Time-resolved adaptive FEM simulation of a DLR F11 full aircraft at realistic Reynolds number

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Introduction

Our team has background in computational math, computer science and industrial CFD.

We develop our own adaptive FEM methods: General Galerkin (G2) and massively parallel general FEM open source software Unicorn/FEniCS.

We contribute results using unique methods and modeling in several aspects which we hope can advance the field in new directions.

Problem setup

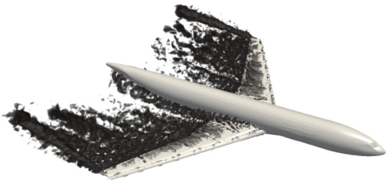
DLR F11 model of commercial aircraft, experiment at B-LSWT and ETW and, considers half of the span of the airplane at $Re = 1.5 \times 10^6$ and $Re = 1.51 \times 10^7$

We model whole aircraft, choose only high Re case 2b which fits best with our slip boundary condition.

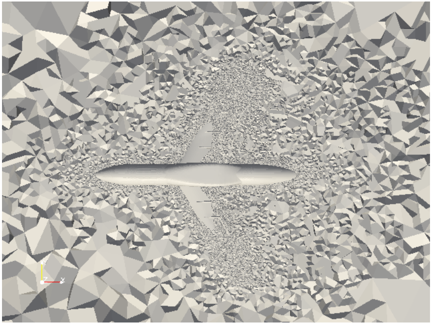
Use mesh sequence from adaptive error control method as mesh study.

Continuum model: incompressible Euler

$$
\begin{aligned}
R(\hat{u}) &= \begin{cases} \partial_t u + (u \cdot \nabla) u - \nabla p = 0 & \text{in } I \times \Omega, \\ \nabla \cdot u = 0 & \text{in } I \times \Omega \end{cases} \\
\hat{u} &= (u, p)
\end{aligned}
$$



$\alpha = 12$, Lambda 2 visualization (vorticity measure)



Slice of the mesh

General Galerkin (G2) method

Developed over a 20+ year period by Johnson, Hoffman, Jansson, etc.

Space-time FEM with Galerkin/least squares stabilization

$$(R(\hat{U}), \hat{v}) + (\delta R(\hat{U}), R(\hat{v})) = 0,\ \delta = h,\ \forall \hat{v} \in \hat{V}_h,\ \hat{U} \in \hat{V}_h$$

Adaptive error control and mesh refinement

$$|M(\hat{e})| = |(\hat{e}, \psi)| \leq \sum_{K \in T} \|hR(\hat{U})\|_K \|\nabla \hat{\phi}\|_K \leq TOL$$

Slip/friction boundary condition as boundary layer model

$$u \cdot n = 0$$

Implicit parameter-free turbulence model based on stabilization

Dissipation: $D = \|\delta^{1/2} R(\hat{U})\|^2$

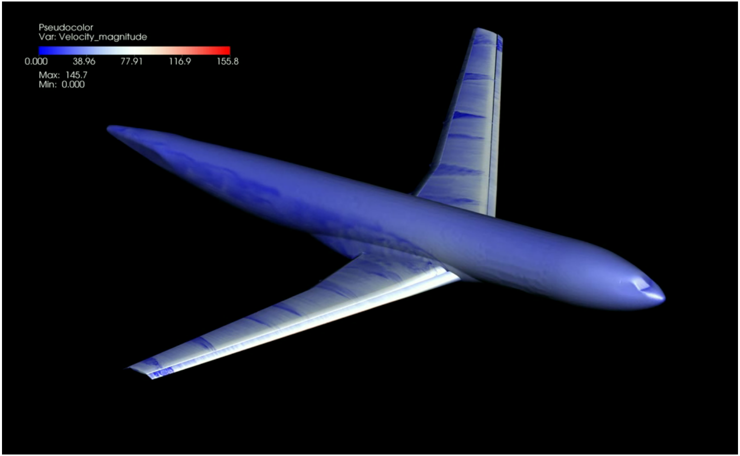
Moving mesh, fluid-structure interaction, shock-capturing, etc.

