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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, une 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 standards. 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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List of Acronyms

DAE *Differential-Algebraic Equation*

dpHs *distributed port-Hamiltonian systems*

FEM *Finite Element Method*

IDA-PBC *Interconnection and Damping Assignment Passivity Based Control*

PDE *Partial Differential Equation*

PFEM *Partitioned Finite Element Method*

pH *port-Hamiltonian*

pHs *port-Hamiltonian systems*

pHDAE *port-Hamiltonian Descriptor System*

Part I

Introduction and state of the art

Chapter 1

Introduction

I was born not knowing and have had only a little time to change that here and there.

Richard Feynman
Letter to Armando Garcia J.

Contents

1.1 Motivation and context

1.2 Overview of chapters

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Chapter 2

Literature review

> Books serve to show a man that those original thoughts of his aren't very new after all.
>
> *Abraham Lincoln*

2.1 Port-Hamiltonian distributed systems

For 1D linear PH systems with a generalized skew-adjoint system operator, [LGZM05] gives conditions on the assignment of boundary inputs and outputs for the system operator to generate a contraction semigroup. The latter is instrumental to show well-posedness of a linear PH system, see [JZ12]. Essentially, at most half the number of boundary port variables can be imposed as control inputs for a well-posed PH system in 1D.

2.2 Structure-preserving discretization

2.3 Mixed finite element for elasticity

2.4 Multibody dynamics

Part II

Port-Hamiltonian elasticity and thermoelasticity

Chapter 3

Elasticity in port-Hamiltonian form

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

Bill Veeck

Contents

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. This leads to a PDE based model. In this chapter, the general linear elastodynamics problem is recalled. A suitable port-Hamiltonian formulation is then derived.

3.1 Continuum mechanics

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].

216 3.1.1 Non linear formulation of elasticity

The bounded region of $\mathbb{R}^d$ ($d = 2, 3$) 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 $\boldsymbol{\Phi} : \Omega \times [0, T_f] \rightarrow \Omega' \subset \mathbb{R}^d$ 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 its 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 $\boldsymbol{x} \in \Omega \rightarrow \boldsymbol{A}(t)\boldsymbol{x} + \boldsymbol{b}(t)$, where $\boldsymbol{A}(t)$ is an orthogonal matrix and $\boldsymbol{b}(t) \in \mathbb{R}^d$ a 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 $\mathbb{R}^{d \times d}$ (for the proof see [Cia88], page 44). For this reason, a suitable measure of the deformation is the Green-St.Venant strain tensor $\frac{1}{2}(\boldsymbol{F}^\top \boldsymbol{F} - \boldsymbol{I})$.

A quantity of interest is the displacement $\boldsymbol{u} : \Omega \times [0, T_f] \rightarrow \mathbb{R}^d$ 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 $\nabla_x \boldsymbol{u} = \boldsymbol{F} - \boldsymbol{I}$. The strain tensor can now be written in terms of the displacement

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

or in components

$$
\frac{1}{2}(F_{ik}^\top F_{kj} - I_{ij}) = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j}\frac{\partial u_j}{\partial x_i}\right).
$$

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

$$
\int_{\omega_t} \rho \, \boldsymbol{v} \, \mathrm{d}\omega_t, \quad \text{and} \quad \int_{\omega_t} \rho \, \boldsymbol{y} \times \boldsymbol{v} \, \mathrm{d}\omega_t,
$$

where ρ is the mass density and the velocity $\boldsymbol{v} = \frac{D\boldsymbol{u}}{Dt}(\boldsymbol{y}, t) = \frac{\partial \boldsymbol{u}}{\partial t}(\boldsymbol{x}, t)$ is the 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 $\boldsymbol{t}(\boldsymbol{y}, \boldsymbol{n}) \in \mathbb{R}^d$. By the Newton third law, the surface force that $\omega_{t,2}$ applies on $\omega_{t,1}$ 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 $\omega_t \in \Omega_t$

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

where $\partial\omega_t$ stands for the boundary surface of the subdomain ω_t, $\boldsymbol{n}$ is the outward normal to the surface $\partial\omega_t$ and $\boldsymbol{f}$ represents an exterior body force. 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 $\mathbb{S} = \mathbb{R}^{d\times d}_{\text{sym}}$ denotes the field of symmetric matrices in $\mathbb{R}^{d\times d}$. The symmetry of the stress tensor $\boldsymbol{\Sigma}$ is due to the balance of angular momentum. The divergence theorem can then be applied

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

where $\nabla_y\cdot$ is the tensor divergence with respect to the deformed configuration, $\nabla_y \cdot \boldsymbol{\Sigma} = \sum_{i=1}^{d} \frac{\partial \Sigma_{ij}}{\partial y_i}$. Because the considered subregion ω_t 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]. To obtain a closed formulation, the constitutive law, namely the link between $\boldsymbol{\Sigma}$ and the strain tensor $\frac{1}{2}(\boldsymbol{F}^\top\boldsymbol{F} - \boldsymbol{I})$, has to be introduced. In the next section such relation will be investigated for the case of linear elasticity.

3.1.2 The linear elastodynamics problem

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

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

The material derivative simplifies to a partial one. The operator Div is the divergence of a tensor field with respect to the reference configuration (see Appendix A for a description of the differential operators)

$$\mathrm{Div}(\boldsymbol{\Sigma}(\boldsymbol{x}, t)) = \nabla_x \cdot \boldsymbol{\Sigma}(\boldsymbol{x}, t) = \left(\sum_{i=1}^{d} \frac{\partial \Sigma_{ij}}{\partial x_i} \right)_{1 \le j \le d}.$$

Furthermore, the non-linear terms in the Green-St. Venant strain tensor can be dropped

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

The linearized strain tensor (also called infinitesimal strain tensor) is the symmetric gradient of the displacement

$$\boldsymbol{\varepsilon} := \mathrm{Grad}\, \boldsymbol{u}, \qquad \text{where} \qquad \mathrm{Grad}\, \boldsymbol{u} = \frac{1}{2}\left[\nabla_x \boldsymbol{u} + (\nabla_x \boldsymbol{u})^\top\right]. \tag{3.1}$$

To obtain a closed system of equations, it is now necessary to characterize the relation between stress and strain. This relation is normally called *constitutive law*. In the following, the particular case of elastic materials is considered. These are able to resist distorting excitations and return to its original size and shape when these excitations are removed. For this class of materials, the stress tensor is solely determined by the deformed configuration at a given time (Hooke's law)

$$\boldsymbol{\Sigma}(\boldsymbol{x}) = \boldsymbol{\mathcal{D}}(\boldsymbol{x})\, \boldsymbol{\varepsilon}(\boldsymbol{u}(\boldsymbol{x})).$$

The *stiffness tensor* or *elasticity tensor* $\boldsymbol{\mathcal{D}} : \mathbb{S} \to \mathbb{S}$ is a rank 4 tensor that is symmetric positive definite and uniformly bounded above and below. Because of symmetry, its components satisfy

$$\mathcal{D}_{ijkl} = \mathcal{D}_{jikl} = \mathcal{D}_{klij}.$$

From the uniform boundedness of $\boldsymbol{\mathcal{D}}$, the map $\boldsymbol{\mathcal{D}} : L^2(\Omega; \mathbb{S}) \to L^2(\Omega; \mathbb{S})$ is a symmetric positive definite bounded linear operator ($L^2(\Omega; \mathbb{S})$ is the space of square integrable symmetric tensor-valued functions). The compliance tensor $\boldsymbol{\mathcal{C}}$ is defined by $\boldsymbol{\mathcal{C}} = \boldsymbol{\mathcal{D}}^{-1}$. Thus $\boldsymbol{\mathcal{C}} : \mathbb{S} \to \mathbb{S}$ is as well symmetric positive definite and uniformly bounded above and below. An isotropic elastic medium has the same kinematic properties in any direction and at each point. If an elastic medium is isotropic, then the stiffness and compliance tensors assume the form

$$\boldsymbol{\mathcal{D}}(\cdot) = 2\mu(\cdot) + \lambda\, \mathrm{Tr}(\cdot)\boldsymbol{I}, \qquad \boldsymbol{\mathcal{C}}(\cdot) = \frac{1}{2\mu}\left[(\cdot) - \frac{\lambda}{2\mu + d\lambda}\mathrm{Tr}(\cdot)\boldsymbol{I}\right], \qquad d = \{2, 3\}, \tag{3.2}$$

where Tr is the trace operator and the positive scalar functions μ, λ, defined on Ω, are called the Lamé coefficients. In engineering applications it is easier to compute experimentally two other parameters: the Young modulus E and Poisson's ratio ν. Those are expressed in terms of the Lamé coefficients as

$$\nu = \frac{\lambda}{2(\lambda + \mu)}, \qquad E = \frac{\mu(3\lambda + 2\mu)}{\lambda + \mu}, \tag{3.3}$$

and conversely

$$\lambda = \frac{E\nu}{(1+\nu)(1-2\nu)}, \qquad \mu = \frac{E}{2(1+\nu)}. \tag{3.4}$$

The stiffness and compliant tensor are expressed as

$$\boldsymbol{\mathcal{D}}(\cdot) = \frac{E}{1+\nu}\left[(\cdot) + \frac{\nu}{1-2\nu}\operatorname{Tr}(\cdot)\boldsymbol{I}\right], \tag{3.5}$$

$$\boldsymbol{\mathcal{C}}(\cdot) = \frac{1+\nu}{E}\left[(\cdot) - \frac{\nu}{1+\nu(d-2)}\operatorname{Tr}(\cdot)\boldsymbol{I}\right]. \tag{3.6}$$

The linear elastodynamics problem is formulated through a vector-valued PDE

$$\rho\frac{\partial^2 \boldsymbol{u}}{\partial t^2} - \operatorname{Div}(\boldsymbol{\mathcal{D}}\operatorname{Grad}\boldsymbol{u}) = \boldsymbol{f}. \tag{3.7}$$

The classical elastodynamics problem is expressed considering the displacement $\boldsymbol{u}$ as the unknown. This PDE goes together with appropriate boundary conditions that will be specified in 3.3.

3.2 Port-Hamiltonian systems

Before introducing the pH formulation of the elastodynamics problem, the main concepts behind this formalism are recalled. First, the concept of Stokes-Dirac structure is presented. This notion was first introduced in the literature by making use of a differential geometry approach [vdSM02]. Despite being really insightful in terms of geometrical structure, this approach does not encompass the case of higher-order differential operators. An extension in this sense is still an open question. Since bending problems in elasticity introduce higher-order differential operators, the language of PDE will be privileged over the one of differential forms. To have the most suitable definition of Stokes-Dirac structure for flexible systems, the approach adopted in [MvdSM04] is here recovered.

Second, distributed port-Hamiltonian systems are introduced, in connection with the underlying Stokes-Dirac structure. PHs as boundary control systems have been analyzed deeply in one geometrical dimension [JZ12, LGZM05]. Here, a more general definition is given. The complete characterization of pH in arbitrary dimension is still an open research field. Two notable exceptions ([KZ15, Skr19]) provide partial answers to this problem. The first demonstrate the well-posedness of the linear wave equation in arbitrary geometrical dimensions. The second generalizes this result to treat the case of generic first order linear pHs in arbitrary geometrical dimensions.

3.2.1 The Stokes-Dirac structure

In the section the concept of Stokes-Dirac structure for distributed, i.e. infinite-dimensional, pHs is introduced. First, the finite-dimensional case is considered. Then, to introduce the infinite-dimensional extension of Dirac structure, namely the Stokes-Dirac structure, the differential operators that come into play are characterized.

3.2.1.1 Dirac Structures

Consider a finite dimensional space F over the field $\mathbb{R}$ and $E \equiv F'$ its dual, i.e. the space of linear operator $\mathbf{e} : F \to \mathbb{R}$. The elements of F are called flows, while the elements of E are called efforts. Those are port variables and their combination gives the power flowing inside the system. The space $B = F \times E$ is called the bond space of power variables. Therefore the power is defined as $\langle \mathbf{e}, \mathbf{f} \rangle = \boldsymbol{e}(\mathbf{f})$, where $\langle \mathbf{e}, \mathbf{f} \rangle$ is the dual product between $\mathbf{f}$ and $\mathbf{e}$.

Definition 1 ([Cou90], Def. 1.1.1)
Given the finite-dimensional space F and its dual E with respect to the inner product $\langle \cdot, \cdot \rangle : F \times E \to \mathbb{R}$, consider the symmetric bilinear form:

$$\langle\langle\, (\mathbf{f}_1, \mathbf{e}_1), (\mathbf{f}_2, \mathbf{e}_2)\, \rangle\rangle := \langle \mathbf{e}_1, \mathbf{f}_2 \rangle + \langle \mathbf{e}_2, \mathbf{f}_1 \rangle\,, \qquad \textit{where} \qquad (\mathbf{f}_i, \mathbf{e}_i) \in B,\ i = 1, 2 \tag{3.8}$$

A Dirac structure on $B := F \times E$ is a subspace $D \subset B$, which is maximally isotropic under $\langle\langle \cdot, \cdot \rangle\rangle$. Equivalently, a Dirac structure on $B := F \times E$ is a subspace $D \subset B$ which equals its orthogonal complement with respect to $\langle\langle \cdot, \cdot \rangle\rangle : D = D^{\perp}$.

This definition can be extended to consider distributed forces and dissipation [Vil07].

Proposition 1
Consider the space of power variables $F \times E$ and let X denote an n-dimensional space, the space of energy variables. Suppose that $F := (F_s,\ F_e)$ and that $E := (E_s,\ E_e)$, with $\dim F_s = \dim E_s = n$ and $\dim F_e = \dim E_e = m$. Moreover, let $\mathbf{J}(\mathbf{x})$ denote a skew-symmetric matrix of dimension n and $\mathbf{B}(\mathbf{x})$ a matrix of dimension $n \times m$. Then, the set

$$D := \left\{ (\mathbf{f}_s, \mathbf{f}_e, \mathbf{e}_s, \mathbf{e}_e) \in F \times E | \quad \mathbf{f}_s = -\mathbf{J}(\mathbf{x})\mathbf{e}_s - \mathbf{B}(\mathbf{x})\mathbf{f}_e,\ \mathbf{e}_e = \mathbf{B}(\mathbf{x})^{\top}\mathbf{e}_s \right\} \tag{3.9}$$

is a Dirac structure.

3.2.1.2 Finite-dimensional port-Hamiltonian systems

Consider the time-invariant dynamical system:

$$\begin{cases} \dot{\mathbf{x}} & = \mathbf{J}(\mathbf{x})\nabla H(\mathbf{x}) + \mathbf{B}(\mathbf{x})\mathbf{u}, \\ \mathbf{y} & = \mathbf{B}(\mathbf{x})^{\top}\nabla H(\mathbf{x}), \end{cases} \tag{3.10}$$

where $H(\mathbf{x}) : X \to \mathbb{R}$, the Hamiltonian, is a real-valued function bounded from below. Such a system is called port-Hamiltonian, as it arises from the Hamiltonian modelling of a physical system and it interacts with the environment through the input $\mathbf{u}$, included in the formulation. The connection with the concept of Dirac structure is achieved by considering the following port behavior:

$$\begin{aligned} \mathbf{f}_s &= -\dot{\mathbf{x}}, & \mathbf{e}_s &= \nabla H(\mathbf{x}), \\ \mathbf{f}_e &= \mathbf{u}, & \mathbf{e}_e &= \mathbf{y}. \end{aligned} \tag{3.11}$$

With this choice of the port variables, system (3.10) defines, by Proposition 1, a Dirac structure. Dissipation and distributed forces can be included and the corresponding system defines an extended Dirac structure, once the proper port variables have been introduced.

3.2.1.3 Constant matrix differential operators

Let Ω denote a compact subset of $\mathbb{R}^d$ representing the spatial domain of the distributed parameter system. Then, let $U = C^\infty(\Omega, \mathbb{R}^{q_u})$ and $V = C^\infty(\Omega, \mathbb{R}^{q_v})$ denote the sets of smooth functions from Ω to $\mathbb{R}^{q_u}$ and $\mathbb{R}^{q_v}$ respectively.

Definition 2
A constant matrix differential operator of order n is a map $\mathcal{L} : U \to V$ such that, given $\boldsymbol{u} = (u_1, \dots, u_{q_u}) \in U$ and $\boldsymbol{v} = (v_1, ..., v_{q_v}) \in V$:

$$\boldsymbol{v} = \mathcal{L}\boldsymbol{u} \iff \boldsymbol{v} := \sum_{|\alpha|=0}^{n} \boldsymbol{P}_\alpha \partial^\alpha \boldsymbol{u}, \tag{3.12}$$

where $\alpha := (\alpha_1, \dots, \alpha_d)$ is a multi-index of order $|\alpha| := \sum_{i=1}^d \alpha_i$, $\boldsymbol{P}_\alpha$ is a set of constant real $q_v \times q_u$ matrices and $\partial^\alpha := \partial_{x_1}^{\alpha_1} \dots \partial_{x_d}^{\alpha_d}$ is a differential operator of order $|\alpha|$ resulting from a combination of spatial derivatives.

The following definition, instrumental for the case of dpHs, is a simplified version of (6).

Definition 3
Consider the constant matrix differential operator (3.12). Its formal adjoint is the map $\mathcal{L}^*$ from V to U such that:

$$\boldsymbol{u} = \mathcal{L}^*\boldsymbol{v} \iff \boldsymbol{u} := \sum_{|\alpha|=0}^{n} (-1)^{|\alpha|} \boldsymbol{P}_\alpha^\top \partial^\alpha \boldsymbol{v}. \tag{3.13}$$

Remark 1 (Differences between adjoint and formal adjoint)
The definition of formal adjoint is such that the integration by parts formula is respected

$$\int_\Omega \boldsymbol{a} \cdot (\mathcal{L}\boldsymbol{b}) \, \mathrm{d}\Omega = \int_\Omega (\mathcal{L}^*\boldsymbol{a}) \cdot \boldsymbol{b} \, \mathrm{d}\Omega,$$

where $\boldsymbol{a} \in C_0^\infty(\Omega, \mathbb{R}^{q_u})$, $\boldsymbol{b} \in C_0^\infty(\Omega, \mathbb{R}^{q_v})$ are smooth functions with compact support. This corresponds to the adjoint definition for a bounded operator between L^2 spaces of square integrable functions

$$\langle \boldsymbol{a}, \mathcal{L}\boldsymbol{b} \rangle_{L^2(\Omega, \mathbb{R}^{q_v})} = \langle \mathcal{L}^*\boldsymbol{a}, \boldsymbol{b} \rangle_{L^2(\Omega, \mathbb{R}^{q_u})}.$$

That means that, contrarily to the adjoint of an operator, the formal adjoint definition does not regard the actual domain of the operator nor the boundary conditions. For example, the differential operators div, grad *are unbounded in the* L^2 *topology. Whenever unbounded operators are considered, it is important to define their domain. To avoid the need of specifying domains, the notion of formal adjoint is used. The formal adjoint respects the integration by parts formula and is defined only for sufficiently smooth functions with compact support. In this sense the formal adjoint of* div *is* $-$ grad*, since for smooth functions with compact support, it holds*

$$\langle \boldsymbol{y}, \, \mathrm{grad}(x) \rangle_{L^2(\Omega, \mathbb{R}^3)} \underbrace{=}_{I.B.P.} - \langle \mathrm{div}(\boldsymbol{y}), \, x \rangle_{L^2(\Omega, \mathbb{R})} \,,$$

for $\boldsymbol{y} \in C_0^\infty(\Omega, \mathbb{R}^n), \; x \in C_0^\infty(\Omega)$ *(I.B.P. stands for integration by parts). The definition of the domain of the operators, that requires the knowledge of the boundary conditions, has not been specified.*

When $q_u = q_v = q \implies U \equiv V = W$, formal skew-adjoint operators can be defined:

Definition 4
Let $W = C^\infty(\Omega, \mathbb{R}^q)$ *be the space of vector-valued smooth functions and* $\mathcal{J} : W \to W$ *a constant matrix differential operator. Then,* $\mathcal{J}$ *is formally skew-adjoint (or skew-symmetric) if and only if* $\mathcal{J} = -\mathcal{J}^*$*. This corresponds to the algebraic condition on* $q \times q$ *square matrices*

$$\boldsymbol{P}_\alpha = (-1)^{|\alpha|+1} \boldsymbol{P}_\alpha^\top, \quad \forall \alpha. \tag{3.14}$$

An important relation between a differential operator and its adjoint is expressed by the following theorem, valid for operators between spaces of different dimensions.

Theorem 2 ([RR04], Chapter 9, theorem 9.37)
Consider a matrix differential operator $\mathcal{L} : U \to V$ *and let* $\mathcal{L}^*$ *denote its formal adjoint. Then, for each function* $\boldsymbol{u} \in U$ *and* $\boldsymbol{v} \in V$*:*

$$\int_\Omega \left(\boldsymbol{v}^\top \mathcal{L} \boldsymbol{u} - \boldsymbol{u}^\top \mathcal{L}^* \boldsymbol{v} \right) \, \mathrm{d}\Omega = \int_{\partial\Omega} \widetilde{\mathcal{A}}_{\mathcal{L}}(\boldsymbol{u}, \boldsymbol{v}) \, \mathrm{d}S, \tag{3.15}$$

where $\widetilde{\mathcal{A}}_{\mathcal{L}}$ *is a differential operator induced on the boundary* $\partial\Omega$ *by* $\mathcal{L}$*, or equivalently:*

$$\boldsymbol{v}^\top \mathcal{L} \boldsymbol{u} - \boldsymbol{u}^\top \mathcal{L}^* \boldsymbol{v} = \mathrm{div} \, \widetilde{\mathcal{A}}_{\mathcal{L}}(\boldsymbol{u}, \boldsymbol{v}). \tag{3.16}$$

It is important to note that $\widetilde{\mathcal{A}}_{\mathcal{L}}$ is a constant differential operator. The quantity $\widetilde{\mathcal{A}}_{\mathcal{L}}(\boldsymbol{u}, \boldsymbol{v})$ is a constant linear combination of the functions $\boldsymbol{u}$ and $\boldsymbol{v}$ together with their spatial derivatives up to a certain order and depending on $\mathcal{L}$.

Corollary 1

Consider a skew-symmetric differential operator $\mathcal{J}$. Then, for each function $\boldsymbol{u}$, $\boldsymbol{v} \in W$:

$$\int_{\Omega} \left(\boldsymbol{v}^{\top} \mathcal{J} \boldsymbol{u} + \boldsymbol{u}^{\top} \mathcal{J} \boldsymbol{v} \right) \, \mathrm{d}\Omega = \int_{\partial\Omega} \widetilde{\mathcal{A}}_{\mathcal{J}}(\boldsymbol{u}, \boldsymbol{v}) \, \mathrm{d}S, \tag{3.17}$$

where $\widetilde{\mathcal{A}}_{\mathcal{J}}$ is a symmetric differential operator on $\partial\Omega$ depending on the differential operator $\mathcal{J}$.

3.2.1.4 Constant Stokes-Dirac structures

Following [MvdSM04], let F denote the space of flows, i.e. the space of smooth functions from the compact set $\Omega \subset \mathbb{R}^d$ to $\mathbb{R}^q$. For simplicity assume that the space of efforts is $E \equiv F$ (generally speaking these spaces are Hilbert spaces linked by duality, as in [Vil07]). Given $\boldsymbol{f} = (f_1, \dots, f_q) \in F$ and $\boldsymbol{e} = (e_1, \dots, e_q) \in E$. Let $\boldsymbol{z} = \mathcal{A}_{\partial}(\boldsymbol{e})$ denote the boundary terms, where $\mathcal{A}_{\partial}$ provides the restriction on $\partial\Omega$ of the effort variables $\boldsymbol{e}$ and of their spatial derivatives of proper order. The associated boundary space is $Z := \{\boldsymbol{z} | \ \boldsymbol{z} = \mathcal{A}_{\partial}(\boldsymbol{e})\}$. Then, it holds

$$\int_{\partial\Omega} \widetilde{\mathcal{A}}_{\mathcal{J}}(\boldsymbol{e}_1, \boldsymbol{e}_2) \, \mathrm{d}S = \int_{\partial\Omega} \mathcal{A}_{\mathcal{J}}(\boldsymbol{z}_1, \boldsymbol{z}_2) \, \mathrm{d}S, \quad \text{with} \quad \widetilde{\mathcal{A}}_{\mathcal{J}}(\cdot, \cdot) = \mathcal{A}_{\mathcal{J}}(\mathcal{A}_{\partial}(\cdot), \mathcal{A}_{\partial}(\cdot)). \tag{3.18}$$

The following theorem characterizes Stokes-Dirac structures for pHs of arbitrary geometrical dimension and differential order.

