive the Euler equations for a rotating stratified fluid. We will follow a similar procedure to the example after the advected quantity theorem. We can take the Lagrangian,

$$L = \int_M \left[\rho(1+b) \left(\frac{1}{2} |\dot{\eta}|^2 + \dot{\eta} \cdot \mathbf{R} - gz \right) - p(\rho - 1) \right].$$

We can now reduce this to the following reduced Lagrangian, much like the compressible fluid example.

$$\ell(\mathbf{u}, D, b) = \int_M \left[\rho_0(1+b)D \left(\frac{1}{2} |\mathbf{u}|^2 + \mathbf{u} \cdot \mathbf{R} - gz \right) - p(D - 1) \right].$$

To deal with more conserved quantities, the Euler-Poincaré equations become,

$$\frac{\partial}{\partial t} \frac{\delta \ell}{\delta \xi} = -\text{ad}_\xi^* \frac{\partial \ell}{\partial \xi} + \frac{\partial \ell}{\partial a} \diamond a + \frac{\partial \ell}{\partial b} \diamond b, \quad (4.3)$$

where a and b are advected quantities. These advected quantities satisfy,

$$\left(\frac{\partial}{\partial t} + \mathcal{L}_\mathbf{u} \right) a = \left(\frac{\partial}{\partial t} + \mathcal{L}_\mathbf{u} \right) b = 0.$$

We can now find the variational derivatives. By performing the calculations, we arrive at the following.

$$\begin{aligned} \left\langle \frac{\delta \ell}{\delta \mathbf{u}}, \phi \right\rangle &= \left\langle \rho_0 D(1+b)(\mathbf{u}^\flat + \mathbf{R}), \phi \right\rangle \\ \left\langle \frac{\delta \ell}{\delta b}, \phi \right\rangle &= \left\langle \rho_0 D \left(\frac{1}{2} |\mathbf{u}^\flat|^2 + \mathbf{u} \cdot \mathbf{R} - gz \right), \phi \right\rangle \\ \left\langle \frac{\delta \ell}{\delta D}, \phi \right\rangle &= \left\langle \rho_0(1+b) \left(\frac{1}{2} |\mathbf{u}^\flat|^2 + \mathbf{u} \cdot \mathbf{R} - gz \right) - p, \phi \right\rangle. \end{aligned}$$

These can now be plugged into Equation (4.3). We then get,

$$\begin{aligned} D(1+b) \frac{\partial}{\partial t} (\mathbf{u}^\flat + \mathbf{R}) + D(1+b) \mathcal{L}_\mathbf{u} (\mathbf{u}^\flat + \mathbf{R}) + D \left(\frac{1}{2} |\mathbf{u}^\flat|^2 + \mathbf{u}^\flat \cdot \mathbf{R} - gz \right) \diamond b \\ + (1+b) \left(\frac{1}{2} |\mathbf{u}^\flat|^2 + \mathbf{u}^\flat \cdot \mathbf{R} - gz \right) \diamond D = 0. \end{aligned}$$

This isn't very manageable, so we can simplify and put this equation back into coordinates. This leaves us with,

$$\frac{\partial \mathbf{u}^\flat}{\partial t} + \text{d}(\mathbf{u}^\flat \cdot \mathbf{R}) - g\hat{\mathbf{z}} + P(\mathbf{u}^\flat, b, D) = 0.$$

We note that P is our pressure gradient term and is defined by,

$$P(\mathbf{u}^\flat, b, D) = \frac{1}{\rho_0} \left[\frac{\left(\frac{1}{2} |\mathbf{u}^\flat|^2 + \mathbf{u}^\flat \cdot \mathbf{R} - gz \right) \diamond b}{1+b} + \frac{\left(\frac{1}{2} |\mathbf{u}^\flat|^2 + \mathbf{u}^\flat \cdot \mathbf{R} - gz \right) \diamond b}{D} \right].$$

For these equations, we have the usual conserved quantities, and Noether Theorem tells us that,

$$\oint_{\gamma} \frac{1}{D} \frac{\delta \ell}{\delta \mathbf{u}} = \oint_{\gamma} \rho_0 (1 + b) (\mathbf{u} + \mathbf{R}) = \oint_{\gamma} \nabla p \cdot d\mathbf{x}.$$

Further, the advection equation for b gives us potential vorticity conservation given $q = \nabla b \cdot \text{curl}(\mathbf{u} + \mathbf{R})$.

