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A port-Hamiltonian formulation of flexible structures

Modelling and symplectic finite element discretization

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Abstract

This thesis aims at extending the port-Hamiltonian (pH) approach to continuum mechanics in higher geometrical dimensions (particularly in 2D). The pH formalism has a strong multiphysics character and represents a unified framework to model, analyze and control both finite- and infinite-dimensional systems. Despite the large literature on this topic, elasticity problems in higher geometrical dimensions have almost never been considered. This work establishes the connection between port-Hamiltonian distributed systems and elasticity problems. The originality resides in three major contributions. First, the novel pH formulation of plate models and coupled thermoelastic phenomena is presented. The use of tensor calculus is mandatory for continuum mechanical models and the inclusion of tensor variables is necessary to obtain an intrinsic, i.e. coordinate free, and equivalent pH description. Second, a finite element based discretization technique, capable of preserving the structure of the infinite-dimensional problem at a discrete level, is developed and validated. The discretization of elasticity problems in port-Hamiltonian form requires the use of non-standard finite elements. Nevertheless, the numerical implementation is performed thanks to well-established open-source libraries, providing external users with an easy to use tool for simulating flexible systems in pH form. Third, flexible multibody systems are recast in pH form by making use of a floating frame description valid under small deformations assumptions. This reformulation include all kinds of linear elastic models and exploits the intrinsic modularity of pH systems.

Résumé

Cette thèse vise à étendre l'approche port-hamiltonienne (pH) à la mécanique des milieux continus dans des dimensions géométriques plus élevées (en particulier on se focalise sur la dimension deux). Le formalisme pH, avec son fort caractère multiphysique, représente un cadre unifié pour modéliser, analyser et contrôler les systèmes de dimension finie et infinie. Malgré l'abondante littérature sur ce sujet, les problèmes d'élasticité en deux ou trois dimensions géométriques n'ont presque jamais été considérés. Dans ce travail de thèse la connexion entre problèmes d'élasticité et systèmes distribués port-Hamiltoniens est établie. L'originalité apportée réside dans trois contributions majeures. Tout d'abord, la nouvelle formulation pH des modèles de plaques et des phénomènes thermoélastiques couplés est présentée. L'utilisation du calcul tensoriel est obligatoire pour modéliser les milieux continus et l'introduction de variables tensorielles est nécessaire pour obtenir une description pH équivalente qui soit intrinsèque, c'est-à-dire indépendante des coordonnées choisies. Deuxièmement, une technique de discrétisation basée sur les éléments finis et capable de préserver la structure du problème de la dimension infinie au niveau discret est développée et validée. La discrétisation des problèmes d'élasticité écrits en forme port-Hamiltonienne nécessite l'utilisation d'éléments finis non standard. Néanmoins, l'implémentation numérique est réalisée grâce à des bibliothèques open source bien établies, fournissant aux utilisateurs externes un outil facile à utiliser pour simuler des systèmes flexibles sous forme pH. Troisièmement, une nouvelle formulation pH de la dynamique multicorps flexible est dérivée. Cette reformulation, valable sous de petites hypothèses de déformations, inclut toutes sortes de modèles élastiques linéaires et exploite la modularité intrinsèque des systèmes pH.

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Alla mia famiglia

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List of Acronyms

ACS	*Attitude Control System*
APM	*Antenna Pointing Mechanism*
ARS	*Angular Rate Sensor*
AS	*Amplitude Spectrum*
CCS	*Controlled Component Synthesis*
CFSM	*Control Fast Steering Mirror*
CG	*Center of Gravity*
CMG	*Control Momentum Gyro*
CMS	*Component Modes Synthesis*
DFSM	*Disturbance Fast Steering Mirror*
DFT	*Discrete Fourier Transform*
DOF	*Degrees of Freedom*
EMC	*Electromagnetic compatibility*
ESA	*European Space Agency*
FEM	*Finite Element Method*
FE-TM	*Finite Element-Transfer Matrix*
FRF	*Frequency Response Function*
FSM	*Fast Steering Mirror*
HST	*Hubble Space Telescope*
IMU	*Inertial Measurement Unit*
JWST	*James Webb Space Telescope*
LFT	*Linear Fractional Transformation*
LPV	*Linear Parameter-Varying*
LQR	*Linear Quadratic Regulator*
LTI	*Linear Time-Invariant*