Proposition 2 (Proposition 3.3 [MvdSM04])
Consider the space of power variables $B = F \times E \times Z$. The linear subspace $D \subset B$

$$D_{\mathcal{J}} = \{ (\boldsymbol{f}, \boldsymbol{e}, \boldsymbol{z}) \in F \times E \times Z \mid \boldsymbol{f} = -\mathcal{J} \boldsymbol{e}, \ \boldsymbol{z} = \mathcal{A}_{\partial}(\boldsymbol{e}) \} \,, \tag{3.19}$$

is a Stokes–Dirac structure on B with respect to the pairing

$$\left\langle \left\langle \, (\boldsymbol{f}^1, \boldsymbol{e}^1, \boldsymbol{z}^1), (\boldsymbol{f}^2, \boldsymbol{e}^2, \boldsymbol{z}^2) \, \right\rangle \right\rangle := \int_{\Omega} \left(\boldsymbol{e}^{1\top} \boldsymbol{f}^2 + \boldsymbol{e}^{2\top} \boldsymbol{f}^1 \right) \, \mathrm{d}\Omega + \int_{\partial\Omega} \mathcal{A}_{\mathcal{J}}(\boldsymbol{z}^1, \boldsymbol{z}^2) \, \mathrm{d}S. \tag{3.20}$$

From this proposition, if $(\boldsymbol{f}, \boldsymbol{e}, \boldsymbol{z}) \in D_{\mathcal{J}}$, then $\langle\langle \, (\boldsymbol{f}, \boldsymbol{e}, \boldsymbol{z}), (\boldsymbol{f}, \boldsymbol{e}, \boldsymbol{z}) \, \rangle\rangle = 0$, that is

$$\int_{\Omega} \boldsymbol{e}^{\top} \boldsymbol{f} \, \mathrm{d}\Omega + \frac{1}{2} \int_{\partial\Omega} \mathcal{A}_{\mathcal{J}}(\boldsymbol{z}, \boldsymbol{z}) \, \mathrm{d}S = 0. \tag{3.21}$$

This relation expresses the power conservation property of the Stokes–Dirac structure. It states the relation between the variation of internal energy (the integral on the domain Ω) with the power flowing through the boundary (the integral over $\partial\Omega$). Thanks to the power conservation property dpHs always dispose of an associated Stokes-Dirac structure. This concept can be extended to consider dissipation or distributed forces. To this aim, it is necessary to include additional ports to account for the power exchange due to these effects (see Theorem 3.4 [MvdSM04]).

Remark 2

The constant Stokes-Dirac structure has been defined in case of smooth vector-valued functions for simplicity. The definition is indeed more general and encompasses the case of more complex functional spaces, in particular the L^2 space of square integrable functions. Linear elasticity for example is defined on a mixed function space of vector- and tensor-valued functions. The constant differential operator may contain intrinsic operators ($\mathrm{Div}, \mathrm{Grad}$*) as it will be shown in §3.3. The result presented here remains valid provided that the proper pairing is being chosen.*

3.2.2 Distributed port-Hamiltonian systems

A distributed lossless port-Hamiltonian system is defined by a set of variables that describes the unknowns, by a formally skew-adjoint differential operator, an energy functional and a set of boundary inputs and corresponding conjugated outputs. Such a system is described by the following set of equations

$$\begin{aligned} \frac{\partial \boldsymbol{\alpha}}{\partial t} &= \mathcal{J} \boldsymbol{e}, \\ \boldsymbol{u}_\partial &= \mathcal{B}_\partial \boldsymbol{e}, \\ \boldsymbol{y}_\partial &= \mathcal{C}_\partial \boldsymbol{e}, \\ \boldsymbol{e} &:= \frac{\delta H}{\delta \boldsymbol{\alpha}}. \end{aligned} \tag{3.22}$$

The unknowns $\boldsymbol{\alpha}$ are called energy variables in the port-Hamiltonian framework, the formally skew-adjoint operator $\mathcal{J}$ is named interconnection operator (see Def. 4 for a precise definition of formal skew adjointness). $\mathcal{B}_\partial, \mathcal{C}_\partial$ are boundary operators, that provide the boundary input $\boldsymbol{u}_\partial$ and output $\boldsymbol{y}_\partial$ [TW09, Chapter 4]. The variational derivative of the Hamiltonian defines the co-energy variables $\boldsymbol{e}$.

Remark 3
It will become clear in this section that the effort variables of the Stokes-Dirac structure are indeed equivalent to the co-energy variables of the pH system. This justifies using the same notation for both.

Definition 5 (Variational derivative, Def. 4.1 in [Olv93])
Consider a functional $H(\boldsymbol{\alpha})$

$$H(\boldsymbol{\alpha}) = \int_\Omega \mathcal{H}(\boldsymbol{\alpha}) \, \mathrm{d}\Omega.$$

Given a variation $\boldsymbol{\alpha} = \bar{\boldsymbol{\alpha}} + \eta \boldsymbol{\delta\alpha}$ the variational derivative $\frac{\delta H}{\delta \boldsymbol{\alpha}}$ is defined as

$$H(\bar{\boldsymbol{\alpha}} + \eta \boldsymbol{\delta\alpha}) = H(\bar{\boldsymbol{\alpha}}) + \eta \int_\Omega \frac{\delta H}{\delta \boldsymbol{\alpha}} \cdot \boldsymbol{\delta\alpha} \, \mathrm{d}\Omega + O(\eta^2).$$

Remark 4
If the integrand does not contain derivative of the argument $\boldsymbol{\alpha}$ then the variational derivative

is equal to the partial derivative of the Hamiltonian density $\mathcal{H}$

$$\frac{\delta H}{\delta \boldsymbol{\alpha}} = \frac{\partial \mathcal{H}}{\partial \boldsymbol{\alpha}}.$$

Lossless port-Hamiltonian systems possess a peculiar property: the energy rate is given by the power due to the boundary ports $\boldsymbol{u}_\partial, \boldsymbol{y}_\partial$

$$\begin{aligned}\dot{H} &= \int_\Omega \frac{\delta H}{\delta \boldsymbol{\alpha}} \cdot \frac{\partial \boldsymbol{\alpha}}{\partial t} \, \mathrm{d}\Omega = \langle \delta_{\boldsymbol{\alpha}} H, \partial_t \boldsymbol{\alpha} \rangle_\Omega \,, \qquad \text{Stokes theorem} \\ &= \int_{\partial\Omega} \boldsymbol{u}_\partial \cdot \boldsymbol{y}_\partial \, \mathrm{d}S = \langle \boldsymbol{u}_\partial, \boldsymbol{y}_\partial \rangle_{\partial\Omega} \,.\end{aligned} \tag{3.23}$$

From the energy rate, the structural power balance is obtained

$$- \langle \delta_{\boldsymbol{\alpha}} H, \partial_t \boldsymbol{\alpha} \rangle_\Omega + \langle \boldsymbol{u}_\partial, \boldsymbol{y}_\partial \rangle_{\partial\Omega} = 0 \tag{3.24}$$

From (3.21), it is clear by identification that $\mathcal{A}_{\mathcal{J}}(\boldsymbol{z}, \boldsymbol{z}) = 2\, \boldsymbol{u}_\partial \cdot \boldsymbol{y}_\partial$. This means that the boundary space can be split into boundary input and output

$$Z := \{\boldsymbol{z} |\ \boldsymbol{z} = \mathcal{A}_\partial(\boldsymbol{e}) = (\boldsymbol{u}_\partial,\, \boldsymbol{y}_\partial)\}$$

If the flow, effort and boundary variables are chosen to be

$$\boldsymbol{f} := -\partial_t \boldsymbol{\alpha}, \quad \boldsymbol{e} := \delta_{\boldsymbol{\alpha}} H, \quad \boldsymbol{z} := (\boldsymbol{u}_\partial,\, \boldsymbol{y}_\partial), \tag{3.25}$$

then system (3.22) defines a Stokes-Dirac structure by Proposition 2. In this rather informal treatment of dpHs, no rigorous characterization whatsoever has been introduced for operators $\mathcal{B}_\partial$, $\mathcal{C}_\partial$ in system (3.22). A formal characterization of these operators has been given in [LGZM05] for pH of generic order only in one geometrical dimensional. In the following examples it is shown that from the power balance appropriate boundary variables can be defined.

3.2.2.1 Wave equation

Given an open bounded connected set $\Omega \subset \mathbb{R}^2$ with Lipschitz continuous boundary $\partial\Omega$, the propagation of sound in air can be described by the following model [TRLGK18]

$$\begin{aligned}\chi_s \partial_t p(\boldsymbol{x}, t) &= -\operatorname{div} \boldsymbol{v}, \\ \mu_0 \partial_t \boldsymbol{v}(\boldsymbol{x}, t) &= -\operatorname{grad} p,\end{aligned} \tag{3.26}$$

where the scalar fields χ_s, μ_0 are the constant adiabatic compressibility factor and the steady state mass density respectively. The scalar field and vector field $p \in \mathbb{R}$, $\boldsymbol{v} \in \mathbb{R}^2$ represents the variation of pressure and velocity from the steady state. The Hamiltonian (total energy) reads

$$H = \frac{1}{2}\int_\Omega \left\{\chi_s p^2 + \mu_0 \left\|\boldsymbol{v}\right\|^2\right\} \, \mathrm{d}\Omega.$$

To recast (3.26) in pH form the energy variables has to be introduced $\boldsymbol{\alpha} = [\alpha_p, \, \boldsymbol{\alpha}_v]^\top$

$$\alpha_p := \chi_s p, \qquad \boldsymbol{\alpha}_v := \mu_0 \boldsymbol{v}.$$

The Hamiltonian is rewritten as

$$H = \frac{1}{2}\int_\Omega \left\{\frac{1}{\chi_s}\alpha_p^2 + \frac{1}{\mu_0}\left\|\boldsymbol{\alpha}_v\right\|^2\right\} \, \mathrm{d}\Omega.$$

By definition, the co-energy are

$$e_p = \frac{\delta H}{\delta \alpha_p} = \frac{1}{\chi_s}\alpha_p = p, \qquad \boldsymbol{e}_v = \frac{\delta H}{\delta \boldsymbol{\alpha}_v} = \frac{1}{\mu_0}\boldsymbol{\alpha}_v = \boldsymbol{v}.$$

Equation (3.26) can be recast in port-Hamiltonian form

$$\frac{\partial}{\partial t}\begin{pmatrix}\alpha_p \\ \boldsymbol{\alpha}_v\end{pmatrix} = \begin{bmatrix} 0 & -\operatorname{div} \\ -\operatorname{grad} & \boldsymbol{0}\end{bmatrix}\begin{pmatrix} e_p \\ \boldsymbol{e}_v\end{pmatrix}.$$

From the energy rate it is possible to identify the boundary variables.

$$\begin{aligned}
\dot{H} &= \int_\Omega \left\{e_p \, \partial_t \alpha_p + \boldsymbol{e}_v \cdot \partial_t \boldsymbol{\alpha}_v\right\} \, \mathrm{d}\Omega, \\
&= \int_\Omega \left\{e_p \, \operatorname{div} \boldsymbol{e}_v + \boldsymbol{e}_v \cdot \operatorname{grad} e_p\right\} \, \mathrm{d}\Omega, && \text{Chain rule,} \\
&= \int_\Omega \operatorname{div}(e_p \, \boldsymbol{e}_v) \, \mathrm{d}\Omega, && \text{Stokes theorem,} \\
&= \int_{\partial\Omega} e_p \, \boldsymbol{e}_v \cdot \boldsymbol{n} \, \mathrm{d}S = \langle e_p, \boldsymbol{e}_v \cdot \boldsymbol{n}\rangle_{\partial\Omega}.
\end{aligned}$$

The boundary term $\langle e_p, \boldsymbol{e}_v\rangle_{\partial\Omega}$ pairs two power variables. One is taken as control input, the other plays the role of power-conjugated output. The assignment of these roles to the boundary power variables is referred to as causality of the boundary port [KML18],[Kot19, Chapter 2]. Under uniform causality assumption, either e_p or $\boldsymbol{e}_v$ can assume the role of (distributed) boundary input, but not both. This leads to two possible selections:

- First case $u_\partial = e_p, \quad y_\partial = \boldsymbol{e}_v \cdot \boldsymbol{n}$.
  This imposes the variable $e_p := p$ as boundary input and corresponds to a classical Dirichlet condition.

- Second case $u_\partial = \boldsymbol{e}_v \cdot \boldsymbol{n}, \quad y_\partial = e_p$.
  This imposes the variable $\boldsymbol{e}_v \cdot \boldsymbol{n} := \boldsymbol{v} \cdot \boldsymbol{n}$ as boundary input and corresponds to a Neumann condition.

3.2.2.2 Euler Bernoulli beam

The Euler-Bernoulli beam is the one-dimensional equivalent of the Kirchhoff-Love plate. This model consists of one PDE, describing the vertical displacement along the beam length:

$$\rho(x)\frac{\partial^2 w}{\partial t^2}(x,t) + \frac{\partial^2}{\partial x^2}\left(EI(x)\frac{\partial^2 w}{\partial x^2}\right) = 0, \quad x \in \Omega = \{0, L\}, \tag{3.27}$$

where $w(x,t)$ is the transverse displacement of the beam. The coefficients $\rho(x), E(x)$ and $I(x)$ are the mass per unit length, Young's modulus of elasticity and the moment of inertia of a cross section. The energy variables are then chosen as follows:

$$\alpha_w = \rho(x)\frac{\partial w}{\partial t}(x,t), \quad \text{Linear Momentum}, \quad \alpha_\kappa = \frac{\partial^2 w}{\partial x^2}(x,t), \quad \text{Curvature}. \tag{3.28}$$

Those variables are collected in the vector $\boldsymbol{\alpha} = (\alpha_w,\, \alpha_\kappa)^T$, so that the Hamiltonian can be written as a quadratic functional in the energy variables:

$$H = \frac{1}{2}\int_\Omega \left\{\frac{1}{\rho}\alpha_w^2 + EI\alpha_\kappa^2\right\} \,\mathrm{d}\Omega \tag{3.29}$$

The co-energy variables are found by computing the variational derivative of the Hamiltonian:

$$\begin{aligned} e_w &:= \frac{\delta H}{\delta \alpha_w} = \frac{\partial w}{\partial t}(x,t), && \text{Vertical velocity}, \\ e_\kappa &:= \frac{\delta H}{\delta \alpha_\kappa} = EI(x)\frac{\partial^2 w}{\partial x^2}(x,t), && \text{Flexural momentum}. \end{aligned} \tag{3.30}$$

The underlying interconnection structure is then found to be:

$$\frac{\partial}{\partial t}\begin{pmatrix}\alpha_w \\ \alpha_\kappa\end{pmatrix} = \begin{bmatrix} 0 & -\partial_{xx} \\ \partial_{xx} & 0 \end{bmatrix}\begin{pmatrix} e_w \\ e_\kappa\end{pmatrix}. \tag{3.31}$$

The power flow gives access to the boundary variables:

$$\begin{aligned} \dot{H} &= \int_\Omega \{e_w \partial_t \alpha_w + e_\kappa \partial_t \alpha_\kappa\} \,\mathrm{d}\Omega, \\ &= \int_\Omega \{-e_w \partial_{xx} e_\kappa + e_\kappa \partial_{xx} e_w\} \,\mathrm{d}\Omega, \qquad \text{Integration by parts}, \\ &= \int_{\partial\Omega} \{-e_w \partial_x e_\kappa + e_\kappa \partial_x e_w\} \,\mathrm{d}s = \langle -e_w, \partial_x e_\kappa \rangle_{\partial\Omega} + \langle e_\kappa, \partial_x e_w \rangle_{\partial\Omega} \end{aligned} \tag{3.32}$$

Since the system is of differential order two, two pairing appears, giving rise to four combination of uniform boundary causality

- First case $u_{\partial,1} = e_w, \quad u_{\partial,2} = \partial_x e_w, \quad y_{\partial,1} = -\partial_x e_\kappa, \quad y_{\partial,2} = e_\kappa$.
  This imposes the vertical $e_w := \partial_t w$ and angular velocity $\partial_x e_w := \partial_{xt} w$ as boundary

inputs. If the inputs are null a clamped boundary condition is obtained.

- Second case $u_{\partial,1} = e_w, \quad u_{\partial,2} = e_\kappa, \quad y_{\partial,1} = -\partial_x e_\kappa, \quad y_{\partial,2} = \partial_x e_w$.
  This imposes the vertical velocity and flexural momentum $e_\kappa := EI\partial_{xx}w$ as boundary inputs. Zero inputs lead to a simply supported condition is found.

- Third case $u_{\partial,1} = -\partial_x e_\kappa, \quad u_{\partial,2} = e_\kappa, \quad y_{\partial,1} = e_w, \quad y_{\partial,2} = \partial_x e_w$.
  This imposes the shear force $\partial_x e_\kappa := \partial_x(EI\partial_{xx}w)$ and flexural momentum as boundary inputs. Null inputs correspond to a free condition.

- Forth case $u_{\partial,1} = -\partial_x e_\kappa, \quad u_{\partial,2} = \partial_x e_w, \quad y_{\partial,1} = e_w, \quad y_{\partial,2} = e_\kappa$.
  This imposes the shear force and angular velocity as boundary inputs.

3.2.2.3 2D shallow water equations

This formulation may be found in [CR16, Section 6.2.]. This model describes a thin fluid layer of constant density in hydrostatic balance, like the propagation of a tsunami wave far from shore. Consider an open bounded connected set $\Omega \subset \mathbb{R}^2$ and a constant bed profile. The mass conservation implies

$$\frac{\partial h}{\partial t} + \mathrm{div}(h\boldsymbol{v}) = 0,$$

where $h(x, y, t) \in \mathbb{R}$ is a scalar field representing the fluid height, $\boldsymbol{v}(x, y, t) \in \mathbb{R}^2$ is the fluid velocity field. The conservation of linear momentum reads

$$\frac{\partial \rho \boldsymbol{v}}{\partial t} + \rho(\boldsymbol{v} \cdot \nabla)\boldsymbol{v} + \nabla(\rho g h) = 0,$$

where ρ is the mass density and g the gravitational acceleration constant. Using the identity

$$(\boldsymbol{v} \cdot \nabla)\boldsymbol{v} = \frac{1}{2}\nabla(\|\boldsymbol{v}\|^2) + (\nabla \times \boldsymbol{v}) \times \boldsymbol{v},$$

where $\nabla\times$ is the rotational of $\boldsymbol{v}$ (also denoted $\mathrm{curl}\,\boldsymbol{v}$), the momentum is rearranged as follows

$$\frac{\partial \rho \boldsymbol{v}}{\partial t} = -\nabla\left(\frac{1}{2}\rho\left\|\boldsymbol{v}\right\|^2 + \rho g h\right) - \rho(\nabla \times \boldsymbol{v}) \times \boldsymbol{v}.$$

The last term on the right-hand side can be rewritten

$$\rho(\nabla \times \boldsymbol{v}) \times \boldsymbol{v} = \begin{bmatrix} 0 & -\rho\omega \\ \rho\omega & 0 \end{bmatrix} \boldsymbol{v},$$

with $\omega = \partial_x v_y - \partial_y v_x$ the local vorticity term. To derive a suitable pH formulation, the total energy, made up of kinetic and potential contribution, has to be invoked

$$H = \frac{1}{2}\int_\Omega \left\{\rho h \left\|\boldsymbol{v}\right\|^2 + \rho g h^2\right\} \, \mathrm{d}\Omega.$$

As energy variable the fluid height and the linear momentum are chosen

$$\alpha_h = h, \qquad \boldsymbol{\alpha}_v = \rho \boldsymbol{v}.$$

The Hamiltonian is a non separable functional of the energy variables

$$H(\alpha_h, \boldsymbol{\alpha}_v) = \frac{1}{2}\int_\Omega \frac{1}{\rho}\alpha_h \left\|\boldsymbol{\alpha}_v\right\|^2 + \rho g \alpha_h^2 \, \mathrm{d}\Omega.$$

The co-energy variables are given by

$$e_h := \frac{\delta H}{\delta \alpha_h} = \frac{1}{2\rho}\left\|\boldsymbol{\alpha}_v\right\|^2 + \rho g \alpha_h, \qquad \boldsymbol{e}_v := \frac{\delta H}{\delta \boldsymbol{\alpha}_v} = \frac{1}{\rho}\alpha_h \boldsymbol{\alpha}_v.$$

The mass and momentum conservation are then rewritten as follows

$$\frac{\partial}{\partial t}\begin{pmatrix}\alpha_h \\ \boldsymbol{\alpha}_v\end{pmatrix} = \begin{bmatrix} 0 & -\operatorname{div} \\ -\operatorname{grad} & \mathcal{G}\end{bmatrix}\begin{pmatrix} e_h \\ \boldsymbol{e}_v\end{pmatrix},$$

The gyroscopic skew-symmetric term $\mathcal{G}$ introduces a non-linearity as it depends on the energy variables

$$\mathcal{G}(\alpha_h, \boldsymbol{\alpha}_v) = \frac{\omega}{\alpha_h}\begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}, \qquad \omega = \partial_x \alpha_{v,y} - \partial_y \alpha_{v,x}.$$

Despite the non-standard formulation, the energy rate provides anyway the boundary variables

$$\begin{aligned}
\dot{H} &= +\int_\Omega \left\{ e_h \, \partial_t \alpha_h + \boldsymbol{e}_v \cdot \partial_t \boldsymbol{\alpha}_v \right\} \, \mathrm{d}\Omega, && \\
&= -\int_\Omega \left\{ e_h \, \operatorname{div} \boldsymbol{e}_v + \boldsymbol{e}_v \cdot (\operatorname{grad} e_h - \mathcal{G}\boldsymbol{e}_v) \right\} \, \mathrm{d}\Omega, && \text{skew-symmetry of } \mathcal{G}, \\
&= -\int_\Omega \left\{ e_h \, \operatorname{div} \boldsymbol{e}_v + \boldsymbol{e}_v \cdot \operatorname{grad} e_h \right\} \, \mathrm{d}\Omega, && \text{Chain rule}, \\
&= -\int_\Omega \operatorname{div}(e_h \, \boldsymbol{e}_v) \, \mathrm{d}\Omega, && \text{Stokes theorem}, \\
&= -\int_{\partial\Omega} e_h \, \boldsymbol{e}_v \cdot \boldsymbol{n} \, \mathrm{d}S = -\left\langle e_h, \boldsymbol{e}_v \cdot \boldsymbol{n} \right\rangle_{\partial\Omega}. &&
\end{aligned}$$

Again two possible cases of uniform boundary causality arise:

- First case $u_\partial = e_h, \quad y_\partial = \boldsymbol{e}_v \cdot \boldsymbol{n}$.
  This imposes the variable $e_h := h$ as boundary input and corresponds to a given water level for a fluid boundary.

- Second case $u_\partial = \boldsymbol{e}_v \cdot \boldsymbol{n}, \quad y_\partial = e_p$.
  This imposes the variable $\boldsymbol{e}_v \cdot \boldsymbol{n} := h\boldsymbol{v} \cdot \boldsymbol{n}$ as boundary input and corresponds to a given volumetric flow rate.

3.3 Port-Hamiltonian formulation of linear elasticity

In this section a port-Hamiltonian formulation for elasticity is deduced from the classical elastodynamics problem. It must be highlighted that already in the seventies a purely hyperbolic formulation for elasticity was detailed [HM78]. The missing point is the clear connection with the theory of Hamiltonian PDEs. An Hamiltonian formulation can be found in [Gri15, Chapter 16], but without any connection to the concept of Stokes-Dirac structure induced by the underlying geometry.

3.3.1 Energy and co-energy variables

Consider an open connected set $\Omega \subset \mathbb{R}^d, \ d = (2, 3)$. The displacement within a deformable continuum is given by Eq. (3.7).

$$\rho \frac{\partial^2 \boldsymbol{u}}{\partial t^2} - \mathrm{Div}(\boldsymbol{\mathcal{D}} \, \mathrm{Grad} \, \boldsymbol{u}) = 0, \qquad \boldsymbol{x} \in \Omega. \tag{3.33}$$

The contribution of the body force $\boldsymbol{f}$ has been removed for ease of presentation. To derive a pH formulation, the total energy, that includes the kinetic and deformation energy, is needed

$$H = \frac{1}{2} \int_\Omega \left\{ \rho \left\| \partial_t \boldsymbol{u} \right\|^2 + \boldsymbol{\Sigma} : \boldsymbol{\varepsilon} \right\} \, \mathrm{d}\Omega. \tag{3.34}$$

The notation $\boldsymbol{A} : \boldsymbol{B} = \mathrm{Tr}(\boldsymbol{A}^\top \boldsymbol{B}) = \sum_{i,j} A_{ij} B_{ij}$ denotes the tensor contraction. Recall that $\boldsymbol{\varepsilon} = \mathrm{Grad} \, \boldsymbol{u}$ and $\boldsymbol{\Sigma} = \boldsymbol{\mathcal{D}} \boldsymbol{\varepsilon}$. The energy variables are then the linear momentum and the deformation field

$$\boldsymbol{\alpha}_v = \rho \boldsymbol{v}, \qquad \boldsymbol{A}_\varepsilon = \boldsymbol{\varepsilon},$$

where $\boldsymbol{v} := \partial_t \boldsymbol{u}$. The Hamiltonian can be rewritten as a quadratic functional in the energy variables

$$H = \frac{1}{2} \int_\Omega \left\{ \frac{1}{\rho} \boldsymbol{\alpha}_v^2 + (\boldsymbol{\mathcal{D}} \boldsymbol{A}_\varepsilon) : \boldsymbol{A}_\varepsilon \right\} \, \mathrm{d}\Omega. \tag{3.35}$$

The co-energy variables are given by

$$\boldsymbol{e}_v := \frac{\delta H}{\delta \boldsymbol{\alpha}_v} = \boldsymbol{v}, \qquad \boldsymbol{E}_\varepsilon := \frac{\delta H}{\delta \boldsymbol{A}_\varepsilon} = \boldsymbol{\Sigma}. \tag{3.36}$$

The tensor-valued co-energy $\boldsymbol{E}_\varepsilon$ is obtained by taking the variational derivative with respect to a tensor.

