



Combining BEM, ALE, DAE, FEM and SUPG in deal.II:
unsteady and **nonlinear** ship-wave interactions

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SISSA mathLab - International School for Advanced Studies

18-22 August 2013
IV deal.II Users Workshop

The OpenSHIP project

OpenSHIP (Supported by Regione FVG - POR FESR 2007-2013)

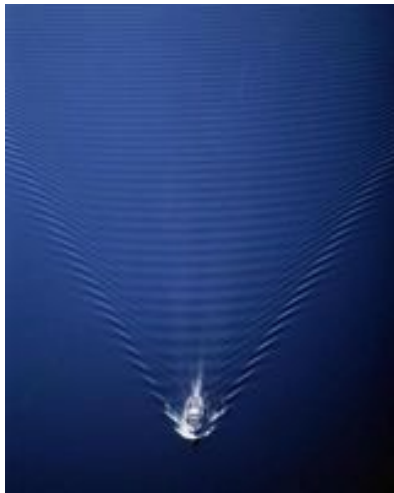
Partners:

- CETENA (Fincantieri)
- University of Trieste
- SISSA
- Friuli Innovazione
- Spring Firm



High quality, OpenSource, CFD simulations and performance prediction of the **ship hull-propeller system**.

The ship-wave interaction problem



Main goal:

Properly estimate the wave resistance of a ship advancing in (calm) water



What tools?

- CAD
- VOF, RANS, FEM, BEM
- ...

Outline

- 1 Continuous Problem
 - Governing Equations
 - ALE (semi-Lagrangian) Formulation
 - Nonlinear Integro-Differential System
- 2 Discretization
 - Isoparametric BEM
 - SUPG Gradient Recovery
 - DAE Formulation (using Sacado to compute Jacobians)
 - Automatic Mesh Refinement
- 3 Results
 - Wigley Hull
 - US Navy Combatant (DTMB 5415)
 - KRISO Tanker (KVLCC2M)

Schematic domain and boundary conditions

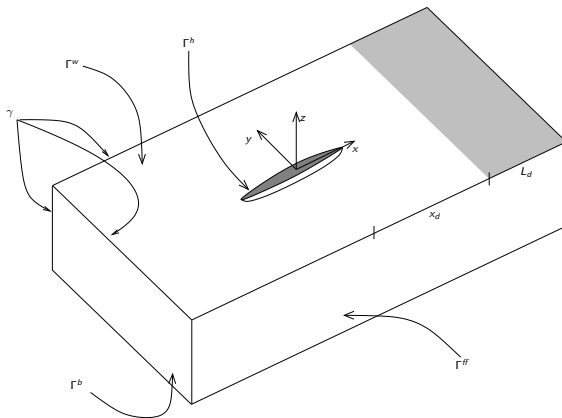


Figure : The computational domain

Three dimensional Flows

Incompressible Navier-Stokes Equations

$$\rho \frac{\partial \mathbf{v}}{\partial t} + \rho(\mathbf{v} \cdot \nabla) \mathbf{v} - \nu \Delta \mathbf{v} + \nabla p = -g \mathbf{e}_z \quad \text{in } \Omega(t)$$

$$\nabla \cdot \mathbf{v} = 0 \quad \text{in } \Omega(t)$$

$$\sigma \mathbf{n} = \sigma_a \mathbf{n} = p_a \mathbf{n} \quad \text{on } \Gamma^w(t)$$

$$\mathbf{v} \cdot \mathbf{n} = \mathbf{v}_g \cdot \mathbf{n} \quad \text{on } \Gamma(t) \setminus \Gamma^w(t)$$

- ρ , ν , g , p_a and \mathbf{v}_g : density, viscosity, gravitational body force, atmospheric pressure and given boundary conditions
- \mathbf{v} , p : unknown velocity and pressure fields
- $\Gamma(t) := \partial\Omega(t)$, $\Gamma^w(t)$: boundary and (unknown) free surface

Irrotational and inviscid assumptions

For an irrotational and inviscid flow, there exists a potential field Φ , such that $\mathbf{v} = \nabla\Phi$.

Momentum conservation \implies unsteady Bernoulli equation
Incompressibility \implies Poisson equation

Unsteady Potential Flow Equations

Perturbation Potential Decomposition

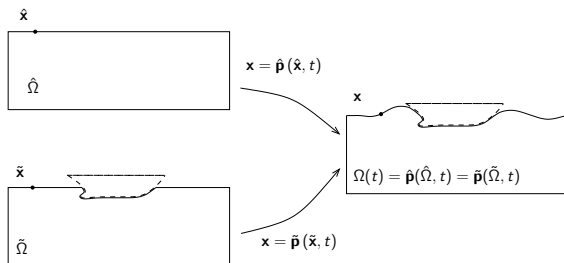
$$\frac{\partial\Phi}{\partial t} + \frac{1}{2} |\nabla\Phi|^2 + \frac{p - p_a}{\rho} + gz = 0 \quad \text{in } \Omega(t)$$

$$\Delta\Phi = 0 \quad \text{in } \Omega(t)$$

$$p = p_a \quad \text{on } \Gamma^w(t)$$

$$\mathbf{v} = \nabla\Phi = \nabla\phi + \mathbf{V}_s - \mathbf{V}_f$$

ALE (semi-Lagrangian) deformation



- $\hat{\mathbf{x}}, \hat{\mathbf{p}}(\hat{\mathbf{x}}, t)$: Material particle and motion
- $\tilde{\mathbf{x}}, \tilde{\mathbf{p}}(\tilde{\mathbf{x}}, t)$: Domain location and motion (ALE)

$\tilde{\mathbf{p}}(\tilde{\mathbf{x}}, t)$ is **arbitrary**, provided that $\tilde{\mathbf{p}}(\tilde{\Omega}, t) \equiv \Omega(t)$

