CFSI, Ibiza, 5 May 2006

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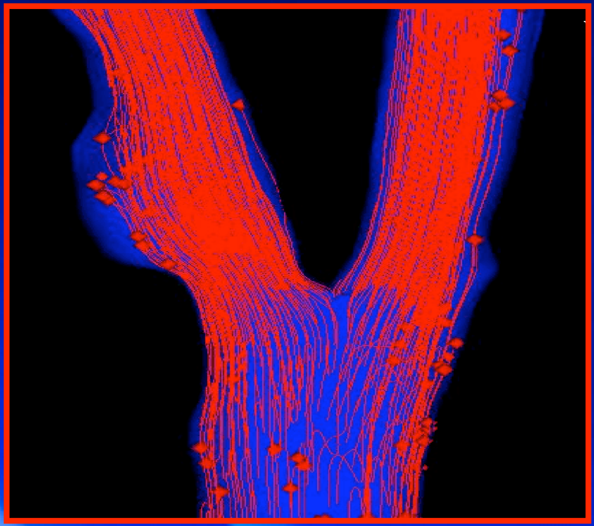
EPFL, Lausanne

and MOX, Politecnico di Milano

FLUID-STRUCTURE INTERACTION

TWO APPLICATIONS and SOME REMARKS



Acknowledgments:

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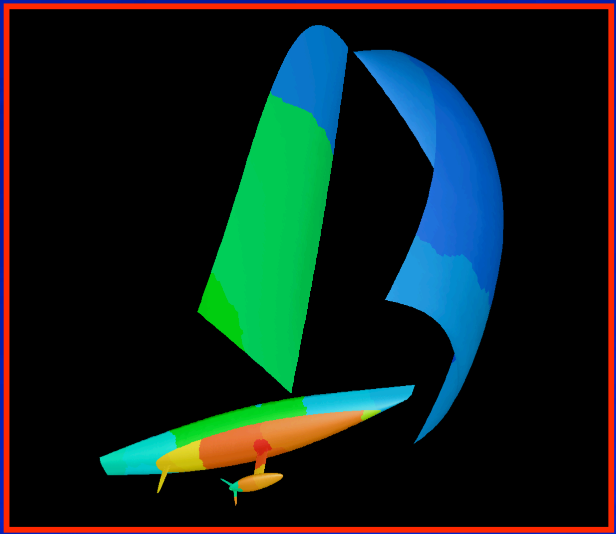
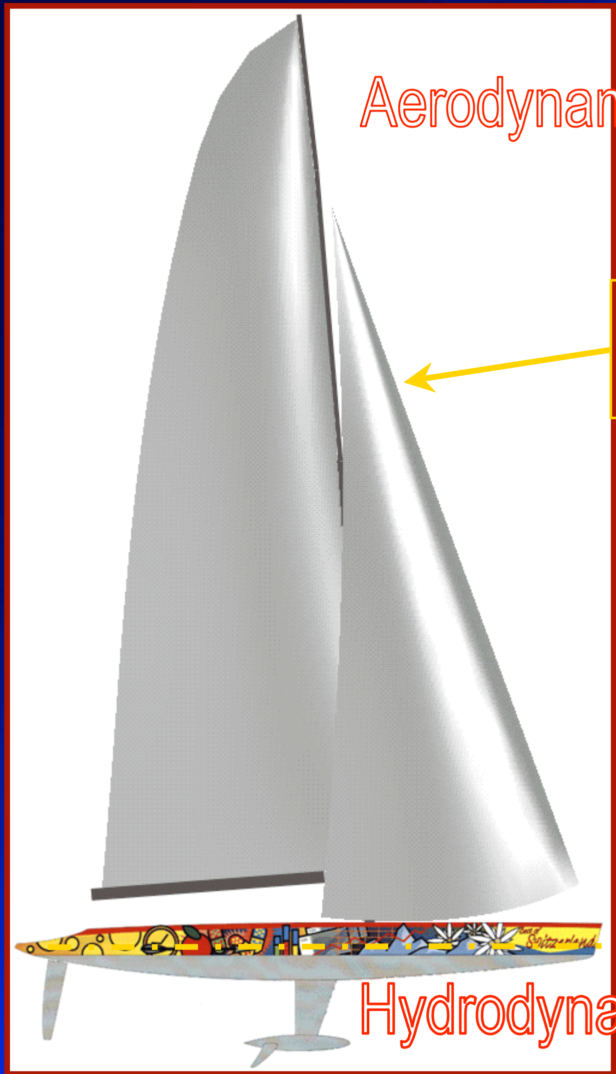
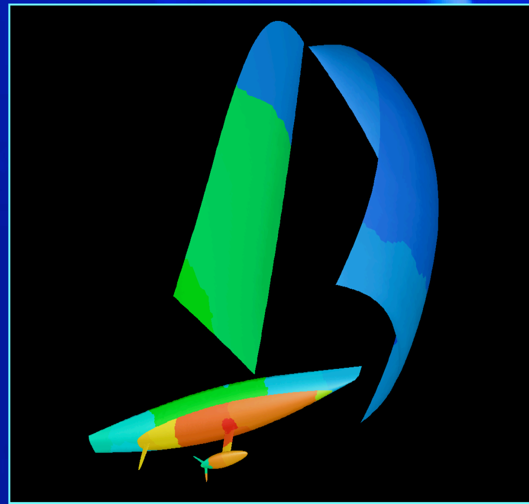
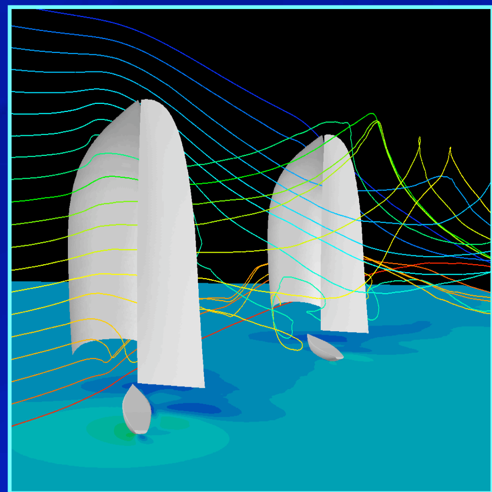


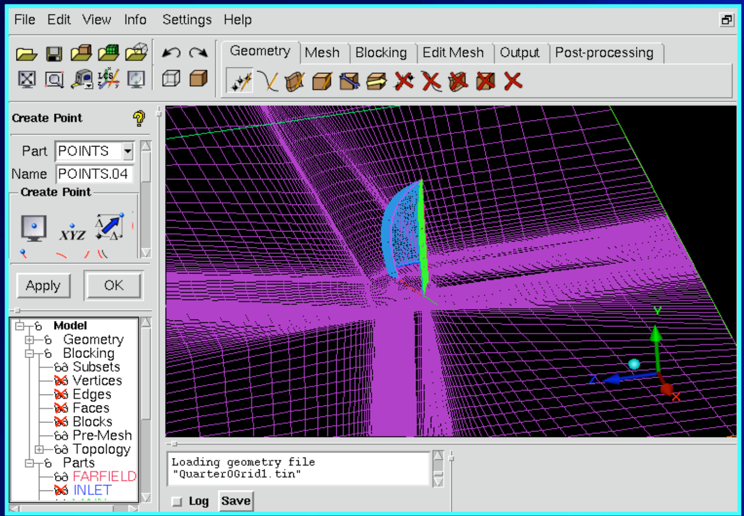
Application 1: Aero-Hydro Dynamics and FSI



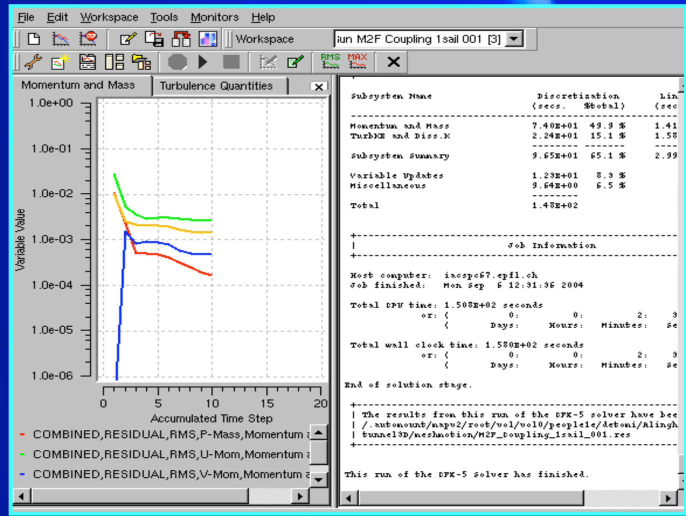




FSI for Sails: Steady state analysis

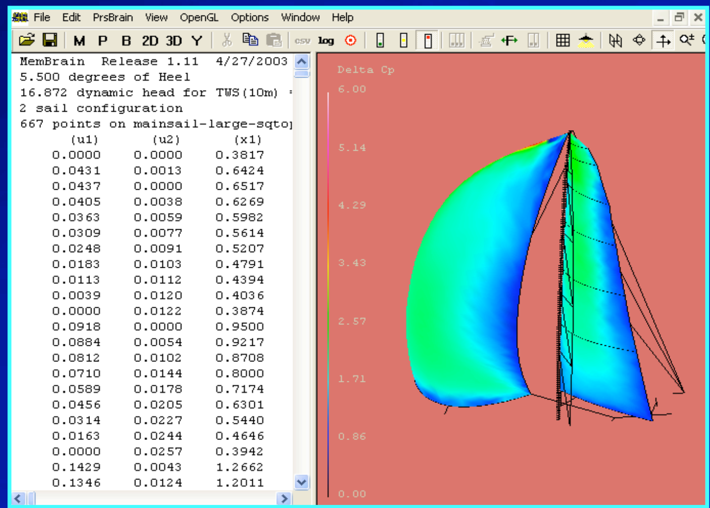


Fluid solver
(Needs mesh -
Velocity is null)