Proposition 3
The variational derivative of the Hamiltonian with respect to the strain tensor is the stress tensor $\delta_{\boldsymbol{A}_\varepsilon} H = \boldsymbol{\Sigma}$.

Proof. Let $\mathbb{S} : \mathbb{R}^{d\times d}_{\text{sym}}$ be the space of symmetric tensor and $L^2(\Omega, \mathbb{S})$ the space of the square integrable symmetric tensors endowed with the tensor contraction as inner product

$$\langle \boldsymbol{A}, \boldsymbol{B} \rangle_{L^2(\Omega,\mathbb{S})} = \int_\Omega \boldsymbol{A} : \boldsymbol{B} \, \mathrm{d}\Omega. \tag{3.37}$$

The contribution due to the deformation part in Hamiltonian is given by:

$$H_{\text{def}}(\boldsymbol{A}_\varepsilon) = \frac{1}{2} \int_\Omega (\boldsymbol{\mathcal{D}} \boldsymbol{A}_\varepsilon) : \boldsymbol{A}_\varepsilon \;\; \mathrm{d}\Omega.$$

A variation $\boldsymbol{\Delta A}_\varepsilon$ of the strain tensor with respect to a given value $\bar{\boldsymbol{A}}_\varepsilon$ leads to:

$$\begin{aligned} H_{\text{def}}(\bar{\boldsymbol{A}}_\varepsilon + \eta \boldsymbol{\Delta A}_\varepsilon) = &+ \frac{1}{2} \int_\Omega (\boldsymbol{\mathcal{D}} \bar{\boldsymbol{A}}_\varepsilon) : \bar{\boldsymbol{A}}_\varepsilon \;\; \mathrm{d}\Omega \\ &+ \eta \frac{1}{2} \int_\Omega \left\{ (\boldsymbol{\mathcal{D}} \bar{\boldsymbol{A}}_\varepsilon) : \boldsymbol{\Delta A}_\varepsilon + (\boldsymbol{\mathcal{D}} \boldsymbol{\Delta A}_\varepsilon) : \bar{\boldsymbol{A}}_\varepsilon \right\} \;\; \mathrm{d}\Omega + O(\eta^2). \end{aligned}$$

The term $(\boldsymbol{\mathcal{D}} \boldsymbol{\Delta A}_\varepsilon) : \bar{\boldsymbol{A}}_\varepsilon$ can be further rearranged using the symmetry of $\boldsymbol{\mathcal{D}}$ and the commutativity of the tensor contraction

$$(\boldsymbol{\mathcal{D}} \boldsymbol{\Delta A}_\varepsilon) : \bar{\boldsymbol{A}}_\varepsilon = (\boldsymbol{\mathcal{D}} \bar{\boldsymbol{A}}_\varepsilon) : \boldsymbol{\Delta A}_\varepsilon,$$

so that

$$H_{\text{def}}(\bar{\boldsymbol{A}}_\varepsilon + \eta \boldsymbol{\Delta A}_\varepsilon) = \frac{1}{2} \int_\Omega (\boldsymbol{\mathcal{D}} \bar{\boldsymbol{A}}_\varepsilon) : \bar{\boldsymbol{A}}_\varepsilon \;\; \mathrm{d}\Omega + \eta \int_\Omega (\boldsymbol{\mathcal{D}} \bar{\boldsymbol{A}}_\varepsilon) : \boldsymbol{\Delta A}_\varepsilon \;\; \mathrm{d}\Omega + O(\eta^2).$$

By definition of variational derivative it can be written:

$$H_{\text{def}}(\bar{\boldsymbol{A}}_\varepsilon + \eta \boldsymbol{\Delta A}_\varepsilon) = H_{\text{def}}(\bar{\boldsymbol{A}}_\varepsilon) + \eta \left\langle \frac{\delta H}{\delta \boldsymbol{A}_\varepsilon}, \boldsymbol{\Delta A}_\varepsilon \right\rangle_{L^2(\Omega,\mathbb{S})} + O(\eta^2),$$

Then, by identification

$$\frac{\delta H_{\text{def}}}{\delta \boldsymbol{A}_\varepsilon} = \boldsymbol{\mathcal{D}} \bar{\boldsymbol{A}}_\varepsilon = \boldsymbol{\Sigma}.$$

Since the Hamiltonian is separable then $\delta_{\boldsymbol{A}_\varepsilon} H_{\text{def}} = \delta_{\boldsymbol{A}_\varepsilon} H$, leading to the final result. □

3.3.2 Final system and associated Stokes-Dirac structure

It is now possible to state the final pH form

$$\frac{\partial}{\partial t} \begin{pmatrix} \boldsymbol{\alpha}_v \\ \boldsymbol{A}_\varepsilon \end{pmatrix} = \begin{bmatrix} \boldsymbol{0} & \text{Div} \\ \text{Grad} & \boldsymbol{0} \end{bmatrix} \begin{pmatrix} \boldsymbol{e}_v \\ \boldsymbol{E}_\varepsilon \end{pmatrix}. \tag{3.38}$$

The first equation of the system is the conservation of linear momentum. The second represents a compatibility condition

$$\begin{aligned}\partial_t \boldsymbol{A}_\varepsilon &= \operatorname{Grad}(\boldsymbol{e}_v),\\ \partial_t \boldsymbol{\varepsilon} &= \operatorname{Grad}(\boldsymbol{v}),\\ \partial_t \operatorname{Grad} \boldsymbol{u} &= \operatorname{Grad}(\partial_t \boldsymbol{u}).\end{aligned} \tag{3.39}$$

Assuming that $\boldsymbol{u} \in C^2$, higher order derivatives commute (Schwarz theorem). Hence, the equation is verified. The following theorem ensures the differential operator is formally skew-adjoint (one can also find this result in the recent article [PZ20, Lemma 3.3], available as arXiv preprint).

Theorem 3
The formal adjoint of the tensor divergence Div *is* $-\operatorname{Grad}$*, the opposite of the symmetric gradient.*

Proof. We denote by $\mathbb{V} = \mathbb{R}^d$ the space of vector field in $\mathbb{R}^d$ and by $\mathbb{S} = \mathbb{R}^{d\times d}$ hte space of symmetric tensor field in $\mathbb{R}^{d\times d}$. Let us consider the Hilbert space of the square integrable symmetric tensors $L^2(\Omega, \mathbb{S})$ with scalar product is defined in (3.37). Moreover consider the Hilbert space of the square integrable vector function $L^2(\Omega, \mathbb{V})$, endowed with the usual scalar product:

$$\langle \boldsymbol{a}, \boldsymbol{b}\rangle_{L^2(\Omega,\mathbb{V})} = \int_\Omega \boldsymbol{a}\cdot\boldsymbol{b} \ \mathrm{d}\Omega = \int_\Omega \boldsymbol{a}^\top \boldsymbol{b} \ \mathrm{d}\Omega, \quad \forall \boldsymbol{a}, \boldsymbol{b} \in L^2(\Omega, \mathbb{V}).$$

Let us consider the tensor divergence operator defined as:

$$\begin{aligned}\operatorname{Div}: \ L^2(\Omega, \mathbb{S}) &\to L^2(\Omega, \mathbb{V}),\\ \boldsymbol{\Psi} &\to \operatorname{Div}\boldsymbol{\Psi} = \boldsymbol{\psi},\end{aligned} \qquad \text{with } \psi_j = \operatorname{div}(\Psi_{ij}) = \sum_{i=1}^d \frac{\partial \Psi_{ij}}{\partial x_i}.$$

We try to identify Div^*

$$\begin{aligned}\operatorname{Div}^*: \ L^2(\Omega, \mathbb{V}) &\to L^2(\Omega, \mathbb{S}),\\ \boldsymbol{\phi} &\to \operatorname{Div}^*\boldsymbol{\phi} = \boldsymbol{\Phi},\end{aligned}$$

such that

$$\langle \operatorname{Div}\boldsymbol{\Psi}, \boldsymbol{\phi}\rangle_{L^2(\Omega,\mathbb{V})} = \langle \boldsymbol{\Psi}, \operatorname{Div}^*\boldsymbol{\phi}\rangle_{L^2(\Omega,\mathbb{S})}, \qquad \begin{aligned}&\forall \boldsymbol{\Psi} \in \operatorname{Domain}(\operatorname{Div}) \subset L^2(\Omega, \mathbb{S})\\ &\forall \boldsymbol{\phi} \in \operatorname{Domain}(\operatorname{Div}^*) \subset L^2(\Omega, \mathbb{V})\end{aligned}$$

Now let us take $\boldsymbol{\Psi} \in C_0^1(\Omega, \mathbb{S}) \subset \operatorname{Domain}(\operatorname{Div})$ the space of differentiable symmetric tensors with compact support in Ω. Additionally $\boldsymbol{\phi}$ will belong to $C_0^1(\Omega, \mathbb{V}) \subset \operatorname{Domain}(\operatorname{Div}^*)$, the space of differentiable vector functions with compact support in Ω. Then

$$\begin{aligned}
\langle \operatorname{Div} \boldsymbol{\Psi}, \boldsymbol{\phi} \rangle_{L^2(\Omega,\mathbb{V})} &= \int_\Omega \boldsymbol{\psi} \cdot \boldsymbol{\phi} \ \mathrm{d}\Omega, \\
&= \int_\Omega \sum_{i=1}^{d} \sum_{j=1}^{d} \frac{\partial \Psi_{ij}}{\partial x_i} \phi_j \ \mathrm{d}\Omega, \\
&= - \int_\Omega \sum_{i=1}^{d} \sum_{j=1}^{d} \Psi_{ij} \frac{\partial \phi_j}{\partial x_i} \ \mathrm{d}\Omega\,, && \text{since the functions vanish at the boundary,} \\
&= - \int_\Omega \sum_{i=1}^{d} \sum_{j=1}^{d} \Psi_{ij} F_{ij} \ \mathrm{d}\Omega, && \text{where} \qquad F_{ij} = \frac{\partial \phi_j}{\partial x_i}, \\
&= - \langle \boldsymbol{\Psi}, \boldsymbol{F} \rangle_{L^2(\Omega,\mathbb{S})}\,, && \boldsymbol{F} = (\nabla \boldsymbol{\phi})^\top.
\end{aligned}$$

But in this latter case, it could not be stated that $\boldsymbol{F} \in L^2(\Omega, \mathbb{S})$. Now, since $\boldsymbol{\Psi} \in L^2(\Omega, \mathbb{S})$, $\Psi_{ji} = \Psi_{ij}$, thus we are allowed to further decompose the last equality as

$$\sum_{i,j} \Psi_{ij} \frac{\partial \phi_j}{\partial x_i} = \sum_{i,j} \Psi_{ij} \frac{1}{2} \left(\frac{\partial \phi_i}{\partial x_j} + \frac{\partial \phi_j}{\partial x_i} \right) = \sum_{i,j} \Psi_{ij} \Phi_{ij}, \qquad \text{with } \Phi_{ij} := \frac{1}{2} \left(\frac{\partial \phi_i}{\partial x_j} + \frac{\partial \phi_j}{\partial x_i} \right).$$

Thus $\boldsymbol{\Phi} = \operatorname{Grad} \boldsymbol{\phi} \in L^2(\Omega, \mathbb{S})$ and it can be stated that:

$$\begin{aligned}
\langle \operatorname{Div} \boldsymbol{\Psi}, \boldsymbol{\phi} \rangle_{L^2(\Omega,\mathbb{V})} &= - \int_\Omega \sum_{i,j} \Psi_{ij} \frac{1}{2} \left(\frac{\partial \phi_i}{\partial x_j} + \frac{\partial \phi_j}{\partial x_i} \right) \ \mathrm{d}\Omega \\
&= - \int_\Omega \sum_{i,j} \Psi_{ij} \Phi_{ij} \ \mathrm{d}\Omega = \langle \boldsymbol{\Psi}, - \operatorname{Grad} \boldsymbol{\phi} \rangle_{L^2(\Omega,\mathbb{S})}\,.
\end{aligned}$$

It can be concluded that the formal adjoint of Div is $\operatorname{Div}^* = - \operatorname{Grad}$. □

The boundary values are then found by evaluating the energy rate

$$\begin{aligned}
\dot{H} &= \int_\Omega \{ \boldsymbol{e}_v \cdot \partial_t \boldsymbol{\alpha}_v + \boldsymbol{E}_\varepsilon : \partial_t \boldsymbol{A}_\varepsilon \} \ \mathrm{d}\Omega, \\
&= \int_\Omega \{ \boldsymbol{e}_v \cdot \operatorname{Div} \boldsymbol{E}_\varepsilon + \boldsymbol{E}_\varepsilon : \operatorname{Grad} \boldsymbol{e}_v \} \ \mathrm{d}\Omega, && \text{Chain rule for tensors, cf. Appendix,} \\
&= \int_\Omega \operatorname{div}(\boldsymbol{E}_\varepsilon \cdot \boldsymbol{e}_v) \ \mathrm{d}\Omega, && \text{Stokes theorem (see [BBF}^+\text{13, Chapter 1]),} \\
&= \int_{\partial\Omega} \boldsymbol{e}_v \cdot (\boldsymbol{E}_\varepsilon \cdot \boldsymbol{n}) \ \mathrm{d}S = \langle \boldsymbol{e}_v, \boldsymbol{E}_\varepsilon \cdot \boldsymbol{n} \rangle_{\partial\Omega}\,.
\end{aligned} \tag{3.40}$$

The imposition of the velocity field along the boundary $\boldsymbol{e}_v = \partial_t \boldsymbol{u}$ corresponds to a Dirichlet condition. Setting $\boldsymbol{E}_\varepsilon \cdot \boldsymbol{n} = \boldsymbol{\Sigma} \cdot \boldsymbol{n}$ (the traction) corresponds to a Neumann condition. Consider a partition of the boundary $\partial\Omega = \Gamma_N \cup \Gamma_D$ and $\Gamma_N \cap \Gamma_D = \{\emptyset\}$, where a Dirichlet and a

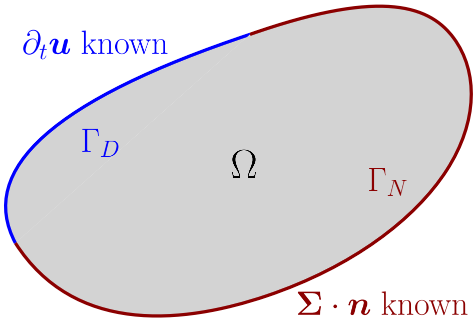

Figure 3.1: A 2D continuum with Neumann and Dirichlet boundary conditions

Neumann condition applies on the subset Γ_D and Γ_N respectively (see Fig. 3.1). Then the final pH formulation reads

$$\begin{aligned}
\frac{\partial}{\partial t}\begin{pmatrix} \boldsymbol{\alpha}_v \\ \boldsymbol{A}_\varepsilon \end{pmatrix} &= \underbrace{\begin{bmatrix} \mathbf{0} & \mathrm{Div} \\ \mathrm{Grad} & \mathbf{0} \end{bmatrix}}_{\mathcal{J}} \begin{pmatrix} \boldsymbol{e}_v \\ \boldsymbol{E}_\varepsilon \end{pmatrix}, \\
\boldsymbol{u}_\partial &= \underbrace{\begin{bmatrix} \gamma_0^{\Gamma_D} & \mathbf{0} \\ \mathbf{0} & \gamma_n^{\Gamma_N} \end{bmatrix}}_{\mathcal{B}_\partial} \begin{pmatrix} \boldsymbol{e}_v \\ \boldsymbol{E}_\varepsilon \end{pmatrix}, \\
\boldsymbol{y}_\partial &= \underbrace{\begin{bmatrix} \mathbf{0} & \gamma_n^{\Gamma_D} \\ \gamma_0^{\Gamma_N} & \mathbf{0} \end{bmatrix}}_{\mathcal{C}_\partial} \begin{pmatrix} \boldsymbol{e}_v \\ \boldsymbol{E}_\varepsilon \end{pmatrix},
\end{aligned} \tag{3.41}$$

where $\gamma_0^{\Gamma_*}$ denotes the trace over the set Γ_*, namely $\gamma_0^{\Gamma_*}\boldsymbol{e}_v = \boldsymbol{e}_v|_{\Gamma_*}$. Furthermore, $\gamma_n^{\Gamma_*}$ denotes the normal trace over the set Γ_*, namely $\gamma_n^{\Gamma_*}\boldsymbol{E}_\varepsilon = \boldsymbol{E}_\varepsilon \cdot \boldsymbol{n}|_{\Gamma_*}$.

Theorem 4 (Stokes-Dirac structure for elastodynamics)
Let $H^{\mathrm{Grad}}(\Omega, \mathbb{V})$ the space of vectors with symmetric gradient in $L^2(\Omega, \mathbb{S})$ and $H^{\mathrm{Div}}(\Omega, \mathbb{S})$ denote the space of symmetric tensors with divergence in $L^2(\Omega, \mathbb{V})$. Consider the following definitions

$$\begin{aligned}
H &:= H^{\mathrm{Grad}}(\Omega, \mathbb{V}) \times H^{\mathrm{Div}}(\Omega, \mathbb{S}), \\
F &:= L^2(\Omega, \mathbb{V}) \times L^2(\Omega, \mathbb{S}), \\
F_\partial &:= L^2(\Gamma_D, \mathbb{V}) \times L^2(\Gamma_N, \mathbb{V}).
\end{aligned}$$

The set

$$D_{\mathcal{J}} = \left\{ \begin{pmatrix} \boldsymbol{f} \\ \boldsymbol{f}_\partial \\ \boldsymbol{e} \\ \boldsymbol{e}_\partial \end{pmatrix} \mid \boldsymbol{e} \in H, \ \boldsymbol{f} = -\mathcal{J}\boldsymbol{e}, \ \boldsymbol{f}_\partial = \mathcal{B}_\partial \boldsymbol{e}, \ \boldsymbol{e}_\partial = \mathcal{C}_\partial \boldsymbol{e} \right\}, \tag{3.42}$$

where $\boldsymbol{e} = (\boldsymbol{e}_v, \boldsymbol{E}_\varepsilon)$ and $\mathcal{J}, \mathcal{B}_\partial, \mathcal{C}_\partial$ are defined in (3.41), is a Stokes–Dirac structure with *respect to the pairing*

$$\left\langle\!\left\langle (\boldsymbol{f}^1, \boldsymbol{f}_\partial^1, \boldsymbol{e}^1, \boldsymbol{e}_\partial^1), (\boldsymbol{f}^2, \boldsymbol{f}_\partial^2, \boldsymbol{e}^2, \boldsymbol{e}_\partial^2) \right\rangle\!\right\rangle := \left\langle \boldsymbol{e}^1, \boldsymbol{f}^2 \right\rangle_F + \left\langle \boldsymbol{e}^2, \boldsymbol{f}^1 \right\rangle_F + \left\langle \boldsymbol{e}_\partial^1, \boldsymbol{f}_\partial^2 \right\rangle_{F_\partial} + \left\langle \boldsymbol{e}_\partial^2, \boldsymbol{f}_\partial^1 \right\rangle_{F_\partial}, \tag{3.43}$$

where

$$\langle (\boldsymbol{a}, \, \boldsymbol{b}), (\boldsymbol{c}, \, \boldsymbol{d}) \rangle_{F_\partial} = \int_{\Gamma_D} \boldsymbol{a} \cdot \boldsymbol{c} \, \mathrm{d}S + \int_{\Gamma_N} \boldsymbol{b} \cdot \boldsymbol{d} \, \mathrm{d}S, \quad \boldsymbol{a}, \; \boldsymbol{b}, \; \boldsymbol{c}, \; \boldsymbol{d} \in \mathbb{V}.$$

Proof. A Stokes-Dirac is characterized by the fact that $D_{\mathcal{J}} = D_{\mathcal{J}}^{\perp}$. Then one has to show that $D_{\mathcal{J}} \subset D_{\mathcal{J}}^{\perp}$ and $D_{\mathcal{J}}^{\perp} \subset D_{\mathcal{J}}$. The proof is found by employing the integration by parts formula already used for (3.40). The main steps of Theorem 3.6 in [LGZM05] are followed here.

Step 1. To show that $D_{\mathcal{J}} \subset D_{\mathcal{J}}^{\perp}$, take $(\boldsymbol{f}, \, \boldsymbol{f}_\partial, \, \boldsymbol{e}, \, \boldsymbol{e}_\partial) \in D_{\mathcal{J}}$. Then

$$\begin{aligned}
\langle\!\langle (\boldsymbol{f}, \boldsymbol{f}_\partial, \boldsymbol{e}, \boldsymbol{e}_\partial), (\boldsymbol{f}, \boldsymbol{f}_\partial, \boldsymbol{e}, \boldsymbol{e}_\partial) \rangle\!\rangle =& 2 \langle \boldsymbol{e}, \boldsymbol{f} \rangle_F + 2 \langle \boldsymbol{e}_\partial, \boldsymbol{f}_\partial \rangle_{F_\partial}, \\
=& 2 \langle \boldsymbol{e}, -\mathcal{J} \boldsymbol{e} \rangle_F + 2 \langle \boldsymbol{e}_\partial, \boldsymbol{f}_\partial \rangle_{F_\partial}, \\
=& - 2 \int_\Omega \left\{ \boldsymbol{e}_v \cdot \mathrm{Div} \, \boldsymbol{E}_\varepsilon + \boldsymbol{E}_\varepsilon : \mathrm{Grad} \, \boldsymbol{e}_v \right\} \, \mathrm{d}\Omega \\
& + 2 \int_{\Gamma_D} \boldsymbol{e}_v \cdot (\boldsymbol{E}_\varepsilon \cdot \boldsymbol{n}) \, \mathrm{d}S + 2 \int_{\Gamma_N} \boldsymbol{e}_v \cdot (\boldsymbol{E}_\varepsilon \cdot \boldsymbol{n}) \, \mathrm{d}S, \\
=& - 2 \int_\Omega \left\{ \boldsymbol{e}_v \cdot \mathrm{Div} \, \boldsymbol{E}_\varepsilon + \boldsymbol{E}_\varepsilon : \mathrm{Grad} \, \boldsymbol{e}_v \right\} \, \mathrm{d}\Omega \\
& + 2 \int_{\partial\Omega} \boldsymbol{e}_v \cdot (\boldsymbol{E}_\varepsilon \cdot \boldsymbol{n}) \, \mathrm{d}S, = 0, \quad \text{from (3.40)}.
\end{aligned}$$

This implies $D_{\mathcal{J}} \subset D_{\mathcal{J}}^{\perp}$.

Step 2. Take $(\boldsymbol{\phi}, \, \boldsymbol{\phi}_\partial, \, \boldsymbol{\epsilon}, \, \boldsymbol{\epsilon}_\partial) \in D_{\mathcal{J}}^{\perp}$ and $\boldsymbol{e}_0 \in H$ with compact support on Ω. This implies $\mathcal{B}_\partial \boldsymbol{e}_0 = (\boldsymbol{0}, \, \boldsymbol{0})$ and $\mathcal{C}_\partial \boldsymbol{e}_0 = (\boldsymbol{0}, \, \boldsymbol{0})$. Taking $(-\mathcal{J} \boldsymbol{e}_0, \boldsymbol{0}, \boldsymbol{e}_0, \boldsymbol{0}) \in D_{\mathcal{J}}$ then

$$\langle\!\langle (\boldsymbol{\phi}, \boldsymbol{\phi}_\partial, \boldsymbol{\epsilon}, \boldsymbol{\epsilon}_\partial), (\mathcal{J} \boldsymbol{e}_0, \boldsymbol{0}, \boldsymbol{e}_0, \boldsymbol{0}) \rangle\!\rangle = \langle \boldsymbol{\epsilon}, -\mathcal{J} \boldsymbol{e}_0 \rangle_F + \langle \boldsymbol{e}_0, \boldsymbol{\phi} \rangle_F = 0, \quad \forall \boldsymbol{e}_0 \in H.$$

It follows that $\boldsymbol{\epsilon} \in H$ and $\boldsymbol{\phi} = -\mathcal{J} \boldsymbol{\epsilon}$.