Chapter 5

Conclusion

This chapter draws the dissertation to a close. In this thesis, we have seen several ideas surrounding the ideas of geometric and topological fluid dynamics and further Geometric Mechanics. We have presented and exposed many results in the area and produced simple examples towards the applications in this area. We have studied boundary conditions on manifolds with boundary and then studied conserved quantities of these systems. We saw examples of axisymmetric flow, the Möbius strip and rotating stratified fluid. Geometric Mechanics is still a huge area, and my two theses have only touched the surface in this area. My PhD thesis will be based upon this work and bring together many more areas.

In the final chapter, we saw applications of all the preceding chapters. In Chapter 1, we explored the area's history and presented some relevant pure background of the thesis. We studied a small amount of Symplectic Geometry, an area with vast branches and one I wish we could have explored more. This will be the basis of further work into multisymplectic reduction and the related numerical methods. In the second chapter, we studied reduction theorems on the diffeomorphism group and in both Lagrangian and Hamiltonian frameworks. These presented some extremely nice groundwork for the third chapter and were something that very nicely led from the author's undergraduate thesis to the Ph.D. thesis. This chapter went into great detail to consider the third chapter. In Chapter 3, we studied conserved quantities in three different ways. Firstly, via Noether Theorems, a usual method to derive conserved quantities. The second Casimirs, a slightly classical way to derive the conserved quantities and then a more interesting way via Reeb Graphs. The Reeb graph method provides an interesting approach that hasn't been generalised but provides an idea of how we can find all the Casimirs of more complicated systems.

Although there are now nearly a hundred pages of Geometric Mechanics written by me, we have again only taken select areas to study. You only have to glance at Darryl Holm's publication list to tell us that. The author undertook some extra work in the area of numerics while writing this thesis; they implemented papers by Cotter and Bridges [7, 23] to show that the conserved quantities that were derived produced the expected numerical observations. The methods were based on a finite element approach. The author's PhD thesis will give a broader idea of the area and develop new multisymplectic numerical methods for this problem.

There is also work towards ideas further than Euler's equations. The author spent some time proving theorems and results about a set of equations called the Lagrangian averaged Navier Stokes, which gives a Geometric Mechanics insight into the Navier Stokes problem. These provide interesting theories about different solutions between the Euler Equations and Navier Stokes. This area was discussed in detail with Darryl Holm, and there's a great wealth of knowledge toward ocean modelling using Stochastic Averaging Lagrangian Transport.

In addition, another whole area towards using variational principles differs from the usual Hamilton's principle. Work by Dr Hamid Alemi Ardakani [2, 1] in this area applied mathematics to wave energy generators and uses Geometric Mechanics in general to study waves.

We conclude this thesis and the author's time at Oxford similarly to my first thesis. Although one year on, a lot more knowledgeable about mathematics and a better mathematician, the author notes that they have equally enjoyed writing this thesis. We have studied some classical results, produced new examples and laid a perfect basis for a Ph.D. This thesis aimed to bring together the skills and knowledge the author attained during their year in Oxford and succeeded. Further, Geometric Mechanics is still a handy tool to the world and one the author will dedicate their life to—solving the more pertinent problems with the most abstract objects. Solving problems need not be easy, but Geometric Mechanics is a toolbox to make it easy.