G2 validation: basic benchmarks

- NACA0012 $Re = 10^6$ [Jansson/Hoffman/Jansson, 2012]
- Cube $Re = \infty$ [Hoffman/Jansson/Vilela, CMAME, 2011]
- Circular cylinder $Re = 3900$ [Hoffman, IJNMF, 2009]
- Sphere $Re = 10000$ [Hoffman, JFM, 2006]
- Square cylinder $Re = 22000$ [Hoffman, SISC, 2005]
- Surface mounted cube $Re = 40000$ [Hoffman, SISC 2005]

Time-resolved adaptive simulation of aircraft

$\alpha = 21$



Adaptive error control

$$\hat{e} = \hat{u} - \hat{U}$$

$$A\hat{u} = f \quad \text{(linearized primal problem)} \quad A^*\hat{\phi} = \psi \quad \text{(dual problem)}$$

$$M(\hat{e}) = (\hat{e}, \psi) = (\hat{e}, A^*\hat{\phi}) = (A\hat{e}, \hat{\phi}) = (-R(\hat{U}), \hat{\phi}) \qquad \text{(error representation)}$$

$$|(\hat{e}, \psi)| \leq \sum_{K \in \mathcal{T}} \|hR(\hat{U})\|_K \|\nabla\hat{\phi}\|_K = \sum_{K \in \mathcal{T}} \mathcal{E}_K \quad \text{(error bound)}$$

Adaptive mesh refinement

1. For the mesh $\mathcal{T}^k$: compute the primal problem and the dual problem.
2. If $\sum_{K \in \mathcal{T}^k} \mathcal{E}_K < TOL$ then stop, else:
3. Mark some chosen percentage of the elements with highest error indicator $\mathcal{E}_K$ for refinement.
4. Generate the refined mesh $\mathcal{T}^{k+1}$ by recursive Rivara bisection , set $k = k + 1$, and goto 1.

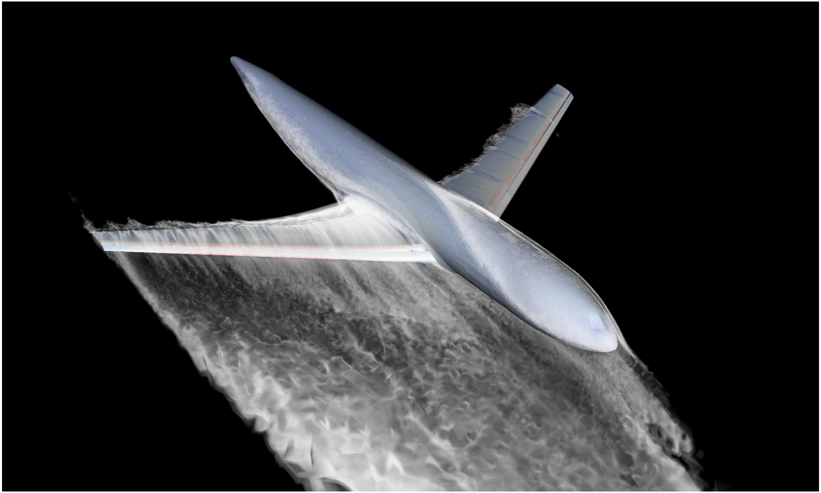
Aerodynamic forces - mean quantities in space and time

Force: $F = \frac{1}{|I|} \int_I \int_{\Gamma_a} pn \, dsdt$,
with Γ_a right half-boundary of aircraft and p the pressure

Drag and lift coeff.: $c_d = \frac{2F_0}{|\bar{u}|^2 A}$, $c_l = \frac{2F_1}{|\bar{u}|^2 A}$,
with A reference area of aircraft and $\bar{u}$ freestream/inflow velocity

Adaptive mesh refinement - adjoint velocity

Goal quantity: drag and lift for right half of airplane



Adaptive mesh refinement - adjoint velocity

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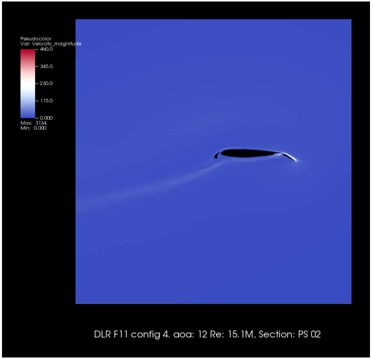
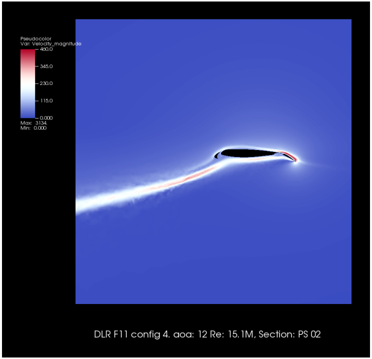