Material and ALE derivatives

Velocities and derivatives

$$\mathbf{v}(\hat{\mathbf{p}}(\hat{\mathbf{x}}, t), t) = \hat{\mathbf{v}}(\hat{\mathbf{x}}, t) := \frac{\partial \hat{\mathbf{p}}(\hat{\mathbf{x}}, t)}{\partial t}$$

$$\mathbf{w}(\tilde{\mathbf{p}}(\tilde{\mathbf{x}}, t), t) = \tilde{\mathbf{w}}(\tilde{\mathbf{x}}, t) := \frac{\partial \tilde{\mathbf{p}}(\tilde{\mathbf{x}}, t)}{\partial t}$$

$$\frac{Dq(\mathbf{x}, t)}{Dt} := \left. \frac{\partial q(\hat{\mathbf{p}}(\hat{\mathbf{x}}, t), t)}{\partial t} \right|_{\hat{\mathbf{x}}=\hat{\mathbf{p}}^{-1}(\mathbf{x}, t)} = \frac{\partial q(\mathbf{x}, t)}{\partial t} + \mathbf{v} \cdot \nabla q(\mathbf{x}, t)$$

$$\frac{\delta q(\mathbf{x}, t)}{\delta t} := \left. \frac{\partial q(\tilde{\mathbf{p}}(\tilde{\mathbf{x}}, t), t)}{\partial t} \right|_{\tilde{\mathbf{x}}=\tilde{\mathbf{p}}^{-1}(\mathbf{x}, t)} = \frac{\partial q(\mathbf{x}, t)}{\partial t} + \mathbf{w} \cdot \nabla q(\mathbf{x}, t)$$

Potential Flow Equations in ALE Form

$$\begin{aligned} \Delta\phi &= 0 && \text{in } \Omega(t) \\ \frac{\delta\phi}{\delta t} + (\mathbf{v} - \mathbf{w}) \cdot \nabla\phi &= -gz + \frac{1}{2}|\nabla\phi|^2 && \text{on } \Gamma^w(t) \\ \phi(\mathbf{x}, 0) &= \phi_0(\mathbf{x}) && \text{on } \Gamma^w(0) \\ \phi_n &= \mathbf{n} \cdot (\mathbf{V}_b - \mathbf{V}_s) && \text{on } \Gamma^h(t) \\ \phi_n &= 0 && \text{on } \Gamma^b(t) \cup \Gamma^{ff}(t) \\ \mathbf{w} \cdot \mathbf{n} &= \mathbf{v} \cdot \mathbf{n} && \text{on } \Gamma^w(t), \end{aligned}$$

$\mathbf{w} \cdot \mathbf{n} = \mathbf{v} \cdot \mathbf{n}$ ensures that the **shape** of $\tilde{\mathbf{p}}(\tilde{\Omega}, t)$ is equal to $\Omega(t)$

Free surface evolution

Assumption: the free surface is the graph of a single valued function: $\mathbf{x} = (x, y, \eta(x, y, t)) = (x, y, \eta(\mathbf{x}, t))$ on $\Gamma^w(t)$

Material and ALE derivatives of η

$$\frac{\partial \hat{\mathbf{p}}}{\partial t}(\hat{\mathbf{x}}, t) \cdot \mathbf{e}_z = \frac{\partial \eta}{\partial t}(\hat{\mathbf{p}}(\hat{\mathbf{x}}, t), t) + \frac{\partial \hat{\mathbf{p}}}{\partial t}(\hat{\mathbf{x}}, t) \cdot \nabla \eta(\hat{\mathbf{p}}(\hat{\mathbf{x}}, t), t)$$

$$\mathbf{v}_z = \frac{\partial \eta}{\partial t} + \mathbf{v} \cdot \nabla \eta = \frac{D\eta}{Dt}$$

$$\mathbf{w}_z = \frac{\partial \eta}{\partial t} + \mathbf{w} \cdot \nabla \eta = \frac{\delta \eta}{\delta t}$$

$$\mathbf{w} \cdot \mathbf{n} = \mathbf{v} \cdot \mathbf{n} \quad \implies \quad \frac{\delta \eta}{\delta t} + (\mathbf{v} - \mathbf{w}) \cdot \nabla \eta = \mathbf{v} \cdot \mathbf{e}_z \quad \text{on } \Gamma^w(t)$$

Fully nonlinear ALE free surface boundary conditions

$$\mathbf{V}_f = (\bar{\mathbf{V}}_b \cdot \mathbf{e}_x) \mathbf{e}_x =: -\mathbf{V}_\infty = (-V_\infty, 0, 0), \quad \mathbf{V}_s = 0$$

Kinematic boundary condition

The shape of the free surface follows the velocity field of the flow

$$\frac{\delta \eta}{\delta t} = \frac{\partial \phi}{\partial z} + \nabla \eta \cdot (\mathbf{w} - \nabla \phi - \mathbf{V}_\infty)$$

Dynamic boundary condition

Equilibrium of the pressure on the water surface

$$\frac{\delta \phi}{\delta t} = -g\eta + \frac{1}{2} |\nabla \phi|^2 + \nabla \phi \cdot (\mathbf{w} - \nabla \phi - \mathbf{V}_\infty)$$

Beck *et al.* (1994) (*semi-Lagrangian* formulation)

Arbitrary Lagrangian Eulerian formulation

At each time, three coupled problems are solved:

- **Eulerian**: a mixed b.c. Poisson problem

$$\left\{ \begin{array}{ll} -\Delta\phi = 0 & \text{in } \Omega(t) \\ \phi = \bar{\phi} & \text{on } \Gamma^w(t) \\ \frac{\partial\phi}{\partial\mathbf{n}} = \mathbf{v}_g \cdot \mathbf{n} & \text{on } \Gamma^{ff}(t) \cup \Gamma^b(t) \cup \Gamma^h(t) \end{array} \right.$$

