

Thesis Title

Optional Subtitle

E. B. Legrand

Master of Science Thesis

Thesis Title

Optional Subtitle

MASTER OF SCIENCE THESIS

For the degree of Master of Science in Systems and Control at Delft
University of Technology

E. B. Legrand

May 18, 2022

DELFT UNIVERSITY OF TECHNOLOGY
DEPARTMENT OF
DELFT CENTER FOR SYSTEMS AND CONTROL (DCSC)

The undersigned hereby certify that they have read and recommend to the Faculty of
Mechanical, Maritime and Materials Engineering for acceptance a thesis entitled

THESIS TITLE

by

E. B. LEGRAND

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE SYSTEMS AND CONTROL

Dated: May 18, 2022

Supervisor(s):

prof.em.dr.ir. M. Mendel

Reader(s):

prof.dr.ir. M.Y. First Reader

dr.ir. F.S.T. Reader-two

ir. Th. Reader-three

Abstract

This is an abstract.

Table of Contents

| | |
|--|-----------|
| Preface | ix |
| Acknowledgements | xi |
| 1 Introduction | 1 |
| 2 Symplectic and Contact Geometry in Economic Engineering | 3 |
| 3 Symplectified Contact Mechanics for Dissipative Systems | 5 |
| 3-1 The damped harmonic oscillator | 5 |
| 3-2 Historical perspectives | 5 |
| 3-2-1 Contact manifolds | 7 |
| 4 Split-Quaternions as Dynamical Systems | 9 |
| 5 Conclusion | 11 |
| Bibliography | 13 |
| Glossary | 15 |
| List of Acronyms | 15 |
| Mathematical notation | 15 |

List of Figures

| | | |
|-----|---|---|
| 3-1 | Schematic of the mass-spring-damper system. | 6 |
|-----|---|---|

List of Tables

| | | |
|-----|-------------------|---|
| 1-1 | Caption | 1 |
|-----|-------------------|---|

Preface

Acknowledgements

I would like to thank my supervisor prof.dr.ir. M.Y. First Reader for his assistance during the writing of this thesis...

By the way, it might make sense to combine the Preface and the Acknowledgements. This is just a matter of taste, of course.

Delft, University of Technology
May 18, 2022

E. B. Legrand

Man must sit in chair with open mouth for very long time before roast duck fly in.

— *Chinese proverb*

Chapter 1

Introduction

Original Liouville ideas:

- Showcase complex behaviour using the van der Pol oscillator
- (Optimal) control of the distributions using the Brockett approach
- (Stochastic) inputs, link with Langevin equations
- Liouville thing (in continuity form, not incompressibility) can be applied to any diff. eq.
- Bayesian inversion of chaotic systems; guess the initial state by sampling after a certain time
- Define as streamtube, continuity equation asserts that streamlines cannot cross; i.e. streamtubes are conserves. To reduce computational complexity, define level sets (curves in 2-D) and check how they deform through the evolution of the phase space fluid; should always contain the same amount of probability throughout the evolution of the system.

Notation check

| Object | Roman lower | Roman upper | Greek lower | Greek upper |
|----------|---------------------|---------------------|--------------------------------------|--|
| Standard | <i>abcde</i> | <i>ABCDE</i> | $\alpha\beta\gamma\delta\varepsilon$ | $\Gamma\Delta\Upsilon\Omega\Theta$ |
| Vector | <i>abcde</i> | <i>ABCDE</i> | $\alpha\beta\gamma\delta\varepsilon$ | $\Gamma\Delta\Upsilon\Omega\Theta$ |
| Tensor | <i>abcde</i> | <i>ABCDE</i> | $\alpha\beta\gamma\delta\varepsilon$ | $\Gamma\Delta\Upsilon\Omega\Theta$ |

Table 1-1: Caption

Math constants: $i\epsilon\pi$

Variation: δS

Musical isomorphism

Flat: X^\flat

Sharp: ω^\sharp

Lie derivative: $\mathcal{L}_X H$

Interior product: $X \lrcorner \omega$

Lowercase mathcal:

Kinematic momentum: $\mathfrak{p}p$

$E \xrightarrow{\pi} B$

$\Gamma(TM)$

$\mathcal{X}(TM)$

About mathematical notation and sign conventions

For symplectic geometry, the sign convention used by Abraham and Marsden [1] and Cannas da Silva [2] is observed — not the one used by Arnol'd in his *Mathematical methods of classical mechanics*, nonetheless often referred to in this text.