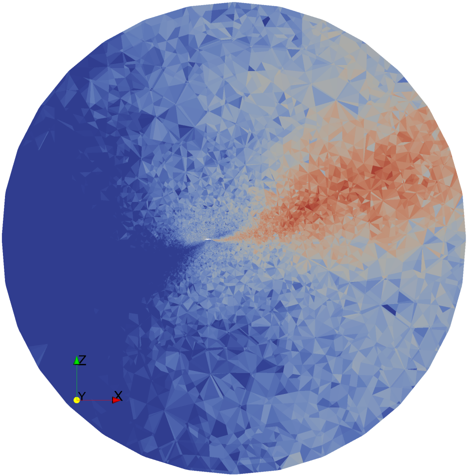
Left (non-target) side



Right (target) side

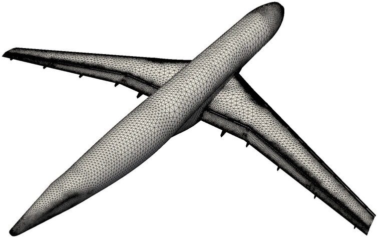
Adaptive mesh refinement - adjoint velocity

Residual, recall: $M(\hat{e}) = (-R(\hat{U}), \hat{\phi})$

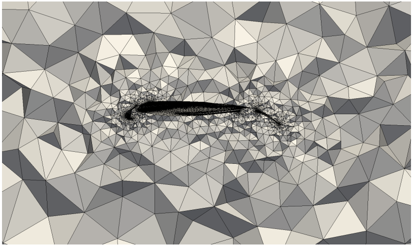


Adaptive mesh refinement - mesh sequence

mesh0: 700k vertices



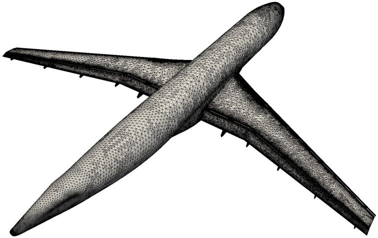
Mesh on surface



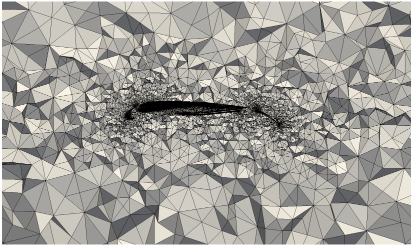
Mesh slice on target side

Adaptive mesh refinement - mesh sequence

mesh1: 1.1M vertices, note upstream refinement



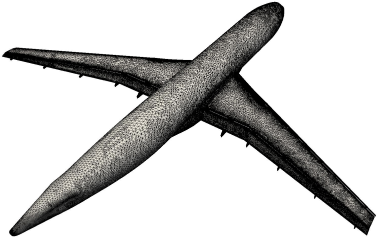
Mesh on surface



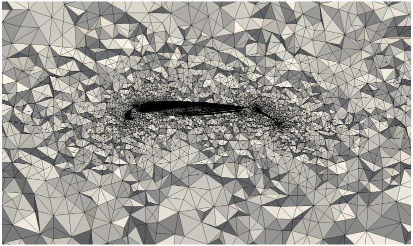
Mesh slice on target side

Adaptive mesh refinement - mesh sequence

mesh2: 1.6M vertices, note upstream refinement



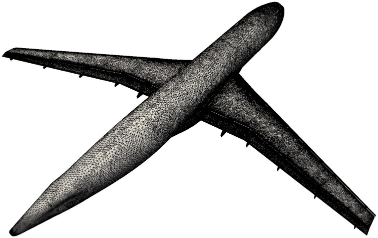
Mesh on surface



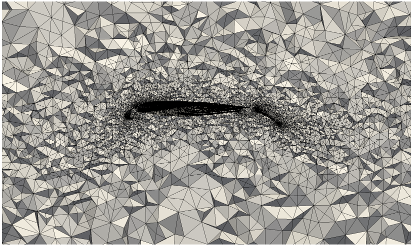
Mesh slice on target side

Adaptive mesh refinement - mesh sequence

mesh3: 2.2M vertices, note upstream refinement



Mesh on surface

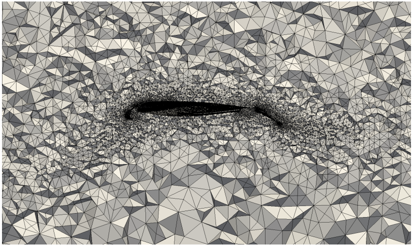