- **ALE**: time evolution of the free surface b.c.

$$\frac{\delta\eta}{\delta t} = \frac{\partial\phi}{\partial z} + \nabla\eta \cdot (\mathbf{w} - \mathbf{V}_\infty - \nabla\phi) \quad \text{on } \Gamma^w(t)$$

$$\frac{\delta\phi}{\delta t} = -g\eta + \frac{1}{2}|\nabla\phi|^2 + \nabla\phi \cdot (\mathbf{w} - \mathbf{V}_\infty - \nabla\phi) \quad \text{on } \Gamma^w(t)$$

- **ALE**: reconstruction of the full ALE deformation on $\Gamma(t)$

Boundary Integral Formulation

Exploit second Green identity

Given two solutions of the Poisson problem and a control volume S , multiply the first equation by the second solution and integrate by parts twice:

Second Green Identity

- $-\Delta u = 0$
- $-\Delta v = f$
- $-\int_S \Delta uv = 0$
- $\int_S \nabla u \nabla v - \int_{\partial S} u \frac{\partial v}{\partial n} = 0$
- $-\int_S u \Delta v + \int_{\partial S} u \frac{\partial v}{\partial n} - \int_{\partial S} \frac{\partial u}{\partial n} v = 0$
- $\int_S uf + \int_{\partial S} u \frac{\partial v}{\partial n} - \int_{\partial S} \frac{\partial u}{\partial n} v = 0$

Choose smart solutions...

- Choose f to be a **Dirac delta** centered in \mathbf{y}

$$\int_S u(\mathbf{x})\delta(\mathbf{x} - \mathbf{y})dV_{\mathbf{x}} = u(\mathbf{y}) \quad \forall \mathbf{y} \in S$$

Boundary Integral Representation:

$$u(\mathbf{y}) + \int_{\partial S} u(\mathbf{x})\frac{\partial v_{\mathbf{y}}}{\partial n}(\mathbf{x})dS_{\mathbf{x}} - \int_{\partial S} v_{\mathbf{y}}(\mathbf{x})\frac{\partial u}{\partial n}(\mathbf{x})dS_{\mathbf{x}} = 0$$

Boundary Integral Equation

Taking $S \equiv \Omega$, and $\mathbf{y} \rightarrow \Gamma$

The Poisson problem is expressed in boundary integral form

$$\alpha(\mathbf{y})\phi(\mathbf{y}) = \int_{\Gamma(t)} \left[\frac{\partial \phi}{\partial n}(\mathbf{x})G(\mathbf{y} - \mathbf{x}) - \frac{\partial G}{\partial n}(\mathbf{y} - \mathbf{x})\phi(\mathbf{x}) \right] d\Gamma_{\mathbf{x}}$$

Free space Green function G

$$G(\mathbf{x} - \mathbf{y}) = \frac{1}{4\pi |\mathbf{x} - \mathbf{y}|}$$

It satisfies the Poisson problem

$$-\Delta G(\mathbf{x} - \mathbf{y}) = \delta(\mathbf{y}) \quad \mathbf{x} \in \mathbf{R}^3$$

ALE motion on the wireframe $\gamma(t)$

- The normal component of the ALE velocity $\mathbf{w} \cdot \mathbf{n}$ is given by the **kinematic** boundary condition
- On the edges of $\Gamma(t)$ (i.e., on $\bar{\Gamma}^w(t) \cap \bar{\Gamma}^h(t) =: \gamma^{w,h}(t)$) two such conditions need to be satisfied *simultaneously*
- On those edges, the third component can be imposed *arbitrarily* (we can set it to zero, or to a *smoothing velocity*)

Evolution equation for $\gamma(t)$, summarizing above conditions with \mathbf{w}_g

$$\begin{aligned} \frac{\partial \tilde{\mathbf{p}}_\gamma}{\partial t}(\tilde{\mathbf{x}}, t) &= \mathbf{w}_g(\tilde{\mathbf{p}}_\gamma(\tilde{\mathbf{x}}, t)) && \text{on } \tilde{\gamma} \\ \tilde{\mathbf{p}}_\gamma(\tilde{\mathbf{x}}, 0) &= \tilde{\mathbf{p}}_0(\tilde{\mathbf{x}}) && \text{on } \tilde{\gamma} \end{aligned}$$

ALE extension on the entire $\Gamma(t)$

Laplace Beltrami on $\tilde{\Gamma}$ ($\tilde{\nabla}_s := (I - \mathbf{n} \otimes \mathbf{n})\tilde{\nabla}$, $\Delta_s := \tilde{\nabla}_s \cdot \tilde{\nabla}_s$)

$$-\tilde{\Delta}_s \tilde{\mathbf{g}} = -2\tilde{\mathbf{n}}\tilde{k} := -\tilde{\Delta}_s \tilde{\mathbf{p}}_0 \quad \text{on } \tilde{\Gamma} \setminus \tilde{\gamma}$$

$$\tilde{\mathbf{g}} = \tilde{\mathbf{p}}_\gamma \quad \text{on } \tilde{\gamma}$$

$$\frac{\partial \tilde{\mathbf{p}}_\gamma}{\partial t}(\tilde{\mathbf{x}}, t) = \mathbf{w}_g(\tilde{\mathbf{p}}_\gamma(\tilde{\mathbf{x}}, t)) \quad \text{on } \tilde{\gamma}$$