Mesher

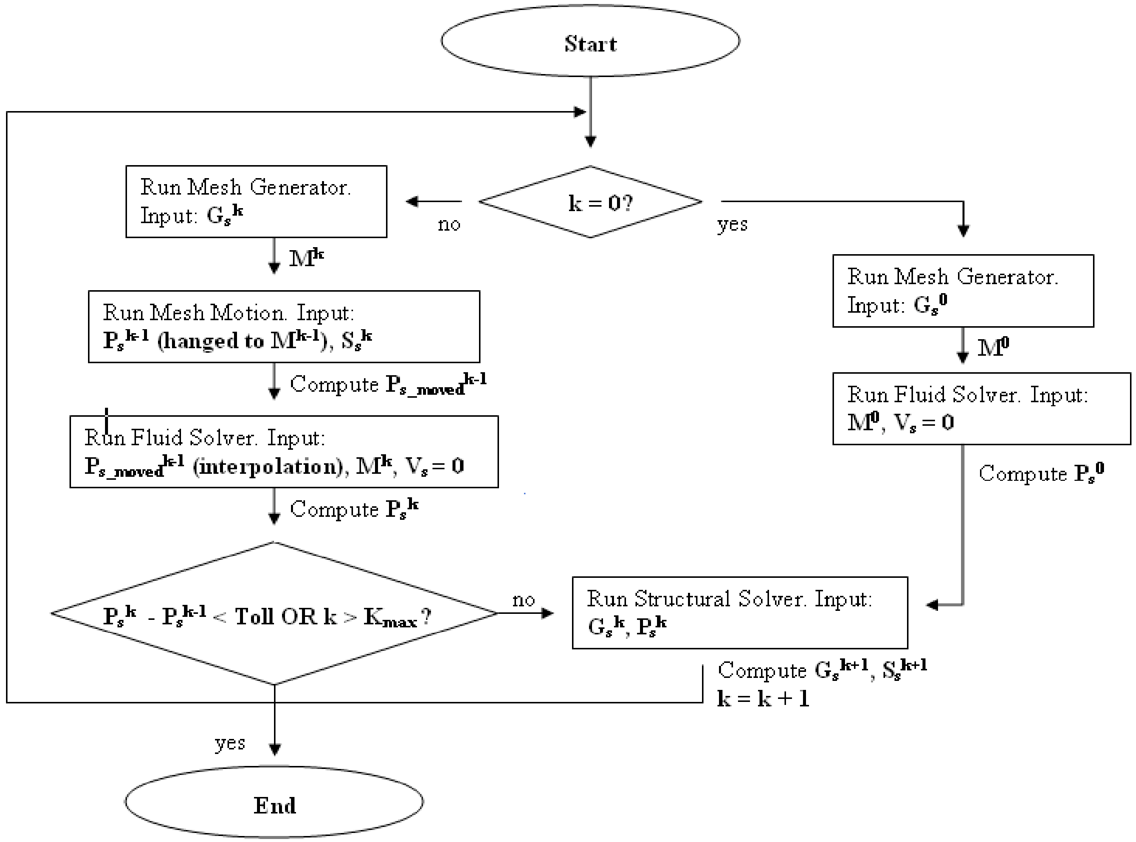
Windows XP → Linux



Structural Solver
(Needs forces)

Linux → Windows XP

Fluid-Structure Coupling Scheme



Legend (pedex "s" refers to sail surface):

G_s^k = Sail geometries at k-th iteration
P_s^k = Pressure on sails at k-th iteration
M^k = Mesh at k-th iteration
S_s^k = Sail displacements at k-th iteration
$P_{s\_moved}^k$ = Pressure on sails after mesh motion at k-th iteration
V_s = Sail velocity (always zero in steady mode)
Toll / K_{max} = Tolerance on pressures/Max # of iterations

Equations for sails and sail-fluid coupling

Elastodynamics equations (small strains, large displacements)

$\psi(x,t)$: deformation map

$$\rho_s \frac{\partial^2 \psi}{\partial t^2} - \mathrm{div}\left(\nabla\psi\, \Sigma\right) = f_s \qquad \text{on } S(0), t > 0$$

$\Sigma = \lambda_s \,\mathrm{Tr}\, E\, I + 2\mu_s E$: Second Piola-Kirchhoff stress tensor

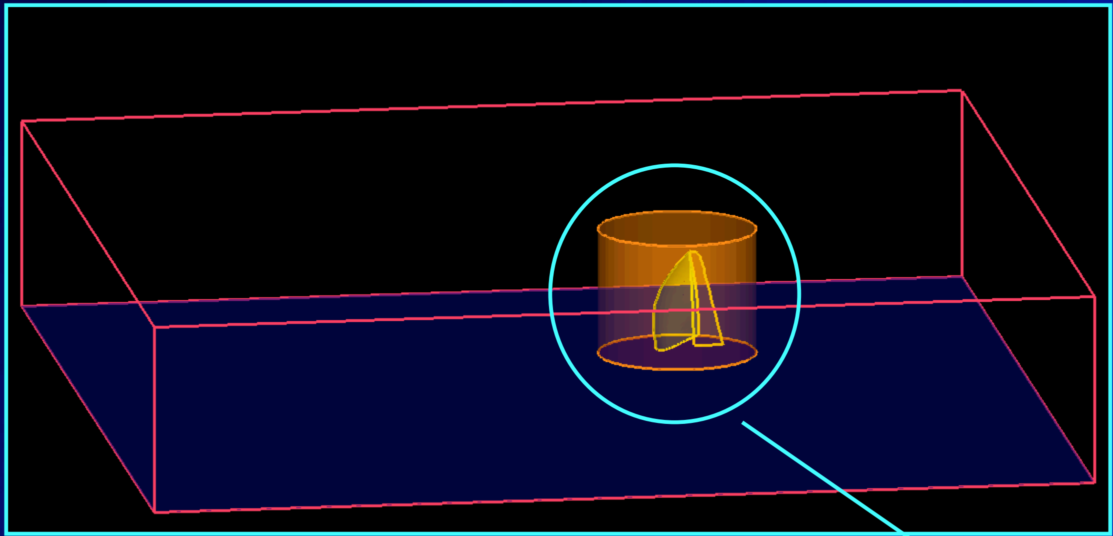
$E = \frac{1}{2}\left(\nabla\psi^T \nabla\psi - I\right)$: Green-S^t Venant strain tensor

Coupling conditions (normal stresses and particle velocities must agree)

$$\begin{cases} \nabla\psi\, \Sigma\, n(0) = T(u,p)\circ\psi \,\mathrm{Cof}\, \left(\nabla\psi\right) n(0) \\ \dfrac{\partial \eta}{\partial t} = u \circ \psi \end{cases} \qquad \text{on } \Gamma(0)$$

$\eta(x,t) = \psi(x,t) - x$: displacement vector field

Domain description

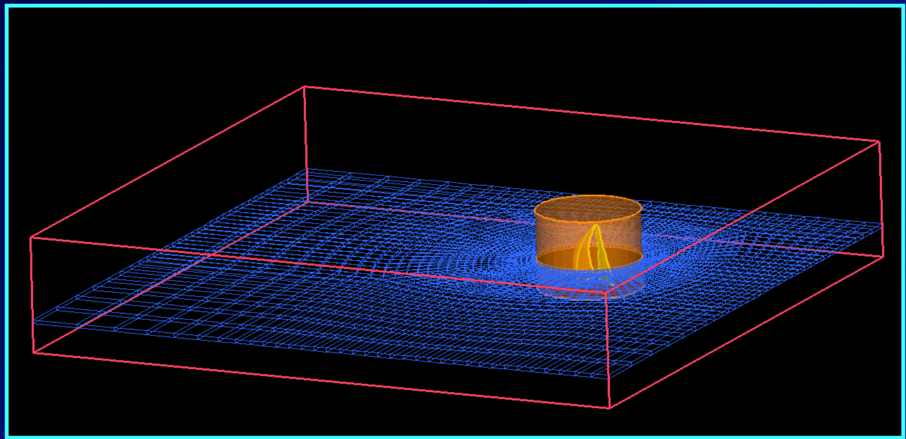


The fluid domain is split in two subdomains, an inner cylinder containing the two sails and a far field region

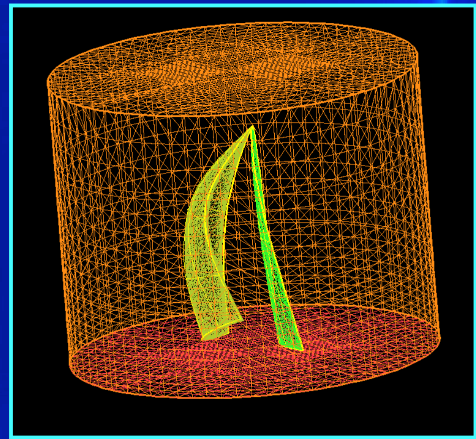
A boundary layer mesh is created by refining the hexahedral grid within cylinder and sea