Mesh slice on target side

Adaptive mesh refinement - mesh sequence

mesh4: 3.1M vertices, note upstream refinement

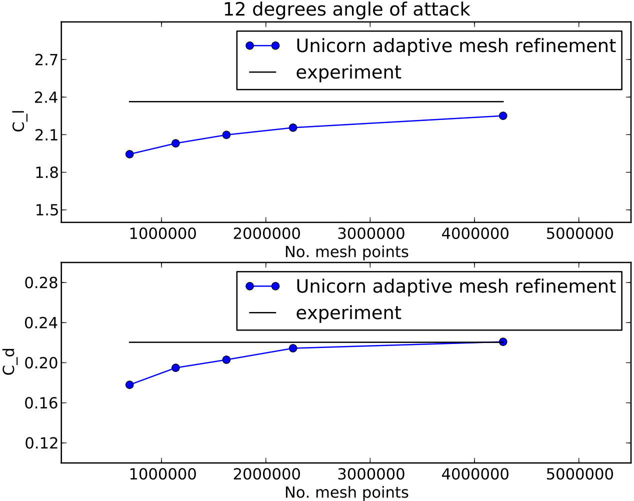
Mesh on surface



Mesh slice on target side

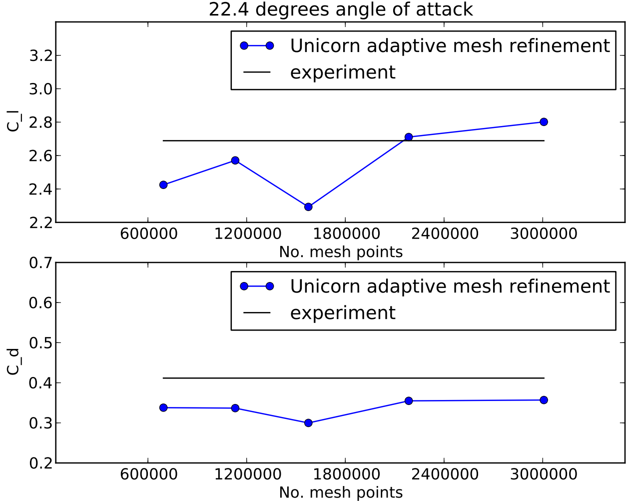
Aerodynamic forces $\alpha = 12^\circ$

Lift within 5% of exp., Drag within 0.1% of exp.
Use 1536 cores on Lindgren supercomputer, ca. 300k core hours total
Would like a few more adaptive iterations



Aerodynamic forces $\alpha = 22.4^\circ$

Lift within 4% of exp., Drag within 13% of exp.
Use 1536 cores on Lindgren supercomputer, ca. 300k core hours total
Would like a few more adaptive iterations



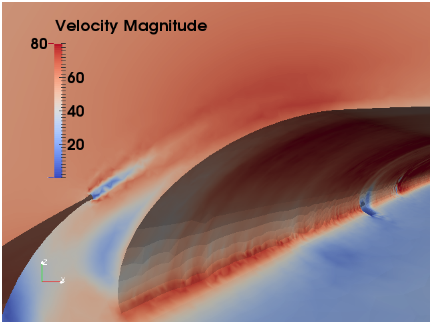
Friction boundary condition

Turbulent boundary layers modeled as a slip boundary condition

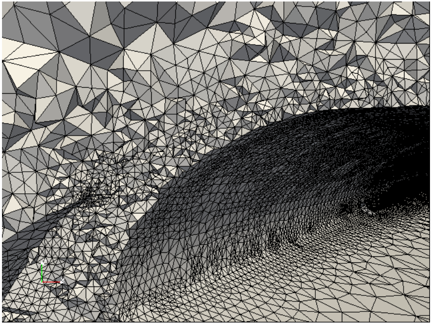
$$u \cdot n = 0,$$

$$(\tau = n^T \sigma t = \beta u \cdot t = 0)$$

with τ the wall shear stress, n the normal and t the tangent.
$\beta = 0$ (slip) good appx. for small friction/wall shear stress, validated for a number of benchmark problems