MHD *Magneto-hydrodynamic*

NINOP *N-Input N-Output Port*

PMA *Proof-Mass Actuator*

PSD *Power Spectral Density*

PZT *Lead Zirconate Titanate piezoelectric actuator*

RW *Reaction Wheel*

RWA *Reaction Wheel Assembly*

SADM *Solar Array Drive Mechanism*

SGS *Strain Gauge Sensor*

STR *Star Tracker*

TITOP *Two-Input Two-Output Port*

Part I

Introduction and state of the art

CHAPTER 1

Introduction

Je n'ai cherché de rien prouver, mais de bien peindre et d'éclairer bien ma peinture

André Gide
Préface de L'Immoraliste

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Whereof one cannot speak, thereof one must be silent.

Ludwig Wittgenstein
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CHAPTER 3

Elasticity in port-Hamiltonian form

I try not to break the rules but merely to test their elasticity.

Bill Veeck

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Continuum mechanics is the mathematical description of how materials behave kinematically under external excitations. In this framework, the microscopic structure of a material body is neglected and a macroscopic viewpoint, that describes the body as a continuum, is adopted. Continua phenomena are modeled using PDE. In this chapter, the general linear elastodynamics problem is recalled. A suitable port-Hamiltonian realization is then derived using a velocity-stress formulation.

3.1 Deformation, strain and stress

In this section, the main concepts behind a deformable continuum are briefly recalled following [Lee12]. For a detailed discussion on this topic, the reader may consult [Abe12, LPKL12].

The bounded region of $\mathbb{R}^n$ $(n = 2, 3)$ occupied by a solid is called configuration. The reference configuration Ω is the domain that a bodies occupies at the initial state. To describe how the body deforms in time the deformation map $\boldsymbol{\Phi} : \Omega \times [0, T_f] \to \Omega' \subset \mathbb{R}^n$ is introduced. This map is differentiable and orientation preserving and the image of Ω under $\boldsymbol{\Phi}(\cdot, t)$ $\forall t \in [0, T_f]$ is called the deformed configuration Ω_t. Given a specific point in the reference frame is image is denoted by $\boldsymbol{y} = \boldsymbol{\Phi}(\boldsymbol{x}, t)$. The gradient of the deformation map is called the deformation gradient $\boldsymbol{F} := \nabla_x \boldsymbol{\Phi} = \frac{\partial \boldsymbol{y}}{\partial \boldsymbol{x}}$. A rigid deformation maps a point $\boldsymbol{x} \in \Omega \to \boldsymbol{A}(t)\boldsymbol{x} + \boldsymbol{b}(t)$, where $\boldsymbol{A}(t)$ is an orthogonal matrix and $\boldsymbol{b}(t)$ a $\mathbb{R}^n$ vector. A differentiable deformation map $\boldsymbol{\Phi}$ is a rigid deformation iff $\boldsymbol{F}^\top \boldsymbol{F} - \boldsymbol{I} = 0$, where $\boldsymbol{I}$ is the identity in $\mathbb{R}^{n \times n}$ (for the proof see [Cia88], page 44). For this reason, a suitable measure of the deformation is the Green-St.Venant strain tensor $\boldsymbol{E} = \frac{1}{2}(\boldsymbol{F}^\top \boldsymbol{F} - \boldsymbol{I})$.