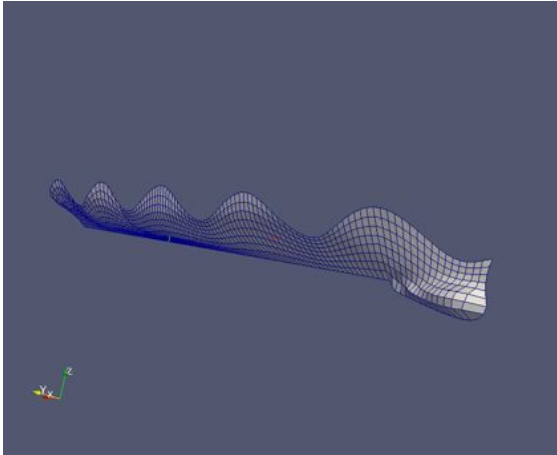
$$\tilde{\mathbf{p}}_\gamma(\tilde{\mathbf{x}}, 0) = \tilde{\mathbf{p}}_0(\tilde{\mathbf{x}}) \quad \text{on } \tilde{\gamma}$$

$$\tilde{\mathbf{p}} = \mathcal{P}_h \tilde{\mathbf{g}} \quad \text{on } \tilde{\Gamma}^h$$

$$\tilde{\mathbf{p}} = \mathcal{P}_\eta \tilde{\mathbf{g}} := \tilde{\mathbf{g}} + (\eta(\tilde{\mathbf{g}}) - \tilde{\mathbf{g}} \cdot \mathbf{e}_z)\mathbf{e}_z \quad \text{on } \tilde{\Gamma}^w$$

$$\tilde{\mathbf{p}} = \tilde{\mathbf{g}} \quad \text{on } \tilde{\Gamma}^b \cup \tilde{\Gamma}^{ff},$$

Reconstruction example on DTMB 5415



Fully nonlinear integro-differential system

Given initial conditions ϕ_0 and η_0 , for each time $t \in [0, T]$, find η , ϕ , ϕ_n that satisfy

$$\int_{\Gamma(t)} \frac{\partial G}{\partial n} \phi \, d\Gamma - \phi \int_{\Gamma(t)} \frac{\partial G}{\partial n} \, d\Gamma = \int_{\Gamma(t)} \phi_n G \, d\Gamma \quad \text{on } \Gamma(t)$$

$$\frac{\delta \eta}{\delta t} = \frac{\partial \phi}{\partial z} + \nabla \eta \cdot (\mathbf{w} - \mathbf{V}_\infty - \nabla \phi) =: V_\eta \quad \text{on } \Gamma^w(t)$$

$$\frac{\delta \phi}{\delta t} = -g\eta + \frac{1}{2} |\nabla \phi|^2 + \nabla \phi \cdot (\mathbf{w} - \mathbf{V}_\infty - \nabla \phi) =: V_\phi \quad \text{on } \Gamma^w(t)$$

+B.C. on the rest of $\Gamma(t)$

+Laplace Beltrami for domain deformation.

Discretization spaces

Grid assumptions

We construct decomposition $\tilde{\Gamma}_h$ for $\tilde{\Gamma}$ made of quadrilaterals in three dimensional space, such that:

- 1 $\tilde{\Gamma} = \cup\{K \in \tilde{\Gamma}_h\}$;
- 2 Any two cells K, K' only intersect in common faces, edges, or vertices;

Finite dimensional space construction (order p)

$$V_h := \left\{ u_h \in V \mid u_h|_K \in \mathcal{Q}^p(K), K \in \tilde{\Gamma}_h \right\} \equiv \text{span}\{\varphi_h^i\}_{i=1}^{N_V}$$

$$\mathbf{V}_h := V_h^3 \equiv \text{span}\{\varphi_h^i \mathbf{e}_x, \varphi_h^i \mathbf{e}_y, \varphi_h^i \mathbf{e}_z\}_{i=1}^{N_V}$$

Iso-parametric finite dimensional representations

We indicate with the notation $\{\phi\}$ and $\{\phi_n\}$ the column vectors of time dependent coefficients $\phi^i(t)$ and $\phi_n^j(t)$ such that

$$\phi_h(\mathbf{x}, t) := \sum_{i=1}^{N_V} \phi^i(t) \varphi_h^i(\tilde{\mathbf{p}}_h^{-1}(\mathbf{x}, t)) \quad \text{on } \Gamma_h(t)$$
$$\phi_{nh}(\mathbf{x}, t) := \sum_{i=1}^{N_V} \phi_n^i(t) \varphi_h^i(\tilde{\mathbf{p}}_h^{-1}(\mathbf{x}, t)) \quad \text{on } \Gamma_h(t)$$

where the map $\tilde{\mathbf{p}}_h^{-1}(\mathbf{x}, t)$ is the inverse of the ALE deformation

$$\tilde{\mathbf{p}}_h(\tilde{\mathbf{x}}, t) := \sum_{i=0}^{N_V} \mathbf{x}^i(t) \varphi_h^i(\tilde{\mathbf{x}}) \quad \text{on } \tilde{\Gamma}$$

and \mathbf{x}^k represents the current location of the vertices or control points that define the current configuration of $\Gamma(t)$.

Iso-parametric BEM

Collocation BEM

$$\begin{aligned} \alpha(\mathbf{y}, t)\phi(\mathbf{y}, t) = & \\ & - \sum_{k=1}^M \sum_{i=1}^{N_V} \phi^i(t) \int_{\hat{K}} \frac{\partial G}{\partial n}(\mathbf{y} - \mathbf{x}^k(u, v, t)) \varphi_k^i(u, v) J^k(u, v, t) du dv \\ & + \sum_{k=1}^M \sum_{i=1}^{N_V} \left(\frac{\partial \phi}{\partial n}(t) \right)^i \int_{\hat{K}} G(\mathbf{y} - \mathbf{x}^k(u, v, t)) \varphi_k^i(u, v) J^k(u, v, t) du dv. \end{aligned}$$

Take $\mathbf{y} = \mathbf{x}^i(t)$, rewrite as a linear system:

$$[\alpha] \{\phi\} + [N] \{\phi\} = [D] \{\phi_n\}$$

Gradient recovery

The full gradient of ϕ appears in both V_ϕ and V_η :

Local gradient reconstruction

$$(\nabla\phi)(\mathbf{x}_k(u, v, t), t) := \nabla_s \phi_k(u, v, t) + \phi_{nk}(u, v, t)\mathbf{n}$$

Discontinuous across element edges!