Meshes

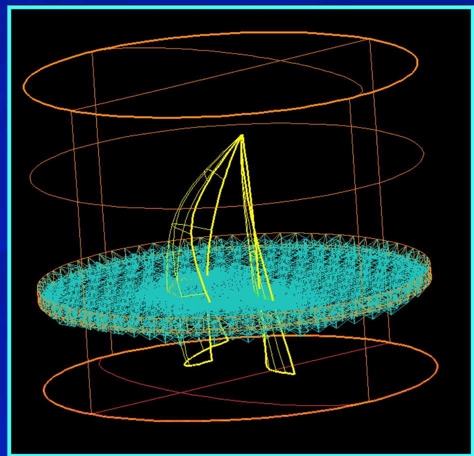
Hexahedra inside the far field



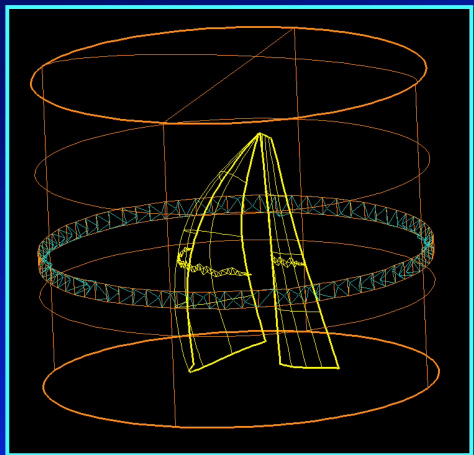
Quad → Tri on cylinder surface



Tetrahedra inside the inner cylinder



Pyramids to connect the two meshes



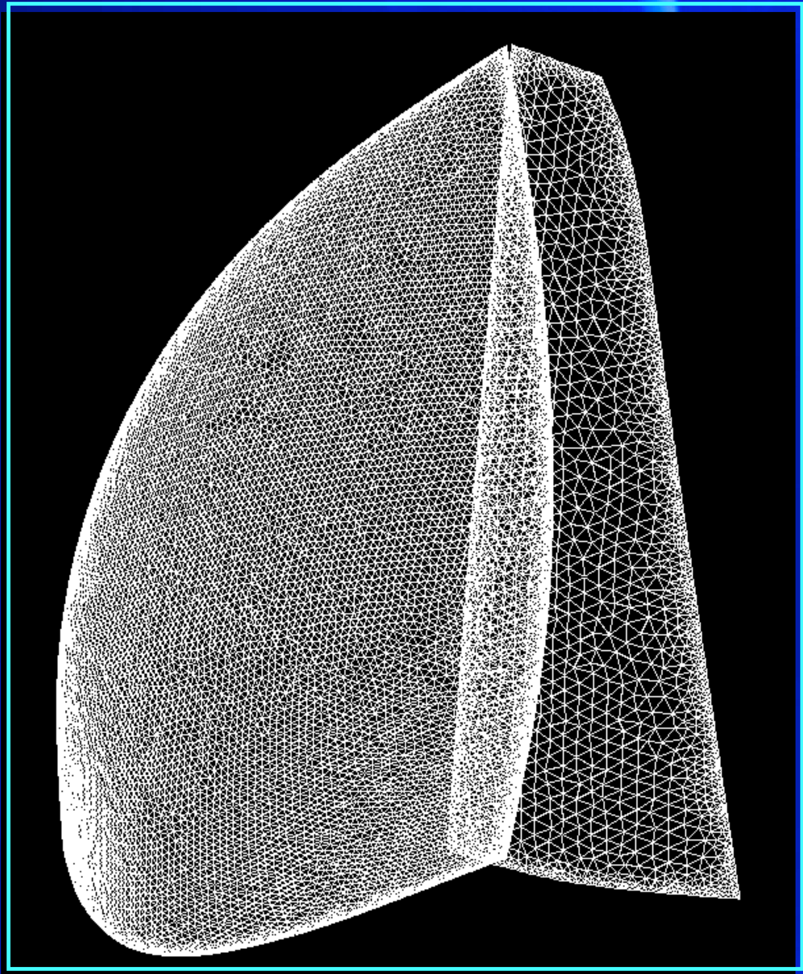
Example of Spinnaker-Mainsail FSI

- 14 FSI iterations

- Mesh (average values):
  ~1.360.000 Tetrahedra
  (around sails)

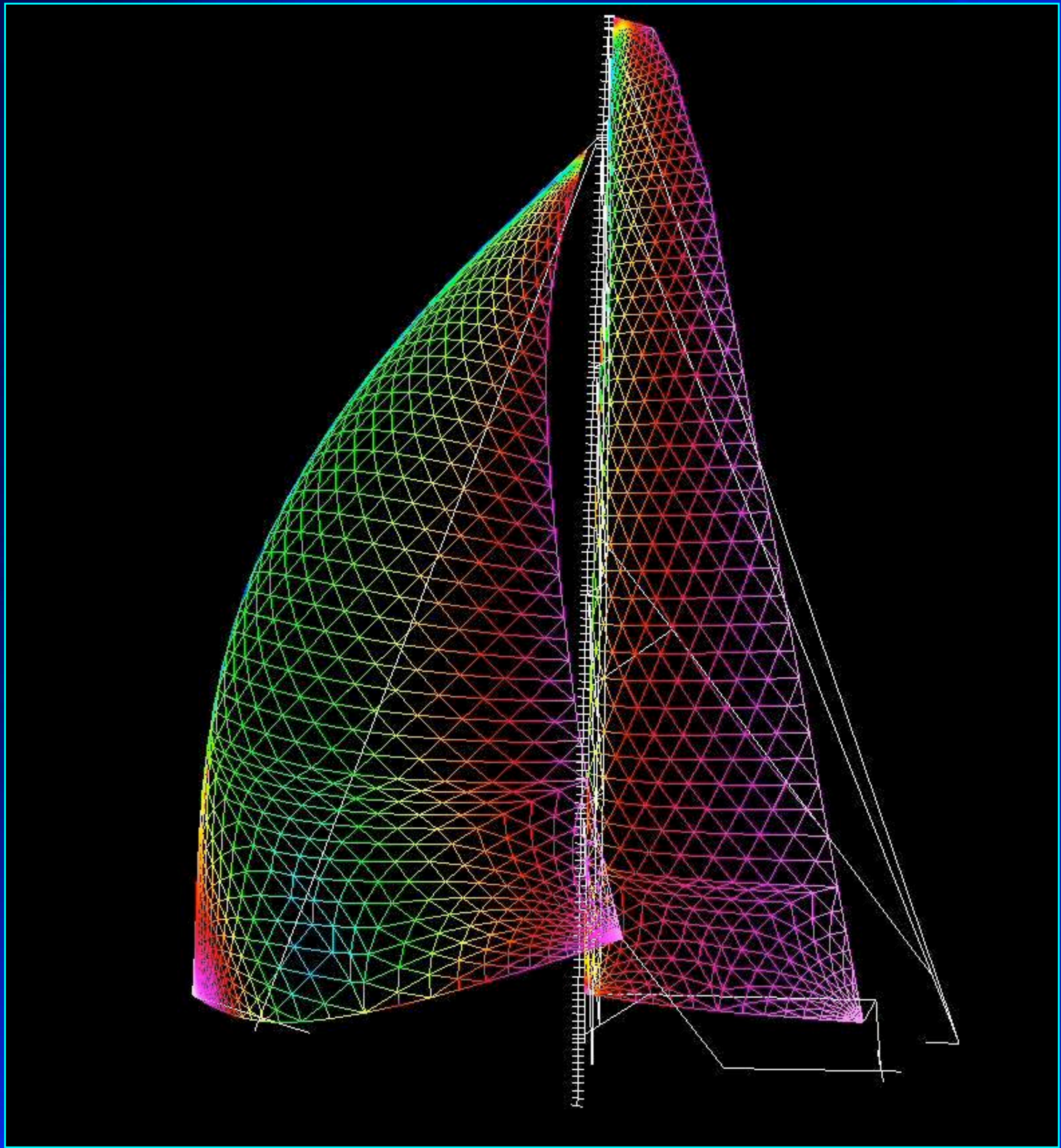
  ~125.500 Hexahedra
  (far field)

  ~3500 Pyramids
  (link Tetra/Hexa)



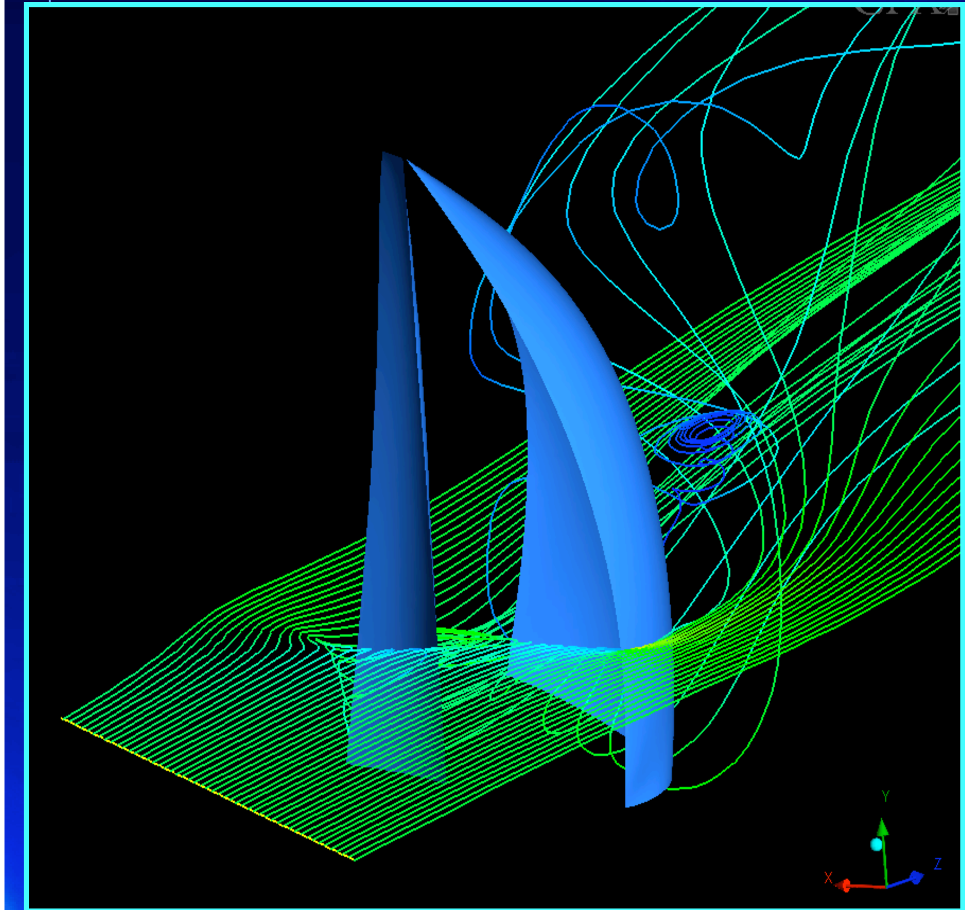
- Stopping test:
  ΔForces < 1% for two consecutive couplings on both sails

FE Grid

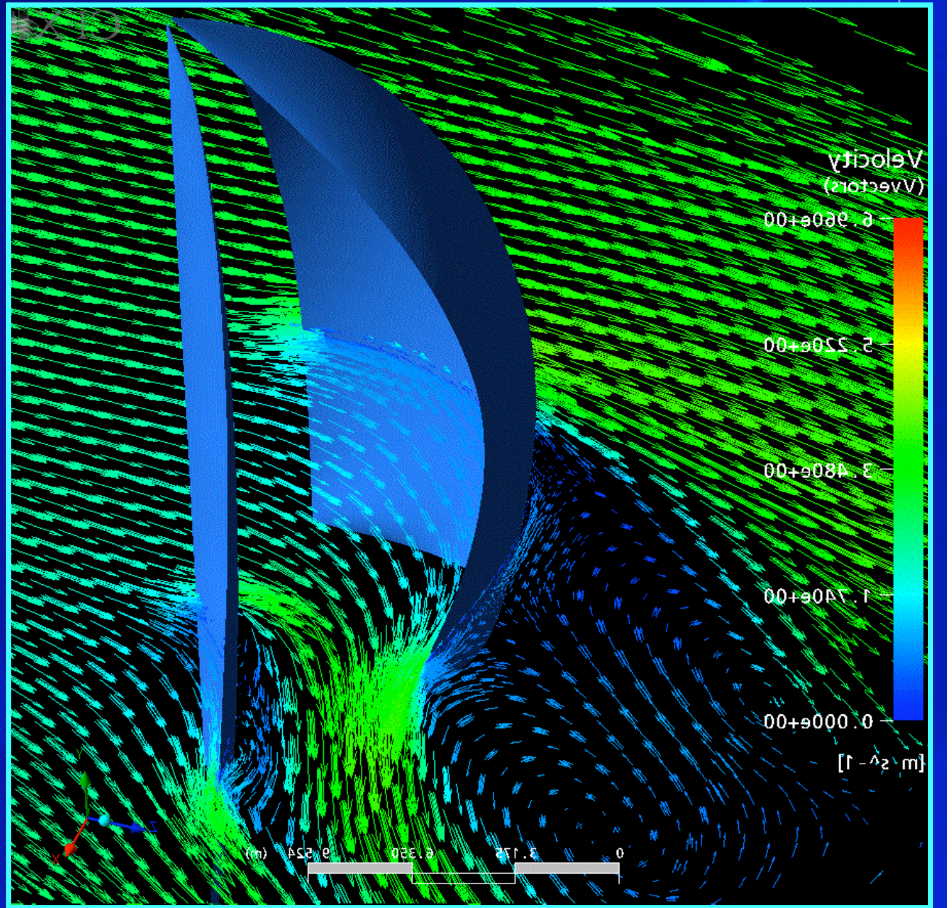


Flow around spinnaker and mainsail

- Boat speed: 5.540 m/s (~ 15.45 kts)
- True Wind Angle: 148 Deg
- True Wind Speed at 10m: 5.660 m/s (~ 17.54 kts)