Bibliography

- [1] Hamid Alemi Ardakani. “A variational principle for three-dimensional interactions between water waves and a floating rigid body with interior fluid motion”. In: *Journal of Fluid Mechanics* 866 (2019), pp. 630–659. DOI: 10.1017/jfm.2019.107.
- [2] H. Alemi Ardakani et al. “A variational principle for fluid sloshing with vorticity, dynamically coupled to vessel motion”. In: *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences* 475.2224 (2019). DOI: 10.1098/rspa.2018.0642. URL: <https://royalsocietypublishing.org/doi/abs/10.1098/rspa.2018.0642>.
- [3] James Arthur. *Connections on Vector Bundles: The Gateway to Curvature and Applications*. University of Oxford, 2023.
- [4] James Arthur. *Getting Groovy with the Hamiltons: A Force-Height relation in AFM*. University of Oxford, 2023.
- [5] James Arthur. “Lie Groups and Applications in Geometric Mechanics”. Supervised by Dr Hamid Alemi Ardakani. Bachelor’s Thesis. University of Exeter.
- [6] Anthony Bloch et al. “The Euler-Poincaré equations and double bracket dissipation”. In: *Communications in Mathematical Physics* 175.1 (1996), pp. 1–42.
- [7] Colin Cotter. *A General Approach for Producing Hamiltonian Numerical Schemes for Fluid Equations*. 2005. arXiv: math/0501468 [math.NA].
- [8] David G. Ebin and Jerrold Marsden. “Groups of Diffeomorphisms and the Motion of an Incompressible Fluid”. In: *Annals of Mathematics* (1970).
- [9] Theodore Frankel. *Geometry of Physics*. Cambridge University Press, 2011. DOI: <https://doi.org/10.1017/CB09781139061377>.
- [10] François Gay-Balmaz and Tudor S. Ratiu. *The Geometric Structure of Complex Fluids*. 2009. arXiv: 0903.4294 [math-ph].
- [11] Allen Hatcher. *Algebraic topology*. Cambridge: Cambridge Univ. Press, 2000. URL: <https://pi.math.cornell.edu/~hatcher/AT/AT+.pdf>.
- [12] D. D. Holm, J. E. Marsden, and T. S. Ratiu. *The Euler-Poincare Equations and Semidirect Products with Applications to Continuum Theories*. 1998.
- [13] Darryl Holm, Tanya Schmah, and Cristina Stoica. *Geometric Mechanics and Symmetry: From Finite to Infinite Dimensions*. Jan. 2009.
- [14] Darryl D. Holm. “Euler-Poincaré Dynamics of Perfect Complex Fluids”. In: *Geometry, Mechanics, and Dynamics* (2002). DOI: https://doi.org/10.1007/0-387-21791-6_4.

- [15] Darryl D. Holm, Jerrold E. Marsden, and Tudor S. Ratiu. *The Euler-Poincare Equations in Geophysical Fluid Dynamics*. 1999. arXiv: [chao-dyn/9903035](#) [chao-dyn].
- [16] Anton Izosimov and Boris Khesin. *Classification of Casimirs in 2D hydrodynamics*. 2017. arXiv: [1702.01843](#) [math.SG].
- [17] Dominic Joyce. *On manifolds with corners*. 2010. arXiv: [0910.3518](#) [math.DG].
- [18] Boris Kolev. “Poisson brackets in Hydrodynamics”. In: *Discrete & Continuous Dynamical Systems - A* 19.3 (2007), pp. 555–574. DOI: [10.3934/dcds.2007.19.555](#). URL: <https://doi.org/10.3934%2Fdcds.2007.19.555>.
- [19] J. E. Marsden, T. S. Ratiu, and S. Shkoller. “The geometry and analysis of the averaged Euler equations and a new diffeomorphism group”. In: *Geometric Functional Analysis* (2000).
- [20] Jerrold E. Marsden and Tudor S. Ratiu. *Introduction to Mechanics and Symmetry: A Basic Exposition of Classical Mechanical Systems*. Springer Publishing Company, Incorporated, 2010. ISBN: 1441931430.
- [21] E. Noether. “Invariante Variationsprobleme”. ger. In: *Nachrichten von der Gesellschaft der Wissenschaften zu Göttingen, Mathematisch-Physikalische Klasse* 1918 (1918), pp. 235–257. URL: <http://eudml.org/doc/59024>.
- [22] Steve Shkoller. *On Incompressible Averaged Lagrangian Hydrodynamics*. 2000. arXiv: [math/9908109](#) [math.AP].
- [23] S. Reich T. Bridges. *Numerical Methods for Hamiltonian PDEs*. University of Surrey, 2006.
- [24] Jacques Vanneste. “Vortex dynamics on a Möbius strip”. In: *Journal of Fluid Mechanics* 923 (2021), A12. DOI: [10.1017/jfm.2021.581](#).
- [25] Sergiy Vasylykevych and Jerrold E. Marsden. *The Lie-Poisson Structure of the Euler Equations of an Ideal Fluid*. 2007. arXiv: [0711.4875](#) [math.AP].
- [26] Boris A. Khesin Vladimir I. Arnold. *Topological Methods in Hydrodynamics*. 2nd ed. Springer, 2021.
- [27] Gary Webb. *Magnetohydrodynamics and Fluid Dynamics: Action Principles and Conservation Laws*. Springer, 2018. ISBN: 978-3-319-72511-6.
- [28] V.E Zakharov. “Stability of periodic waves of finite amplitude on the surface of a deep fluid”. In: *Journal of Applied Mechanics* (1968).