We use the weak form of the evolution equation to make an L^2 projection of V_ϕ and V_η in V_h :

$$\begin{aligned} \left(\frac{\delta\phi_h}{\delta t}, \varphi_h^i\right) &= (V_\phi, \varphi_h^i) & \left(\frac{\delta\eta_h}{\delta t}, \varphi_h^i\right) &= (V_\eta, \varphi_h^i) \\ [M]\{\phi\}' &= \{V_\phi\} & [M]\{\eta\}' &= \{V_\eta\} \end{aligned}$$

Gradient recovery

The full gradient of ϕ appears in both V_ϕ and V_η :

Local gradient reconstruction

$$(\nabla\phi)(\mathbf{x}_k(u, v, t), t) := \nabla_s \phi_k(u, v, t) + \phi_{nk}(u, v, t)\mathbf{n}$$

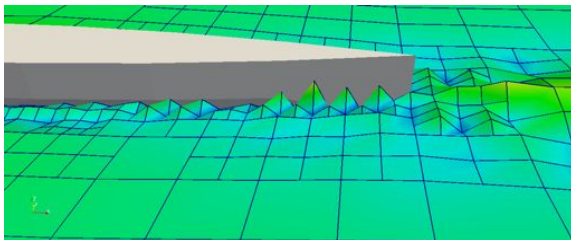
Discontinuous across element edges!

We use the weak form of the evolution equation to make an L^2 projection of V_ϕ and V_η in V_h : **It doesn't work for non negligible stream velocity!**

$$\begin{aligned} \left(\frac{\delta\phi_h}{\delta t}, \varphi_h^i\right) &= (V_\phi, \varphi_h^i) & \left(\frac{\delta\eta_h}{\delta t}, \varphi_h^i\right) &= (V_\eta, \varphi_h^i) \\ [M]\{\phi\}' &= \{V_\phi\} & [M]\{\eta\}' &= \{V_\eta\} \end{aligned}$$

Sawtooth Instability

Whenever the semi-Lagrangian free surface boundary conditions are used with an appreciable average body velocity \mathbf{V}_∞ , a sawtooth instability develops in proximity of the hull stern causing blow up of the simulations



$$\frac{\delta\eta}{\delta t} = \frac{\partial\phi}{\partial z} + \nabla\eta \cdot (\mathbf{w} - \mathbf{V}_\infty - \nabla\phi) \quad \leftarrow$$

When \mathbf{V}_∞ is high, the transport term in the equations becomes dominant!

Our solution: SUPG stabilization

Substitute the weak form of the evolution equations with

Streamwise Upwind Petrov Galerkin projection

$$\left(\frac{\delta \phi}{\delta t}, \varphi + \mathbf{d} \cdot \nabla_s \varphi \right) = (V_\phi, \varphi + \mathbf{d} \cdot \nabla_s \varphi) \quad \forall \varphi \in V$$

$$\left(\frac{\delta \eta}{\delta t}, \varphi + \mathbf{d} \cdot \nabla_s \varphi \right) = (V_\eta, \varphi + \mathbf{d} \cdot \nabla_s \varphi) \quad \forall \varphi \in V$$

$$\mathbf{d} := \tau \left(\frac{\mathbf{v} - \mathbf{w}}{|\mathbf{v} - \mathbf{w}|} \right)$$

where τ is a function of the local cell diameter

Fully discrete system

Essential discrete system (minus I.C. and some B.C.)

$$[\alpha] \{\phi\} + [N] \{\phi\} - [D] \{\phi_n\} = 0$$

$$[M_{SUPG}] \{\phi\}' - \{V_{\phi, SUPG}\} = 0$$

$$[M_{SUPG}] \{\eta\}' - \{V_{\eta, SUPG}\} = 0$$

All expressed in the **reference** (fixed) domain $\tilde{\Omega}$

Time advancing scheme

The fully discrete version of the integro-differential problem can be recast in the form

$$F(t, y, y') = 0$$

- ⇒ system of nonlinear differential algebraic equations (**DAE**)
- ⇒ **IDA** package of the **SUNDIALS** OpenSource library
- ⇒ implicit backward difference formulas (**BDF**) of variable order and variable step size:

$$\sum_{i=0}^q \alpha_{n,i} y_{n-i} = h_n y'_n,$$

- ⇒ Nonlinear algebraic system to be solved at each step:

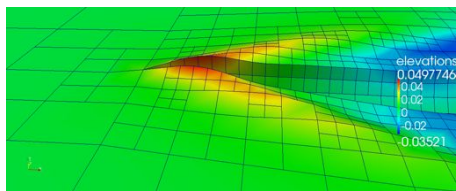
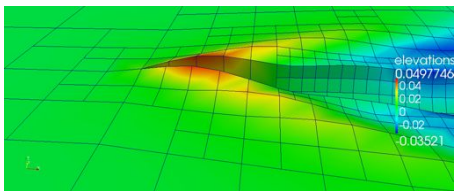
$$R(y_n) \equiv F\left(t_n, y_n, h_n^{-1} \sum_{i=0}^q \alpha_{n,i} y_{n-i}\right) = 0$$

- ⇒ Newton Krilov subspace method (preconditioned **GMRES**)

A posteriori error estimates

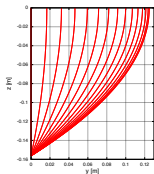
Kelly error estimator (Kelly *et al.* 1983)

- For each K compute $\tau_K^2 := \frac{h}{24} \int_{\partial K} [\nabla_s \phi \cdot \mathbf{n}_{\partial K}]^2 d\gamma$
- number the cells according to decreasing values of τ_K ,
- refine and coarsen fixed fractions of the total cells accordingly.