- Matrices, vectors and tensors are bold upper case.
- Differential forms are typically denoted by Greek letters, with their rank as a superscript (cf. Arnol'd).

Chapter 2

Symplectic and Contact Geometry in Economic Engineering

Symplectified Contact Mechanics for Dissipative Systems

The traditional view is that the methods of analytical mechanics, such as the Lagrangian and Hamiltonian formalisms, are only suited for conservative systems. However, several attempts, especially in the previous century, have been made to extend these principles to dissipative systems as well.

3-1 The damped harmonic oscillator

This chapter (and the application in the following chapter) is primarily concerned with the prototypical dissipative mechanical system: the linearly damped harmonic oscillator depicted in fig. 3-1, with the governing second-order differential equation being

$$m\ddot{q} + b\dot{q} + kq = 0. \quad (3-1)$$

The choice for this system is rather perspicuous, since it is arguably the ‘easiest’ dissipative system that also exhibits second-order dynamics and is linear in all terms. Furthermore, as discussed below, it serves as the test case of the overwhelming majority of research into dissipative Lagrangian and Hamiltonian mechanics [3, 4]. However, the method described in this section can be generalized directly to a general (possibly time-dependent) potential function $V = V(q, t)$.

3-2 Historical perspectives

A traditional, engineering-inclined method to incorporate damping in the framework is to include a Rayleigh damping term in the Lagrangian to emulate linear damping forces, and this works ‘mathematically’ to derive the correct equations of motion [5]. Although frequently

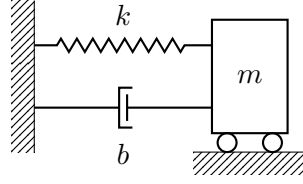


Figure 3-1: Schematic of the mass-spring-damper system.

used for practical problems, this damping term is not really part of the *actual* Lagrangian — rather, it simply makes use of the notion of a generalized force that is not inherently part of the system. As such, this method only ‘works’ on a superficial level: the pristine differential geometric foundations of mechanics do not leave room for such ad hoc tricks. There is, as a result, also no Hamiltonian counterpart for this method.

The historical attempts to do better than the Rayleigh method were primarily motivated by the application of the (dissipative) Hamiltonian formalism in quantum mechanics through discretization. For this application, a sound mathematical structure is of the essence, which calls for a more rigorous approach. A celebrated paper by Dekker [3] provides an excellent summary of many attempts up to 1981. Indeed, the well-studied approach developed by Caldirola [6] and Kanai [7] was intended exactly for this purpose. This method features an explicit time-dependence both in the Lagrangian function

$$L_{\text{CK}}(q, \dot{q}, t) = e^{\gamma t} \left(\frac{1}{2} m \dot{q}^2 - \frac{1}{2} k q^2 \right), \quad (3-2)$$

and the corresponding Hamiltonian function:

$$H_{\text{CK}}(q, \rho, t) = \frac{\rho^2}{2m} e^{-\gamma t} + \frac{1}{2} k q^2 e^{\gamma t}. \quad (3-3)$$

In latter equation, ρ refers to a special ‘canonical momentum’, that is

$$\rho \equiv \frac{\partial L_{\text{CK}}}{\partial \dot{q}},$$

which is related to the ‘true’ kinematic momentum by the relation $\rho = p e^{\gamma t} = m \dot{q} e^{\gamma t}$. As such, it is also clear that the Caldirola-Kanai Lagrangian and Hamiltonian functions are related by the Legendre transform *with respect to the canonical momentum*:¹

$$H_{\text{CK}} = \rho \dot{q} - L_{\text{CK}}.$$

¹In the first place, the ‘Legendre transform’ refers, in the context of fiber bundles, to the so-called fiber derivative. On a manifold M , let $L \in C^\infty(M)$. Then the fiber derivative is defined als

$$\mathbb{F}L : TL \rightarrow T^*L : \mathbb{F}L(v) \cdot w = \left. \frac{d}{ds} \right|_{s=0} L(v + sw).$$

Hence, the Legendre transform is in the first place the mapping that associates the generalized velocities with the associated (canonical) generalized momenta. Importantly, this mapping is a diffeomorphism (that is, invertible and onto) if the Hessian of L is nondegenerate - roughly equivalent to the statement that every generalized velocity has an associated ‘mass’ to it.