Step 3. Take $(\boldsymbol{\phi}, \, \boldsymbol{\phi}_\partial, \, \boldsymbol{\epsilon}, \, \boldsymbol{\epsilon}_\partial) \in D_{\mathcal{J}}^{\perp}$ and $(\boldsymbol{f}, \, \boldsymbol{f}_\partial, \, \boldsymbol{e}, \, \boldsymbol{e}_\partial) \in D_{\mathcal{J}}$. Variables $\boldsymbol{e}, \boldsymbol{\epsilon}$ are indeed tuples containing a vector and a tensor, namely $\boldsymbol{e} = (\boldsymbol{e}_v, \, \boldsymbol{E}_\varepsilon)$, $\boldsymbol{\epsilon} = (\boldsymbol{\epsilon}_v, \, \boldsymbol{\mathcal{E}}_\varepsilon)$. From step 2 and (3.43)

$$\begin{aligned}
0 =& - \langle \boldsymbol{e}, \mathcal{J} \boldsymbol{\epsilon} \rangle_F - \langle \mathcal{J} \boldsymbol{e}, \boldsymbol{\epsilon} \rangle_F + \langle \boldsymbol{e}_\partial, \boldsymbol{\phi}_\partial \rangle_{F_\partial} + \langle \boldsymbol{\epsilon}_\partial, \boldsymbol{f}_\partial \rangle_{F_\partial}, \\
=& - \int_{\partial\Omega} \left\{ \boldsymbol{e}_v \cdot (\boldsymbol{\mathcal{E}}_\varepsilon \cdot \boldsymbol{n}) + \boldsymbol{\epsilon}_v \cdot (\boldsymbol{E}_\varepsilon \cdot \boldsymbol{n}) \right\} \, \mathrm{d}S + \langle \boldsymbol{e}_\partial, \boldsymbol{\phi}_\partial \rangle_{F_\partial} + \langle \boldsymbol{\epsilon}_\partial, \boldsymbol{f}_\partial \rangle_{F_\partial}
\end{aligned}$$

Consider the splitting of the boundary $\partial\Omega = \Gamma_N \cup \Gamma_D$

$$\begin{aligned}\int_{\partial\Omega} \left\{\boldsymbol{e}_v \cdot (\boldsymbol{\mathcal{E}}_\varepsilon \cdot \boldsymbol{n}) + \boldsymbol{\epsilon}_v \cdot (\boldsymbol{E}_\varepsilon \cdot \boldsymbol{n})\right\} \, \mathrm{d}S = &+ \int_{\Gamma_N} \left\{\boldsymbol{e}_{\partial,2} \cdot (\boldsymbol{\mathcal{E}}_\varepsilon \cdot \boldsymbol{n}) + \boldsymbol{\epsilon}_v \cdot \boldsymbol{f}_{\partial,2}\right\} \, \mathrm{d}S, \\ &+ \int_{\Gamma_D} \left\{\boldsymbol{f}_{\partial,1} \cdot (\boldsymbol{\mathcal{E}}_\varepsilon \cdot \boldsymbol{n}) + \boldsymbol{\epsilon}_v \cdot \boldsymbol{e}_{\partial,1}\right\} \, \mathrm{d}S,\end{aligned}$$

where the elements of the vectors $\boldsymbol{f}_\partial = (\boldsymbol{f}_{\partial,1}, \boldsymbol{f}_{\partial,2}),\ \boldsymbol{e}_\partial = (\boldsymbol{e}_{\partial,1}, \boldsymbol{e}_{\partial,2})$ have been considered. By expanding of the terms $\langle \boldsymbol{e}_\partial, \boldsymbol{\phi}_\partial \rangle_{F_\partial} + \langle \boldsymbol{\epsilon}_\partial, \boldsymbol{f}_\partial \rangle_{F_\partial}$ and given the fact that $\boldsymbol{e}_\partial$, $\boldsymbol{f}_\partial$ have arbitrary values then

$$\boldsymbol{\phi}_\partial = \begin{bmatrix} \gamma_0^{\Gamma_D} & \boldsymbol{0} \\ \boldsymbol{0} & \gamma_n^{\Gamma_N} \end{bmatrix} \begin{pmatrix} \boldsymbol{\epsilon}_v \\ \boldsymbol{\mathcal{E}}_\varepsilon \end{pmatrix}, \qquad \boldsymbol{\epsilon}_\partial = \begin{bmatrix} \boldsymbol{0} & \gamma_n^{\Gamma_D} \\ \gamma_0^{\Gamma_N} & \boldsymbol{0} \end{bmatrix} \begin{pmatrix} \boldsymbol{\epsilon}_v \\ \boldsymbol{\mathcal{E}}_\varepsilon \end{pmatrix},$$

meaning that $D_{\mathcal{J}}^{\perp} \subset D_{\mathcal{J}}$. This concludes the proof. □

Linear elasticity falls within the assumption of [Skr19]. Therefore, it is a well posed boundary control pH system. A question that naturally arises is how to reformulate this system using the language of differential geometry. This is possible through the usage of vector-valued differential forms. The interested reader may consult [Bre08].

3.4 Conclusion

In this chapter, the pH formulation of elasticity have been obtained. This model represents a generalization of the wave equation to higher dimensional variables. This leads to the introduction of symmetric tensorial quantities describing the state of stress and deformation within the body.
For a plane continuum with moderate thickness, it is possible to reduce the general three-dimensional mode to two uncoupled systems: one representing the in plane behavior ruled by 2D elasticity and one representing the out-of-plane deflection. This will be the object of the next chapter dedicated to the study of a pH formulation of plate bending. It is important to remember that plate models are just particular cases of three-dimensional elasticity.

Chapter 4

Port-Hamiltonian plate theory

You get tragedy where the tree, instead of bending, breaks.

Culture and Value
Ludwig Wittgenstein

Contents

Plates are plane structural elements with a small thickness compared to the planar dimension. Thanks to this feature, it is not necessary to model plate structures using three-dimensional elasticity. Dimensional reduction strategies are employed to describe plate structures as two-dimensional problems. These strategies rely on an educated guess of the displacement field. For beams and plates this field is expressed in terms of unknown functions $\phi_i^j(x, y, t)$ that solely depends on the midplane coordinates (x, y)

$$u_i(x, y, z, t) = \sum_{j=0}^{m} (z)^j \phi_i^j(x, y, t).$$

where u_i, $i = \{x, y, z\}$ are the components of the displacement field. A first-order approximation is commonly used, meaning that a linear dependence on z is considered. Two main models arise from such a framework:

- the Mindlin-Reissner model for thick plates;

- the Kirchhoff-Love model for thin plates.

In this chapter it its shown how to formulate first-order plate models as pHs.

4.1 First order plate theory

As previously stated, first order theories assume a linear dependence on the vertical coordinate (cf. [Red06])

$$u_i(x, y, z, t) = \phi_i^0(x, y, t) + z\phi_i^1(x, y, t).$$

This hypothesis implies that the fibers, i.e. segments perpendicular to the mid-plane before deformation, remain straight after deformation. Additionally, for plate with moderate thickness the fibers are considered inextensible, meaning that $\phi_z^1 = 0$. These assumptions lead to the following displacement field

$$\begin{aligned} u_x(x, y, z, t) &= u_x^0(x, y, t) - z\theta_x(x, y, t), \\ u_y(x, y, z, t) &= u_y^0(x, y, t) - z\theta_y(x, y, t), \\ u_z(x, y, z, t) &= u_z^0(x, y, t), \end{aligned} \tag{4.1}$$

where $u_i(x, y, t) = \phi_i^0(x, y, t)$, $\theta_i(x, y, t) = -\phi_i^1(x, y, t)$. Assuming a linear elastic behavior, the 3D strain tensor for such a displacement field takes the form

$$\varepsilon_{\alpha\beta} = \frac{1}{2}\left(\partial_\beta u_\alpha + \partial_\alpha u_\beta\right) - z\frac{1}{2}\left(\partial_\beta \theta_\alpha + \partial_\alpha \theta_\beta\right) = \varepsilon_{\alpha\beta}^0 - z\kappa_{\alpha\beta}, \tag{4.2}$$

$$\varepsilon_{\alpha z} = \frac{1}{2}\left(\partial_a u_z - \theta_\alpha\right) = \frac{1}{2}\gamma_\alpha, \tag{4.3}$$

where $\alpha = \{x, y\}$, $\beta = \{x, y\}$. The tensors $\boldsymbol{\varepsilon}^0$, $\boldsymbol{\kappa}$, $\boldsymbol{\gamma}$ are called membrane, bending (or curvature) and shear strain tensor

$$\boldsymbol{\varepsilon}^0 = \operatorname{Grad} \boldsymbol{u}^0, \tag{4.4}$$

$$\boldsymbol{\kappa} = \operatorname{Grad} \boldsymbol{\theta}, \tag{4.5}$$

$$\boldsymbol{\gamma} = \operatorname{grad} u_z - \boldsymbol{\theta}. \tag{4.6}$$

where $\boldsymbol{u}^0 = (u_x, u_y)^\top$, $\boldsymbol{\theta} = (\theta_x, \theta_y)^\top$. For now, it is assumed that the material is isotropic, linear elastic (in Section §4.3 this hypothesis is removed). Recall the Hooke's law for 3D continua (see Eq. (3.5))

$$\boldsymbol{\Sigma} = \frac{E}{1+\nu}\left[\boldsymbol{\varepsilon} + \frac{\nu}{1-2\nu}\operatorname{Tr}(\boldsymbol{\varepsilon})\boldsymbol{I}_{3\times 3}\right].$$

where E, ν are the Young modulus and Poisson ratio. The hypothesis of inextensible fibers implies $\varepsilon_{zz} = 0$. However, imposing a plane strain condition provides a model that is too stiff. Rather than a plain strain assumption, a plain stress hypothesis is used to derive the constitutive law for plates. The displacement field (4.1) is left unchanged, but, instead of ε_{zz},

Σ_{zz} is set to zero. If $\Sigma_{zz} = 0$, one gets

$$\varepsilon_{zz} = -\frac{\nu}{1-\nu}(\varepsilon_{xx} + \varepsilon_{yy}).$$

Consequently, it is computed

$$\mathrm{Tr}(\boldsymbol{\varepsilon}) = \frac{1-2\nu}{1-\nu}(\varepsilon_{xx} + \varepsilon_{yy}).$$

The constitutive law for the in-plane stress takes the form

$$\boldsymbol{\Sigma}_{2D} = \boldsymbol{\mathcal{D}}_{2D}\, \boldsymbol{\varepsilon}_{2D},$$

where $\boldsymbol{\Sigma}_{2D} = \Sigma_{\alpha\beta}$, $\boldsymbol{\varepsilon}_{2D} = \varepsilon_{\alpha\beta}$ and

$$\boldsymbol{\mathcal{D}}_{2D} = \frac{E}{1-\nu^2}\left[(1-\nu)(\cdot) + \nu\, \mathrm{Tr}(\cdot)\boldsymbol{I}_{2\times 2}\right]. \tag{4.7}$$

Concerning the shear deformation, the constitutive law reduces to

$$\boldsymbol{\sigma}_s = G\boldsymbol{\gamma}, \tag{4.8}$$

where $\boldsymbol{\sigma}_s := \boldsymbol{\Sigma}_{\alpha,3}$ and $G = \frac{E}{2(1+\nu)}$ is the shear modulus. In the following sections, the most common plate models will be presented.

4.1.1 Mindlin-Reissner model

The Mindlin-Reissner model [Rei47, Min51] represents a first-order shear deformation theory for describing the bending of plate. The in-plane midplane displacement are zero $\boldsymbol{u}^0(x, y) = \mathbf{0}$ for an isotropic plate that experiences only bending. Hence, the displacement field reduces to

$$\begin{aligned} u_x(x, y, z) &= -z\partial_x\theta_x, \\ u_y(x, y, z) &= -z\partial_y\theta_y, \\ u_z(x, y, z) &= u_z^0(x, y). \end{aligned} \tag{4.9}$$

In pure bending, the strain tensor is given by

$$\boldsymbol{\varepsilon}_b := \boldsymbol{\varepsilon}_{2D}(\boldsymbol{u}^0 = \mathbf{0}) = -z\boldsymbol{\kappa},$$

with $\boldsymbol{\kappa}$ given by (4.5). Consequently, the stress tensor reads

$$\boldsymbol{\Sigma}_b := \boldsymbol{\Sigma}_{2D}(\boldsymbol{u}^0 = \mathbf{0}) = -z\boldsymbol{\mathcal{D}}_{2D}\boldsymbol{\kappa},$$

where $\boldsymbol{\mathcal{D}}_{2D}$ is defined in Eq. (4.7).

The undeformed middle plane of the plate is denoted by Ω. The total domain of the plate is the product $\Omega \times (-h/2, h/2)$, where h is the constant thickness. To effectively reduce the problem from three- to two-dimensional, the stresses have to be integrated along the fibers. Since the stress varies linearly across the thickness, the stress has to be multiplied by z before the integration to get a non null contribution. The resulting quantity is called bending momenta tensor and is given by

$$\boldsymbol{M} := -\int_{-h/2}^{h/2} z\boldsymbol{\Sigma}_b \, \mathrm{d}z = \boldsymbol{\mathcal{D}}_b \, \boldsymbol{\kappa}, \tag{4.10}$$

where

$$\boldsymbol{\mathcal{D}}_b = D_b \left[(1-\nu)(\cdot) + \nu \, \mathrm{Tr}(\cdot) \boldsymbol{I}_{2\times 2}\right], \qquad \text{where} \qquad D_b = \frac{Eh^3}{12(1-\nu^2)}. \tag{4.11}$$

The shear stress has to be integrated along the fibers as well. Given the excessive rigidity of the shear contribution, a correction factor $k = 5/6$ [Red06, Chapter 10] is introduced

$$\boldsymbol{q} = \int_{-h/2}^{h/2} k \boldsymbol{\sigma_s} = kGh\boldsymbol{\gamma}, \tag{4.12}$$

where $\boldsymbol{\gamma}$ is defined in Eq. (4.6). The equations of motion can be obtained using Hamilton's principle. It consists in minimizing the total Lagrangian, given by $L = E_{\mathrm{def}} - E_{\mathrm{kin}}$, where E_{def}, E_{kin} are the deformation and kinetic energy

$$E_{\mathrm{def}} = \frac{1}{2} \int_\Omega \int_{-h/2}^{h/2} \boldsymbol{\Sigma} : \boldsymbol{\varepsilon} \; \mathrm{d}\Omega \, \mathrm{d}z = \frac{1}{2} \int_\Omega \left\{ \boldsymbol{M} : \boldsymbol{\kappa} + \boldsymbol{q} \cdot \boldsymbol{\gamma} \right\} \, \mathrm{d}\Omega, \tag{4.13}$$

$$E_{\mathrm{kin}} = \frac{1}{2} \int_\Omega \int_{-h/2}^{h/2} \rho \, \|\partial_t \boldsymbol{u}\|^2 \; \mathrm{d}\Omega \, \mathrm{d}z = \frac{1}{2} \int_\Omega \left\{ \frac{\rho h^3}{12} \|\partial_t \boldsymbol{\theta}\|^2 + \rho h (\partial_t u_z)^2 \right\} \, \mathrm{d}\Omega, \tag{4.14}$$

where ρ is the mass density. The Hamilton principle states that

$$\int_0^T \delta L \; \mathrm{d}t = \int_0^T \left\{ \delta E_{\mathrm{def}} - \delta E_{\mathrm{kin}} \right\} \; \mathrm{d}t = 0.$$

The final result is the following system of PDEs (for the detailed computations see [Red06, Chapter 10])

$$\begin{aligned} \rho h \frac{\partial^2 u_z}{\partial t^2} &= \mathrm{div}\, \boldsymbol{q}, \qquad (x,y) \in \Omega, \\ \frac{\rho h^3}{12} \frac{\partial^2 \boldsymbol{\theta}}{\partial t^2} &= \mathrm{Div}\, \boldsymbol{M} + \boldsymbol{q}, \end{aligned} \tag{4.15}$$

with $\boldsymbol{M} = \boldsymbol{\mathcal{D}}_b \, \mathrm{Grad}\, \boldsymbol{\theta}$ and $\boldsymbol{q} = kGh\,(\mathrm{grad}\, u_z - \boldsymbol{\theta})$. This PDE goes together with specified boundary conditions. Those will be detailed in 4.2.1.

4.1.2 Kirchhoff-Love model

The Kirchhoff model was formulated around 1850 and it is referred to as classical plate theory. The hypotheses on the displacement field consist of the following three points (see Fig. 4.1):

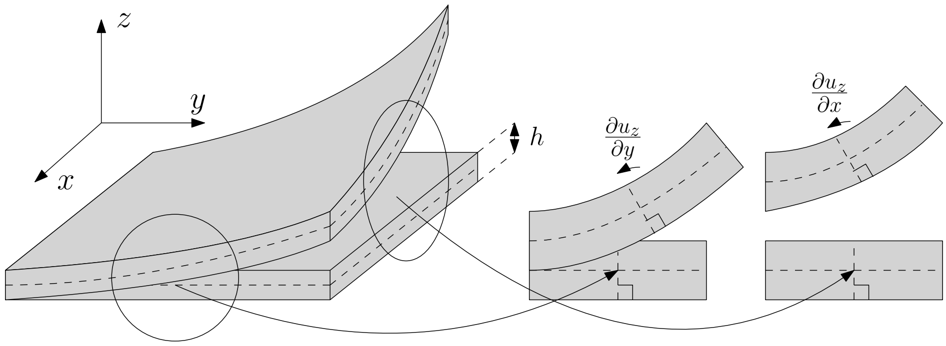

Figure 4.1: Kinematic assumption for the Kirchhoff plate

1. The fibers, segments perpendicular to the mid-plane before deformation, remain straight after deformation.

2. The fibers are inextensible.

3. While rotating, fibers remain perpendicular to the middle surface after deformation.

While the first two points are valid also for the Mindlin plate, the third assumption is specific to the Kirchhoff-Love model. Such an approximation is valid for plates having span-to-thickness ratio of the order of $L/h \approx 100-1000$ and implies zero transverse shear deformation

$$\boldsymbol{\gamma} = 0 \implies \varepsilon_{xz} = -\theta_x + \frac{\partial u_z}{\partial x} = 0, \qquad \varepsilon_{yz} = -\theta_y + \frac{\partial u_z}{\partial y} = 0.$$

The rotation vector is then related to the vertical displacement $\boldsymbol{\theta} = \operatorname{grad} u_z$. Plugging this into (4.5), it is found

$$\boldsymbol{\kappa} = \operatorname{Grad} \operatorname{grad} u_z = \operatorname{Hess} u_z. \tag{4.16}$$

Since the focus is on bending behavior, the in-plane displacement of the mid-plane are assumed to be zero $\boldsymbol{u}^0(x, y) = \mathbf{0}$. Hence, the displacement field assumes the form

$$\begin{aligned} u_x(x, y, z) &= -z\partial_x u_z, \\ u_y(x, y, z) &= -z\partial_y u_z, \\ u_z(x, y, z) &= u_z^0(x, y). \end{aligned} \tag{4.17}$$

For the Kirchhoff plate, the same link between the momenta and bending tensor holds

$$\boldsymbol{M} = \boldsymbol{\mathcal{D}}_b \boldsymbol{\kappa},$$

where $\boldsymbol{\mathcal{D}}_b$ and $\boldsymbol{\kappa}$ are given in (4.11), (4.16) respectively. The equations of motion can be obtained using Hamilton's principle [Red06, Chapter 2]. The deformation energy, kinetic energy and external work read

$$E_{\text{def}} = \frac{1}{2}\int_\Omega \int_{-h/2}^{h/2} \boldsymbol{\Sigma} : \boldsymbol{\varepsilon} \, \mathrm{d}\Omega \, \mathrm{d}z = \frac{1}{2}\int_\Omega \{\boldsymbol{M} : \boldsymbol{\kappa}\} \, \mathrm{d}\Omega, \tag{4.18}$$

$$E_{\text{kin}} = \frac{1}{2}\int_\Omega \int_{-h/2}^{h/2} \rho \, \|\partial_t \boldsymbol{u}\|^2 \, \mathrm{d}\Omega \, \mathrm{d}z \approx \frac{1}{2}\int_\Omega \rho h (\partial_t u_z)^2 \, \mathrm{d}\Omega. \tag{4.19}$$

Remark 5 (Rotational energy)
For the kinetic energy the rotational contribution

$$E_{rot} = \frac{1}{2}\int_\Omega \int_{-h/2}^{h/2} \left\{\rho \, (\partial_t u_x)^2 + (\partial_t u_y)^2\right\} \, \mathrm{d}\Omega \, \mathrm{d}z = \frac{h^3}{24}\int_\Omega \rho \left\{ (\partial_{tx} u_z)^2 + (\partial_{ty} u_z)^2 \right\} \, \mathrm{d}\Omega = O(h^3),$$

is neglected given the small thickness assumption.

The final result from the Hamilton's principle is the following PDE (for the detailed computations the reader may consult [Red06, Chapter 3])

$$\rho h \frac{\partial^2 u_z}{\partial t^2} = - \operatorname{div} \operatorname{Div}(\boldsymbol{\mathcal{D}}_b \operatorname{Grad} \operatorname{grad} u_z), \qquad (x, y) \in \Omega. \tag{4.20}$$

Developing the calculations, one obtains

$$\rho h \frac{\partial^2 u_z}{\partial t^2} = -D_b \Delta^2 u_z, \qquad (x, y) \in \Omega,$$

where $\Delta^2 = \frac{\partial^4}{\partial x^4} + 2\frac{\partial^2}{\partial x^2}\frac{\partial^2}{\partial y^2} + \frac{\partial^4}{\partial y^4}$ is the bi-Laplacian. Appropriate boundary conditions for this problem will be detailed in 4.2.2.

4.2 Port-Hamiltonian formulation of plates

In this section the pH formulation of the Mindlin and Kirchhoff plate models is detailed. In [MMB05], the Mindlin plate model was put in pH form by appropriate selection of the energy variables. However, the final system does not consider the nature of the different variables that come into play, leading to a non intrinsic final formulation. Additionally, this model was presented using the jet bundle formalism in [SS17]. The Kirchhoff model was never explored in the pH framework and represents an original contribution of this thesis. The interested reader can find in [RZ18] a rigorous mathematical treatment of the biharmonic problem and its decomposition in 2D geometries, but only for the static case (the 3D case, that does not relate to plate bending, is treated in [DZ18]).

4.2.1 Port-Hamiltonian Mindlin plate

Let $w := u_z$ denote the vertical displacement of the plate. Consider a bounded, connected domain $\Omega \subset \mathbb{R}^2$ and the Hamiltonian (total energy)

$$H = \frac{1}{2} \int_\Omega \left\{ \rho h \left(\frac{\partial w}{\partial t} \right)^2 + \frac{\rho h^3}{12} \left\| \frac{\partial \boldsymbol{\theta}}{\partial t} \right\|^2 + \boldsymbol{M} : \boldsymbol{\kappa} + \boldsymbol{q} \cdot \boldsymbol{\gamma} \right\} \, \mathrm{d}\Omega, \tag{4.21}$$

where $\boldsymbol{M}$, $\boldsymbol{\kappa}$, $\boldsymbol{q}$, $\boldsymbol{\gamma}$ are defined in Eqs. (4.10), (4.5), (4.12), (4.6) respectively. The choice of the energy variables is the same as in [MMB05] but here scalar-, vector- and tensor-valued variables are gathered together:

$$\begin{aligned} \alpha_w &= \rho h \frac{\partial w}{\partial t}, && \text{Linear momentum}, & \boldsymbol{\alpha}_\theta &= \frac{\rho h^3}{12} \frac{\partial \boldsymbol{\theta}}{\partial t}, && \text{Angular momentum}, \\ \boldsymbol{A}_\kappa &= \boldsymbol{\kappa}, && \text{Curvature tensor}, & \boldsymbol{\alpha}_\gamma &= \boldsymbol{\gamma}. && \text{Shear deformation}. \end{aligned} \tag{4.22}$$

The energy is now a quadratic function of the energy variables

$$H = \frac{1}{2} \int_\Omega \left\{ \frac{1}{\rho h} \alpha_w^2 + \frac{12}{\rho h^3} \left\| \boldsymbol{\alpha}_\theta \right\|^2 + (\boldsymbol{\mathcal{D}}_b \boldsymbol{A}_\kappa) : \boldsymbol{A}_\kappa + (\boldsymbol{\mathcal{D}}_s \boldsymbol{\alpha}_\gamma) \cdot \boldsymbol{\alpha}_\gamma \right\} \, \mathrm{d}\Omega, \tag{4.23}$$

where $\boldsymbol{\mathcal{D}}_s := Ghk \boldsymbol{I}_{2\times 2}$ and G is the shear modulus k the correction factor. The co-energy variables are found by computing the variational derivative of the Hamiltonian:

$$\begin{aligned} e_w &:= \frac{\delta H}{\delta \alpha_w} = \frac{\partial w}{\partial t}, && \text{Linear velocity}, & \boldsymbol{e}_\theta &:= \frac{\delta H}{\delta \boldsymbol{\alpha}_\theta} = \frac{\partial \boldsymbol{\theta}}{\partial t}, && \text{Angular velocity}, \\ \boldsymbol{E}_\kappa &:= \frac{\delta H}{\delta \boldsymbol{A}_\kappa} = \boldsymbol{M}, && \text{Momenta tensor}, & \boldsymbol{e}_\gamma &:= \frac{\delta H}{\delta \boldsymbol{\alpha}_\gamma} = \boldsymbol{q} && \text{Shear stress}. \end{aligned} \tag{4.24}$$

Proposition 4
The variational derivative of the Hamiltonian with respect to the curvature tensor is the momenta tensor $\frac{\delta H}{\delta \boldsymbol{A}_\kappa} = \boldsymbol{M}$.