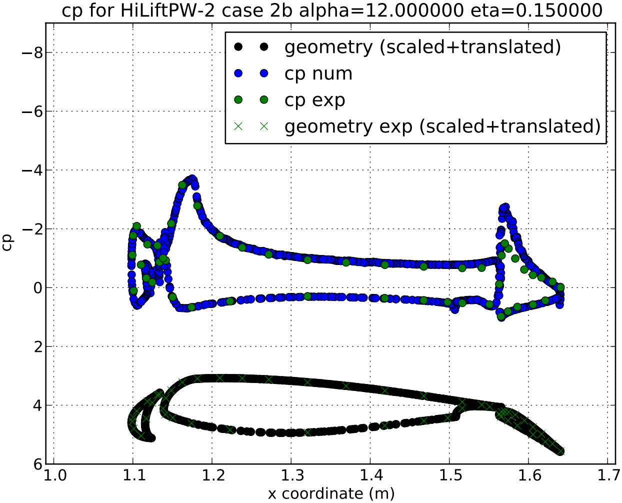


Velocity at $\eta = 0.15$, $\alpha = 12$


Mesh at $\eta = 0.15$, $\alpha = 12$ (slice retains whole tets)

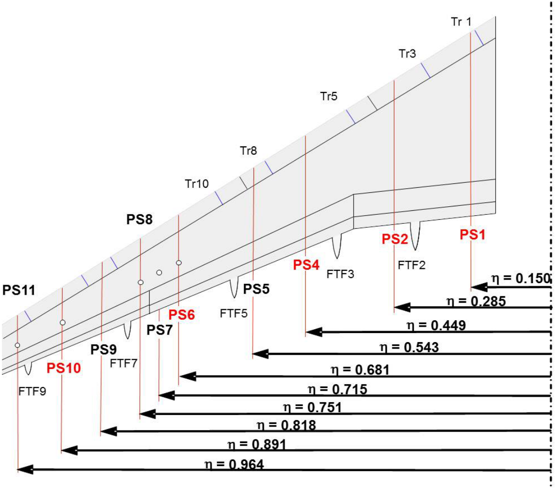
Friction boundary condition

Plot of pressure distribution (cp) corresponding to velocity/mesh plots on previous slide.