Test case: the Wigley hull

The Wigley hull is a boat hull shape often used as benchmark in naval engineering



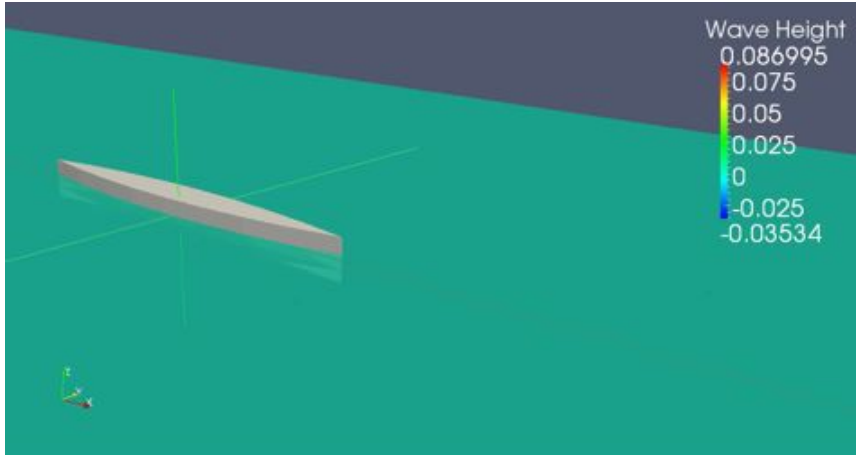
$$y(x, z) = \frac{B}{2} \left[1 - \left(\frac{2x}{L} \right)^2 \right] \left[1 - \left(\frac{z}{T} \right)^2 \right]$$

$$L = 2.5 \text{ m}, \quad B = 0.25 \text{ m}, \quad T = 0.15625 \text{ m}$$

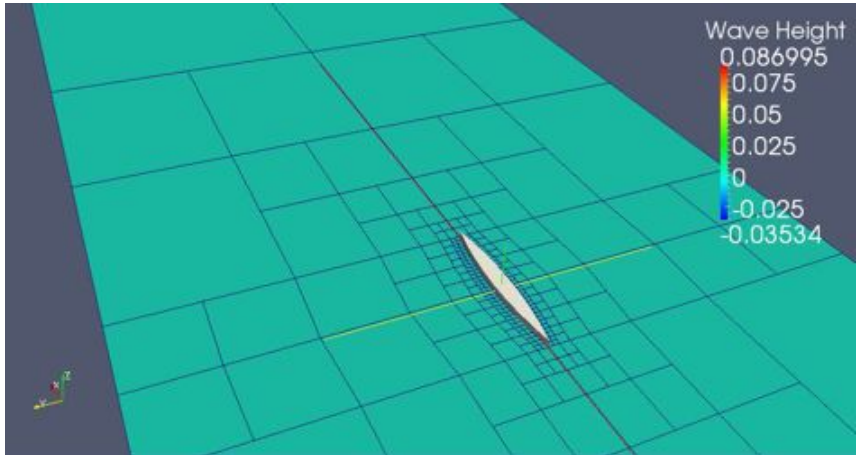
Fixed trim and sinkage simulations are performed at the velocities

V_∞	1.2381	1.3223	1.4312	1.5649	1.7531	2.0205
$Fr = \frac{V_\infty}{\sqrt{gL}}$	0.250	0.267	0.289	0.316	0.354	0.408