Proof. The proof is analogous to the one already detailed in Prop. 3 □

Once the variables are concatenated together, the pH system is expressed as follows

$$\frac{\partial}{\partial t} \begin{pmatrix} \alpha_w \\ \boldsymbol{\alpha}_\theta \\ \boldsymbol{A}_\kappa \\ \boldsymbol{\alpha}_\gamma \end{pmatrix} = \begin{bmatrix} 0 & 0 & 0 & \mathrm{div} \\ \boldsymbol{0} & \boldsymbol{0} & \mathrm{Div} & \boldsymbol{I}_{2\times 2} \\ \boldsymbol{0} & \mathrm{Grad} & \boldsymbol{0} & \boldsymbol{0} \\ \mathrm{grad} & -\boldsymbol{I}_{2\times 2} & \boldsymbol{0} & \boldsymbol{0} \end{bmatrix} \begin{pmatrix} e_w \\ \boldsymbol{e}_\theta \\ \boldsymbol{E}_\kappa \\ \boldsymbol{e}_\gamma \end{pmatrix}. \tag{4.25}$$

The first two equations are equivalent to (4.15). The last two equations, like (3.39) for 3D elasticity, represent the fact the higher order derivatives commute. We shall now establish the total energy balance in terms of boundary variables as they will be part of the underlying

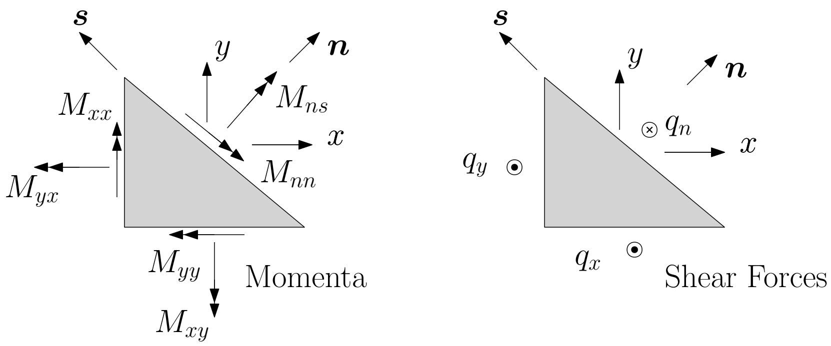

Figure 4.2: Cauchy law for momenta and forces at the boundary.

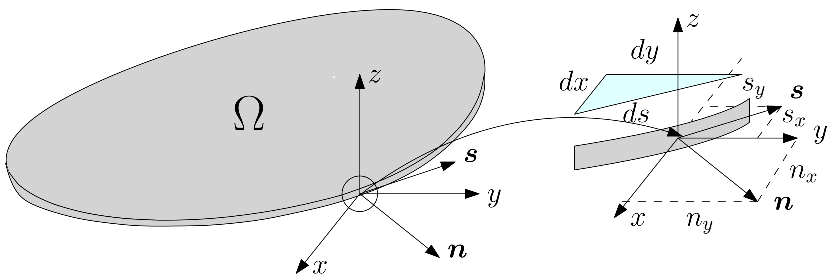

Figure 4.3: Reference frames and notations.

Stokes-Dirac structure of this model. The energy rate reads

$$
\begin{aligned}
\dot{H} &= \int_\Omega \left\{ \frac{\partial \alpha_w}{\partial t} e_w + \frac{\partial \boldsymbol{\alpha}_\theta}{\partial t} \cdot \boldsymbol{e}_\theta + \frac{\partial \boldsymbol{A}_\kappa}{\partial t} : \boldsymbol{E}_\kappa + \frac{\partial \boldsymbol{\alpha}_\gamma}{\partial t} \cdot \boldsymbol{e}_\gamma \right\} \, \mathrm{d}\Omega \\
&= \int_\Omega \left\{ \mathrm{div}(\boldsymbol{e}_\gamma) e_w + \mathrm{Div}(\boldsymbol{E}_\kappa) \cdot \boldsymbol{e}_\theta + \ \mathrm{Grad}(\boldsymbol{e}_\theta) : \boldsymbol{E}_\kappa + \mathrm{grad}(e_w) \cdot \boldsymbol{e}_\gamma \right\} \, \mathrm{d}\Omega \qquad \text{Stokes theorem,} \\
&= \int_{\partial\Omega} \left\{ w_t \, q_n + \omega_n \, M_{nn} + \omega_s \, M_{ns} \right\} \, \mathrm{d}s,
\end{aligned} \tag{4.26}
$$

where s is the curvilinear abscissa. The last integral is obtained by applying the Stokes theorem. The boundary variables appearing in the last line of (4.26) and illustrated in Fig. 4.2 are defined as follows:

$$
\begin{aligned}
\text{Shear force} \quad & q_n := \boldsymbol{q} \cdot \boldsymbol{n} = \boldsymbol{e}_\gamma \cdot \boldsymbol{n}, \\
\text{Flexural momentum} \quad & M_{nn} := \boldsymbol{M} : (\boldsymbol{n} \otimes \boldsymbol{n}) = \boldsymbol{E}_\kappa : (\boldsymbol{n} \otimes \boldsymbol{n}), \\
\text{Torsional momentum} \quad & M_{ns} := \boldsymbol{M} : (\boldsymbol{s} \otimes \boldsymbol{n}) = \boldsymbol{E}_\kappa : (\boldsymbol{s} \otimes \boldsymbol{n}),
\end{aligned} \tag{4.27}
$$

Vectors $\boldsymbol{n}$ and $\boldsymbol{s}$ designate the normal and tangential unit vectors to the boundary, as shown in Fig. 4.3. Given two vectors $\boldsymbol{a} \in \mathbb{R}^n$, $\boldsymbol{a} \in \mathbb{R}^m$, the notation $\boldsymbol{a} \otimes \boldsymbol{b} = \boldsymbol{a}\boldsymbol{b}^\top \in \mathbb{R}^{n \times m}$ denotes the

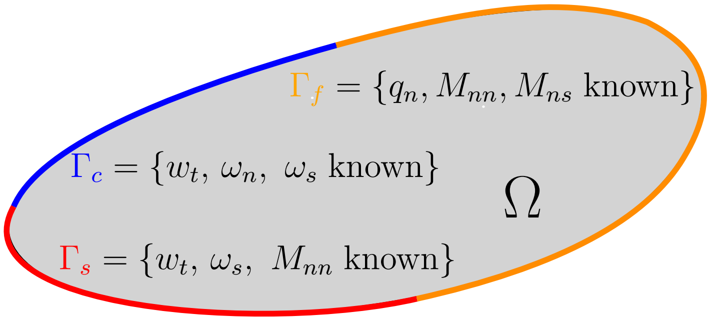

Figure 4.4: Boundary conditions for the Mindlin plate.

outer (or dyadic) product of two vectors. The corresponding power conjugated variables are

$$\begin{aligned}
\text{Vertical velocity} \quad & w_t := \frac{\partial w}{\partial t} = e_w, \\
\text{Flexural rotation} \quad & \omega_n := \frac{\partial \boldsymbol{\theta}}{\partial t} \cdot \boldsymbol{n} = \boldsymbol{e}_\theta \cdot \boldsymbol{n}, \\
\text{Torsional rotation} \quad & \omega_s := \frac{\partial \boldsymbol{\theta}}{\partial t} \cdot \boldsymbol{s} = \boldsymbol{e}_\theta \cdot \boldsymbol{s}.
\end{aligned} \tag{4.28}$$

Consider a partition of the boundary $\partial\Omega = \Gamma_C \cup \Gamma_S \cup \Gamma_F$, $\Gamma_C \cap \Gamma_S \cap \Gamma_F = \{\emptyset\}$. The set Γ_C, Γ_S, Γ_F could be empty. Given definitions (4.27), (4.28), the boundary conditions for the Mindlin plate [DHNLS99] (see Fig. 4.4) that are considered are:

- Clamped (C) on $\Gamma_C \subseteq \partial\Omega : \ w_t = 0,\ \omega_n = 0,\ \omega_s = 0;$

- Simply supported hard (S) on $\Gamma_S \subseteq \partial\Omega$: $w_t = 0,\ \omega_s = 0,\ M_{nn} = 0;$

- Free (F) on $\Gamma_F \subseteq \partial\Omega$: $M_{nn} = 0,\ M_{ns} = 0,\ q_n = 0.$

Then the final pH formulation reads

$$
\begin{aligned}
\frac{\partial}{\partial t}\begin{pmatrix}\alpha_w \\ \boldsymbol{\alpha}_\theta \\ \boldsymbol{A}_\kappa \\ \boldsymbol{\alpha}_\gamma\end{pmatrix} &= \underbrace{\begin{bmatrix} 0 & 0 & 0 & \mathrm{div} \\ \boldsymbol{0} & \boldsymbol{0} & \mathrm{Div} & \boldsymbol{I}_{2\times 2} \\ \boldsymbol{0} & \mathrm{Grad} & \boldsymbol{0} & \boldsymbol{0} \\ \mathrm{grad} & -\boldsymbol{I}_{2\times 2} & \boldsymbol{0} & \boldsymbol{0}\end{bmatrix}}_{\mathcal{J}} \begin{pmatrix} e_w \\ \boldsymbol{e}_\theta \\ \boldsymbol{E}_\kappa \\ \boldsymbol{e}_\gamma\end{pmatrix}, \\
\boldsymbol{u}_\partial &= \underbrace{\begin{bmatrix} \gamma_0^{\Gamma_C} & 0 & 0 & 0 \\ 0 & \gamma_n^{\Gamma_C} & 0 & 0 \\ 0 & \gamma_s^{\Gamma_C} & 0 & 0 \\ \gamma_0^{\Gamma_S} & 0 & 0 & 0 \\ 0 & \gamma_s^{\Gamma_S} & 0 & 0 \\ 0 & 0 & \gamma_{nn}^{\Gamma_S} & 0 \\ 0 & 0 & \gamma_{nn}^{\Gamma_F} & 0 \\ 0 & 0 & \gamma_{ns}^{\Gamma_F} & 0 \\ 0 & 0 & 0 & \gamma_n^{\Gamma_F} \end{bmatrix}}_{\mathcal{B}_\partial} \begin{pmatrix} e_w \\ \boldsymbol{e}_\theta \\ \boldsymbol{E}_\kappa \\ \boldsymbol{e}_\gamma\end{pmatrix}, \\
\boldsymbol{y}_\partial &= \underbrace{\begin{bmatrix} 0 & 0 & 0 & \gamma_n^{\Gamma_C} \\ 0 & 0 & \gamma_{nn}^{\Gamma_C} & 0 \\ 0 & 0 & \gamma_{ns}^{\Gamma_C} & 0 \\ 0 & 0 & 0 & \gamma_n^{\Gamma_S} \\ 0 & 0 & \gamma_{ns}^{\Gamma_S} & 0 \\ 0 & \gamma_n^{\Gamma_S} & 0 & 0 \\ 0 & \gamma_n^{\Gamma_F} & 0 & 0 \\ 0 & \gamma_s^{\Gamma_F} & 0 & 0 \\ \gamma_0^{\Gamma_F} & 0 & 0 & 0 \end{bmatrix}}_{\mathcal{C}_\partial} \begin{pmatrix} e_w \\ \boldsymbol{e}_\theta \\ \boldsymbol{E}_\kappa \\ \boldsymbol{e}_\gamma\end{pmatrix},
\end{aligned}
\tag{4.29}
$$

where $\boldsymbol{\gamma}_0^{\Gamma_*} a = a|_{\Gamma_*}$ denotes the trace over the set Γ_*. Furthermore, notations $\gamma_n^{\Gamma_*}\boldsymbol{a} = \boldsymbol{a} \cdot \boldsymbol{n}|_{\Gamma_*}$, $\gamma_s^{\Gamma_*}\boldsymbol{a} = \boldsymbol{a} \cdot \boldsymbol{s}|_{\Gamma_*}$ indicate the normal and tangential trace over the set Γ_* respectively. Symbols $\gamma_{nn}^{\Gamma_*}, \gamma_{ns}^{\Gamma_*}$ denote the normal-normal trace and the normal-tangential trace of tensor-valued functions, $\gamma_{nn}^{\Gamma_*}\boldsymbol{A} = \boldsymbol{A} : (\boldsymbol{n} \otimes \boldsymbol{n})|_{\Gamma_*}$, $\gamma_{ns}^{\Gamma_*}\boldsymbol{A} = \boldsymbol{A} : (\boldsymbol{n} \otimes \boldsymbol{s})|_{\Gamma_*}$.

Remark 6
It can be observed that the interconnection structure given by $\mathcal{J}$ in (4.29) mimics that of the Timoshenko beam [JZ12, Chapter 7].

Theorem 5 (Stokes-Dirac structure for the Mindlin plate)
Consider $\mathbb{V} = \mathbb{R}^2$, $\mathbb{S} = \mathbb{R}^{2\times 2}_{sym}$ and let $H^1(\Omega)$ be the space of functions with gradient in $L^2(\Omega, \mathbb{V})$ and $H^{\mathrm{div}}(\Omega, \mathbb{V})$ the space of vector-valued functions with divergence in $L^2(\Omega)$. Furthermore, $H^1(\Omega, \mathbb{V})$ is the space of vectors with symmetric gradient in $L^2(\Omega, \mathbb{S})$ and $H^{\mathrm{Div}}(\Omega, \mathbb{S})$ denote

the space of symmetric tensors with divergence in $L^2(\Omega, \mathbb{V})$. Consider the definitions

$$
\begin{aligned}
H &:= H^1(\Omega) \times H^{\mathrm{Grad}}(\Omega, \mathbb{V}) \times H^{\mathrm{Div}}(\Omega, \mathbb{S}) \times H^{\mathrm{div}}(\Omega, \mathbb{V}), \\
F &:= L^2(\Omega) \times L^2(\Omega, \mathbb{V}) \times L^2(\Omega, \mathbb{S}) \times L^2(\Omega, \mathbb{V}), \\
F_\partial &:= L^2(\Gamma_C, \mathbb{R}^3) \times L^2(\Gamma_S, \mathbb{R}^3) \times L^2(\Gamma_F, \mathbb{R}^3).
\end{aligned}
$$

The set

$$
D_{\mathcal{J}} = \left\{ \begin{pmatrix} \boldsymbol{f} \\ \boldsymbol{f}_\partial \\ \boldsymbol{e} \\ \boldsymbol{e}_\partial \end{pmatrix} \mid \boldsymbol{e} \in H, \ \boldsymbol{f} = -\mathcal{J}\boldsymbol{e}, \ \boldsymbol{f}_\partial = \mathcal{B}_\partial \boldsymbol{e}, \ \boldsymbol{e}_\partial = \mathcal{C}_\partial \boldsymbol{e} \right\}, \tag{4.30}
$$

where $\boldsymbol{e} = (e_w, \, \boldsymbol{e}_\theta, \, \boldsymbol{E}_\kappa, \, \boldsymbol{e}_\gamma)$ and $\mathcal{J}, \mathcal{B}_\partial, \mathcal{C}_\partial$ are defined in (4.29), is a Stokes–Dirac structure with respect to the pairing

$$
\left\langle\left\langle (\boldsymbol{f}^1, \boldsymbol{f}^1_\partial, \boldsymbol{e}^1, \boldsymbol{e}^1_\partial), (\boldsymbol{f}^2, \boldsymbol{f}^2_\partial, \boldsymbol{e}^2, \boldsymbol{e}^2_\partial) \right\rangle\right\rangle := \left\langle \boldsymbol{e}^1, \boldsymbol{f}^2 \right\rangle_F + \left\langle \boldsymbol{e}^2, \boldsymbol{f}^1 \right\rangle_F + \left\langle \boldsymbol{e}^1_\partial, \boldsymbol{f}^2_\partial \right\rangle_{F_\partial} + \left\langle \boldsymbol{e}^2_\partial, \boldsymbol{f}^1_\partial \right\rangle_{F_\partial}, \tag{4.31}
$$

where $\boldsymbol{e}^i_\partial = (\boldsymbol{e}^i_{\partial,1}, \ \boldsymbol{e}^i_{\partial,2}, \ \boldsymbol{e}^i_{\partial,3})$, $\boldsymbol{f}^i_\partial = (\boldsymbol{f}^i_{\partial,1}, \ \boldsymbol{f}^i_{\partial,2}, \ \boldsymbol{f}^i_{\partial,3})$ and

$$
\langle (\boldsymbol{a}, \, \boldsymbol{b}, \, \boldsymbol{c}), (\boldsymbol{d}, \, \boldsymbol{e}, \, \boldsymbol{f}) \rangle_{F_\partial} = \int_{\Gamma_C} \boldsymbol{a} \cdot \boldsymbol{d} \, \mathrm{d}S + \int_{\Gamma_S} \boldsymbol{b} \cdot \boldsymbol{e} \, \mathrm{d}S + \int_{\Gamma_F} \boldsymbol{c} \cdot \boldsymbol{f} \, \mathrm{d}S, \quad \boldsymbol{a}, \ \boldsymbol{b}, \ \boldsymbol{c}, \ \boldsymbol{d}, \ \boldsymbol{e}, \ \boldsymbol{f} \in \mathbb{R}^3.
$$

Proof. The proof is analogous to the one of Th. 4. The integration by parts has to be carried as in Eq. (4.26). □

The Mindlin plate falls within the assumption of [Skr19], hence it is a well posed boundary control pH systems.

4.2.2 Port-Hamiltonian Kirchhoff plate

Again the starting point is the Hamiltonian (total energy)

$$
H = \frac{1}{2} \int_\Omega \left\{ \rho h \left(\frac{\partial w}{\partial t} \right)^2 + \boldsymbol{M} : \boldsymbol{\kappa} \right\} \mathrm{d}\Omega, \tag{4.32}
$$

where $\boldsymbol{M}, \ \boldsymbol{\kappa}$ are defined in Eqs. (4.10), (4.16). For what concerns the choice of the energy variables, a scalar and a tensor variable are considered:

$$
\alpha_w = \rho h \frac{\partial w}{\partial t}, \quad \text{Linear momentum}, \qquad \boldsymbol{A}_\kappa = \boldsymbol{\kappa}, \quad \text{Curvature tensor}. \tag{4.33}
$$

The co-energy variables are found by computing the variational derivative of the Hamiltonian:

$$
e_w := \frac{\delta H}{\delta \alpha_w} = \frac{\partial w}{\partial t}, \quad \text{Linear velocity}, \qquad \boldsymbol{E}_\kappa := \frac{\delta H}{\delta \boldsymbol{A}_\kappa} = \boldsymbol{M}, \quad \text{Curvature tensor}. \tag{4.34}
$$

The port-Hamiltonian system is then written as

$$\frac{\partial}{\partial t}\begin{pmatrix}\alpha_w \\ \boldsymbol{A}_\kappa\end{pmatrix} = \begin{bmatrix} 0 & -\operatorname{div}\circ\operatorname{Div} \\ \operatorname{Grad}\circ\operatorname{grad} & \mathbf{0}\end{bmatrix}\begin{pmatrix} e_w \\ \boldsymbol{E}_\kappa\end{pmatrix}. \tag{4.35}$$

The first equation is equivalent to (4.20). The last equation represent the fact the higher order derivatives commute

$$\begin{aligned}
\partial_t \boldsymbol{A}_\kappa &= \operatorname{Grad}\operatorname{grad} e_w, \\
\partial_t \boldsymbol{\kappa} &= \operatorname{Grad}\operatorname{grad} \partial_t w, \\
\partial_t \operatorname{Grad}\operatorname{grad} w &= \operatorname{Grad}\operatorname{grad} \partial_t w,
\end{aligned}$$

The last equation holds for $w \in C^3(\Omega)$.

Theorem 6
The operator Grad $\circ$ grad*, corresponding to the Hessian operator, is the adjoint of the double divergence* div $\circ$ Div*.*

Proof. Let $\mathbb{S} = \mathbb{R}^{d\times d}_{\text{sym}}$ and consider the Hilbert space of the square integrable symmetric square tensors $L^2(\Omega, \mathbb{S})$ over an open connected set Ω (its inner product is defined in (3.37)). Consider the Hilbert space $L^2(\Omega)$ of scalar square integrable functions, endowed with the standard inner product. Consider the double divergence operator defined as:

$$\begin{aligned}
\operatorname{div}\operatorname{Div}:\ L^2(\Omega,\mathbb{S}) &\rightarrow L^2(\Omega), \\
\boldsymbol{\Psi} &\rightarrow \operatorname{div}\operatorname{Div}\boldsymbol{\Psi} = \psi,
\end{aligned} \qquad \text{with } \psi = \operatorname{div}\operatorname{Div}\boldsymbol{\Psi} = \sum_{i=1}^{d}\sum_{j=1}^{d}\frac{\partial^2 \boldsymbol{\Psi}_{ij}}{\partial x_i \partial x_j}.$$

We shall identify $(\operatorname{div}\operatorname{Div})^*$

$$\begin{aligned}
(\operatorname{div}\operatorname{Div})^*:\ L^2(\Omega) &\rightarrow L^2(\Omega,\mathbb{S}), \\
f &\rightarrow (\operatorname{div}\operatorname{Div})^* f = \boldsymbol{F},
\end{aligned}$$

such that

$$\langle \operatorname{div}\operatorname{Div}\boldsymbol{\Psi}, f\rangle_{L^2(\Omega)} = \langle \boldsymbol{\Psi}, (\operatorname{div}\operatorname{Div})^* f\rangle_{L^2(\Omega,\mathbb{S})}, \qquad \begin{aligned} &\forall\, \boldsymbol{\Psi} \in \operatorname{Domain}(\operatorname{div}\operatorname{Div}) \subset L^2(\Omega,\mathbb{S}) \\ &\forall\, f \in \operatorname{Domain}((\operatorname{div}\operatorname{Div})^*) \subset L^2(\Omega)\end{aligned}$$

The function have to belong to the operator domain, so for instance $f \in C_0^2(\Omega) \in \operatorname{Domain}((\operatorname{div}\operatorname{Div})^*)$ the space of twice differentiable scalar functions with compact support and $\boldsymbol{\Psi}$ can be chosen in the set $C_0^2(\Omega,\mathbb{S}) \in \operatorname{Domain}(\operatorname{div}\operatorname{Div})$, the space of twice differentiable symmetric tensors with compact support on Ω. A classical result is the fact that the adjoint of the vector divergence is $\operatorname{div}^* = -\operatorname{grad}$ as stated in [KZ15]. By theorem 3, it holds $\operatorname{Div}^* = -\operatorname{Grad}$. Considering that $\operatorname{div}\operatorname{Div} = \operatorname{div}\circ\operatorname{Div}$ is the composition of two different operators and that the adjoint of a composed operator is the adjoint of each operator in reverse order, i.e. $(B \circ C)^* = C^* \circ B^*$, then it can be stated

$$(\mathrm{div} \circ \mathrm{Div})^* = \mathrm{Div}^* \circ \mathrm{div}^* = \mathrm{Grad} \circ \mathrm{grad}\,.$$