A quantity of interest is the displacement $\boldsymbol{u} : \Omega \times [0, T_f] \to \mathbb{R}^n$ with respect to the reference configuration. It is defined as $\boldsymbol{u}(\boldsymbol{x}, t) = \boldsymbol{\Phi}(\boldsymbol{x}, t) - \boldsymbol{x}$. The gradient of the displacement verifies $\operatorname{grad} \boldsymbol{u} = \boldsymbol{F} - \boldsymbol{I}$. The strain tensor can now be written in terms of the displacement

$$\begin{aligned} \boldsymbol{E} &= \frac{1}{2}\left[(\nabla_x \boldsymbol{u} + \boldsymbol{I})^\top (\nabla_x \boldsymbol{u} + \boldsymbol{I}) - \boldsymbol{I}\right] \\ &= \frac{1}{2}\left[\nabla_x \boldsymbol{u} + (\nabla_x \boldsymbol{u})^\top + (\nabla_x \boldsymbol{u})^\top (\nabla_x \boldsymbol{u})\right], \end{aligned}$$

or in components

$$E_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j}\frac{\partial u_j}{\partial x_i}\right).$$

To state the balance laws the actual deformed configuration is considered. The linear and angular momentum in a subdomain $\omega_t \subset \Omega_t$ are computed as

$$\int_{\omega_t} \rho \, \boldsymbol{v} \, \mathrm{d}\omega_t, \qquad \int_{\omega_t} \rho \, \boldsymbol{y} \times \boldsymbol{v} \, \mathrm{d}\omega,$$

where ρ is the mass density and the velocity $\boldsymbol{v} = \frac{D\boldsymbol{u}}{Dt}(\boldsymbol{y}, t)$ is material time derivative of the displacement (see [Abe12, Chapter 1]). Let $\omega_{t,1}$, $\omega_{t,2}$ be two subregions in a deformed continuum Ω_t with contacting surface S_{12}. There is a force acting on this surface for a continuum that is called stress vector or traction. If $\boldsymbol{n}$ is the outward normal at $\boldsymbol{y}$ on S_{12} with respect to $\omega_{t,1}$, then the surface force that $\omega_{t,1}$ exerts on $\omega_{t,2}$ is denoted by $\boldsymbol{t}(\boldsymbol{y}, \boldsymbol{n}) \in \mathbb{R}^n$. By the Newton third law, the surface force that $\omega_{t,1}$ applies on $\omega_{t,2}$ is given by $\boldsymbol{t}(\boldsymbol{y}, -\boldsymbol{n}) = -\boldsymbol{t}(\boldsymbol{y}, \boldsymbol{n})$. It is assumed that the linear and angular momentum balance hold for any subregion $\omega \in \Omega_t$

$$\begin{aligned} \frac{d}{dt}\int_{\omega_t} \rho \boldsymbol{v} \, \mathrm{d}\omega_t &= \int_{\partial \omega_t} \boldsymbol{t}(\boldsymbol{y}, \boldsymbol{n}) \, \mathrm{d}S + \int_{\omega_t} \boldsymbol{f} \, \mathrm{d}\omega_t, \\ \frac{d}{dt}\int_{\omega_t} \rho \boldsymbol{y} \times \boldsymbol{v} \, \mathrm{d}\omega_t &= \int_{\partial \omega_t} \boldsymbol{y} \times \boldsymbol{t}(\boldsymbol{y}, \boldsymbol{n}) \, \mathrm{d}S + \int_{\omega_t} \boldsymbol{y} \times \boldsymbol{f} \, \mathrm{d}\omega_t, \end{aligned}$$

where $\boldsymbol{n}$ is the outward normal to the surface $\partial \omega_t$. The following theorem characterizes the stress vector (see [Cia88, Chapter 2]):

Theorem 1 (Cauchy's theorem)
If the linear and angular momenta balance hold, then there exists a matrix valued function $\boldsymbol{\Sigma}$ *from* Ω_t *to* $\mathbb{S}$ *such that* $\boldsymbol{t}(\boldsymbol{y}, \boldsymbol{n}) = \boldsymbol{\Sigma}(\boldsymbol{y})\boldsymbol{n}$, $\forall \boldsymbol{y} \in \Omega_t$ *where the right-hand side is the matrix-vector multiplication.*