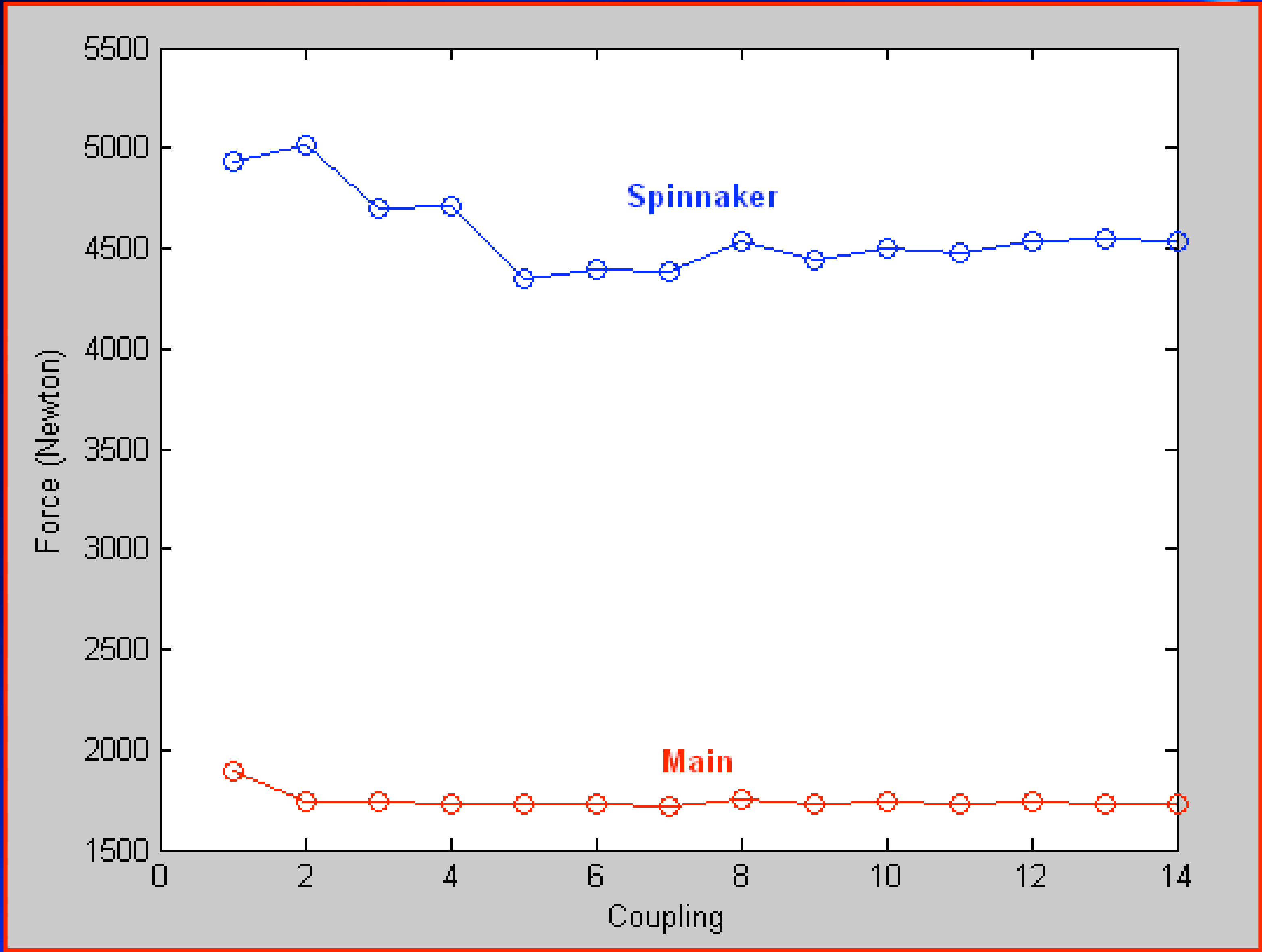


streamlines



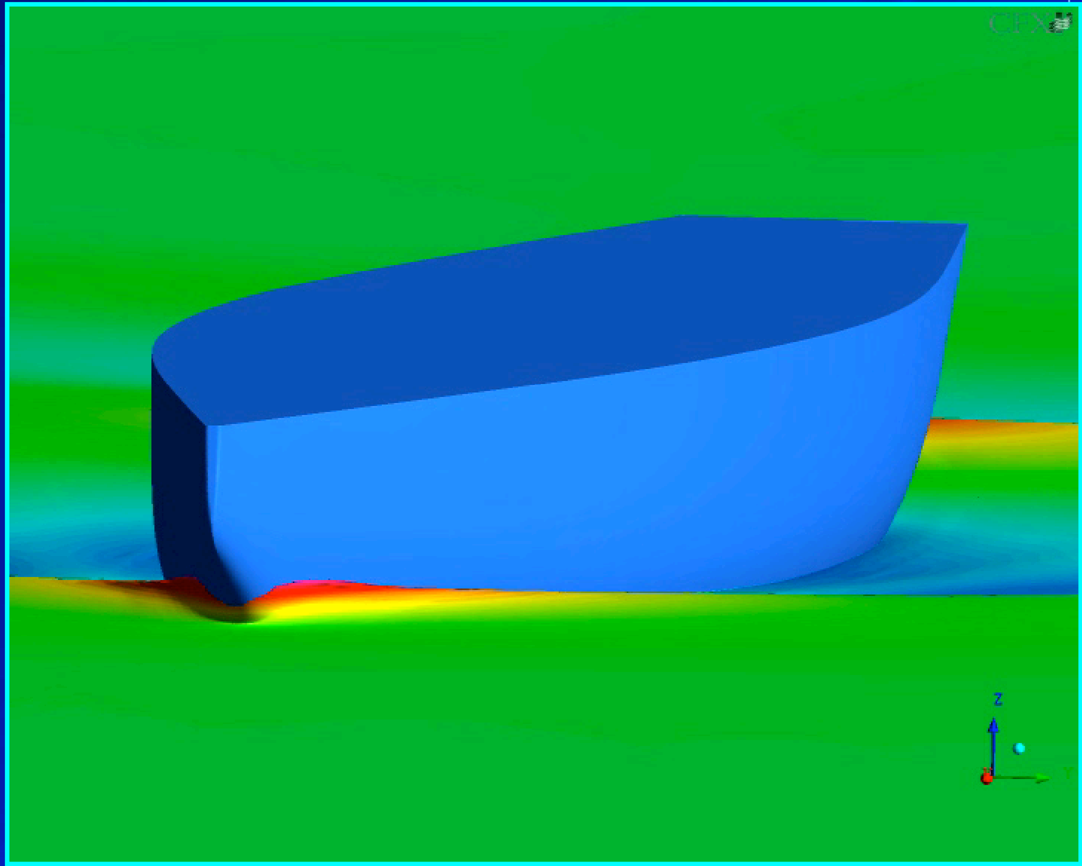
velocity and flow separation

Convergence history (forces)



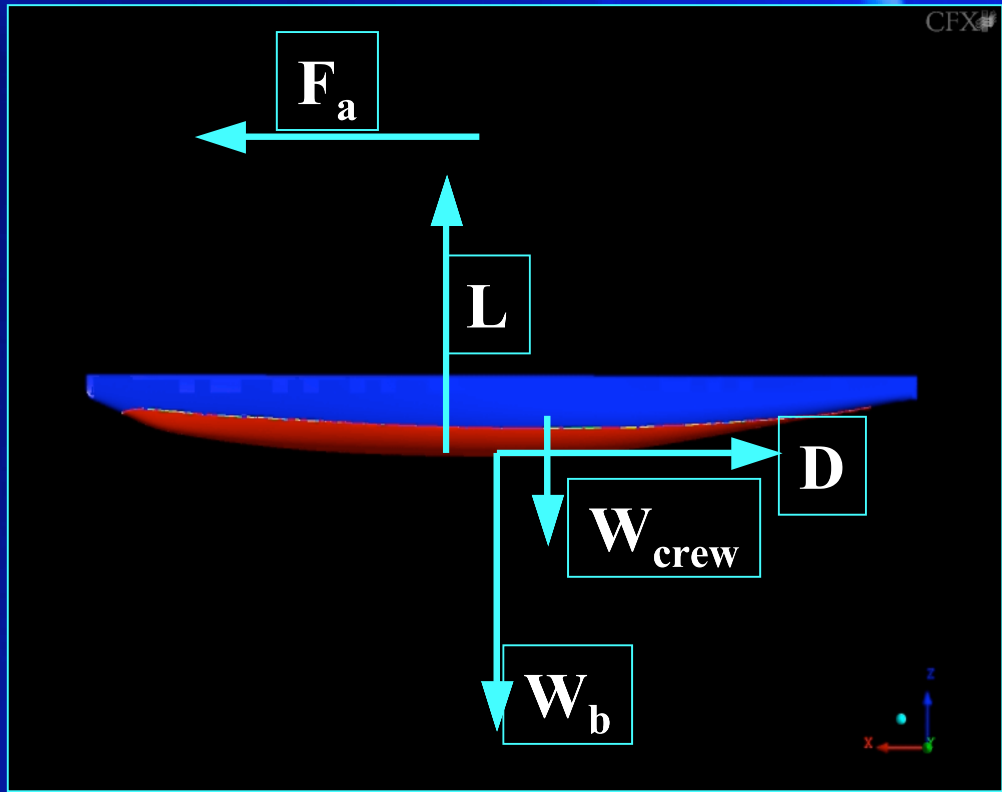
FSI for hull design

- Coupling between a CFD solver and a rigid body dynamical system for the hull
- Evaluation of forces and sink and trim attitude
- Numerical tool to complement towing tank results on hull performances