Since only formal adjoints are being looked for, this concludes the proof. □

The energy rate provides the boundary port variables

$$\begin{aligned}
\dot{H} &= \int_\Omega \left\{ \partial_t \alpha_w \, e_w + \partial_t \boldsymbol{A}_\kappa : \boldsymbol{E}_\kappa \right\} \, \mathrm{d}\Omega \\
&= \int_\Omega \left\{ -\mathrm{div}\,\mathrm{Div}\, \boldsymbol{E}_\kappa \, e_w + \mathrm{Grad}\,\mathrm{grad}\, e_w : \boldsymbol{E}_\kappa \right\} \, \mathrm{d}\Omega, && \text{Stokes theorem} \\
&= \int_{\partial\Omega} \left\{ -\boldsymbol{n} \cdot \mathrm{Div}\, \boldsymbol{E}_\kappa \, e_w + (\boldsymbol{n} \otimes \mathrm{grad}\, e_w) : \boldsymbol{E}_\kappa \right\} \, \mathrm{d}s, \\
&= \int_{\partial\Omega} \left\{ -\boldsymbol{n} \cdot \mathrm{Div}\, \boldsymbol{E}_\kappa \, e_w + \partial_{\boldsymbol{n}} e_w \, (\boldsymbol{n} \otimes \boldsymbol{n}) : \boldsymbol{E}_\kappa + \partial_{\boldsymbol{s}} e_w \, (\boldsymbol{n} \otimes \boldsymbol{s}) : \boldsymbol{E}_\kappa \right\} \, \mathrm{d}s, && \text{Dyadic properties} \\
&= \int_{\partial\Omega} \left\{ \widehat{q}_n \, w_t + \partial_{\boldsymbol{n}} w_t \, M_{nn} + \partial_{\boldsymbol{s}} w_t \, M_{ns} \right\} \, \mathrm{d}s.
\end{aligned} \tag{4.36}$$

where s is the curvilinear abscissa, $w_t := \partial_t w$ and $\partial_{\boldsymbol{s}} w_t$ denotes the directional derivative along the tangential versor at the boundary. Additionally, the following definitions have been introduced

$$\widehat{q}_n := -\boldsymbol{n} \cdot \mathrm{Div}(\boldsymbol{E}_\kappa), \quad M_{nn} := (\boldsymbol{n} \otimes \boldsymbol{n}) : \boldsymbol{E}_\kappa, \quad M_{ns} := (\boldsymbol{n} \otimes \boldsymbol{s}) : \boldsymbol{E}_\kappa. \tag{4.37}$$

Variables w_t and $\partial_{\boldsymbol{s}} w_t$ are not independent as they are differentially related with respect to derivation along $\boldsymbol{s}$ (see for instance [TWK59, Chapter 4]). The tangential derivative has to be moved on the torsional momentum M_{ns}. For sake of simplicity, $\partial\Omega$ is supposed to be regular. Then the integration by parts provides

$$\int_{\partial\Omega} \partial_{\boldsymbol{s}} w_t \, M_{ns} \;\; \mathrm{d}s = -\int_{\partial\Omega} \partial_{\boldsymbol{s}} M_{ns} \, w_t \;\; \mathrm{d}s. \tag{4.38}$$

The final energy balance reads

$$\dot{H} = \int_{\partial\Omega} \left\{ w_t \, \widetilde{q}_n + \partial_{\boldsymbol{n}} w_t \, M_{nn} \right\} \;\; \mathrm{d}s, \tag{4.39}$$

where the boundary variables are

$$\begin{aligned}
&\text{Effective shear force} && \widetilde{q}_n := \widehat{q}_n - \partial_{\boldsymbol{s}} M_{ns}, \\
&\text{Flexural momentum} && M_{nn} := \boldsymbol{M} : (\boldsymbol{n} \otimes \boldsymbol{n}) = \boldsymbol{E}_\kappa : (\boldsymbol{n} \otimes \boldsymbol{n}),
\end{aligned} \tag{4.40}$$

and $\widehat{q}_n$ is defined in (4.37). The corresponding power conjugated variables are:

$$\begin{aligned}
&\text{Vertical velocity} && w_t := \frac{\partial w}{\partial t} = e_w, , \\
&\text{Flexural rotation} && \partial_{\boldsymbol{n}} w_t := \nabla e_w \cdot \boldsymbol{n}.
\end{aligned} \tag{4.41}$$

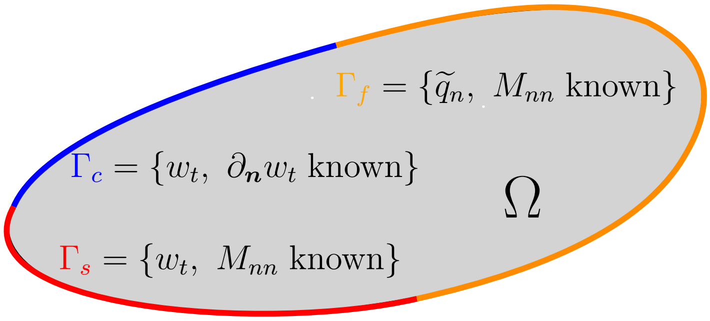

Figure 4.5: Boundary conditions for the Kirchhoff plate.

Consider a partition of the boundary $\partial\Omega = \Gamma_C \cup \Gamma_S \cup \Gamma_F$, $\Gamma_C \cap \Gamma_S \cap \Gamma_F = \{\emptyset\}$. Given definitions (4.40), (4.41), the boundary conditions for the Kirchhoff plate [GSV18] are the following:

- Clamped (C) on $\Gamma_C \subseteq \partial\Omega : \ w_t = 0, \ \partial_{\boldsymbol{n}} w_t = 0$;
- Simply supported (S) on $\Gamma_S \subseteq \partial\Omega$: $w_t = 0, \ M_{nn} = 0$;
- Free (F) on $\Gamma_F \subseteq \partial\Omega$: $\widetilde{q}_n = 0, \ M_{nn} = 0$.

Then the final pH formulation reads

$$
\begin{aligned}
\frac{\partial}{\partial t}\begin{pmatrix} \alpha_w \\ \boldsymbol{A}_\kappa \end{pmatrix} &= \underbrace{\begin{bmatrix} 0 & -\operatorname{div}\circ\operatorname{Div} \\ \operatorname{Grad}\circ\operatorname{grad} & \mathbf{0} \end{bmatrix}}_{\mathcal{J}} \begin{pmatrix} e_w \\ \boldsymbol{E}_\kappa \end{pmatrix}, \\
\boldsymbol{u}_\partial &= \underbrace{\begin{bmatrix} \gamma_0^{\Gamma_C} & 0 \\ \gamma_1^{\Gamma_C} & 0 \\ \gamma_0^{\Gamma_S} & 0 \\ 0 & \gamma_{nn}^{\Gamma_S} \\ 0 & \gamma_{nn,1}^{\Gamma_F} \\ 0 & \gamma_{nn}^{\Gamma_F} \end{bmatrix}}_{\mathcal{B}_\partial} \begin{pmatrix} e_w \\ \boldsymbol{E}_\kappa \end{pmatrix}, \\
\boldsymbol{y}_\partial &= \underbrace{\begin{bmatrix} 0 & \gamma_{nn,1}^{\Gamma_C} \\ 0 & \gamma_{nn}^{\Gamma_C} \\ 0 & \gamma_{nn,1}^{\Gamma_S} \\ \gamma_1^{\Gamma_S} & 0 \\ \gamma_0^{\Gamma_F} & 0 \\ \gamma_1^{\Gamma_F} & 0 \end{bmatrix}}_{\mathcal{C}_\partial} \begin{pmatrix} e_w \\ \boldsymbol{E}_\kappa \end{pmatrix},
\end{aligned}
\tag{4.42}
$$

where $\boldsymbol{\gamma}_0^{\Gamma_*} a = a|_{\Gamma_*}$ and $\gamma_1^{\Gamma_*} a = \partial_{\boldsymbol{n}} a|_{\Gamma_*}$ denote the standard and the normal derivative trace over the set Γ_* respectively. The symbol $\gamma_{nn,1}^{\Gamma_*}$ denotes the map $\gamma_{nn,1}^{\Gamma_*}\boldsymbol{A} = -\boldsymbol{n}\cdot\operatorname{Div}\boldsymbol{A} - \partial_{\boldsymbol{s}}(\boldsymbol{A}:$

$(\boldsymbol{n} \otimes \boldsymbol{s}))|_{\Gamma_*}$,, while $\gamma_{nn}^{\Gamma_*}\boldsymbol{A} = \boldsymbol{A} : (\boldsymbol{n} \otimes \boldsymbol{n})|_{\Gamma_*}$ indicates the normal-normal trace of a tensor-valued function.

Remark 7

The interconnection structure $\mathcal{J}$ in (4.42) resembles that of the Bernoulli beam [CRMPB17]. The double divergence and the Hessian coincide, in dimension one, with the second derivative.

Theorem 7 (Stokes-Dirac structure for the Kirchhoff plate)
Consider $\mathbb{S} = \mathbb{R}^{2\times 2}_{sym}$ and let $H^2(\Omega)$ be the space of functions with Hessian in $L^2(\Omega, \mathbb{S})$ and $H^{\mathrm{div\,Div}}(\Omega, \mathbb{S})$ the space of vector-valued functions with double divergence in $L^2(\Omega)$. Consider the definitions

$$\begin{aligned}
H &:= H^2(\Omega) \times H^{\mathrm{div\,Div}}(\Omega, \mathbb{S}), \\
F &:= L^2(\Omega) \times L^2(\Omega, \mathbb{S}), \\
F_\partial &:= L^2(\Gamma_C, \mathbb{R}^2) \times L^2(\Gamma_S, \mathbb{R}^2) \times L^2(\Gamma_F, \mathbb{R}^2).
\end{aligned}$$

The set

$$D_{\mathcal{J}} = \left\{ \begin{pmatrix} \boldsymbol{f} \\ \boldsymbol{f}_\partial \\ \boldsymbol{e} \\ \boldsymbol{e}_\partial \end{pmatrix} \mid \boldsymbol{e} \in H, \ \boldsymbol{f} = -\mathcal{J}\boldsymbol{e}, \ \boldsymbol{f}_\partial = \mathcal{B}_\partial \boldsymbol{e}, \ \boldsymbol{e}_\partial = \mathcal{C}_\partial \boldsymbol{e} \right\}, \tag{4.43}$$

where $\boldsymbol{e} = (e_w, \boldsymbol{E}_\kappa)$ and $\mathcal{J}, \mathcal{B}_\partial, \mathcal{C}_\partial$ are defined in (4.42), is a Stokes–Dirac structure with respect to the pairing

$$\left\langle\left\langle (\boldsymbol{f}^1, \boldsymbol{f}^1_\partial, \boldsymbol{e}^1, \boldsymbol{e}^1_\partial), (\boldsymbol{f}^2, \boldsymbol{f}^2_\partial, \boldsymbol{e}^2, \boldsymbol{e}^2_\partial) \right\rangle\right\rangle := \left\langle \boldsymbol{e}^1, \boldsymbol{f}^2 \right\rangle_F + \left\langle \boldsymbol{e}^2, \boldsymbol{f}^1 \right\rangle_F + \left\langle \boldsymbol{e}^1_\partial, \boldsymbol{f}^2_\partial \right\rangle_{F_\partial} + \left\langle \boldsymbol{e}^2_\partial, \boldsymbol{f}^1_\partial \right\rangle_{F_\partial}, \tag{4.44}$$

where $\boldsymbol{e}^i_\partial = (\boldsymbol{e}^i_{\partial,1}, \ \boldsymbol{e}^i_{\partial,2})$, $\boldsymbol{f}^i_\partial = (\boldsymbol{f}^i_{\partial,1}, \ \boldsymbol{f}^i_{\partial,2})$ and

$$\langle (\boldsymbol{a}, \boldsymbol{b}, \boldsymbol{c}), (\boldsymbol{d}, \boldsymbol{e}, \boldsymbol{f}) \rangle_{F_\partial} = \int_{\Gamma_C} \boldsymbol{a} \cdot \boldsymbol{d} \, \mathrm{d}S + \int_{\Gamma_S} \boldsymbol{b} \cdot \boldsymbol{e} \, \mathrm{d}S + \int_{\Gamma_F} \boldsymbol{c} \cdot \boldsymbol{f} \, \mathrm{d}S, \quad \boldsymbol{a}, \ \boldsymbol{b}, \ \boldsymbol{c}, \ \boldsymbol{d}, \ \boldsymbol{e}, \ \boldsymbol{f} \in \mathbb{R}^2.$$

Proof. The proof is analogous to the one of Th. 4. The integration by parts has to be carried as in Eq. (4.36). □

4.3 Laminated anisotropic plates

Until now homogeneous isotropic materials have been considered. For this class of materials, the membrane and bending problems are decoupled. In aeronautical applications, structure are made up of laminae of different materials to enhance the mechanical properties of the resulting structure. In some cases, a certain coupling is desired, to increase the aerodynamical performance of the wing as it deforms.

Consider again the deformation field given by (4.1)

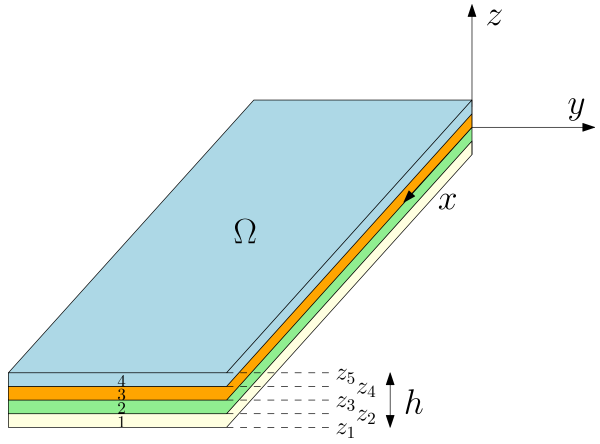

Figure 4.6: Laminated plate with 4 layers.

$$
\begin{aligned}
\boldsymbol{u}(x,y,z,t) &= \boldsymbol{u}^0(x,y,t) - z\boldsymbol{\theta}(x,y,t),\\
u_z(x,y,z,t) &= u_z^0(x,y,t),
\end{aligned}
$$

where $\boldsymbol{u} = (u_x,\, u_y)$. The link between in-plane deformation (4.2) and the membrane and bending contribution (4.4), (4.5).

$$
\boldsymbol{\varepsilon}_{2D} = \boldsymbol{\varepsilon}^0 - z\boldsymbol{\kappa} \qquad \text{where} \qquad \boldsymbol{\varepsilon}^0 = \operatorname{Grad}\boldsymbol{u}^0, \quad \boldsymbol{\kappa} = \operatorname{Grad}\boldsymbol{\theta}. \tag{4.45}
$$

Assume that each layer is an anisotropic material under plane stress condition. Then, it holds (see [Red03, Chapter 1] for details)

$$
\boldsymbol{\Sigma}_{2D}^i = \boldsymbol{\mathcal{D}}_{2D}^i \boldsymbol{\varepsilon}_{2D}^i,
$$

where i indicates the layer under consideration. The matrix $\boldsymbol{\mathcal{D}}_{2D}^i$ depends on the properties of each material. To reduce the problem to bi-dimensional, the stresses have to be integrated along the thickness. Differently from isotropic plate, for laminated anisotropic plates the membrane and bending behavior are coupled. To see this consider the membrane and bending resultant of the stress

$$
\boldsymbol{N} := \int_{-h/2}^{h/2} \boldsymbol{\Sigma}_{2D}\, \mathrm{d}z, \qquad \boldsymbol{M} := \int_{-h/2}^{h/2} -z\boldsymbol{\Sigma}_{2D}\, \mathrm{d}z. \tag{4.46}
$$

Since the stress are discontinuous due to the change of constitutive law along the thickness, the integration has to be performed lamina-wise. Once the computations are carried out, it is found

$$
\begin{pmatrix} \boldsymbol{N} \\ \boldsymbol{M} \end{pmatrix} = \begin{bmatrix} \boldsymbol{\mathcal{D}}_m & \boldsymbol{\mathcal{D}}_c \\ \boldsymbol{\mathcal{D}}_c & \boldsymbol{\mathcal{D}}_b \end{bmatrix} \begin{pmatrix} \boldsymbol{\varepsilon}^0 \\ \boldsymbol{\kappa} \end{pmatrix}, \tag{4.47}
$$

where

$$\boldsymbol{\mathcal{D}}_m = \sum_{i=1}^{n_{\text{layer}}} \boldsymbol{\mathcal{D}}_{2D}^i (z_{i+1} - z_i), \quad \boldsymbol{\mathcal{D}}_c = -\frac{1}{2} \sum_{i=1}^{n_{\text{layer}}} \boldsymbol{\mathcal{D}}_{2D}^i (z_{i+1}^2 - z_i^2), \quad \boldsymbol{\mathcal{D}}_b = \frac{1}{3} \sum_{i=1}^{n_{\text{layer}}} \boldsymbol{\mathcal{D}}_{2D}^i (z_{i+1}^3 - z_i^3), \tag{4.48}$$

and n_{layer} is the number of layers and z_i represents the height of the i^{th} layer (see Fig. 4.6). The coupling term $\boldsymbol{\mathcal{D}}_c$ disappears if a symmetric configuration is considered. For the shear contribution it is obtained

$$\boldsymbol{q} := \int_{-h/2}^{h/2} \boldsymbol{\sigma}_s \, \mathrm{d}z = \boldsymbol{\mathcal{D}}_s \boldsymbol{\gamma}, \qquad \text{where} \qquad \boldsymbol{\gamma} = \operatorname{grad} u_z - \boldsymbol{\theta}. \tag{4.49}$$

The tensor $\boldsymbol{\mathcal{D}}_s$ is not diagonal as in the isotropic case, cf.§4.2.1.

In the following section it is shown how anisotropic laminated plates can be formulated as pHs.

4.3.1 Port-Hamiltonian laminated Mindlin plate

For a shear deformable laminated plate the kinetic and deformation energy read

$$\begin{aligned} E_{\text{kin}} &= \frac{1}{2} \int_\Omega \left\{ \rho h \left\| \frac{\partial \boldsymbol{u}^0}{\partial t} \right\|^2 + \rho h \left(\frac{\partial u_z}{\partial t} \right)^2 + \frac{\rho h^3}{12} \left\| \frac{\partial \boldsymbol{\theta}}{\partial t} \right\|^2 \right\} \mathrm{d}\Omega, \\ E_{\text{def}} &= \frac{1}{2} \int_\Omega \left\{ \boldsymbol{N} : \boldsymbol{\varepsilon}^0 + \boldsymbol{M} : \boldsymbol{\kappa} + \boldsymbol{q} \cdot \boldsymbol{\gamma} \right\} \mathrm{d}\Omega. \end{aligned}$$

By using Hamilton's principle the equations of motion are retrieved (see [Red03, Chapter 3] for an exhaustive explanation)

$$\begin{aligned} \rho h \frac{\partial^2 \boldsymbol{u}^0}{\partial t^2} &= \operatorname{Div} \boldsymbol{N}, \\ \rho h \frac{\partial^2 u_z}{\partial t^2} &= \operatorname{div} \boldsymbol{q}, \\ \frac{\rho h^3}{12} \frac{\partial^2 \boldsymbol{\theta}}{\partial t^2} &= \operatorname{Div} \boldsymbol{M} + \boldsymbol{q}, \end{aligned} \tag{4.50}$$

where $\boldsymbol{N}$, $\boldsymbol{M}$, $\boldsymbol{q}$ are defined in Eqs. (4.47), (4.49). To get a port-Hamiltonian formulation, the following energy variable are chosen

$$\begin{aligned} \boldsymbol{\alpha}_u &= \rho h \frac{\partial \boldsymbol{u}^0}{\partial t}, \qquad & \alpha_w &= \rho h \frac{\partial u_z}{\partial t}, \qquad & \boldsymbol{\alpha}_\theta &= \frac{\rho h^3}{12} \frac{\partial \boldsymbol{\theta}}{\partial t}, \\ \boldsymbol{A}_{\varepsilon^0} &= \boldsymbol{\varepsilon}^0, & \boldsymbol{A}_\kappa &= \boldsymbol{\kappa}, & \boldsymbol{\alpha}_\gamma &= \boldsymbol{\gamma}. \end{aligned} \tag{4.51}$$

This choice highlights the nature of the problem in which the membrane part (equivalent to a 2D elasticity problem) and the bending part interact. The total energy $H = E_{\text{kin}} + E_{\text{def}}$ is now a quadratic function of the energy variables

$$
\begin{aligned}
E_{\text{kin}} &= \frac{1}{2}\int_{\Omega} \left\{ \frac{1}{\rho h} \left\| \frac{\partial \boldsymbol{\alpha}_u}{\partial t} \right\|^2 + \frac{1}{\rho h} \left(\frac{\partial \alpha_w}{\partial t} \right)^2 + \frac{12}{\rho h^3} \left\| \frac{\partial \boldsymbol{\alpha}_\theta}{\partial t} \right\|^2 \right\} \, \mathrm{d}\Omega, \\
E_{\text{def}} &= \frac{1}{2}\int_{\Omega} \left\{ (\boldsymbol{\mathcal{D}}_m \boldsymbol{A}_{\varepsilon^0} + \boldsymbol{\mathcal{D}}_c \boldsymbol{A}_\kappa) : \boldsymbol{A}_{\varepsilon^0} + (\boldsymbol{\mathcal{D}}_c \boldsymbol{A}_{\varepsilon^0} + \boldsymbol{\mathcal{D}}_b \boldsymbol{A}_\kappa) : \boldsymbol{A}_\kappa + (\boldsymbol{\mathcal{D}}_s \boldsymbol{\alpha}_\gamma) \cdot \boldsymbol{\alpha}_\gamma \right\} \, \mathrm{d}\Omega,
\end{aligned}
$$

The co-energies are equal to

$$
\begin{aligned}
e_w &:= \frac{\delta H}{\delta \boldsymbol{\alpha}_u} = \frac{\partial \boldsymbol{u}^0}{\partial t}, \qquad & e_w &:= \frac{\delta H}{\delta \alpha_w} = \frac{\partial u_z}{\partial t}, \qquad & \boldsymbol{e}_\theta &:= \frac{\delta H}{\delta \boldsymbol{\alpha}_\theta} = \frac{\partial \boldsymbol{\theta}}{\partial t}, \\
\boldsymbol{E}_\kappa &:= \frac{\delta H}{\delta \boldsymbol{A}_{\varepsilon^0}} = \boldsymbol{N}, \qquad & \boldsymbol{E}_\kappa &:= \frac{\delta H}{\delta \boldsymbol{A}_\kappa} = \boldsymbol{M}, \qquad & \boldsymbol{e}_\gamma &:= \frac{\delta H}{\delta \boldsymbol{\alpha}_\gamma} = \boldsymbol{q}
\end{aligned}
\tag{4.52}
$$

The final pH formulation is found as usual considering the dynamics (4.50) and fact that higher derivatives commute

$$
\frac{\partial}{\partial t}
\begin{pmatrix} \boldsymbol{\alpha}_u \\ \alpha_w \\ \boldsymbol{\alpha}_\theta \\ \boldsymbol{A}_{\varepsilon^0} \\ \boldsymbol{A}_\kappa \\ \boldsymbol{\alpha}_\gamma \end{pmatrix}
=
\begin{bmatrix}
\boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \mathrm{Div} & \boldsymbol{0} & \boldsymbol{0} \\
0 & 0 & 0 & 0 & 0 & \mathrm{div} \\
\boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \mathrm{Div} & \boldsymbol{I}_{2\times 2} \\
\mathrm{Grad} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} \\
\boldsymbol{0} & \boldsymbol{0} & \mathrm{Grad} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} \\
\boldsymbol{0} & \mathrm{grad} & -\boldsymbol{I}_{2\times 2} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0}
\end{bmatrix}
\begin{pmatrix} \boldsymbol{e}_u \\ e_w \\ \boldsymbol{e}_\theta \\ \boldsymbol{E}_{\varepsilon^0} \\ \boldsymbol{E}_\kappa \\ \boldsymbol{e}_\gamma \end{pmatrix}.
\tag{4.53}
$$

The coupling between the membrane and bending part is clear when considering the link between energy and co-energy variables

$$
\begin{pmatrix} \boldsymbol{e}_u \\ e_w \\ \boldsymbol{e}_\theta \\ \boldsymbol{E}_{\varepsilon^0} \\ \boldsymbol{E}_\kappa \\ \boldsymbol{e}_\gamma \end{pmatrix}
=
\begin{bmatrix}
\frac{1}{\rho h}\boldsymbol{I}_{2\times 2} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} \\
0 & \frac{1}{\rho h} & 0 & 0 & 0 & 0 \\
\boldsymbol{0} & \boldsymbol{0} & \frac{12}{\rho h^3}\boldsymbol{I}_{2\times 2} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} \\
\boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{\mathcal{D}}_m & \boldsymbol{\mathcal{D}}_c & \boldsymbol{0} \\
\boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{\mathcal{D}}_c & \boldsymbol{\mathcal{D}}_b & \boldsymbol{0} \\
\boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{\mathcal{D}}_s
\end{bmatrix}
\begin{pmatrix} \boldsymbol{\alpha}_u \\ \alpha_w \\ \boldsymbol{\alpha}_\theta \\ \boldsymbol{A}_{\varepsilon^0} \\ \boldsymbol{A}_\kappa \\ \boldsymbol{\alpha}_\gamma \end{pmatrix}.
\tag{4.54}
$$

Again appropriate boundary variables and a suitable Stokes-Dirac structure can be found for this model. The final formulation is just a superposition of systems (3.41) and (4.29).