The set $\mathbb{S} = \mathbb{R}^{n \times n}_{\mathrm{sym}}$ denotes the field of symmetric matrices in $\mathbb{R}^{n \times n}$. The symmetric of the stress tensor $\boldsymbol{\Sigma}$ is due to the balance of angular momentum. The divergence theorem can then be applied

$$\int_{\partial\omega} \boldsymbol{\Sigma}\,\boldsymbol{n}\;\mathrm{d}S = \int_{\omega} \nabla_y \cdot \boldsymbol{\Sigma}\;\mathrm{d}\omega,$$

where $\nabla_y \cdot$ is the tensor divergence with respect to the deformed configuration, $\nabla_y \cdot \boldsymbol{\Sigma} = \sum_{i=1}^{n} \frac{\partial \Sigma_{ij}}{\partial y_i}$. Because the considered subregion ω is arbitrary, using the linear balance momentum and the conservation of mass the following PDE is found

$$\rho \frac{D\boldsymbol{v}}{Dt} - \nabla_y \cdot \boldsymbol{\Sigma} = \boldsymbol{f}, \qquad \boldsymbol{y} \in \Omega_t.$$

This equation is written with respect to the deformed configuration Ω_t. For a detailed derivation of this equation the reader may consult [Abe12, Chapter 4].

3.2 The linear elastodynamics problem

Whenever deformations are small, $\nabla_x \boldsymbol{u} \ll 1$, there the reference and deformed configuration are almost indistinguishable $\boldsymbol{y} = \boldsymbol{x} + \boldsymbol{u} = \boldsymbol{x} + O(\nabla_x \boldsymbol{u}) \approx \boldsymbol{x}$. This allows to write the linear momentum balance in the reference configuration

$$\rho \frac{\partial \boldsymbol{v}}{\partial t}(\boldsymbol{x}, \boldsymbol{t}) - \mathrm{Div}(\Sigma(\boldsymbol{x}, t)) = \boldsymbol{f}.$$

The material derivative simplifies to a partial one. The operator Div is the divergence of a tensor field with respect to the reference configuration

$$\mathrm{Div}(\Sigma(\boldsymbol{x}, t)) = \nabla_x \cdot \Sigma(\boldsymbol{x}, t) = \sum_{i=1}^{n} \frac{\partial \Sigma_{ij}}{\partial x_i}.$$

Furthermore the Green-St. Venant strain tensor simplifies to the infinitesimal strain tensor

$$\boldsymbol{E} = \frac{1}{2}\left[\nabla_x \boldsymbol{u} + (\nabla_x \boldsymbol{u})^\top + (\nabla_x \boldsymbol{u})^\top (\nabla_x \boldsymbol{u})\right] \approx \frac{1}{2}\left[\nabla_x \boldsymbol{u} + (\nabla_x \boldsymbol{u})^\top\right] =: .$$

An elastic material is able to resist distorting excitations and return to its original size and shape when these are removed. For an elastic material the stress

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Appendix A

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A.1 Differential operators

The space of all, symmetric and skew-symmetric $d \times d$ matrices are denoted by $\mathbb{M}, \mathbb{S}, \mathbb{K}$ respectively. The space of $\mathbb{R}^d$ vectors is denoted by $\mathbb{V}$. $\Omega \subset \mathbb{R}^d$ is an open connected set. For a scalar field $u : \Omega \to \mathbb{R}$ the gradient is defined as

$$\mathrm{grad}(u) = \nabla u := \left(\partial_{x_1} u \dots \partial_{x_d} u\right)^\top .$$

For a vector field $\boldsymbol{u} : \Omega \to \mathbb{V}$, with components u_j, the gradient (Jacobian) is defined as

$$\mathrm{grad}(\boldsymbol{u})_{ij} := (\nabla \boldsymbol{u})_{ij} = \partial_{x_j} u_i.$$

The symmetric part of the gradient operator Grad (i. e. the deformation gradient in continuum mechanics) is thus given by

$$\mathrm{Grad}(\boldsymbol{u}) := \frac{1}{2}\left(\nabla \boldsymbol{u} + \nabla^\top \boldsymbol{u}\right).$$

The Hessian operator of u is then computed as follows

$$\mathrm{Hess}(u) = \nabla^2 u = \mathrm{Grad}(\mathrm{grad}(u)),$$

For a tensor field $\boldsymbol{U} : \Omega \to \mathbb{M}$, with components u_{ij}, the divergence is a vector, defined column-wise as

$$\mathrm{Div}(\boldsymbol{U}) = \nabla \cdot \boldsymbol{U} := \left(\sum_{i=1}^{d} \partial_{x_i} u_{ij}\right)_{j=1,\dots,d}.$$

