Study guide: Computing with variational forms for systems of PDEs

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1. Systems of differential equations

Systems of differential equations

Consider $m+1$ unknown functions: $u^{(0)}, \ldots, u^{(m)}$ governed by $m+1$ differential equations:

$$\mathcal{L}_0(u^{(0)}, \ldots, u^{(m)}) = 0$$
$$\vdots$$
$$\mathcal{L}_m(u^{(0)}, \ldots, u^{(m)}) = 0,$$

Goals

- How do we derive variational formulations of systems of differential equations?
- How do we apply the finite element method?

Variational forms: treat each PDE as a scalar PDE

- First approach: treat each equation as a scalar equation
- For equation no. i, use test function $v^{(i)} \in V^{(i)}$

$$\int_\Omega \mathcal{L}^{(0)}(u^{(0)},\ldots,u^{(m)})v^{(0)}\,\mathrm{d}x = 0$$

$$\vdots$$

$$\int_\Omega \mathcal{L}^{(m)}(u^{(0)},\ldots,u^{(m)})v^{(m)}\,\mathrm{d}x = 0$$

Terms with second-order derivatives may be integrated by parts, with Neumann conditions inserted in boundary integrals.

$$V^{(i)} = \text{span}\{\varphi_0^{(i)},\ldots,\varphi_{N_i}^{(i)}\},$$

$$u^{(i)} = B^{(i)}(\boldsymbol{x}) + \sum_{j=0}^{N_i} c_j^{(i)}\varphi_j^{(i)}(\boldsymbol{x}),$$

Variational forms: treat the PDE system as a vector PDE

- Second approach: work with vectors (and vector notation)
- $\boldsymbol{u} = (u^{(0)}, \ldots, u^{(m)})$
- $\boldsymbol{v} = (u^{(0)}, \ldots, u^{(m)})$
- $\boldsymbol{u}, \boldsymbol{v} \in \boldsymbol{V} = V^{(0)} \times \cdots \times V^{(m)}$
- Note: if $\boldsymbol{B} = (B^{(0)}, \ldots, B^{(m)})$ is needed for nonzero Dirichlet conditions, $\boldsymbol{u} - \boldsymbol{B} \in \boldsymbol{V}$ (not $\boldsymbol{u}$ in $\boldsymbol{V}$)
- $\boldsymbol{\mathcal{L}}(\boldsymbol{u}) = 0$
- $\boldsymbol{\mathcal{L}}(\boldsymbol{u}) = (\mathcal{L}^{(0)}(\boldsymbol{u}), \ldots, \mathcal{L}^{(m)}(\boldsymbol{u}))$

The variational form is derived by taking the *inner product* of $\boldsymbol{\mathcal{L}}(\boldsymbol{u})$ and $\boldsymbol{v}$:

$$\int_\Omega \boldsymbol{\mathcal{L}}(\boldsymbol{u}) \cdot \boldsymbol{v} = 0 \quad \forall \boldsymbol{v} \in \boldsymbol{V}$$

- Observe: this is a scalar equation (!).
- Can derive m independent equation by choosing m independent $\boldsymbol{v}$
- E.g.: $\boldsymbol{v} = (v^{(0)}, 0, \ldots, 0)$ recovers (??)

A worked example

$$\mu \nabla^2 w = -\beta$$
$$\kappa \nabla^2 T = -\mu ||\nabla w||^2 \quad (= \mu \nabla w \cdot \nabla w)$$

- Unknowns: $w(x, y)$, $T(x, y)$
- Known constants: μ, β, κ
- Application: fluid flow in a straight pipe, w is velocity, T is temperature
- Ω: cross section of the pipe
- Boundary conditions: $w = 0$ and $T = T_0$ on $\partial\Omega$
- Note: T depends on w, but w does not depend on T (one-way coupling)

Identical function spaces for the unknowns

Let $w, (T - T_0) \in V$ with test functions $v \in V$.

$$V = \text{span}\{\varphi_0(x,y), \ldots, \varphi_N(x,y)\},$$

$$w = \sum_{j=0}^{N} c_j^{(w)} \varphi_j, \quad T = T_0 + \sum_{j=0}^{N} c_j^{(T)} \varphi_j$$

Variational form of each individual PDE

Inserting (??) in the PDEs, results in the residuals

$$R_w = \mu \nabla^2 w + \beta$$
$$R_T = \kappa \nabla^2 T + \mu ||\nabla w||^2$$

Galerkin's method: make residual orthogonal to V,

$$\int_\Omega R_w v \,\mathrm{d}x = 0 \quad \forall v \in V$$
$$\int_\Omega R_T v \,\mathrm{d}x = 0 \quad \forall v \in V$$

Integrate by parts and use $v = 0$ on $\partial\Omega$ (Dirichlet conditions!):

$$\int_\Omega \mu \nabla w \cdot \nabla v \,\mathrm{d}x = \int_\Omega \beta v \,\mathrm{d}x \quad \forall v \in V$$

Compound scalar variational form

- Test vector function $\boldsymbol{v} \in \boldsymbol{V} = V \times V$
- Take the inner product of $\boldsymbol{v}$ and the system of PDEs (and integrate)

$$\int_\Omega (R_w, R_T) \cdot \boldsymbol{v} \, \mathrm{d}x = 0 \quad \forall \boldsymbol{v} \in \boldsymbol{V}$$

With $\boldsymbol{v} = (v_0, v_1)$:

$$\int_\Omega (R_w v_0 + R_T v_1) \, \mathrm{d}x = 0 \quad \forall \boldsymbol{v} \in \boldsymbol{V}$$

$$\int_\Omega (\mu \nabla w \cdot \nabla v_0 + \kappa \nabla T \cdot \nabla v_1) \, \mathrm{d}x = \int_\Omega (\beta v_0 + \mu \nabla w \cdot \nabla w \, v_1) \, \mathrm{d}x, \quad \forall \boldsymbol{v} \in \boldsymbol{V}$$

Choosing $v_0 = v$ and $v_1 = 0$ gives the variational form (??), while $v_0 = 0$ and $v_1 = v$ gives (??).