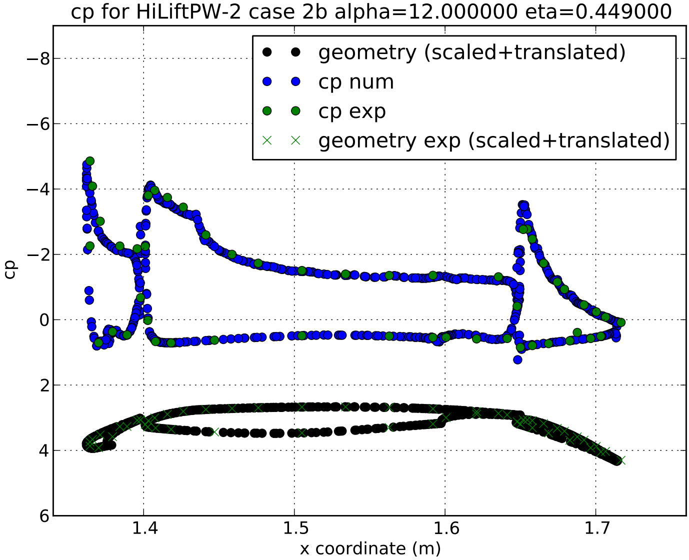


Pressure distributions

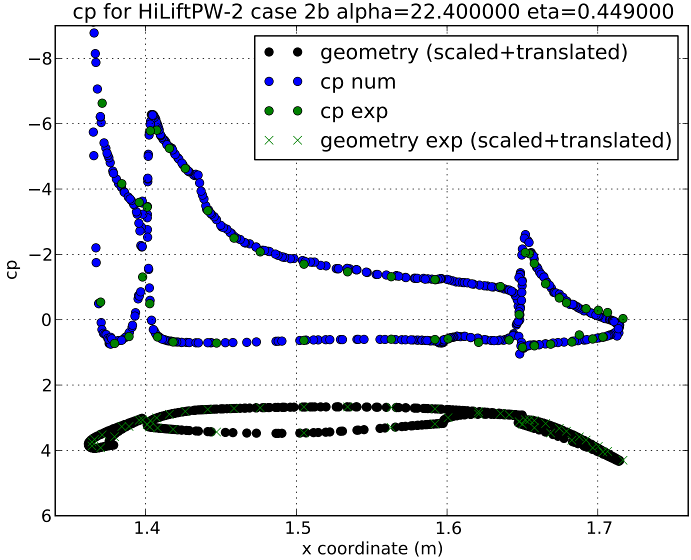
Experimental pressure data extracted along slices for several angles of attack.



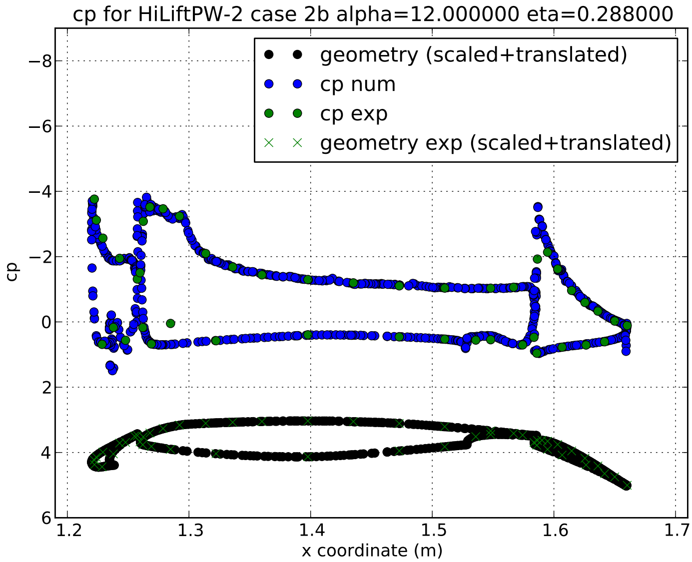
Pressure distributions



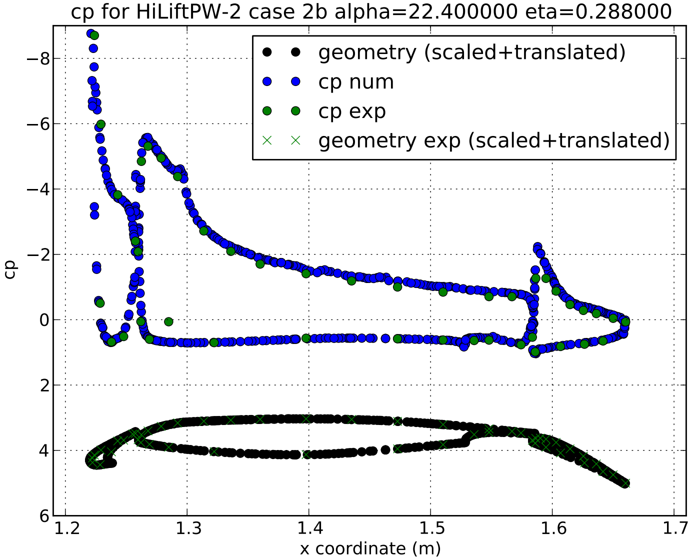
Pressure distributions



Pressure distributions



Pressure distributions



Summary/Conclusions

- Overview of General Galerkin (G2) method and Unicorn/FEniCS software framework: **time-resolved, goal-oriented adaptive error control, no explicit turbulence model, slip boundary condition as boundary layer model**
- Predicts experiments for full DLR F11 aircraft at realistic Reynolds number $Re = 1.51 \times 10^7$: lift and drag within 5% and 15% resp. of experiments, pointwise pressure values within 10% except in localized regions. Consistent with 5% and 15%tolerance on target goal for error control of mean lift and drag in space-time.