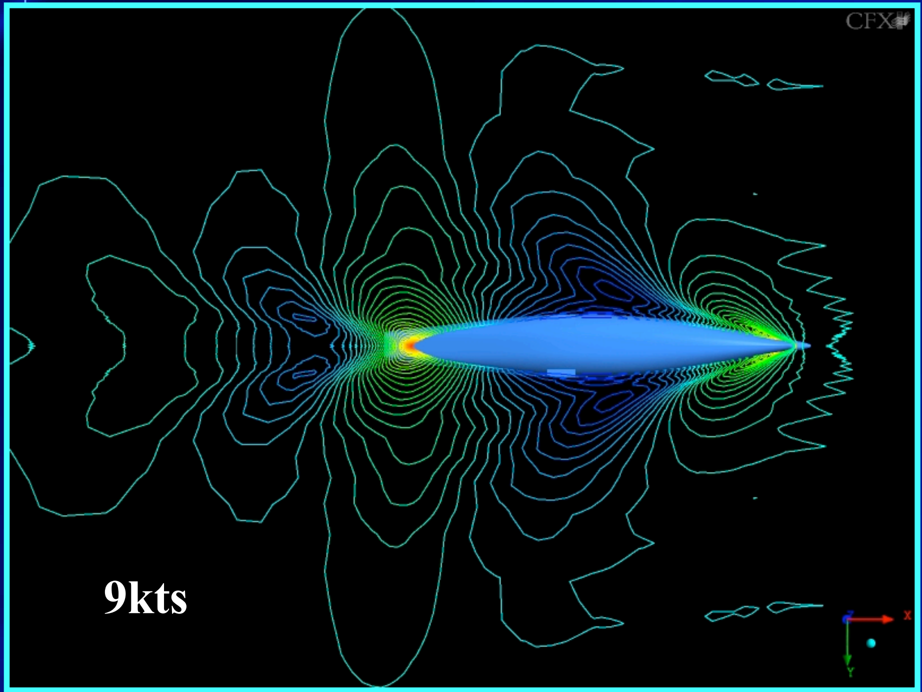
Rigid body dynamical system

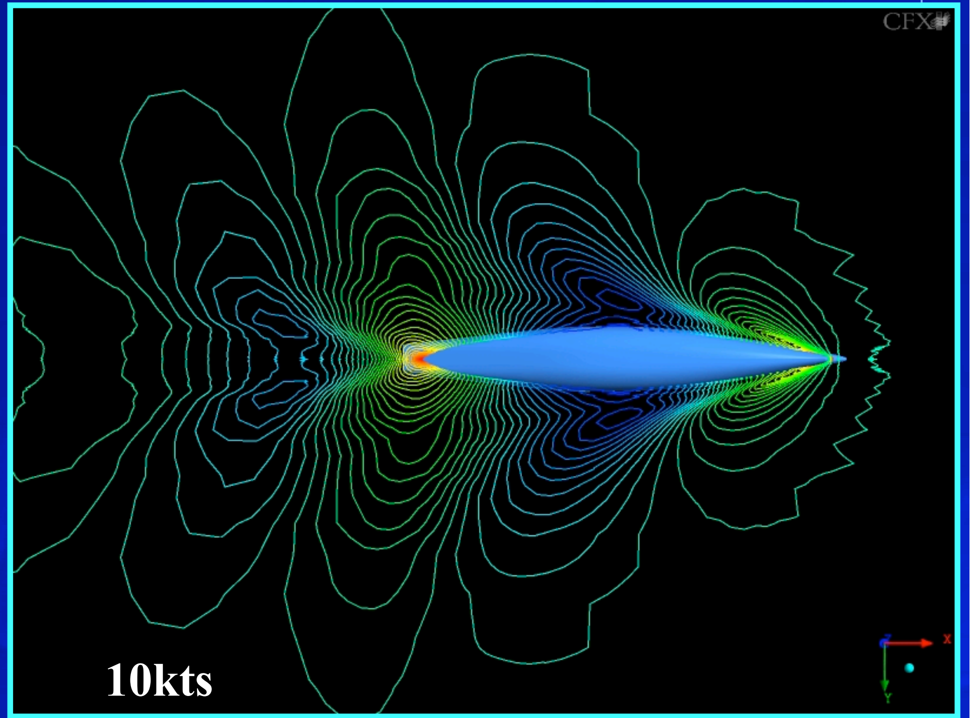
- 2 degrees of freedom:
  - vertical translation (sink)
  - pitching rotation (trim)
- Displacement and external sail moment imposed
- Crew and gear moment imposed
- First order fixed point iteration scheme



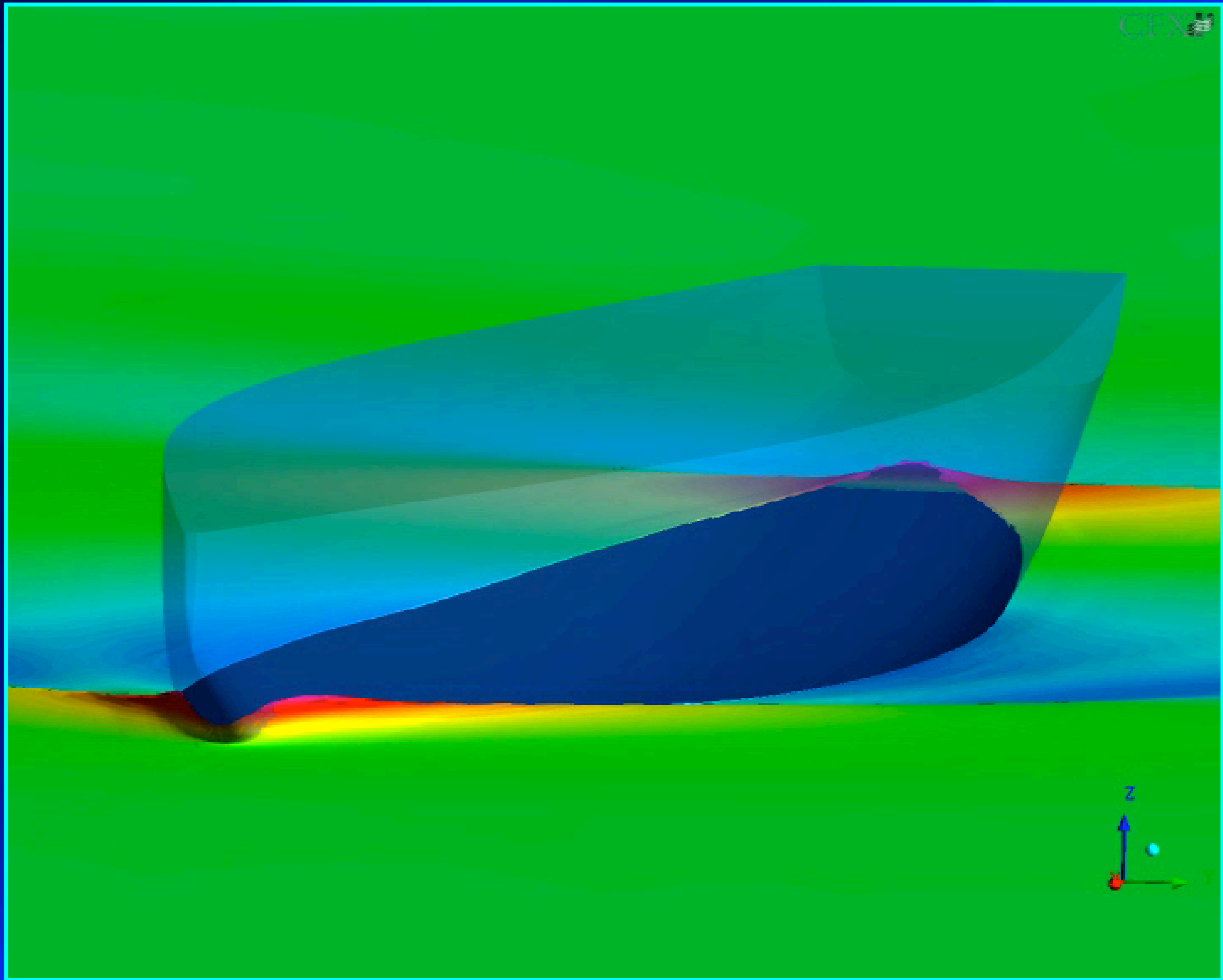
F_a: Sail Thrust
L: Hydrodynamic Lift
D: Hydrodynamic Drag
W_b: Boat weight
W_{crew}: Crew weight