From either eq. (3-2) or eq. (3-3), the equations of motion are readily derived (for the Hamiltonian case with respect to ρ after which the transformation to p can be effected). Indeed, after taking the appropriate derivatives, one obtains:

$$\begin{aligned} \frac{d}{dt} \left(\frac{\partial L_{\text{CK}}}{\partial \dot{q}} \right) - \frac{\partial L_{\text{CK}}}{\partial q} &= 0 \\ \Rightarrow e^{\gamma t} (m\ddot{q} + m\gamma\dot{q} + kq) &= 0 \end{aligned}$$

for the Lagrangian case. Hamilton's equations amount to: [8]

$$\begin{aligned} \dot{q} &= \frac{\partial H_{\text{CK}}}{\partial \rho} = \frac{\rho}{m} e^{-\gamma t} = \frac{p}{m}, \\ \dot{\rho} &= -\frac{\partial H_{\text{CK}}}{\partial q} = -kq e^{\gamma t}. \end{aligned}$$

The relation between the time derivatives of the momenta \dot{p} and $\dot{\rho}$ is slightly more involved since one must invoke the product rule as a result of their time-dependence relation:

$$\dot{\rho} = e^{\gamma t} (\dot{p} + \gamma p).$$

Substitution yields the correct equation for p , though the equation is again multiplied by $e^{\gamma t}$. Because the latter is very well-behaved (that is, it has no zeros), it can be removed without any problems.

Geometric perspective The derivation stated above corresponds to the *suspension* of the time-dependent Hamiltonian vector field: ²

$$X_{H_{\text{CK}}} = -kq e^{\gamma t} \frac{\partial}{\partial \rho} + \frac{\rho}{m} e^{-\gamma t} \frac{\partial}{\partial q} + \frac{\partial}{\partial t}$$

dictated by the symplectic 2-form (in terms of the canonical momentum)

$$\omega = dq \wedge d\rho,$$

such that $X_{H_{\text{CK}}}|_t \lrcorner \omega = d(H_C K)$!!! not yet correct

Suspension includes the $\frac{\partial}{\partial t}$ coordinate in the vector field, see Foundations p. 373

Some peculiarities of the Caldirola-Kanai method deserve to be pointed out, since they will play a vital role in what is to come in the remainder of this chapter. [...]

3-2-1 Contact manifolds

The contact-geometric counterpart of Hamiltonian and Lagrangian mechanics has been the subject of academic interest in very recent years, see for example van der Schaft and Maschke [10], van der Schaft [11, 12], Bravetti et al. [13], de León and Lainz [14], while dating back to the original works of [15] and

²A *time-dependent vector field* on a manifold M is a mapping $X : N \times \mathbb{R} \rightarrow TM$ such that for each $t \in \mathbb{R}$, the restriction X_t of X to $N \times \{t\}$ is a vector field on M . [9] An additional construction of importance, called the *suspension* of the vector field, (...)

Our Lagrangian *is* CK-Lagrangian, but derivative wrt $\dot{q} \Rightarrow$ obtain correct momentum for Hamiltonian formulation. In Hamiltonian formulation, choose p_0 and q_0 accordingly

‘Contact’ Hamiltonian (naive, from CK \rightarrow not complete!)

$$\hat{H} = \frac{p^2}{2m} + V(q)$$

Look at CK, call $p_0 = e^{\gamma t}$ and $p = p_1/p_0$ (for now explicit definition). Symplectify, i.e.

$$H = p_0 \left[\frac{1}{2m} \left(\frac{p_1}{p_0} \right)^2 + V(q) \right]$$

such that indeed,

$$H(p_0, p_1, q) = p_0 \hat{H}(p, q) = p_0 \hat{H}(p_1/p_0, q)$$

and we can use the contact relations given. Clearly, they are equivalent to the CK-method. HOWEVER:

observe that, $q_0 = \int L dt$, and that $\frac{\partial \hat{H}}{\partial q_0} = \frac{\dot{p}_0}{p_0}$. Hence, the contact Hamiltonian can be modified to incorporate this, and presto, there is Bravetti’s Hamiltonian. Hence, these methods are precisely equivalent through symplectization.

Split-Quaternions as Dynamical Systems

! orthogonal refers to 'regular' orthogonal, Lorentz-orthogonal makes the distinction.

Motivation: \mathbf{u} seems to be 'aligned' with major direction of the elliptic trajectory in the Lorentz-orthogonal subspace, generated by the action of its cross-product. Show this formally by making use of the eigenvectors.

The basis vectors $\{\mathbf{e}_2, \mathbf{e}_3\}$, where \mathbf{e}_2 is the orthogonal projection of the vector $\mathbf{e}_1 = \hat{\mathbf{u}}$ on its Lorentz-orthogonal subspace, and $\mathbf{e}_3 \triangleq \mathbf{e}_1 \times_L \mathbf{e}_2$, form the real and imaginary parts of two of the eigenvectors of the matrix \mathbf{U}_{\times_L} .