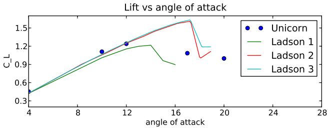
Outlook:

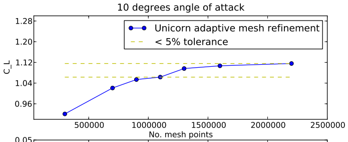
- Run a few more adaptive iterations, more (and higher for stall) angles of attack
- Try different outputs, for example target only lift and drag for the flap

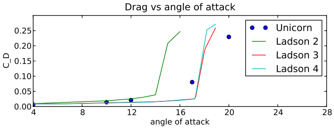
Acknowledgements:

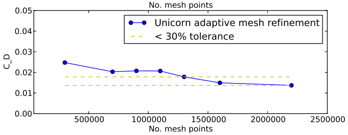
Extra material

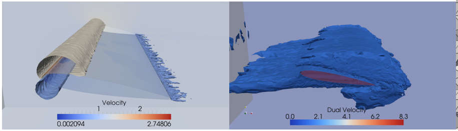
NACA 0012 at realistic flight conditions, $\alpha = 10^\circ$

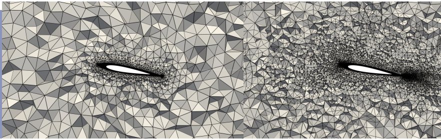






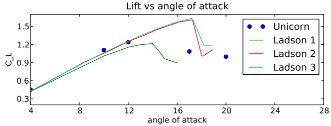


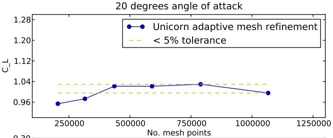


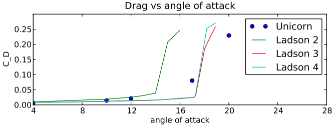


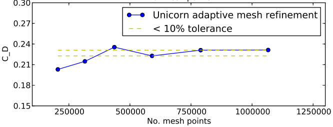
[Jansson, Hoffman, Jansson, 2012 preprint available on home page]

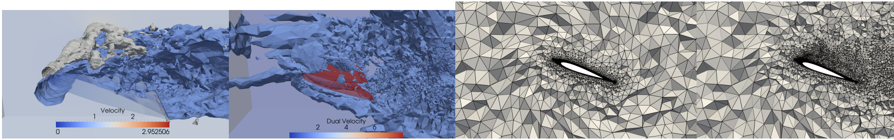
NACA 0012 at realistic flight conditions, $\alpha = 20^\circ$







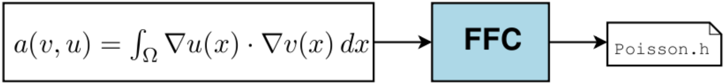




[Jansson, Hoffman, Jansson, 2012 preprint available on home page]
For the NACA0012 problem at $\alpha = 10^\circ$ on the finest mesh with 2.2 million mesh points on 768 cores, the simulation takes 16 hours, enabling overnight simulation for a wing at realistic flight conditions.

FEniCS form compilation/code generation

- Automates a key step in the implementation of finite element methods for partial differential equations
- Input: a variational form and a finite element
- Output: C/C++ function for element tensor



Input form in (ASCII) mathematical notation:

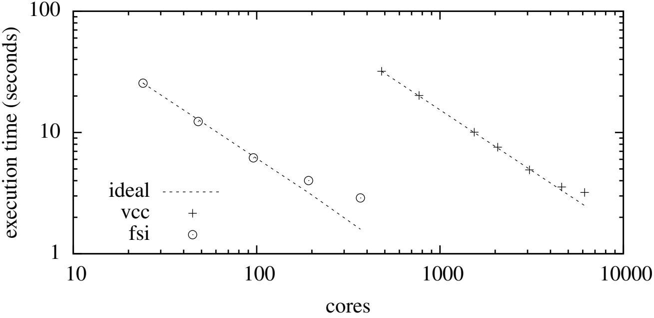
```
a = inner(grad(v), grad(u))*dx
```

Compiler:

```
>> ffc [-l language] poisson.form
```

Strong scaling verification

Strong linear scaling of full adaptive solve of incompressible flow up to ca. 5000 cores on Lindgren (PDC) supercomputer.



[Hoffman, Jansson, et. al., 2012 C&F], [Hoffman, Jansson, Jansson, 2011, SISC]

lift and drag vs aoa

$\alpha = 12, 22.4$ run adaptively, $\alpha = 20, 21$ run using grid generated for $\alpha = 12$.