Results - Wave patterns



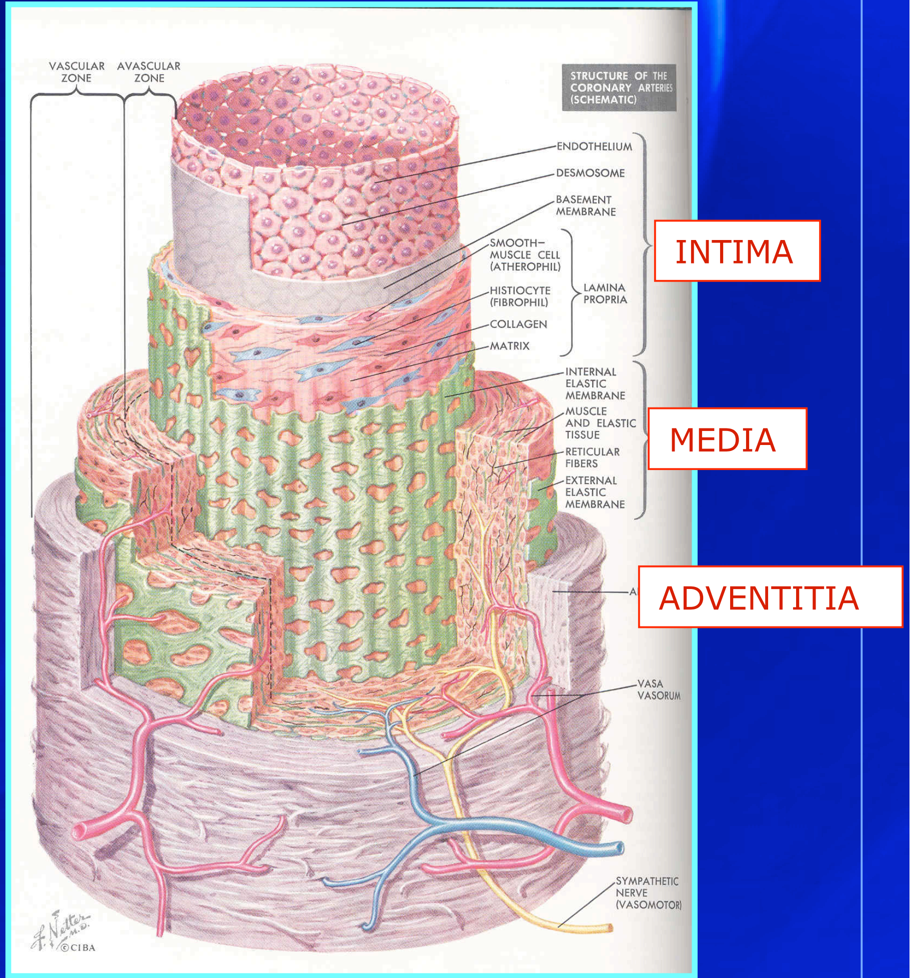


Hull dynamics

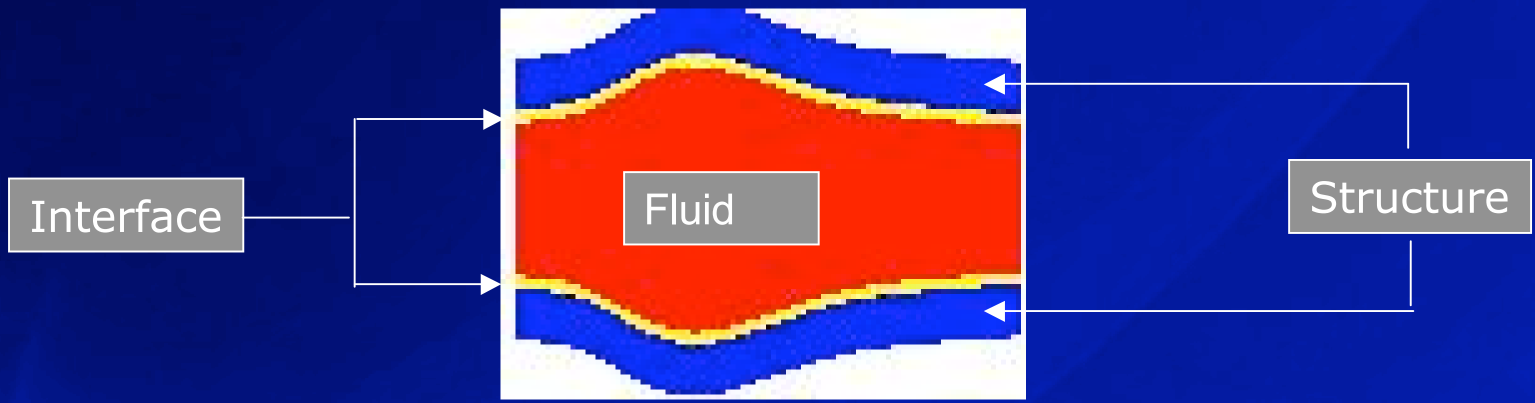


Boat Speed = 10 kts

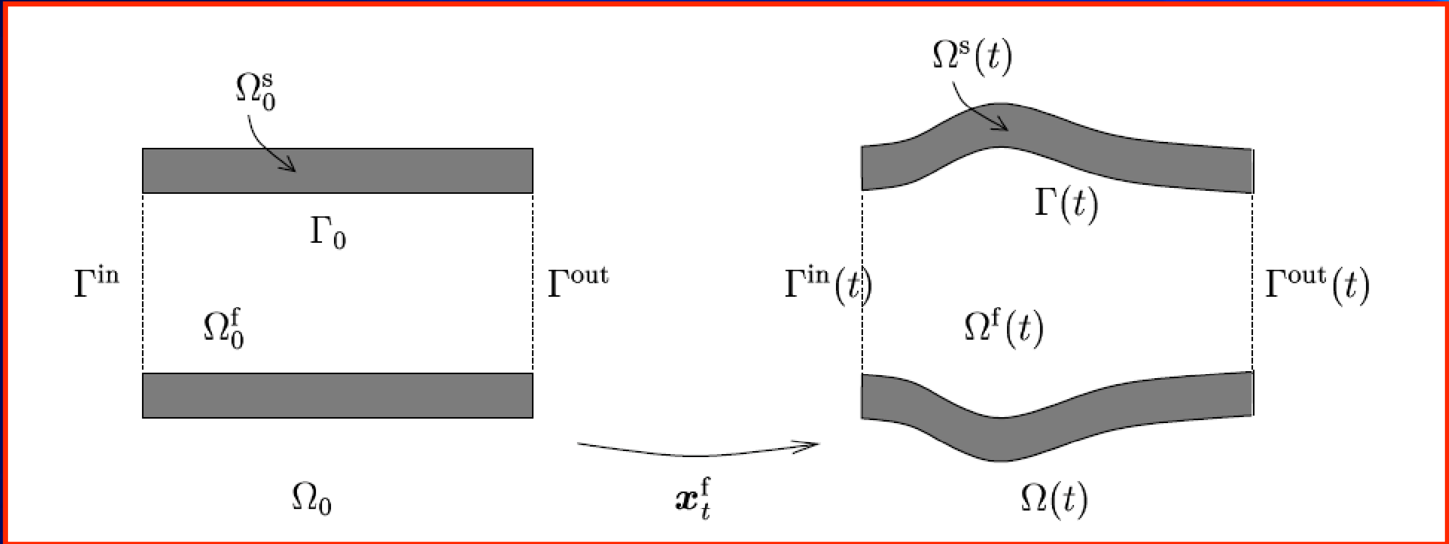
Application 2: Blood Flow in Large Vessels



Schematic representation



ALE Formulation



- Mapping for the solid domain:

  $\forall t,\ \Omega_0^s \to \Omega^s(t)$

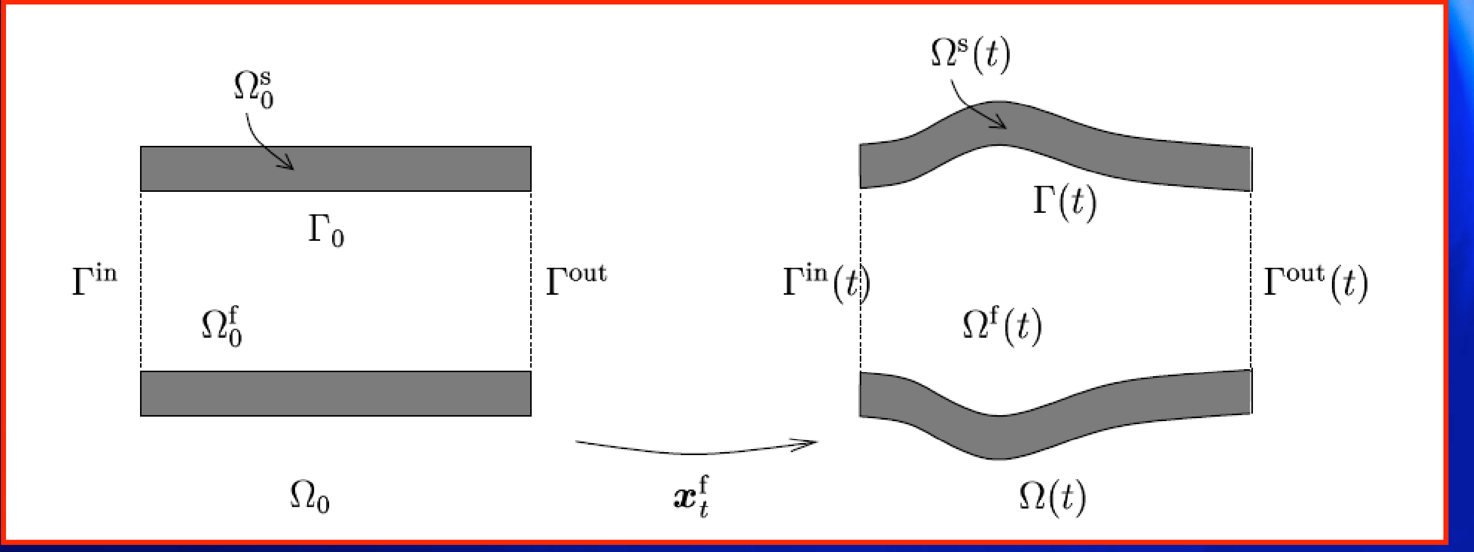
  $x_0 \to x^s(x_0, t) = x_0 + d^s(x_0,t),\ x_0 \in \Omega^s_0$

- Mapping for the fluid domain:

  $\forall t,\ \Omega_0^f \to \Omega^f(t)$

  $x_0 \to x^f(x_0, t) = x_0 + d^f(x_0,t),\ x_0 \in \Omega^f_0$

ALE Formulation

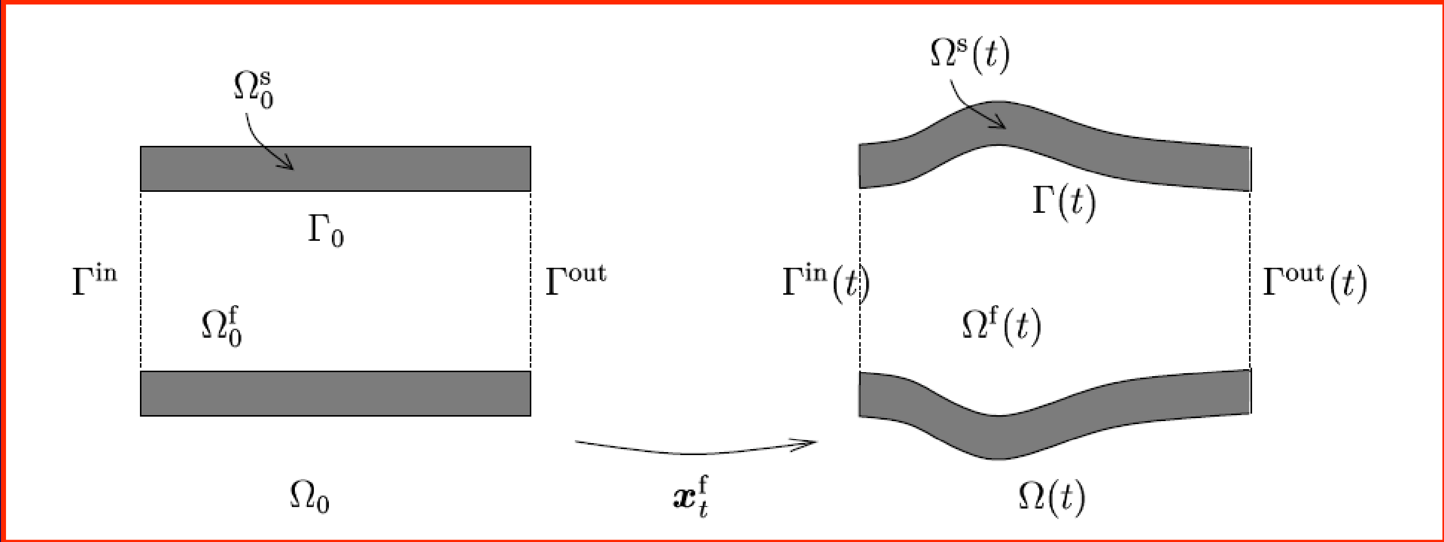


d^f can be defined as an extension of the solid $d^s{}_{|\Gamma_0}$

$d^f = \mathrm{Ext}(d^s{}_{|\Gamma_0})$, with Ext defined as, e.g.,

$$\begin{aligned} \Delta\, d^f &= 0 && \text{in } \Omega^f_0 \\ d^f &= 0 && \text{on } \partial\, \Omega^f_0 \setminus \Gamma_0 \\ d^f &= d^s && \text{on } \Gamma_0 \end{aligned}$$