The double divergence of a tensor field $\boldsymbol{U}$ is then a scalar field defined as

$$\mathrm{div}(\mathrm{Div}(\boldsymbol{U})) := \sum_{i,j=1}^{d} \partial_{x_i} \partial_{x_j} u_{ij}.$$

Appendix B

Finite elements gallery

Appendix C

Implementation using FEniCS and Firedrake

Bibliography

[Abe12] R. Abeyaratne. *Lecture Notes on the Mechanics of Elastic Solids. Volume II: Continuum Mechanics.* Cambridge, MA and Singapore, 1st edition, 2012.

[Cia88] P. G. Ciarlet. *Mathematical Elasticity: Three-Dimensional Elasticity.* Studies in mathematics and its applications. North-Holland, 1988.

[Lee12] Jeonghun Lee. *Mixed methods with weak symmetry for time dependent problems of elasticity and viscoelasticity.* PhD thesis, University of Minnesota, 2012.

[LPKL12] L. D. Landau, L. P. Pitaevskii, A. M. Kosevich, and E. M. Lifshitz. *Theory of Elasticity.* Butterworth Heinemann, third edition, Dec 2012.

Résumé — Malgré l'abondante littérature sur le formalisme pH, les problèmes d'élasticité en deux ou trois dimensions géométriques n'ont presque jamais été considérés. Cette thèse vise à étendre l'approche port-Hamiltonienne (pH) à la mécanique des milieux continus. L'originalité apportée réside dans trois contributions majeures. Tout d'abord, la nouvelle formulation pH des modèles de plaques et des phénomènes thermoélastiques couplés est présentée. L'utilisation du calcul tensoriel est obligatoire pour modéliser les milieux continus et l'introduction de variables tensorielles est nécessaire pour obtenir une description pH équivalente qui soit intrinsèque, c'est-à-dire indépendante des coordonnées choisies. Deuxièmement, une technique de discrétisation basée sur les éléments finis et capable de préserver la structure du problème de la dimension infinie au niveau discret est développée et validée. La discrétisation des problèmes d'élasticité nécessite l'utilisation d'éléments finis non standard. Néanmoins, l'implémentation numérique est réalisée grâce à des bibliothèques open source bien établies, fournissant aux utilisateurs externes un outil facile à utiliser pour simuler des systèmes flexibles sous forme pH. Troisièmement, une nouvelle formulation pH de la dynamique multicorps flexible est dérivée. Cette reformulation, valable sous de petites hypothèses de déformations, inclut toutes sortes de modèles élastiques linéaires et exploite la modularité intrinsèque des systèmes pH.

Mots clés : Systèmes port-Hamiltonien, méchanique des solides, discretisation symplectique, méthode des éléments finis, dynamique multicorps

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Abstract — Despite the large literature on pH formalism, elasticity problems in higher geometrical dimensions have almost never been considered. This work establishes the connection between port-Hamiltonian distributed systems and elasticity problems. The originality resides in three major contributions. First, the novel pH formulation of plate models and coupled thermoelastic phenomena is presented. The use of tensor calculus is mandatory for continuum mechanical models and the inclusion of tensor variables is necessary to obtain an intrinsic, i.e. coordinate free, and equivalent pH description. Second, a finite element based discretization technique, capable of preserving the structure of the infinite-dimensional problem at a discrete level, is developed and validated. The discretization of elasticity problems requires the use of non-standard finite elements. Nevertheless, the numerical implementation is performed thanks to well-established open-source libraries, providing external users with an easy to use tool for simulating flexible systems in pH form. Third, flexible multibody systems are recast in pH form by making use of a floating frame description valid under small deformations assumptions. This reformulation include all kinds of linear elastic models and exploits the intrinsic modularity of pH systems.

Keywords: Port-Hamiltonian systems, continuum mechanics, structure preserving discretization, finite element method, multibody dynamics.