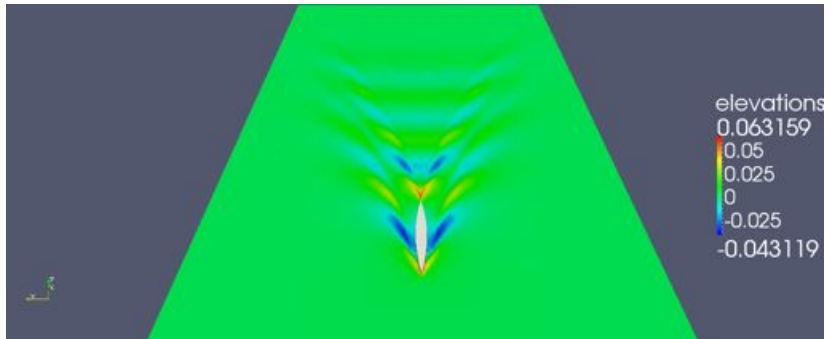
Wigley Hull $Fr=0.408$: transient



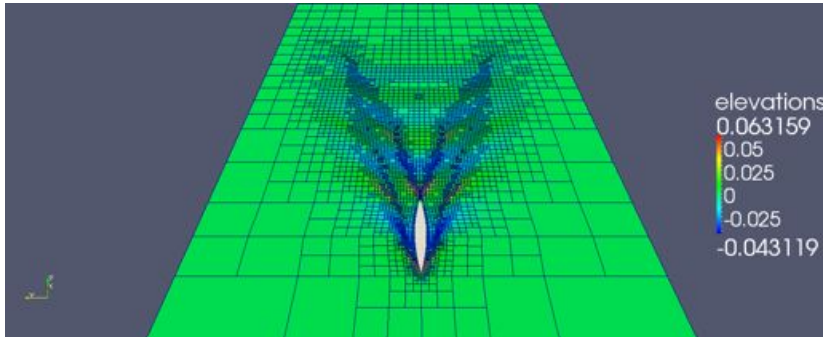
Wigley Hull $Fr=0.408$: mesh adaptation



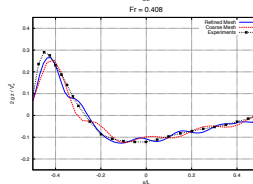
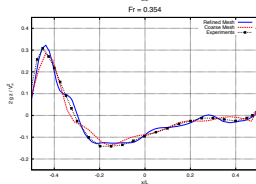
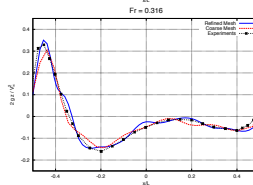
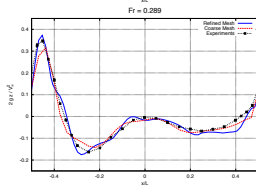
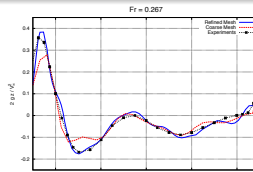
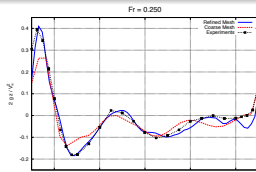
Wigley Hull $Fr=0.408$: Wave Pattern



Wigley Hull $Fr=0.408$: Final Mesh (~ 5000 nodes)

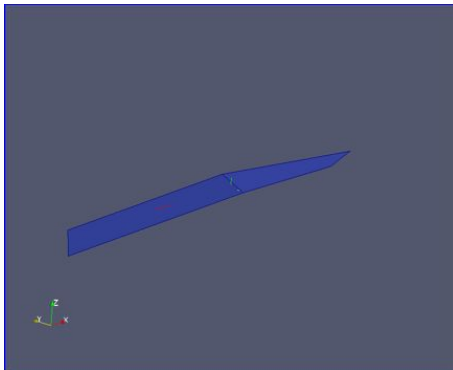


Wigley Hull: Water Elevations on the Hull Surface



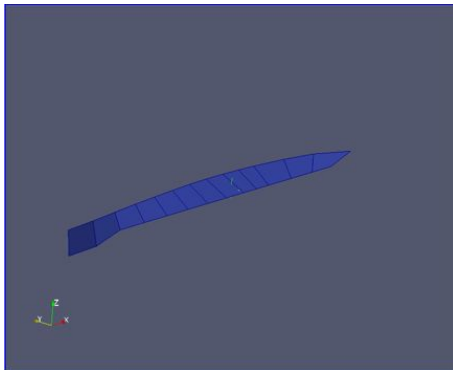
CAD Interface for Arbitrary Geometries

- **OpenCASCADE** library for NURBS manipulation
- Automatic mesh generation via direct CAD interrogation



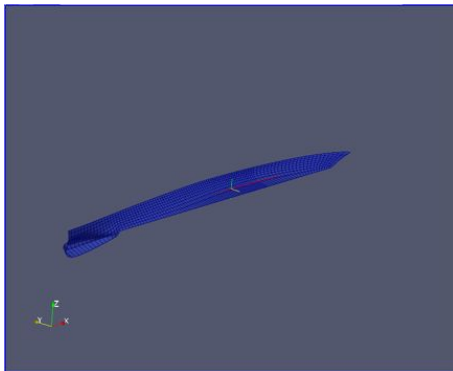
CAD Interface for Arbitrary Geometries

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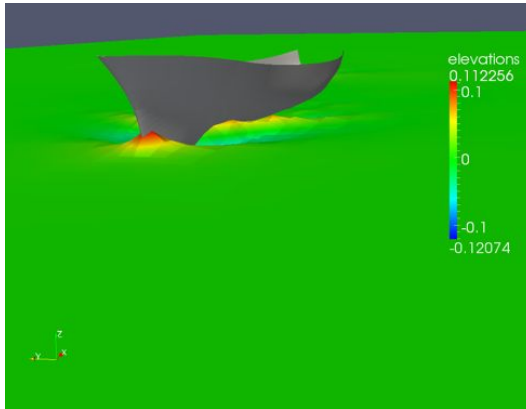
CAD Interface for Arbitrary Geometries

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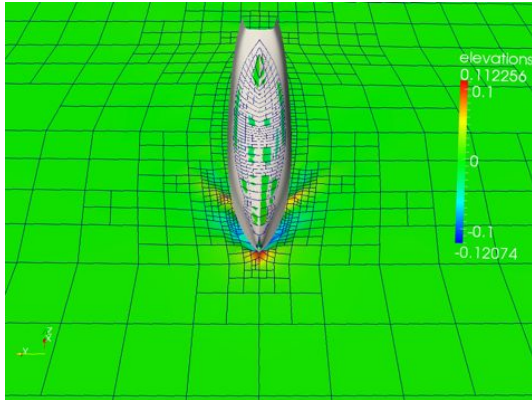
Goteborg DTBM 5415 ($Fr=0.2$)

First attempts



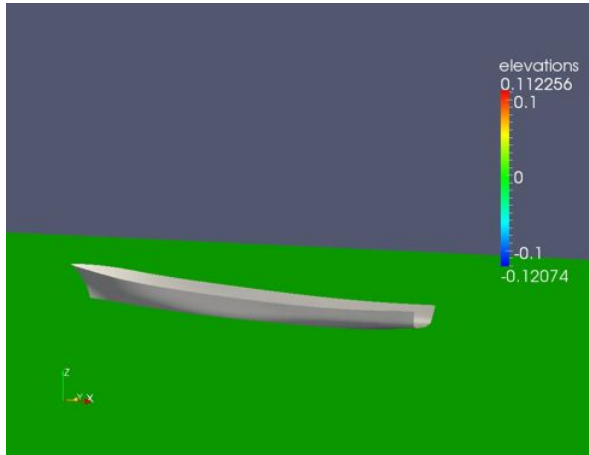
Goteborg DTBM 5415 ($Fr=0.2$) (2)

First attempts



Goteborg DTBM 5415 (Fr=0.2) (3)