ALE Formulation



- Domain velocity

  $w = d\, x^f_t / dt$

- ALE time derivative

  $\{\partial u / \partial t\}_{|x_0}(x,t) = du(x_t^f(x_0),t)/dt$ with $x_0 = (x_f^t)^{-1}(x)$

Problem Setting

- Fluid(u, p, x^f_t, g_f, f_f)

$$\rho_f(\partial u/\partial t\,|_{x_0} + (u - w)\cdot\nabla u) = \nabla\cdot(\sigma_f(u,p)) + f_f \qquad \text{in } \Omega^f(t)$$

$$\nabla . u = 0 \qquad \text{in } \Omega^f(t)$$

$$\sigma_f(u,p)\cdot n_f = g_f \qquad \text{on } \Gamma^{in}(t) \cup \Gamma^{out}(t)$$

- Solid(d^s, g_s, f_s)

$$\rho_s\, \partial^2 d^s/\partial t^2 - \nabla_{|x_0}\cdot(\sigma_s(d^s)) = f_s \qquad \text{in } \Omega^s_0$$

$$\sigma_s(d^s)\cdot n_s = g_s \qquad \text{on } \partial\,\Omega^s_0 \setminus \Gamma_0$$

- Matching conditions

Let $\lambda(t) = \lambda$ be an interface variable corresponding to d^s on Γ_0

$$x^f_t = x_0 + \lambda$$

$$u \circ x^f_t = \partial\lambda/\partial t$$

$$(\sigma_f(u,p)\cdot n_f)\circ x^f_t = -\,\sigma_s(d^s)\cdot n_s$$

WARNING:

For time-discretization, geometric conservation laws (GCL) can be a concern for stability. This is a general issue for evolution equations in changing domains.
(see D.Boffi's talk)

Donea,
Hughes,
Farhat,
Nobile and Formaggia,
Boffi and Gastaldi,
…

Strongly vs weakly coupled methods

- Density of structure ~ density of fluid makes implicit scheme ideal as they guarantee energy conservation (strong coupling: matching conditions satisfied exactly at each time-step)
- Numerical instability observed (and even proven theoretically) for weakly (or loosely) coupled schemes

- Strongly coupled → no numerical instabilities
  → high computational costs
- Weakly coupled → efficiency and simplicity of implementation
  → unstable when there is an important "added-mass" effect ($\rho_s \simeq \rho_f$) as in blood flows

The fluid acts as an "added-mass" on the structure (H.Morand and R.Ohayon, 1995)

Example: a simple linear fluid-structure problem

Fluid model (linear incompressible inviscid model:
$\rightarrow$ potential pressure field)

$$\begin{cases} \triangle p = 0 & \text{in } \Omega_f \\ p = p_{in}(t) & \text{on } \Gamma^{inflow} \\ p = 0 & \text{on } \Gamma^{out} \end{cases}$$

Structure model (linear elasticity, small thickness cylinder, assumption of membrane deformation: $\rightarrow$ generalized string model)

$$\rho_s h_s \frac{\partial^2 d}{\partial t^2} - kG h_s \frac{\partial^2 d}{\partial x^2} + \frac{E h_s}{1-\nu^2} \frac{d}{R_0^2} = \vec{\sigma}_s$$

Physical parameters: $\rho_s = 1.1, h_s = 0.1,$ **Poisson** $\nu = 0.5$
Young modulus $E = 7.5 \cdot 10^5\ dynes/cm^2$
Shear modulus $kG = 2.5 \cdot 10^5\ dynes/cm^2$
Vessel 6 cm long and 1cm wide

Coupling conditions:

Continuity of velocity

$$\frac{\partial p}{\partial n} = -\rho_f \frac{\partial^2 d}{\partial t^2}$$

($\rho_f = 1g/cm^2$ **blood density)**

Continuity of stress

$$p = -\overrightarrow{\sigma}_s$$

Physical parameters: $\rho_s = 1.1, h_s = 0.1,$ **Poisson** $\nu = 0.5$
Young modulus $E = 7.5 \cdot 10^5 \; dynes/cm^2$
Shear modulus $kG = 2.5 \cdot 10^5 \; dynes/cm^2$

Analysis

Explicit time-marching schemes:

The scheme is unconditionally unstable if $\boxed{\dfrac{\rho_s h_s}{\rho_f \mu_{max}} < 1}$

with μ_{max} maximal eigenvalue of the "added-mass" operator $\mathcal{M}_A$ (the more Ω_F becomes a slender geometry, i.e. for fixed R, the length L increases, or for fixed L, the radius R decreases, the larger μ_{max} becomes)

$\mathcal{M}_A$ is the Neumann-to-Dirichlet map.

Implicit time-marching schemes (Implicit Euler):

A Dirichlet-Neumann scheme = fluid solve + structure solve converges iff the relaxation parameter ω satisfies

$$\boxed{0 < \omega < \frac{2(\rho_s h_s + a\delta t^2)}{\rho_s h_s + \rho_f \mu_{max} + a\delta t^2}}$$

(Causin, Gerbeau, Nobile (2004))

FSI algorithms, I

- Monolithic (direct) method: solve simultaneously the fluid and the structure problems in a unique solver

↓

Strongly coupled by construction

- Partitioned procedure: the fluid and the structure are solved with two different codes (at any rate, separately)

↙ ↘

strongly coupled:
sub-iterations at each time step until convergence

most often weakly coupled:
a single fluid-structure solve at each time step , or a few (inexact solution)

See Hermann Matthies' lecture on strongly coupled approaches

FSI algorithms, II

1. Fixed point, Gauss-Seidel or Schwarz multiplicative
2. Newton based methods: requires the evaluation of the Jacobian associated to fluid-solid coupled state equations

   2a. Exact Newton

   2b. Block, Quasi, or Inexact-Jacobian Newton

3. Fractional step schemes: differential and algebraic
4. Schur-based domain decomposition

Several analogies exist among these strategies

FSI algorithms, III: fixed point and Newton

- Fixed point are common practice, with several variants: steepest descent, Aitken acceleration, transpiration conditions, to avoid computation of the fluid matrix at each iteration.

  Methods slow (in general) or even non-convergent (unless properly relaxed and/or accelerated), depending upon the physical characteristics of the two media.

- Remedy: use Newton method, however it requires the Jacobian evaluation (for FS system). In particular, the cross-jacobian expresses the sensitivity of the fluid state to solid motion.

- Cross Jacobian can be evaluated inexactly: FD approximation of derivatives, or by replacing the tangent operator by a simpler one. To recover convergence, acceleration techniques based on Krylov methods have been proposed.

FSI algorithms, IV: Fractional steps, differential and algebraic

(weakly coupled, variable degree)

1. Projection semi-implicit scheme
2. Algebraic fractional step scheme

They couple implicitly the pressure stress to the structure

$\longrightarrow$ implicit coupling of the added mass term

$\longrightarrow$ good stability properties

The remaining terms of the fluid equations are explicitly coupled

Projection and Fractional step: common steps

- Step 0: extrapolation of FS interface

$$\boxed{\overline{\eta}^{n+1} = \eta^n + \delta t\left(\frac{3}{2}\dot{\eta}^n - \frac{1}{2}\dot{\eta}^{n-1}\right)}$$

- Step 1: definition of the new domain (and ALE velocity)

$$\boxed{\mathbf{w}^{n+1}\,|_\Gamma = \frac{\overline{\eta}^{n+1} - \eta^n}{\delta t}\,|_\Gamma} \qquad \boxed{\mathbf{w}^{n+1} = \mathrm{Ext}(\mathbf{w}^{n+1}\,|_\Gamma)}$$

$$\boxed{\Omega_f^{n+1} = \Omega_f^n + \delta t\,\mathbf{w}^{n+1}}$$

ALE framework : $\mathbf{w}^{n+1}$ is the fluid domain velocity at time t^{n+1}

Projection based *semi-implicit* coupling (case: low Re)

It splits the **differential** operator (Chorin-Temam projection scheme) and then discretizes in time and space

- Step 2: diffusion step (explicit coupling):

$$\rho_f \frac{\tilde{\mathbf{u}}^{n+1} - \mathbf{u}^{n+1}}{\delta t}\Big|_{\hat{x}} - \mu \triangle \tilde{\mathbf{u}}^{n+1} = 0 \quad \text{in} \quad \Omega_f^{n+1}$$

$$\tilde{\mathbf{u}}^{n+1} = \mathbf{w}^{n+1} \quad \text{on} \quad \Gamma^{n+1}$$

- Step 3: projection step (implicit coupling):

  - Step 3.1:

$$\rho_f \frac{\mathbf{u}^{n+1} - \tilde{\mathbf{u}}^{n+1}}{\delta t} + \nabla p^{n+1} = 0 \quad \text{in} \quad \Omega_f^{n+1}$$

$$\text{div } \mathbf{u}^{n+1} = 0 \quad \text{in} \quad \Omega_f^{n+1}$$

$$\mathbf{u}^{n+1} \cdot \mathbf{n}^f = \frac{\eta^{n+1} - \eta^n}{\delta t} \cdot \mathbf{n}^f \quad \text{on} \quad \Gamma^{n+1}$$

Projection based *semi-implicit* coupling (II)

- Step 3.2 (mid-point rule discretization for the structure):

$$\boxed{\begin{aligned} \rho_s \frac{\dot{\eta}^{n+1} - \dot{\eta}^n}{\delta t} - \mathrm{div}_{\hat{x}}\left(\frac{\sigma_s^{n+1} + \sigma_s^n}{2}\right) = 0 \quad \text{in} \quad \hat{\Omega}_s \\ \frac{\eta^{n+1} - \eta^n}{\delta t} = \frac{\dot{\eta}^{n+1} + \dot{\eta}^n}{2} \quad \text{in} \quad \hat{\Omega}_s \\ \sigma_s^{n+1} \cdot \mathbf{n}^s = \sigma_{f,\hat{x}}^{n+1}(\tilde{\mathbf{u}}^{n+1}, p^{n+1}) \cdot \mathbf{n}_{\hat{x}}^f \quad \text{on} \quad \hat{\Gamma} \end{aligned}}$$

Step 1 and 2 are performed only once per time step

Step 3 is solved by sub-iterating (in a fixed domain) between 3.1 and 3.2, e.g. using fixed-point or Newton iterations.