Because the basis vectors \mathbf{e}_2 and \mathbf{e}_3 are also orthogonal in the Euclidean sense, the

Proof. Let $\hat{\mathbf{u}} = u_1 \hat{\mathbf{i}} + u_2 \hat{\mathbf{j}} + u_3 \hat{\mathbf{k}}$. A normal vector to the Lorentz-orthogonal subspace is $\hat{\mathbf{n}} = u_1 \hat{\mathbf{i}} - u_2 \hat{\mathbf{j}} - u_3 \hat{\mathbf{k}}$. Then, the basis vectors are

$$\begin{aligned} \mathbf{e}_2 &= \hat{\mathbf{u}} - \frac{\langle \hat{\mathbf{u}}, \hat{\mathbf{n}} \rangle}{\langle \hat{\mathbf{n}}, \hat{\mathbf{n}} \rangle} \hat{\mathbf{n}} \\ \mathbf{e}_3 &= \hat{\mathbf{u}} \times_L \mathbf{e}_2 = -\frac{\langle \hat{\mathbf{u}}, \hat{\mathbf{n}} \rangle}{\langle \hat{\mathbf{n}}, \hat{\mathbf{n}} \rangle} (\hat{\mathbf{u}} \times_L \hat{\mathbf{n}}), \end{aligned} \tag{4-1}$$

because the Lorentz-cross product distributes over addition and $\hat{\mathbf{u}} \times_L \hat{\mathbf{u}} = \mathbf{0}$. The proposition above claims that $\mathbf{e}_2 + i\mathbf{e}_3$ is an eigenvector of the matrix \mathbf{U}_{\times_L} . Hence, it must be the case that $\mathbf{U}_{\times_L}(\mathbf{e}_2 + i\mathbf{e}_3) = \lambda(\mathbf{e}_2 + i\mathbf{e}_3)$, where λ is then an eigenvalue of the matrix. This can be verified by replacing the action of \mathbf{U}_{\times_L} with the cross product. Plugging in the definition and exploiting the linearity of the Lorentz cross-product, one obtains:

$$\begin{aligned} \hat{\mathbf{u}} \times_L (\mathbf{e}_2 + i\mathbf{e}_3) &= \hat{\mathbf{u}} \times_L \mathbf{e}_2 + i(\hat{\mathbf{u}} \times_L \mathbf{e}_3) \\ &= \mathbf{e}_3 + (\hat{\mathbf{u}} \times_L \mathbf{e}_3)i \\ &= \mathbf{e}_3 + (\hat{\mathbf{u}} \times_L (\hat{\mathbf{u}} \times_L \mathbf{e}_2))i \\ &= \mathbf{e}_3 - \frac{\langle \hat{\mathbf{u}}, \hat{\mathbf{n}} \rangle}{\langle \hat{\mathbf{n}}, \hat{\mathbf{n}} \rangle} (\hat{\mathbf{u}} \times_L (\hat{\mathbf{u}} \times_L \hat{\mathbf{n}}))i. \end{aligned}$$

The triple cross-product expansion, or ‘Lagrange formula’, relates the regular cross product to the corresponding dot product:

$$\mathbf{a} \times (\mathbf{b} \times \mathbf{c}) = \mathbf{b} \langle \mathbf{c}, \mathbf{a} \rangle - \mathbf{c} \langle \mathbf{a}, \mathbf{b} \rangle.$$

This well-known identity generalizes (easily verified) to the Lorentzian counterpart of the cross- and inner products:

$$\mathbf{a} \times_L (\mathbf{b} \times_L \mathbf{c}) = \mathbf{b} \langle \mathbf{c}, \mathbf{a} \rangle_L - \mathbf{c} \langle \mathbf{a}, \mathbf{b} \rangle_L.$$