First attempts



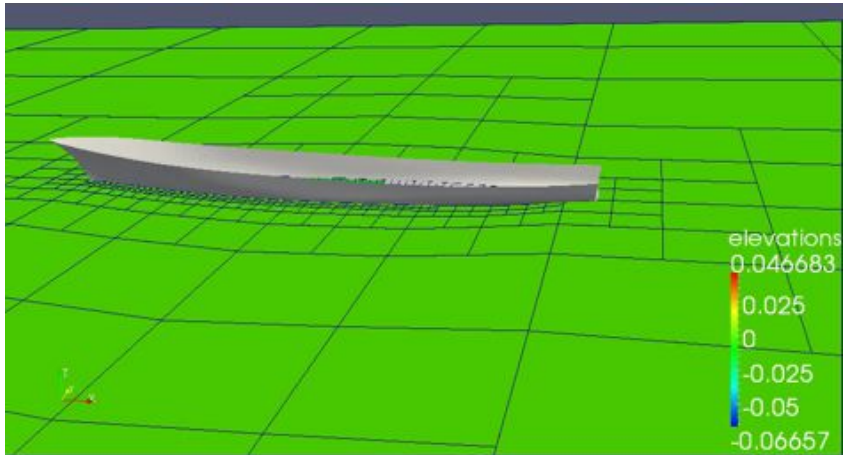
Goteborg DTBM 5415 ($Fr=0.2$)

Final results



Goteborg DTBM 5415 (Fr=0.2) (2)

Final results



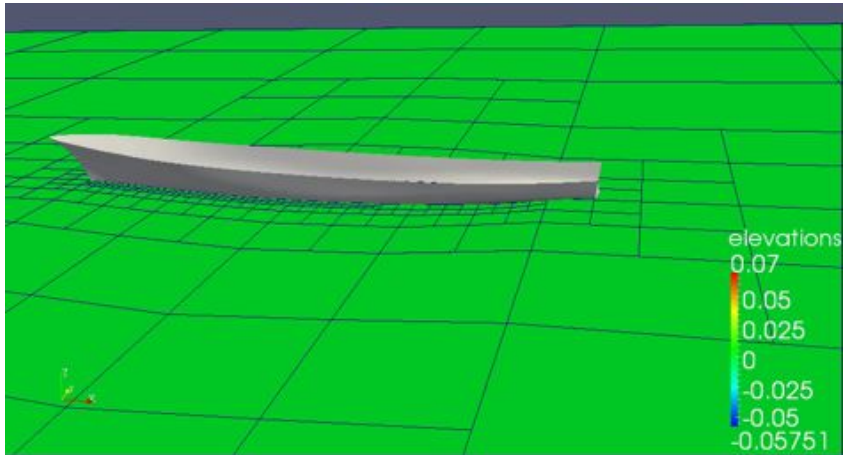
Goteborg DTBM 5415 ($Fr=0.28$)

Side View



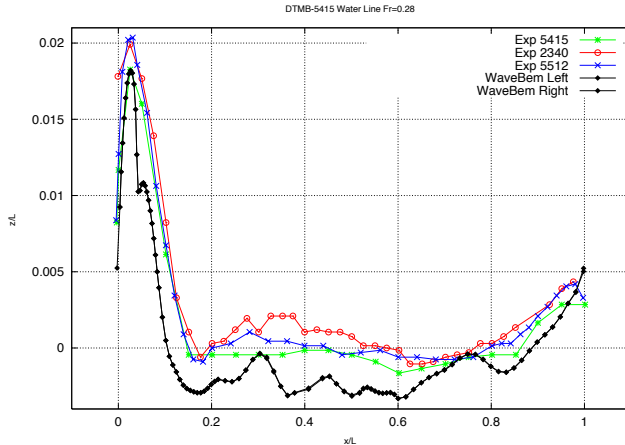
Goteborg DTBM 5415 ($Fr=0.28$) (2)

Side View of Mesh Refinement



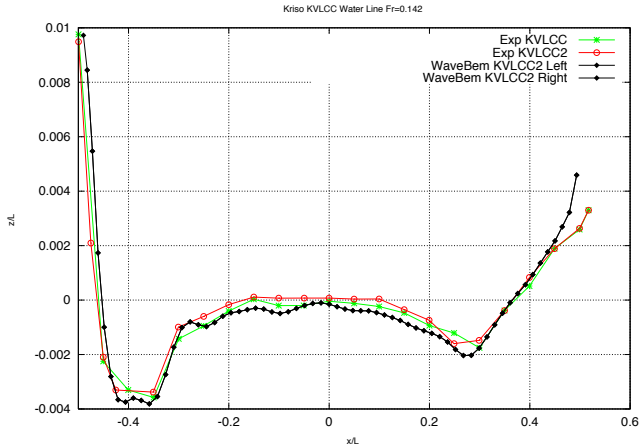
Goteborg DTBM 5415 (Fr=0.28) Waterline

Experimental Comparison (wrong weight!!!)



KRISO Tanker KVLCC2M ($Fr=0.142$) Waterline

Experimental Comparison



Conclusions

- Nonlinear, unsteady potential codes can effectively capture several features of the physical behavior of wave-ship interaction, making them a valid tool for **cheap** wave resistance estimation in early stage of ship design
- *“A stable and adaptive discretization of a semi-Lagrangian potential model for the simulation of unsteady and nonlinear ship-wave interactions”*, A. DeSimone, L. Heltai, A. Mola
Engineering Analysis with Boundary Elements, 37(1):128 - 143, 2013.

Openings for deal.II aware people!



- **New Joint SISSA-ICTP Master in HPC:** we are looking for two postdocs (1 senior, 1 junior)
- **ERC Grant in mathLab group (Prof. Antonio DeSimone):** we are looking for both PhD Students and Postdocs