4.3.2 Port-Hamiltonian laminated Kirchhoff plate

According to the Kirchhoff hypotheses the kinetic and deformation energies reduce to

$$
\begin{aligned}
E_{\text{kin}} &= \frac{1}{2}\int_{\Omega} \left\{ \rho h \left\| \frac{\partial \boldsymbol{u}^0}{\partial t} \right\|^2 + \rho h \left(\frac{\partial u_z}{\partial t} \right)^2 \right\} \, \mathrm{d}\Omega, \\
E_{\text{def}} &= \frac{1}{2}\int_{\Omega} \left\{ \boldsymbol{N} : \boldsymbol{\varepsilon}^0 + \boldsymbol{M} : \boldsymbol{\kappa} \right\} \, \mathrm{d}\Omega,
\end{aligned}
$$

where $\boldsymbol{\kappa}$ is defined in Eq. (4.5). Furthermore, as stated in Remark 5, the rotational contribution in the kinetic energy has been neglected. The equations of motion are (see [Red03, Chapter 3] for an exhaustive explanation)

$$\begin{aligned} \rho h \frac{\partial^2 \boldsymbol{u}^0}{\partial t^2} &= \mathrm{Div}\, \boldsymbol{N}, \\ \rho h \frac{\partial^2 u_z}{\partial t^2} &= -\,\mathrm{div}\,\mathrm{Div}\, \boldsymbol{M}, \end{aligned} \tag{4.55}$$

where $\boldsymbol{N}$, $\boldsymbol{M}$ are defined in Eqs. (4.47). To get a port-Hamiltonian formulation, the following energy variable are chosen

$$\begin{aligned} \boldsymbol{\alpha}_u &= \rho h \frac{\partial \boldsymbol{u}^0}{\partial t}, & \alpha_w &= \rho h \frac{\partial u_z}{\partial t}, \\ \boldsymbol{A}_{\varepsilon^0} &= \boldsymbol{\varepsilon}^0, & \boldsymbol{A}_\kappa &= \boldsymbol{\kappa}. \end{aligned} \tag{4.56}$$

The total energy $H = E_{\text{kin}} + E_{\text{def}}$ is now a quadratic function of the energy variables

$$\begin{aligned} E_{\text{kin}} &= \frac{1}{2}\int_\Omega \left\{ \frac{1}{\rho h} \left\| \frac{\partial \boldsymbol{\alpha}_u}{\partial t} \right\|^2 + \frac{1}{\rho h} \left(\frac{\partial \alpha_w}{\partial t} \right)^2 \right\} \mathrm{d}\Omega, \\ E_{\text{def}} &= \frac{1}{2}\int_\Omega \left\{ (\boldsymbol{\mathcal{D}}_m \boldsymbol{A}_{\varepsilon^0} + \boldsymbol{\mathcal{D}}_c \boldsymbol{A}_\kappa) : \boldsymbol{A}_{\varepsilon^0} + (\boldsymbol{\mathcal{D}}_c \boldsymbol{A}_{\varepsilon^0} + \boldsymbol{\mathcal{D}}_b \boldsymbol{A}_\kappa) : \boldsymbol{A}_\kappa \right\} \mathrm{d}\Omega, \end{aligned}$$

The co-energies are equal to

$$\begin{aligned} e_w &:= \frac{\delta H}{\delta \boldsymbol{\alpha}_u} = \frac{\partial \boldsymbol{u}^0}{\partial t}, & e_w &:= \frac{\delta H}{\delta \alpha_w} = \frac{\partial u_z}{\partial t}, \\ \boldsymbol{E}_\kappa &:= \frac{\delta H}{\delta \boldsymbol{A}_{\varepsilon^0}} = \boldsymbol{N}, & \boldsymbol{E}_\kappa &:= \frac{\delta H}{\delta \boldsymbol{A}_\kappa} = \boldsymbol{M}, \end{aligned} \tag{4.57}$$

The final pH formulation is found as usual considering the dynamics (4.55) and fact that higher derivatives commute

$$\frac{\partial}{\partial t} \begin{pmatrix} \boldsymbol{\alpha}_u \\ \alpha_w \\ \boldsymbol{A}_{\varepsilon^0} \\ \boldsymbol{A}_\kappa \end{pmatrix} = \begin{bmatrix} \boldsymbol{0} & \boldsymbol{0} & \mathrm{Div} & \boldsymbol{0} \\ 0 & 0 & 0 & -\,\mathrm{div} \circ \mathrm{Div} \\ \mathrm{Grad} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{0} & \mathrm{Grad} \circ \mathrm{grad} & \boldsymbol{0} & \boldsymbol{0} \end{bmatrix} \begin{pmatrix} \boldsymbol{e}_u \\ e_w \\ \boldsymbol{E}_{\varepsilon^0} \\ \boldsymbol{E}_\kappa \end{pmatrix}. \tag{4.58}$$

Again, the coupling appears when considering the link between energy and co-energy variables

$$\begin{pmatrix} \boldsymbol{e}_u \\ e_w \\ \boldsymbol{E}_{\varepsilon^0} \\ \boldsymbol{E}_\kappa \end{pmatrix} = \begin{bmatrix} \frac{1}{\rho h} \boldsymbol{I}_{2\times 2} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} \\ 0 & \frac{1}{\rho h} & 0 & 0 \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{\mathcal{D}}_m & \boldsymbol{\mathcal{D}}_c \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{\mathcal{D}}_c & \boldsymbol{\mathcal{D}}_b \end{bmatrix} \begin{pmatrix} \boldsymbol{\alpha}_u \\ \alpha_w \\ \boldsymbol{A}_{\varepsilon^0} \\ \boldsymbol{A}_\kappa \end{pmatrix}. \tag{4.59}$$

The energy rate provides the appropriate boundary conditions from which one can construct the Stokes-Dirac structure. The necessary computations are not performed here as the final result is just a juxtaposition of systems (3.41), (4.42).

4.4 Conclusion

In this chapter, a pH formulation for the most commonly used plate models has been detailed. Many open questions remain. In particular, how to generalize the results to shell problems, for which the domain is a surface embedded in the three dimensional space (a manifold). Computations get more involved in this case since the usage of differential geometry concepts is unavoidable. These models are important since they are widely used in the aerospace industry and ubiquitous in nature.

The reformulation of plate models using the language of differential geometry is another open research topic. Indeed, while for the Mindlin plate it should be possible to use vector-valued forms to obtain an equivalent system, for the Kirchhoff plate the task appears more involved. An interesting reference that can provide some ideas in this direction is [Yao11].

Chapter 5

Thermoelasticity in port-Hamiltonian form

Eh bien, mon ami, la terre sera un jour ce cadavre refroidi. Elle deviendra inhabitable et sera inhabitée comme la lune, qui depuis longtemps a perdu sa chaleur vitale.

Vingt mille lieues sous les mers
Jules Verne

Contents

Thermoelasticity is the study of deformable bodies undergoing thermal excitations. It is a clear example of a multiphysics phenomenon since the heat transfer and elastic vibrations within the body mutually interact. In this chapter, a linear model of thermoelasticity is obtained under the pH formalism. Each physics is described separately and the final system is obtained considering a power-preserving interconnection of two pHs.

5.1 Port-Hamiltonian linear coupled thermoelasticity

In this section, a pH formulation of heat transfer is first introduced. The classical model of thermoelasticity is then recalled. The same model is found by interconnecting the heat equation and the linear elastodynamics problem seen as pHs. It is shown that the interconnection preserves a quadratic functional that plays the role of a fictitious energy. The resulting system is dissipative with respect to this functional. The construction makes use of the intrinsic modularity of pHs [KZvdSB10].

5.1.1 The heat equation as a pH descriptor system

Consider the heat equation in a bounded connected set $\Omega \subset \mathbb{R}^d$, $d = \{1, 2, 3\}$, describing the evolution of the temperature field $T(\boldsymbol{x}, t)$

$$\rho c_\epsilon \frac{\partial T}{\partial t} = k\Delta T + r_Q, \qquad \boldsymbol{x} \in \Omega, \tag{5.1}$$

where ρ, c_ϵ, k, r_Q are the mass density, the specific heat density at constant strain, the thermal diffusivity and an heat source. Symbol Δ denotes the Laplacian in $\mathbb{R}^d$.The Dirichlet and Neumann condition of this problem are

$$\begin{aligned} T \text{ known on } \Gamma_D^T, &\qquad \text{Dirichlet condition}, \\ -k \operatorname{grad} T \cdot \boldsymbol{n} \text{ known on } \Gamma_N^T, &\qquad \text{Neumann condition}, \end{aligned}$$

where a partition of the boundary $\partial\Omega = \Gamma_D^T \cup \Gamma_N^T$ has been considered. This model can be put in pH form by means of a canonical interconnection structure. An algebraic relationship that describes the Fourier law has to be incorporated in the model (cf. [Kot19, Chapter 2]). Here, a differential-algebraic formulation is exploited to obtain the same system.

Let T_0 be a constant reference temperature (the introduction of this variables is instrumental for coupled thermoelasticity). The functional

$$H_T = \frac{1}{2} \int_\Omega \rho c_\epsilon T_0 \left(\frac{T - T_0}{T_0}\right)^2 \mathrm{d}\Omega$$

has the physical dimension of an energy and represents a Lyapunov functional of this system. Even though it does not represent the internal energy, it has some important properties. Select as energy variable

$$\alpha_T := \rho c_\epsilon (T - T_0),$$

whose corresponding co-energy is

$$e_T := \frac{\delta H_T}{\delta \alpha_T} = \frac{\alpha_T}{\rho c_\epsilon T_0} = \frac{T - T_0}{T_0} =: \theta.$$

Introducing the heat flux $\boldsymbol{j}_Q := -k \operatorname{grad} T$ as additional variable, the heat equation (5.1) is equivalently reformulated as

$$
\begin{aligned}
\begin{bmatrix} 1 & 0 \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \frac{\partial}{\partial t} \begin{pmatrix} \alpha_T \\ \boldsymbol{j}_Q \end{pmatrix} &= \begin{bmatrix} 0 & -\operatorname{div} \\ -\operatorname{grad} & -(T_0 k)^{-1} \end{bmatrix} \begin{pmatrix} e_T \\ \boldsymbol{j}_Q \end{pmatrix} + \begin{bmatrix} 1 \\ \mathbf{0} \end{bmatrix} u_T, \\
y_T &= \begin{bmatrix} 1 & \mathbf{0} \end{bmatrix} \begin{pmatrix} e_T \\ \boldsymbol{j}_Q \end{pmatrix}.
\end{aligned} \tag{5.2}
$$

with $u_T := r_Q$ and y_T represents the corresponding power-conjugated variable. In matrix notation, it is obtained

$$
\begin{aligned}
\mathcal{E}_T \partial_t \boldsymbol{\alpha}_T &= (\mathcal{J}_T - \mathcal{R}_T)\, \boldsymbol{e}_T + \mathcal{B}_T\, u_T, \\
y_d &= \mathcal{B}_T^* \, \boldsymbol{e}_T
\end{aligned} \tag{5.3}
$$

where $\boldsymbol{\alpha}_T = (\alpha_T,\ \boldsymbol{j}_Q)$, $\boldsymbol{e}_T = (e_T,\ \boldsymbol{j}_Q)$ and

$$
\mathcal{E}_T = \begin{bmatrix} 1 & 0 \\ \mathbf{0} & \mathbf{0} \end{bmatrix}, \quad \mathcal{J}_T = \begin{bmatrix} 0 & -\operatorname{div} \\ -\operatorname{grad} & \mathbf{0} \end{bmatrix}, \quad \mathcal{R}_T = \begin{bmatrix} 0 & 0 \\ \mathbf{0} & (T_0 k)^{-1} \end{bmatrix}, \quad \mathcal{B}_T = \begin{bmatrix} 1 \\ \mathbf{0} \end{bmatrix}.
$$

The system is an example of pH descriptor system (cf. [BMXZ18] for the finite dimensional case). The Hamiltonian reads

$$
H_T = \frac{1}{2} \int_\Omega \boldsymbol{e}_T \cdot \mathcal{E}_T \boldsymbol{\alpha}_T \, \mathrm{d}\Omega. \tag{5.4}
$$

The power rate is then deduced

$$
\begin{aligned}
\dot{H}_T &= \int_\Omega \boldsymbol{e}_T \cdot \mathcal{E}_T \, \partial_t \boldsymbol{\alpha}_T \, \mathrm{d}\Omega, \\
&= \int_\Omega \boldsymbol{e}_T \cdot \{(\mathcal{J}_T - \mathcal{R}_T)\boldsymbol{e} + \mathcal{B}_T u_T\} \, \mathrm{d}\Omega, \\
&= \int_\Omega u_T \, y_T \, \mathrm{d}\Omega - \int_\Omega \left(e_T \operatorname{div} \boldsymbol{j}_Q + \boldsymbol{j}_Q \operatorname{grad} e_T + \frac{\|\boldsymbol{j}_Q\|^2}{k T_0} \right) \mathrm{d}\Omega, \\
&\leq \int_\Omega u_T \, y_T \, \mathrm{d}\Omega - \int_{\partial\Omega} e_T \, \boldsymbol{j}_Q \cdot \boldsymbol{n} \, \mathrm{d}S.
\end{aligned} \tag{5.5}
$$

This choice of Hamiltonian allows retrieving the classical boundary conditions and leads to a dissipative system. Other formulations, based on an entropy or internal energy functionals, are possible for the heat equation [DMSB09, SHM19a]. These provide an accrescent or a lossless system. Unfortunately these formulations are non linear and their discretization is a difficult task [SHM19b].

5.1.2 Classical thermoelasticity

The derivation of the classical theory of thermoelasticity is not carried out here. The reader may consult in [HE09, Chapter 1] or [Abe12, Chapter 8] for a detailed discussion on this topic.

Consider a bounded connected set $\Omega \subset \mathbb{R}^d$, $d = \{1, 2, 3\}$. The classical equations for linear fully-coupled thermoelasticity for an isotropic thermoelastic material are [Bio56, Car73]

$$
\begin{aligned}
\rho \frac{\partial^2 \boldsymbol{u}}{\partial t^2} &= \mathrm{Div}(\boldsymbol{\Sigma}_{ET}), \\
\rho c_\epsilon \frac{\partial T}{\partial t} &= -\,\mathrm{div}(\boldsymbol{j}_Q) - \mathcal{C}_\beta : \frac{\partial \boldsymbol{\varepsilon}}{\partial t}, \\
\boldsymbol{\Sigma}_{ET} &= \boldsymbol{\Sigma}_E + \boldsymbol{\Sigma}_T, \\
\boldsymbol{\Sigma}_E &= 2\mu \boldsymbol{\varepsilon} + \lambda \,\mathrm{Tr}(\boldsymbol{\varepsilon}) \boldsymbol{I}_{d\times d}, \\
\boldsymbol{\Sigma}_T &= -\mathcal{C}_\beta \theta, \\
\boldsymbol{\varepsilon} &= \mathrm{Grad}(\boldsymbol{u}), \\
\boldsymbol{j}_Q &= -k \;\mathrm{grad}\, T.
\end{aligned}
\tag{5.6}
$$

For simplicity the coupling term

$$
\mathcal{C}_\beta := T_0 \beta (2\mu + d\lambda) \boldsymbol{I}_{d\times d}
$$

has been introduced. Field $\boldsymbol{u}$ is the displacement, $\boldsymbol{\varepsilon}$ is the infinitesimal strain tensor, $\boldsymbol{\Sigma}_E, \boldsymbol{\Sigma}_T$ are the stress tensor contribution due to mechanical deformation and a thermal field. Coefficients λ, μ are the Lamé parameters, and β the thermal expansion coefficient. Given a partition of the boundary $\partial\Omega = \Gamma_D^E \cup \Gamma_N^E = \Gamma_D^T \cup \Gamma_N^T$ for the elastic and thermal domain. The general boundary conditions read

$$
\begin{aligned}
\boldsymbol{u} \text{ known on } \Gamma_D^E \times (0, +\infty), &\qquad T \text{ known on } \Gamma_D^T \times (0, +\infty), \\
\boldsymbol{\Sigma}_{ET} \cdot \boldsymbol{n} \text{ known on } \Gamma_N^E \times (0, +\infty), &\qquad \boldsymbol{j}_Q \cdot \boldsymbol{n} \text{ known on } \Gamma_N^T \times (0, +\infty).
\end{aligned}
\tag{5.7}
$$

In the following section an equivalent system is constructed by interconnecting the heat equation and the elastodynamics system in a structured manner.

5.1.3 Thermoelasticity as two coupled pHs

Consider again the equation of elasticity on $\Omega \subset \mathbb{R}^d$, $d = \{2, 3\}$ (cf. Eq. (3.41)), together with a distributed input $\boldsymbol{u}_E$ that plays the role of a distributed force

$$
\begin{aligned}
\frac{\partial}{\partial t}\begin{pmatrix} \boldsymbol{\alpha}_v \\ \boldsymbol{A}_\varepsilon \end{pmatrix} &= \begin{bmatrix} \boldsymbol{0} & \mathrm{Div} \\ \mathrm{Grad} & \boldsymbol{0} \end{bmatrix} \begin{pmatrix} \boldsymbol{e}_v \\ \boldsymbol{E}_\varepsilon \end{pmatrix} + \begin{bmatrix} \boldsymbol{I}_{d\times d} \\ \boldsymbol{0} \end{bmatrix} \boldsymbol{u}_E, \\
\boldsymbol{y}_E &= \begin{bmatrix} \boldsymbol{I}_{d\times d} & \boldsymbol{0} \end{bmatrix} \begin{pmatrix} \boldsymbol{e}_v \\ \boldsymbol{E}_\varepsilon \end{pmatrix},
\end{aligned}
\tag{5.8}
$$

with Hamiltonian

$$
H_E = \frac{1}{2} \int_\Omega \left\{ \boldsymbol{\alpha}_v \cdot \boldsymbol{e}_v + \boldsymbol{A}_\varepsilon : \boldsymbol{E}_\varepsilon \right\} \, \mathrm{d}\Omega.
$$

Recall the pH formulation of the heat equation (5.2)

$$
\begin{aligned}
\begin{bmatrix} 1 & 0 \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \frac{\partial}{\partial t} \begin{pmatrix} \alpha_T \\ \boldsymbol{j}_Q \end{pmatrix} &= \begin{bmatrix} 0 & -\operatorname{div} \\ -\operatorname{grad} & -(T_0 k)^{-1} \end{bmatrix} \begin{pmatrix} e_T \\ \boldsymbol{j}_Q \end{pmatrix} + \begin{bmatrix} 1 \\ \mathbf{0} \end{bmatrix} u_T, \\
y_T &= \begin{bmatrix} 1 & \mathbf{0} \end{bmatrix} \begin{pmatrix} e_T \\ \boldsymbol{j}_Q \end{pmatrix},
\end{aligned} \tag{5.9}
$$

with Hamiltonian H_T defined in (5.4). The linear thermoelastic problem can be expressed as a coupled port-Hamiltonian system. Consider the following interconnection

$$
\boldsymbol{u}_E = -\operatorname{Div}(\mathcal{C}_\beta \, y_T), \qquad u_T = -\mathcal{C}_\beta : \operatorname{Grad}(\boldsymbol{y}_E). \tag{5.10}
$$

The interconnection is power preserving as it can be compactly written as

$$
\boldsymbol{u}_E = \mathcal{A}_\beta(y_T), \qquad u_T = -\mathcal{A}_\beta^*(\boldsymbol{y}_E),
$$

where the coupling operator $\mathcal{A}_\beta := -\operatorname{Div}(\mathcal{C}_\beta \, \cdot) : L^2(\Omega) \to L^2(\Omega, \mathbb{R}^d)$ has formal adjoint $\mathcal{A}_\beta^* = \mathcal{C}_\beta^* : \operatorname{Grad}(\cdot) = \mathcal{C}_\beta : \operatorname{Grad}(\cdot) : L^2(\Omega, \mathbb{R}^3) \to L^2(\Omega)$ ($\mathcal{C}_\beta$ is self adjoint given its diagonal structure). As a consequence, under the assumption that $\boldsymbol{y}_E, y_T$ have compact support, it holds $\langle u_T, y_T \rangle_{L^2(\Omega)} + \langle \boldsymbol{u}_E, \boldsymbol{y}_E \rangle_{L^2(\Omega, \mathbb{R}^3)} = 0$. If the compact support assumption is removed, it is obtained

$$
\begin{aligned}
\langle u_T, y_T \rangle_{L^2(\Omega)} + \langle \boldsymbol{u}_E, \boldsymbol{y}_E \rangle_{L^2(\Omega, \mathbb{R}^3)} &= -\int_\Omega \left\{ (\mathcal{C}_\beta : \operatorname{Grad} \boldsymbol{e}_v) e_T + \operatorname{Div}(\mathcal{C}_\beta e_T) \cdot \boldsymbol{e}_v \right\} \, \mathrm{d}\Omega, \\
&= -\int_\Omega \operatorname{div}(e_T \mathcal{C}_\beta \cdot \boldsymbol{e}_v) \, \mathrm{d}\Omega, \\
&= -\int_{\partial\Omega} (e_T \mathcal{C}_\beta \cdot \boldsymbol{n}) \cdot \boldsymbol{e}_v \, \mathrm{d}S.
\end{aligned} \tag{5.11}
$$

Using the expression of $y_T, \boldsymbol{y}_E$, considering that T_0 is constant and applying Schwarz theorem for smooth function, the inputs are equal to

$$
\boldsymbol{u}_E = \operatorname{Div}(\boldsymbol{\Sigma}_T), \qquad u_T = -\mathcal{C}_\beta : \operatorname{Grad}(\boldsymbol{v}) = -\mathcal{C}_\beta : \frac{\partial \boldsymbol{\varepsilon}}{\partial t}.
$$

The coupled thermoelastic problem can now be written as

$$
\begin{bmatrix} \mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{1} & \mathbf{0} & \mathbf{0} \\ 0 & 0 & 1 & 0 \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \end{bmatrix} \frac{\partial}{\partial t} \begin{pmatrix} \boldsymbol{\alpha}_v \\ \boldsymbol{A}_\varepsilon \\ \alpha_T \\ \boldsymbol{j}_Q \end{pmatrix} = \begin{bmatrix} \mathbf{0} & \operatorname{Div} & -\operatorname{Div}(\mathcal{C}_\beta \, \cdot) & \mathbf{0} \\ \operatorname{Grad} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ -\mathcal{C}_\beta : \operatorname{Grad}(\cdot) & 0 & 0 & -\operatorname{div} \\ \mathbf{0} & \mathbf{0} & -\operatorname{grad} & -(T_0 k)^{-1} \end{bmatrix} \begin{pmatrix} \boldsymbol{e}_v \\ \boldsymbol{E}_\varepsilon \\ e_T \\ \boldsymbol{j}_Q \end{pmatrix}, \tag{5.12}
$$

with total energy given by $H = H_E + H_T$. The power balance for each subsystem is given by

$$
\dot{H}_E = \int_\Omega \boldsymbol{u}_E \cdot \boldsymbol{y}_E \, \mathrm{d}\Omega + \int_{\partial\Omega} \boldsymbol{e}_v \cdot (\boldsymbol{E}_\varepsilon \cdot \boldsymbol{n}) \, \mathrm{d}S, \tag{5.13}
$$

$$
\dot{H}_T \leq \int_\Omega u_T \, y_T \, \mathrm{d}\Omega - \int_{\partial\Omega} \theta \, \boldsymbol{j}_Q \cdot \boldsymbol{n} \, \mathrm{d}S, \tag{5.14}
$$

The overall power balance is easily computed considering Eqs. (5.13) (5.14) and (5.11)

$$\dot{H} = \dot{H}_E + \dot{H}_T \leq \int_{\partial\Omega} \{[\boldsymbol{E}_\varepsilon - e_T \mathcal{C}_\beta] \cdot \boldsymbol{n}\} \cdot \boldsymbol{e}_v \, \mathrm{d}S - \int_{\partial\Omega} \theta \, \boldsymbol{j}_Q \cdot \boldsymbol{n} \, \mathrm{d}S. \tag{5.15}$$

From the power balance the classical boundary conditions are retrieved. This allows defining appropriate boundary operators for the thermoelastic problem

$$\boldsymbol{u}_\partial = \underbrace{\begin{bmatrix} \boldsymbol{\gamma}_0^{\Gamma_D^E} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \boldsymbol{\gamma}_n^{\Gamma_N^E} & -\boldsymbol{\gamma}_n^{\Gamma_N^E}(\mathcal{C}_\beta \, \cdot) & \mathbf{0} \\ 0 & 0 & \gamma_0^{\Gamma_D^T} & 0 \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \boldsymbol{\gamma}_n^{\Gamma_N^T} \end{bmatrix}}_{\mathcal{B}_\partial} \begin{pmatrix} \boldsymbol{e}_v \\ \boldsymbol{E}_\varepsilon \\ e_T \\ \boldsymbol{j}_Q \end{pmatrix}, \quad \boldsymbol{y}_\partial = \underbrace{\begin{bmatrix} \mathbf{0} & \boldsymbol{\gamma}_n^{\Gamma_D^E} & -\boldsymbol{\gamma}_n^{\Gamma_D^E}(\mathcal{C}_\beta \, \cdot) & \mathbf{0} \\ \boldsymbol{\gamma}_0^{\Gamma_N^E} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \boldsymbol{\gamma}_n^{\Gamma_D^T} \\ 0 & 0 & \gamma_0^{\Gamma_N^T} & 0 \end{bmatrix}}_{\mathcal{C}_\partial} \begin{pmatrix} \boldsymbol{e}_v \\ \boldsymbol{E}_\varepsilon \\ e_T \\ \boldsymbol{j}_Q \end{pmatrix}. \tag{5.16}$$

System (5.12) together with (5.16) is a pH system with boundary control and observation. Indeed, the classical thermoelastic problem can be modeled as two coupled systems, demonstrating the modularity of the pH paradigm.