Using the Lagrange formula, the above expression becomes

$$\begin{aligned} \mathbf{e}_3 - \frac{\langle \hat{\mathbf{u}}, \hat{\mathbf{n}} \rangle}{\langle \hat{\mathbf{n}}, \hat{\mathbf{n}} \rangle} (\hat{\mathbf{u}} \langle \hat{\mathbf{u}}, \hat{\mathbf{n}} \rangle_L - \hat{\mathbf{n}} \langle \hat{\mathbf{u}}, \hat{\mathbf{u}} \rangle_L) \mathbf{i} \\ = \mathbf{e}_3 - \left(\hat{\mathbf{u}} \frac{\langle \hat{\mathbf{u}}, \hat{\mathbf{n}} \rangle_L \langle \hat{\mathbf{u}}, \hat{\mathbf{n}} \rangle}{\langle \hat{\mathbf{n}}, \hat{\mathbf{n}} \rangle} - \hat{\mathbf{n}} \frac{\langle \hat{\mathbf{u}}, \hat{\mathbf{n}} \rangle}{\langle \hat{\mathbf{n}}, \hat{\mathbf{n}} \rangle} \right) \mathbf{i} \\ = \mathbf{e}_3 - \left(\hat{\mathbf{u}} - \hat{\mathbf{n}} \frac{\langle \hat{\mathbf{u}}, \hat{\mathbf{n}} \rangle}{\langle \hat{\mathbf{n}}, \hat{\mathbf{n}} \rangle} \right) \mathbf{i} \\ = \mathbf{e}_3 - \mathbf{e}_2 \mathbf{i}. \end{aligned}$$

The latter is the scalar multiple of the vector $\mathbf{e}_2 + \mathbf{e}_3$ by $-\mathbf{i}$ - hence, this is indeed an eigenvector of the corresponding matrix. ■

Because \mathbf{e}_2 and \mathbf{e}_3 are also orthogonal in the normal sense, they are aligned with the major axes of the elliptic trajectories generated by the cross product. Hence, they can be used to find a basis of the invariant subspace which makes the trajectories identical to those in the phase plane.

Chapter 5

Conclusion

Bibliography

- [1] R. Abraham and J. E. Marsden, *Foundations of Mechanics*. Addison-Wesley Publishing Company, 1978.
- [2] A. Cannas da Silva, *Lectures on Symplectic Geometry*, ser. Lecture Notes in Mathematics, 1, Ed. Berlin, Heidelberg: Springer, 2001.
- [3] H. Dekker, “Classical and Quantum Mechanics of the Damped Harmonic Oscillator,” Physics Laboratory, TNO, Den Haag, Tech. Rep., 1981.
- [4] C. Hutters and M. Mendel, “Overcoming the dissipation obstacle with Bicomplex Port-Hamiltonian Mechanics,” 2020.
- [5] H. Goldstein, C. P. Poole, and J. Safko, *Classical Mechanics*, 3rd ed. Noida, India: Pearson Education, 2011.
- [6] P. Caldirola, “Forze Non Conservative Nella Meccanica Quantistica,” *Il Nuovo Cimento*, vol. 18, no. 9, pp. 393–400, 1941.
- [7] E. Kanai, “On the Quantization of the Dissipative Systems,” *Progress of Theoretical Physics*, vol. 3, no. 4, pp. 440–442, 1948.
- [8] M. Tokieda and S. Endo, “Equivalence of Dissipative and Dissipationless Dynamics of Interacting Quantum Systems With Its Application to the Unitary Fermi Gas,” *Frontiers in Physics*, vol. 9, no. September, pp. 1–9, 2021.
- [9] P. Libermann and C.-M. Marle, *Symplectic Geometry and Analytical Mechanics*. Dordrecht, Holland: D. Reidel Publishing Company, 1987.
- [10] A. van der Schaft and B. Maschke, “Homogeneous Hamiltonian Control Systems Part I: Geometric Formulation,” *IFAC-PapersOnLine*, vol. 51, no. 3, pp. 1–6, 2018. [Online]. Available: <https://doi.org/10.1016/j.ifacol.2018.06.001>
- [11] A. van der Schaft, “Liouville geometry of classical thermodynamics,” *Journal of Geometry and Physics*, vol. 170, 2021.

- [12] —, “Liouville geometry of classical thermodynamics,” *Journal of Geometry and Physics*, vol. 170, p. 104365, 2021. [Online]. Available: <https://doi.org/10.1016/j.geomphys.2021.104365>
- [13] A. Bravetti, H. Cruz, and D. Tapias, “Contact Hamiltonian mechanics,” *Annals of Physics*, vol. 376, pp. 17–39, 2017.
- [14] M. de León and M. Lainz, “A Review on Contact Hamiltonian and Lagrangian Systems,” Tech. Rep., 2020. [Online]. Available: <http://arxiv.org/abs/2011.05579>
- [15] V. Arnol’d, *Mathematical Methods of Classical Mechanics*, 2nd ed., J. Ewing, F. Gehring, and P. Halmos, Eds. New York: Springer-Verlag, 1989.

Glossary

List of Acronyms

Mathematical notation

v A (tangent) vector