Alternative inner product notation

$$\mu(\nabla w, \nabla v) = (\beta, v) \quad \forall v \in V$$
$$\kappa(\nabla T, \nabla v) = \mu(\nabla w \cdot \nabla w, v) \quad \forall v \in V$$

Decoupled linear systems

$$\sum_{j=0}^{N} A_{i,j}^{(w)} c_j^{(w)} = b_i^{(w)}, \quad i = 0, \ldots, N$$

$$\sum_{j=0}^{N} A_{i,j}^{(T)} c_j^{(T)} = b_i^{(T)}, \quad i = 0, \ldots, N$$

$$A_{i,j}^{(w)} = \mu(\nabla\varphi_j, \nabla\varphi_i)$$

$$b_i^{(w)} = (\beta, \varphi_i)$$

$$A_{i,j}^{(T)} = \kappa(\nabla\varphi_j, \nabla\varphi_i)$$

$$b_i^{(T)} = (\mu\nabla w_- \cdot (\sum_k c_k^{(w)} \nabla\varphi_k), \varphi_i)$$

Matrix-vector form (alternative notation):

$$\mu K c^{(w)} = b^{(w)}$$

$$\kappa K c^{(T)} = b^{(T)}$$

Coupled linear systems

- Pretend two-way coupling, i.e., need to solve for w and T simultaneously
- Want to derive *one system* for $c_j^{(w)}$ and $c_j^{(T)}$, $j = 0, \ldots, N$
- The system is nonlinear because of $\nabla w \cdot \nabla w$
- Linearization: pretend an iteration where $\hat{w}$ is computed in the previous iteration and set $\nabla w \cdot \nabla w \approx \nabla \hat{w} \cdot \nabla w$ (so the term becomes linear in w)

$$\sum_{j=0}^{N} A_{i,j}^{(w,w)} c_j^{(w)} + \sum_{j=0}^{N} A_{i,j}^{(w,T)} c_j^{(T)} = b_i^{(w)}, \quad i = 0, \ldots, N,$$

$$\sum_{j=0}^{N} A_{i,j}^{(T,w)} c_j^{(w)} + \sum_{j=0}^{N} A_{i,j}^{(T,T)} c_j^{(T)} = b_i^{(T)}, \quad i = 0, \ldots, N,$$

$$A_{i,j}^{(w,w)} = \mu(\nabla\varphi_j, \varphi_i)$$

$$A_{i,j}^{(w,T)} = 0$$

$$b_i^{(w)} = (\beta, \varphi_i)$$

Alternative notation for coupled linear system

$$\mu K c^{(w)} = b^{(w)}$$
$$L c^{(w)} + \kappa K c^{(T)} = 0$$

L is the matrix from the $\nabla w_{-} \cdot \nabla$ operator: $L_{i,j} = A_{i,j}^{(w,T)}$.

Corresponding block form:

$$\begin{pmatrix} \mu K & 0 \\ L & \kappa K \end{pmatrix} \begin{pmatrix} c^{(w)} \\ c^{(T)} \end{pmatrix} = \begin{pmatrix} b^{(w)} \\ 0 \end{pmatrix}$$

Different function spaces for the unknowns

- Generalization: $w \in V^{(w)}$ and $T \in V^{(T)}$, $V^{(w)} \neq V^{(T)}$
- This is called a *mixed finite element method*

$$V^{(w)} = \text{span}\{\varphi_0^{(w)}, \ldots, \varphi_{N_w}^{(w)}\}$$
$$V^{(T)} = \text{span}\{\varphi_0^{(T)}, \ldots, \varphi_{N_T}^{(T)}\}$$

$$\int_\Omega \mu \nabla w \cdot \nabla v^{(w)} \,\mathrm{d}x = \int_\Omega \beta v^{(w)} \,\mathrm{d}x \quad \forall v^{(w)} \in V^{(w)}$$
$$\int_\Omega \kappa \nabla T \cdot \nabla v^{(T)} \,\mathrm{d}x = \int_\Omega \mu \nabla w \cdot \nabla w \, v^{(T)} \,\mathrm{d}x \quad \forall v^{(T)} \in V^{(T)}$$

Take the inner product with $\boldsymbol{v} = (v^{(w)}, v^{(T)})$ and integrate:

$$\int_\Omega (\mu \nabla w \cdot \nabla v^{(w)} + \kappa \nabla T \cdot \nabla v^{(T)}) \,\mathrm{d}x = \int_\Omega (\beta v^{(w)} + \mu \nabla w \cdot \nabla w \, v^{(T)}) \,\mathrm{d}x,$$

valid $\forall \boldsymbol{v} \in \boldsymbol{V} = V^{(w)} \times V^{(T)}$.