Schur-based domain decomposition

Variational Formulation

Harmonic Extension:

find $d^{f,t^{n+1}} \in H^1(\Omega^1{}_0)$ such that

$$\int_{\Omega^f{}_0} \nabla d^{f,t^{n+1}} \cdot \nabla \phi = 0$$
$$d^{f,t^{n+1}} = \lambda(t^{n+1}) \qquad \text{on } \Gamma_0$$

for all $\phi \in H^1{}_0(\Omega^1{}_0)^3$ with appropriate boundary conditions on $\Gamma^{in} \cup \Gamma^{out}$

We can then compute the velocity of the fluid domain:

$$w^{f,n+1}{}_{|\Gamma(t^{n+1})} = 1/\delta\, t\, (d^f{}_{t^{n+1}|\Gamma_0} - d^f{}_{t^n|\Gamma_0}) \circ (x^f{}_{t^{n+1}})^{-1}$$

Variational Formulation

Fluid: Find $(u^{n+1}, p^{n+1}) \in V^f(t^{n+1}) \times Q^f(t^{n+1})$ such that (Dirichlet data)

$$u^{n+1}{}_{|\Gamma(t^{n+1}} = w^{f,n+1}{}_{|\Gamma(t^{n+1})}$$

$$u^{n+1}{}_{\Gamma^{in}(t^{n+1})} = u_{in}(t^{n+1})$$

$$1/\delta t \int_{\Omega^f(t^{n+1})} \rho_f\, u^{n+1}\, v^f + \int_{\Omega^f(t^{n+1})} \rho_f\, [(u^{n+1} - w^{f,n+1}) \cdot \nabla u^{n+1}]\, v^f + \mu \int_{\Omega^f(t^{n+1})} \sigma_f(u^{n+1}, p^{n+1}) \cdot \nabla v^f = 1/\delta t \int_{\Omega^f(t^{n+1})} \rho_f\, u^n\, v^f$$

$$+ \int_{\Gamma^{in}(t^{n+1}) \cup \Gamma^{out}(t^{n+1})} g^f\, v^f$$

$$\int_{\Omega^f(t^{n+1})} q^f\, \nabla \cdot u^{n+1} = 0$$

$\forall (v^f, q^f) \in V_0^f(t^{n+1}) \times Q^f(t^{n+1})$ with

$$V^f(t) = \{v^f \mid v^f \circ x^f_t \in H^1(\Omega^f_0)^3\}$$

$$V^f_0(t) = \{v^f \in V^f(t) \mid v^f \circ x^f_t = 0 \text{ on } \Gamma_0 \cup \Gamma^{in}\}$$

$$Q^f(t) = \{q^f \mid q^f \circ x^f_t \in L^2(\Omega^f_0)\}$$

Variational Formulation

Structure (Neumann data):

$$2/\delta t^2 \int_{\Omega^s_0} \rho_s\, d^{s,n+1}\, v^s - 2/\delta t^2 \int_{\Omega^s_0} \rho_s\, (d^{s,n} + \delta\, t\, w^{s,n})\, v^s$$
$$+ \int_{\Omega^s_0} \sigma_s(d^{s,n+1}) \cdot \nabla v^s = \int_{\partial\, \Omega^s_0 \setminus \Gamma_0} g_s \cdot v^s$$
$$+ \int_{\Gamma_0} \sigma_f(u^{n+1}, p^{n+1}) \cdot x^f_t{}^{n+1}$$

$\forall\, v^s \in V^s$ such that $v^s{}_{|\Gamma_0} = 0$, and $V^s = H^1(\Omega^s{}_0)^3$

$$w^{s,n+1} = 2/\delta t(d^{s,n+1} - d^{s,n}) - w^{s,n}$$

$$d^{s,n+1} = \lambda(t^{n+1}) \text{ on } \Gamma_0$$

Interface Operators

Fluid operator S_f: (Dirichlet-to-Neumann)

$$S_f(\lambda) = \sigma_f := (\sigma_f(u,p) \cdot n_f) \circ x_t^f \text{ on } \Gamma_0$$

where (u,p) is the solution of the Navier-Stokes problem

Structure operator S_s: (Dirichlet-to-Neumann)

$$S_s(\lambda) = \sigma_s := (\sigma_s(d^s) \cdot n_s) \text{ on } \Gamma_0$$

where d^s is the solution of the structure problem

We can also define the associated inverse and derived operators

$$S_f^{-1}, S_s^{-1}, S'_f{}^{-1}, S'_s{}^{-1}, \ldots$$

Interface Problem

Fixed Point Formulation:

$$S_s^{-1}(-S_f(\lambda)) = \lambda$$

relaxed fixed point iterations:

$$\Lambda^k = S_s^{-1}(-S_f(\lambda^k))$$
$$\lambda^{k+1} = \lambda^k + \alpha^k(\Lambda^k - \lambda^k)$$

Rootfinding Formulation:

$$\Phi(\lambda) := S_s^{-1}(-S_f(\lambda)) - \lambda = 0$$

Newton algorithm :

$$\Lambda^k = S_s^{-1}(-S_f(\lambda_k))$$
$$J_\Phi(\lambda^k)\mu^k = -(\Lambda^k - \lambda^k)$$
$$\lambda^{k+1} = \lambda^k + \alpha^k\mu^k$$

With:

α^k is a relaxation parameter (constant, Aitken's method, …)

J_Φ is the Jacobian of $S_s^{-1}(-S_f(\lambda))$

$$J_\Phi(\lambda^k) = -\,[S_s'(\Lambda^k)]^{-1}.S_f'(\lambda^k)$$

Interface Problem

Steklov-Poincaré Formulation:

$$S_s(\lambda) + S_f(\lambda) = 0$$

Non-Linear Richardson:

$$\begin{aligned} \sigma^k &= -\,(S_s(\lambda^k) + S_f(\lambda^k)) \\ \mu^k &= P^{-1}\sigma^k \\ \lambda^{k+1} &= \lambda^k + \alpha^k\mu^k \end{aligned}$$

How do we define the preconditioner P^{-1} ?

Interface Problem

Domain Decomposition preconditioners:

$$P^{-1} = \alpha_f\, S_f^{-1} + \alpha_s\, S_s^{-1}$$
$$\alpha_f + \alpha_s = 1$$

Problem: the operators S_f and S_s are non-linear

Idea: replace S_f and S_s by S_f' and S_s'

Interface Problem: Preconditioning the Richardson Algorithm

Generalized Aitken:

Let $\alpha_{f/s}^k = \alpha^k \alpha_{f/s}^k$ and

$$\mu^k_{f/s} = -(S_f'(\lambda^k) + S_s'(\lambda^k))(\alpha_f^k S_f'(\lambda^k)^{-1} + \alpha_s^k S_s'(\lambda^k)^{-1})\,\sigma^k$$

We want to minimize (w.r.t α_f and α_s)

$$||(\lambda^k - \lambda^{k-1} + \alpha_f(\mu_f^k - \mu_f^{k-1}) + \alpha_s(\mu_s^k - \mu_s^{k-1})\ ||$$

Which corresponds to solving the linear system

$$A^T A(\alpha_f^k,\alpha_s^k)^T = -A^T(\lambda^k - \lambda^{k-1})$$

where A is the two column matrix

$$A = ((\mu_f^k - \mu_f^{k-1});(\mu_s^k - \mu_s^{k-1}))$$

Reconsidering the previous Example:

A vessel 6 cm long and 1cm wide

Fluid model (linear incompressible inviscid model

$\rightarrow$ potential pressure field)

$$\begin{cases} \triangle p = 0 \quad \text{in } \Omega_f \\ p = p_{in}(t) \quad \text{on } \Gamma^{inflow} \\ p = 0 \quad \text{on } \Gamma^{out} \end{cases}$$

Structure model (string model)

$$\rho_s h_s \frac{\partial^2 d}{\partial t^2} - kG h_s \frac{\partial^2 d}{\partial x^2} + \frac{E h_s}{1-\nu^2}\frac{d}{R_0^2} = \vec{\sigma}_s$$

Physical parameters: $\rho_s = 1.1, h_s = 0.1,$ **Poisson** $\nu = 0.5$

Young modulus $E = 7.5 \cdot 10^5 \; dynes/cm^2$

Shear modulus $kG = 2.5 \cdot 10^5 \; dynes/cm^2$

DD with Flexible Neumann-Neumann preconditioner

On the same problem (both string and fluid acting as preconditioners)

For fixed $h = 0.15$

(ω_{f} average of ω_{f}^k; ω_{s} average of ω_{s}^k)

δt	ω_{f}	ω_{s}	iterations
1.e-4	3.e-3	3.e-2	33
1.e-5	2.e-3	3.8e-2	30
1.e-6	2.8e-3	3.9e-2	27

For fixed $\delta t = 1.e - 4$

h	ω_{f}	ω_{s}	iterations
0.3	6.e-3	8.e-2	33
0.15	3.e-3	3.e-2	33
0.1	3.3e-3	2.e-2	37

The 3D case

3D Geometry:

Straight cilinder of radius R=0.25cm and length L=5cm

Structure with thickness of 0.05cm

Physical characteristics:

Fluid: viscosity μ=0.03 poise, density ρ_f=1 g/cm^3

Solid: density ρ_s=1.2 g/cm^3, Young modulus E = 3.e6 dynes/cm^3,

Poisson ratio ν = 0.3

Space discretization

Fluid: Navier-Stokes equations, $\mathbb{P}_1$ -bubble/ $\mathbb{P}_1$

Solid: Linear Saint Venant-Kirckhoff, $\mathbb{P}_1$, no time derivative

Time discretization

Time interval [0,0.02s] and Δt = 1.e-3, 5.e-4, 1e-4.

At t=0 the system is at rest. The structure is clamped at inlet and outlet. Pressure of 1.3e4 dynes/cm^2 imposed at the inlet for 3.e-3s