5.2 Thermoelastic port-Hamiltonian bending

In this section, the thermoelastic bending of thin beam and plate structures is described as coupled interconnection pf pHs. Starting from classical thermoelastic models and introducing a linear approximation of the temperature field along the thickness coordinate, a suitable pH formulation can be obtained.

5.2.1 Thermoelastic port-Hamiltonian Euler-Bernoulli beam

The model for the linear thermoelastic vibrations of an isotropic thin rod is ruled by equations [Cha62, LR00]

$$\begin{aligned} \rho A \frac{\partial^2 w}{\partial t^2} &= -EI \frac{\partial^4 w}{\partial x^4} - \beta E T_0 \frac{\partial^2}{\partial x^2} \int_S z\theta \, \mathrm{d}S, \\ \rho c_{\epsilon,B} T_0 \frac{\partial \theta}{\partial t} &= k T_0 \Delta\theta + \beta T_0 E z \frac{\partial^3 w}{\partial x^2 \partial t}, \end{aligned} \tag{5.17}$$

where $w(x,t)$ is the vertical displacement of the beam $I = \int_S z^2 \, \mathrm{d}S$ the second moment of area, E the Young modulus and A the cross section. The constant $c_{\epsilon,B}$ is due to the thermoelastic coupling (cf. [Cha62] for a detailed explanation). The other terms have meaning than in Section §5.1. Since the normalized temperature $\theta(x,y,z,t)$ depends on all spatial coordinates, the symbol $\Delta = \partial_{xx} + \partial_{yy} + \partial_{zz}$ is the Laplacian in three dimensions. To derive a coupled pH model, it is assumed

Assumption 1

The temperature field can be approximated by the Taylor expansion

$$\theta(x, y, z, t) \approx \theta_0(x, t) + z\theta_1(x, t). \tag{5.18}$$

Plugging this approximation into System (5.17), it is computed

$$\begin{aligned} \rho A \frac{\partial^2 w}{\partial t^2} &= -EI \frac{\partial^4 w}{\partial x^4} - C_{\beta,B} \frac{\partial^2}{\partial x^2} \theta_1, \\ \rho c_{\epsilon,B} T_0 I \frac{\partial \theta_1}{\partial t} &= k T_0 I \frac{\partial^2 \theta_1}{\partial x^2} + C_{\beta,B} \frac{\partial^3 w}{\partial x^2 \partial t}, \end{aligned} \tag{5.19}$$

where $C_{\beta,B} := \beta T_0 EI$. The second equation was first multiplied by the z coordinate and then integrated across the beam cross section. Since the x axis passes through the centroid of the cross section, the contribution due to θ_0 disappears. Consider the Hamiltonian functional

$$H = H_E + H_T = \frac{1}{2} \int_\Omega \left\{ \rho A \left(\frac{\partial w}{\partial t} \right)^2 + EI \left(\frac{\partial^2 w}{\partial x^2} \right)^2 + \rho c_{\epsilon,B} T_0 I \theta_1^2 \right\} \mathrm{d}\Omega. \tag{5.20}$$

The energy variables are chosen to make the Hamiltonian functional quadratic

$$\alpha_w = \rho A \partial_t w, \qquad \alpha_\kappa = \partial_{xx} w, \qquad \alpha_T = \rho c_{\epsilon,B} T_0 I \theta_1. \tag{5.21}$$

The corresponding co-energy variables evaluate to

$$e_w := \frac{\delta H}{\delta \alpha_w} = \partial_t w, \qquad e_\kappa := \frac{\delta H}{\delta \alpha_\kappa} = EI \partial_{xx} w, \qquad e_T := \frac{\delta H}{\delta \alpha_T} = \theta_1. \tag{5.22}$$

System (5.19) can now be rewritten as

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \frac{\partial}{\partial t} \begin{pmatrix} \alpha_w \\ \alpha_\kappa \\ \alpha_T \\ j_Q \end{pmatrix} = \begin{bmatrix} 0 & -\partial_{xx} & -C_{\beta,B} \partial_{xx} & 0 \\ \partial_{xx} & 0 & 0 & 0 \\ C_{\beta,B} \partial_{xx} & 0 & 0 & -\partial_x \\ 0 & 0 & -\partial_x & -(kT_0 I)^{-1} \end{bmatrix} \begin{pmatrix} e_w \\ e_\kappa \\ e_T \\ j_Q \end{pmatrix}, \tag{5.23}$$

where $j_Q = -kT_0 I \partial_x \theta_1$ is the heat flux. This system is the equivalent of (5.12) for bending of beams. Hence, following the same reasoning, it can be obtained starting from each subsystem in pH form by means of an appropriate interconnection.

5.2.2 Thermoelastic port-Hamiltonian Kirchhoff plate

For the bending of thin plate, several different models have been proposed [Cha62, Lag89, Sim99, Nor06]. Here, the Chadwick model [Cha62] is recovered:

$$
\begin{aligned}
\rho h \frac{\partial^2 w}{\partial t^2} &= -D_b \Delta^2 w + D\beta(1+\nu) T_0 \Delta \Theta, \\
\rho c_{\epsilon,P} T_0 \frac{\partial \theta}{\partial t} &= -k T_0 (\Delta \theta + \partial_{zz}\theta) + \frac{\beta T_0 E z}{1-\nu} \Delta(\partial_t w),
\end{aligned}
\tag{5.24}
$$

where $w(x, y, t)$ is the vertical deflection, h the plate thickness, $D_b = \frac{Eh^3}{12(1-\nu^2)}$ the bending rigidity (cf. Eq. (4.11)), ν the Poisson modulus and $c_{\epsilon,P}$ a constant (depending on the heat capacity at constant strain and other coupling parameters, cf. [Cha62]). Symbol $\Delta = \partial_{xx} + \partial_{yy}$ is the in plane Laplacian and

$$
\Theta := \frac{1}{I_h} \int_{-h/2}^{h/2} z\theta \, \mathrm{d}z, \qquad \text{where} \qquad I_h := \frac{h^3}{12}
$$

is the first moment of the normalized temperature. Similarly to the assumption made for the Euler Bernoulli beam, a linear approximation for the temperature field is introduced:

$$
\theta(x, y, z, t) \approx \theta_0(x, y, t) + z\theta_1(x, y, t). \tag{5.25}
$$

Consequently, Θ approximates to $\Theta \approx \theta_1$. Analogously to what was done for the Euler-Bernoulli beam, the heat equation is manipulated (multiplication by z and integration over the plate thickness), to obtain

$$
\begin{aligned}
\rho h \frac{\partial^2 w}{\partial t^2} &= -D_b \Delta^2 w + C_{\beta,P} \Delta \theta_1, \\
\rho c_{\epsilon,P} T_0 I_h \frac{\partial \theta_1}{\partial t} &= -k T_0 I_h \Delta \theta_1 + C_{\beta,P} \Delta(\partial_t w),
\end{aligned}
\tag{5.26}
$$

where $C_{\beta,P} := D\beta(1+\nu)T_0$ is the coupling parameter. The Hamiltonian functional equals

$$
H = H_E + H_T = \frac{1}{2} \int_\Omega \left\{ \rho h \left(\frac{\partial w}{\partial t}\right)^2 + (\boldsymbol{\mathcal{D}}_b \operatorname{Hess} w) : \operatorname{Hess} w + \rho c_{\epsilon,P} T_0 I_h \theta_1^2 \right\} \mathrm{d}\Omega, \tag{5.27}
$$

where $\boldsymbol{\mathcal{D}}_b$ was defined in (4.11) (cf. Sec. §4.1.1). The energy and co-energy variables are

$$
\begin{aligned}
\alpha_w &= \rho h \partial_t w, & \boldsymbol{A}_\kappa &= \operatorname{Hess} w, & \alpha_T &= \rho c_{\epsilon,P} T_0 I_h \, \theta_1, \\
e_w &= \partial_t w, & \boldsymbol{E}_\kappa &= \boldsymbol{\mathcal{D}}_b \operatorname{Hess} w, & e_T &= \theta_1.
\end{aligned}
\tag{5.28}
$$

System (5.26) is rewritten as

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ \mathbf{0} & \mathbf{1} & \mathbf{0} & \mathbf{0} \\ 0 & 0 & 1 & 0 \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \end{bmatrix} \frac{\partial}{\partial t} \begin{pmatrix} \alpha_w \\ \boldsymbol{A}_\kappa \\ \alpha_T \\ \boldsymbol{j}_Q \end{pmatrix} = \begin{bmatrix} 0 & -\operatorname{div} \circ \operatorname{Div} & -C_{\beta,P}\Delta & 0 \\ \operatorname{Grad} \circ \operatorname{grad} & \mathbf{0} & \mathbf{0} & 0 \\ C_{\beta,P}\Delta & 0 & 0 & -\operatorname{div} \\ \mathbf{0} & \mathbf{0} & -\operatorname{grad} & -(kT_0 I_h)^{-1} \end{bmatrix} \begin{pmatrix} e_w \\ \boldsymbol{E}_\kappa \\ e_T \\ \boldsymbol{j}_Q \end{pmatrix}, \tag{5.29}$$

where $\boldsymbol{j}_Q = -kT_0 I_h \operatorname{grad} \theta_1$ is the heat flux. The final system reproduces the same structured coupling already observed for (5.12), (5.23). Generic boundary conditions for this problem [AL00] are obtained by considering the total energy rate.

Remark 8

The contribution θ_0 of the temperature field can be included if the in-plane behavior (namely the axial contribution in the beam case and the membrane one for plates) is considered. Similarly to what was done in Sec. §4.3, a generic anisotropic thermoelastic material can be modeled by considering both the membrane and bending behavior.

5.3 Conclusion

In this chapter, it was shown how to derive linear thermoelastic problem as coupled pHs. This is especially interesting for the simulation of thermoelastic phenomena: each subsystem can be discretized separately and then coupled to the other using the discretized coupling operator.

To achieve a suitable formulation for the bending of plates and beams a linear approximation was introduced. However, if higher order theories are used for the bending behavior, the approximation of temperature field modifies accordingly, allowing for a better representation of temperature trend along the thickness.

Part III

Finite element structure preserving discretization

Chapter 6

Partitioned finite element method

Every truth is simple... is that not doubly a lie?

Twilight of the Idols
Friedrich Nietzsche

Contents

Discretization is the process of transferring continuous models into discrete counterparts. The discrete model should be faithful to the continuous one. To this aim, it is usually essential that the main properties of the continuous system are preserved at the discrete level. An algorithm that is capable of conserving properties at the discrete level is called structure-preserving [CMKO11]. In this chapter, a finite element method to spatially discretize infinite-dimensional pHs into finite-dimensional ones in a structure preserving manner is illustrated.

6.1 General procedure

A discrete version of a infinite-dimensional pH system is meant to preserve the underlying properties related to power continuity. To achieve this purpose, the discretization procedure consists of two steps [KML18]:

- Finite-dimensional approximation of the Stokes-Dirac structure, i.e. the formally skew symmetric differential operator that defines the structure. The duality of the power variables has to be mapped onto the finite approximation. The subspace of the discrete variables will be represented by a Dirac structure.

- The Hamiltonian requires as well a suitable discretization, which gives rise to a discrete Hamiltonian.

A structure-preserving discretization is able to construct an equivalent pH system that possess the structural properties of the original model:

Infinite dimensional pH system	Structure-preserving discretization
PDE with distributed inputs: $$\frac{\partial \boldsymbol{\alpha}}{\partial t}(\boldsymbol{x}, t) = \mathcal{J}\frac{\delta H}{\delta \boldsymbol{\alpha}} + \mathcal{B}\boldsymbol{u}(\boldsymbol{x}, t), \quad \boldsymbol{y}(\boldsymbol{x}, t) = \mathcal{B}^* \frac{\delta H}{\delta \boldsymbol{\alpha}}.$$	Resulting ODE: $$\dot{\boldsymbol{\alpha}}_d = \mathbf{J}\,\nabla H_d + \mathbf{B}_d \mathbf{u}_d + \mathbf{B}_\partial \mathbf{u}_\partial, \quad \mathbf{y}_d = \mathbf{B}_d^\top \nabla H_d, \quad \mathbf{y}_\partial = \mathbf{B}_\partial^\top \nabla H_d.$$
Boundary conditions: $$\boldsymbol{u}_\partial = \mathcal{B}_\partial \frac{\delta H}{\delta \boldsymbol{\alpha}}, \quad \boldsymbol{y}_\partial = \mathcal{C}_\partial \frac{\delta H}{\delta \boldsymbol{\alpha}}.$$	Discretized Hamiltonian: $$H_d := H(\boldsymbol{\alpha} \equiv \boldsymbol{\alpha}_d).$$
Power balance (Stokes Theorem): $$\dot{H} = \int_{\partial\Omega} \boldsymbol{u}_\partial \cdot \boldsymbol{y}_\partial \, \mathrm{d}S + \int_\Omega \boldsymbol{u} \cdot \boldsymbol{y} \, \mathrm{d}\Omega.$$	Power balance: $$\dot{H} = \mathbf{u}_\partial^\top \mathbf{y}_\partial + \mathbf{u}_d^\top \mathbf{y}_d.$$

In this work the partitioned finite element method (PFEM), originally presented in [CRML18, CRML19], is chosen to obtain discretized models of dpHs. This procedure boils down to three simple steps

1. The system is written in weak form;
2. An integration by parts is applied to highlight the appropriate boundary control;
3. A Galerkin method is employed to obtain a finite-dimensional system.

Once the system has been put into weak form, a subset of the equations is integrated by parts, so that boundary variables are naturally included into the formulation and appear as control inputs, the collocated outputs being defined accordingly. The discretization of energy and co-energy variables (and the associated test functions) leads directly to a full rank representation for the finite-dimensional port-Hamiltonian system. This approach makes possible the usage of FEM software, like FEniCS [LMW+12], or Firedrake [RHM+17].

Despite the many advantages, this methodology allows obtaining a canonical pH finite dimensional system only under a uniform causality assumption. The case of mixed boundary conditions requires additional care and will be treated in the subsequent Section §6.2.

6.1.1 Non-linear case

Given an open connected set $\Omega \in \mathbb{R}^d, d = \{1, 2, 3\}$, consider a generic pH system defined on Ω

$$\begin{aligned} \partial_t \boldsymbol{\alpha} &= \mathcal{J}\boldsymbol{e}, & \boldsymbol{\alpha} &\in X, \\ \boldsymbol{u}_\partial &= \mathcal{B}_\partial \boldsymbol{e}, & \boldsymbol{u}_\partial &\in L^2(\partial\Omega, \mathbb{R}^m), \\ \boldsymbol{y}_\partial &= \mathcal{C}_\partial \boldsymbol{e}, & \boldsymbol{y}_\partial &\in L^2(\partial\Omega, \mathbb{R}^m), \\ \boldsymbol{e} &:= \delta_{\boldsymbol{\alpha}} H. \end{aligned} \tag{6.1}$$

The Hilbert space X, whose inner product is denoted by $\langle \cdot, \cdot \rangle_X$, is an appropriate Cartesian product of L^2 spaces which account for the nature of each variable (that can be scalar, vectorial or tensorial quantities).

To applied this methodology the non linearities are restricted to the Hamiltonian and a uniform causality condition is supposed to characterize the system. These hypotheses are resumed in the following assumptions

Assumption 2
Consider system (6.1). It is assumed that the Hilbert space X admits the splitting $X = X_1 \times X_2$ (meaning that the system does not consist of a single scalar equation). The operator $\mathcal{J}$ is assumed to be skew-symmetric (or formally skew-adjoint) on X and linear:

$$\mathcal{J} = \mathcal{J}_a + \mathcal{J}_d, \tag{6.2}$$

where $\mathcal{J}_a$ is the algebraic contribution (a skew-symmetric matrix) and $\mathcal{J}_d$ the differential contribution. Since $\mathcal{J}$ is skew-symmetric on X, the linear differential operator $\mathcal{J}_d$ can be expressed as

$$\mathcal{J}_d = \begin{bmatrix} 0 & -\mathcal{L}^* \\ \mathcal{L} & 0 \end{bmatrix} = \mathcal{J}_{d,1} + \mathcal{J}_{d,2}, \qquad \begin{aligned} \mathcal{L}^* &: X_2 \rightarrow X_1, \\ \mathcal{L} &: X_1 \rightarrow X_2, \end{aligned} \tag{6.3}$$

where $\mathcal{L}^*$ denotes the formal adjoint of the linear differential operator $\mathcal{L}$ and

$$\mathcal{J}_{d,1} := \begin{bmatrix} 0 & -\mathcal{L}^* \\ 0 & 0 \end{bmatrix}, \qquad \mathcal{J}_{d,2} := \begin{bmatrix} 0 & 0 \\ \mathcal{L} & 0 \end{bmatrix}.$$

The operator $\mathcal{L}$ can be either a first order or a second order differential operator. In the latter case it can be expressed as $\mathcal{L} = \mathcal{L}_1 \circ \mathcal{L}_2$. By definition $\mathcal{J}_{d,1} = -\mathcal{J}_{d,2}^*$.

From parametrization 6.3 and Theorem 2, given $(\boldsymbol{u}, \boldsymbol{v}) \in X_1 \times X_2 = X$, it can be stated

$$(\mathcal{L}\,\boldsymbol{u}) \cdot \boldsymbol{v} - \boldsymbol{u} \cdot (\mathcal{L}^*\,\boldsymbol{v}) = \operatorname{div} \widetilde{\mathcal{A}}_{\mathcal{L}}(\boldsymbol{u}, \boldsymbol{v}), \tag{6.4}$$

Then, the boundary operators are supposed to fulfill the following assumption, that guarantees a uniform causality condition.

Assumption 3
Given $\boldsymbol{a} = (\boldsymbol{a}_1,\, \boldsymbol{a}_2) \in X_1 \times X_2 = X$ *and* $\boldsymbol{b} = (\boldsymbol{b}_1,\, \boldsymbol{b}_2) \in X_1 \times X_2 = X$ *the boundary operators* $\mathcal{B}_\partial$, $\mathcal{C}_\partial$ *are assumed to verify, in an exclusive manner, either*

$$\langle \boldsymbol{a}, \mathcal{J}_{d,1}\, \boldsymbol{b}\rangle_X + \langle \mathcal{J}_{d,2}\, \boldsymbol{a}, \boldsymbol{b}\rangle_X = \langle C_\partial \boldsymbol{a}, B_\partial \boldsymbol{b}\rangle_{L^2(\partial\Omega, \mathbb{R}^m)}\,, \tag{6.5}$$

or

$$\langle \boldsymbol{a}, \mathcal{J}_{d,2}\, \boldsymbol{b}\rangle_X + \langle \mathcal{J}_{d,1}\, \boldsymbol{a}, \boldsymbol{b}\rangle_X = \langle C_\partial \boldsymbol{a}, B_\partial \boldsymbol{b}\rangle_{L^2(\partial\Omega, \mathbb{R}^m)}\,. \tag{6.6}$$

These are equivalent to

$$\text{Condition (6.5)} \implies \quad \langle \mathcal{L}\, \boldsymbol{a}_1, \boldsymbol{b}_2\rangle_{X_2} - \langle \boldsymbol{a}_1, \mathcal{L}^*\, \boldsymbol{b}_2\rangle_{X_1} = \langle C_{\partial,1} \boldsymbol{a}_1, B_{\partial,2} \boldsymbol{b}_2\rangle_{L^2(\partial\Omega, \mathbb{R}^m)}\,, \tag{6.7}$$

$$\text{Condition (6.6)} \implies \quad \langle \boldsymbol{a}_2, \mathcal{L}\, \boldsymbol{b}_1\rangle_{X_2} - \langle \mathcal{L}^*\, \boldsymbol{a}_2, \boldsymbol{b}_1\rangle_{X_1} = \langle C_{\partial,2} \boldsymbol{a}_2, B_{\partial,1} \boldsymbol{b}_1\rangle_{L^2(\partial\Omega, \mathbb{R}^m)}\,. \tag{6.8}$$

Than means that the boundary operators are parametrized as

$$\text{Condition (6.5)} \implies \quad B_\partial = \begin{bmatrix} B_{\partial,1} & 0 \end{bmatrix}, \quad C_\partial = \begin{bmatrix} 0 & C_{\partial,2} \end{bmatrix}, \tag{6.9}$$

$$\text{Condition (6.6)} \implies \quad B_\partial = \begin{bmatrix} 0 & B_{\partial,2} \end{bmatrix}, \quad C_\partial = \begin{bmatrix} C_{\partial,1} & 0 \end{bmatrix}, \tag{6.10}$$

The Hamiltonian functional is allowed to non linear in the energy variables.

Step 1 Consider the weak form of system (6.1)

$$\langle \boldsymbol{v}, \partial_t \boldsymbol{\alpha}\rangle_X = \langle \boldsymbol{v}, \mathcal{J} \boldsymbol{e}\rangle_X\,. \tag{6.11}$$

The weak form is obtained by taking the L^2 inner product introducing an appropriate test function $\boldsymbol{v} \in X$ and integrating over the domain Ω. From equations (6.2), (6.3), one gets

$$\langle \boldsymbol{v}, \partial_t \boldsymbol{\alpha}\rangle_X = \langle \boldsymbol{v}, (\mathcal{J}_a + \mathcal{J}_{d,1} + \mathcal{J}_{d,2}) \boldsymbol{e}\rangle_X\,. \tag{6.12}$$

Step 1 Next the integration by part has to be carried out

6.1.2 Linear case

6.1.3 Examples

6.2 Inhomogeneous boundary conditions

6.2.1 Solution using Lagrange multipliers

6.2.2 Virtual domain decomposition

6.3 Connection with mixed finite elements

Chapter 7

Convergence numerical study

7.1 Plate problems using known mixed finite elements

7.2 Non-standard discretization of flexible structures

Chapter 8

Numerical applications

8.1 Boundary stabilization

8.2 Thermoelastic wave propagation

8.3 Mixed boundary conditions

8.3.1 Trajectory tracking of a thin beam

8.3.2 Vibroacoustic under mixed boundary conditions

8.4 Modal analysis of plates

Part IV

Port-Hamiltonian flexible multibody dynamics

Chapter 9

Modular multibody systems in port-Hamiltonian form

9.1 Reminder of the rigid case

9.2 Flexible floating body

9.3 Modular construction of multibody systems

Chapter 10

Validation

10.1 Beam systems

10.1.1 Modal analysis of a flexible mechanism

10.1.2 Non-linear crank slider

10.1.3 Hinged beam

10.2 Plate systems

10.2.1 Boundary interconnection with a rigid element

10.2.2 Actuated plate

Conclusion

Conclusions and future directions

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

André Gide
Préface de L'Immoraliste

Appendix A

Mathematical tools

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_i, 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

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

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

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

Definition 6 (Formal adjoint, Def. 5.80 [RR04])
Consider the differential operator defined on Ω

$$\mathcal{L}(\boldsymbol{x}, \partial) = \sum_{|\alpha| \leq k} a_\alpha(\boldsymbol{x}) \partial^\alpha, \tag{A.1}$$

where $\alpha := (\alpha_1, \ldots, \alpha_d)$ is a multi-index of order $|\alpha| := \sum_{i=1}^{d} \alpha_i$, a_α are a set of real scalars and $\partial^\alpha := \partial_{x_1}^{\alpha_1} \ldots \partial_{x_d}^{\alpha_d}$ is a differential operator of order $|\alpha|$ resulting from a combination of spatial derivatives. The formal adjoint of $\mathcal{L}$ is the operator defined by

$$\mathcal{L}^*(\boldsymbol{x}, \partial)u = \sum_{|\alpha| \leq k} (-1)^\alpha \partial^\alpha (a_\alpha(\boldsymbol{x}) u(\boldsymbol{x})). \tag{A.2}$$

The importance of this definition lies in the fact that

$$\langle \phi, \mathcal{L}(\boldsymbol{x}, \partial)\psi \rangle \, \Omega = \langle \mathcal{L}^*(\boldsymbol{x}, \partial)\phi, \psi \rangle \, \Omega \tag{A.3}$$

for every $\phi, \psi \in C_0^\infty(\Omega)$. If the assumption of compact support is removed, then (A.3) no longer holds; instead the integration by parts yields additional terms involving integrals over the boundary $\partial\Omega$. However, these boundary terms vanish if ϕ and ψ satisfy certain restrictions on the boundary.

Appendix B

Finite elements gallery

Appendix C

Implementation using FEniCS and Firedrake

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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.
