HiLiftPW4 AIAA Video - Euler CFD RFS

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KTH/Icarus Digital Math

http://digitalmath.org (Research Environment)

http://icarusmath.com (Commercial)

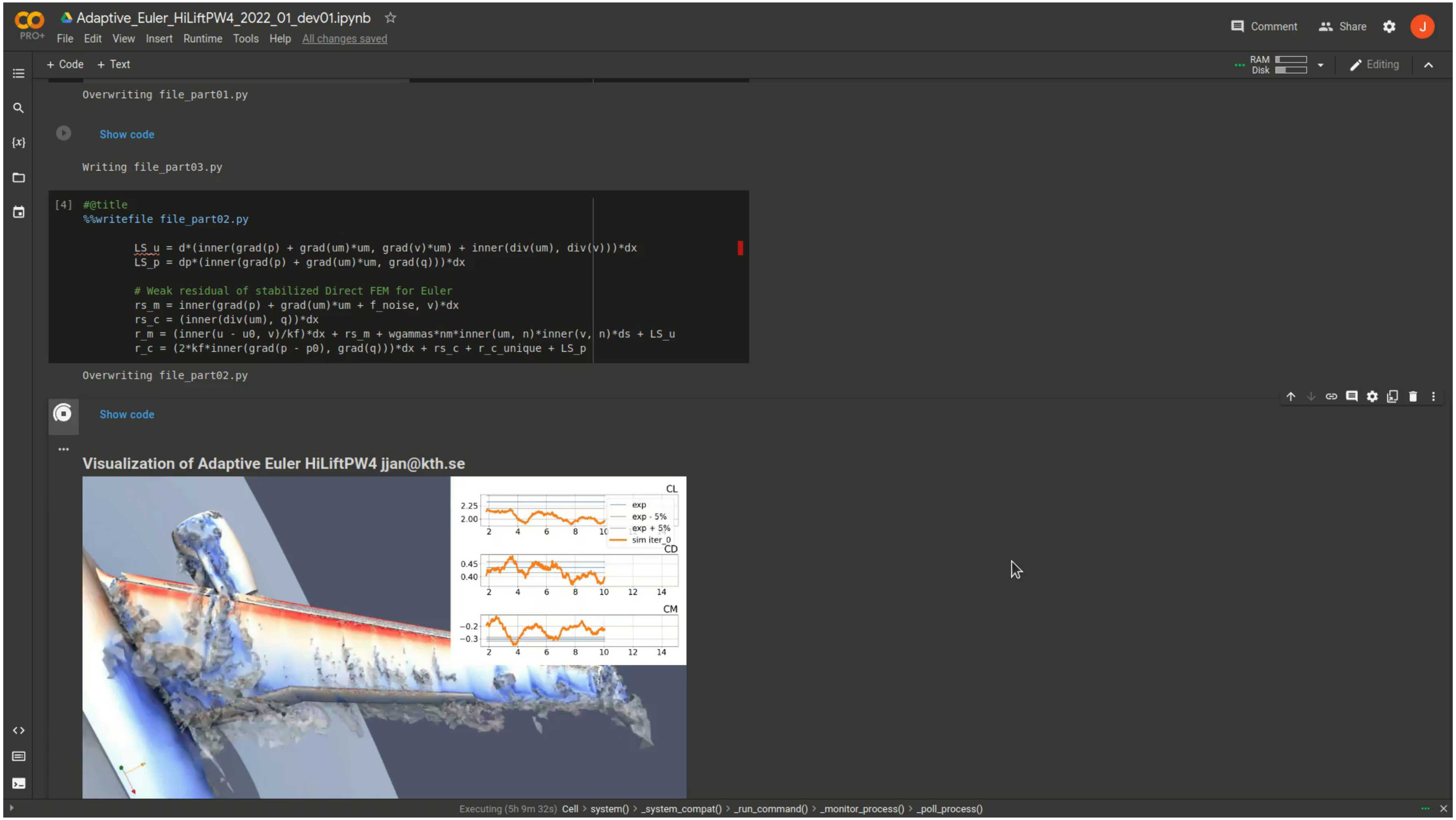
Methodology

- Proposed Euler CFD/Real Flight Simulator (RFS) as solution to the NASA Vision 2030 challenges.
- Predictive incompressible Euler - first principles - no modeling parameters - slip BC.
- Direct FEM cG(1)cG(1) in FEniCS with adjoint-based adaptive error control.
- Extremely fast and cheap: < 100 core hours - "zero" computational cost
- Coarse starting meshes for adaptive methodology from ANSA: 500k-800k vertices giving good validation.
- Vision: Design and certification of aircraft and engineering systems should be done by simulation (e.g. Digital Math Real Flight Simulator) within 5 years.

Run and modify the simulations yourself in your web browser!

Solving the reproducibility crisis with Digital Math. More detailed presentation and results:

http://digitalmath.tech/hiliftpw4-aiaa



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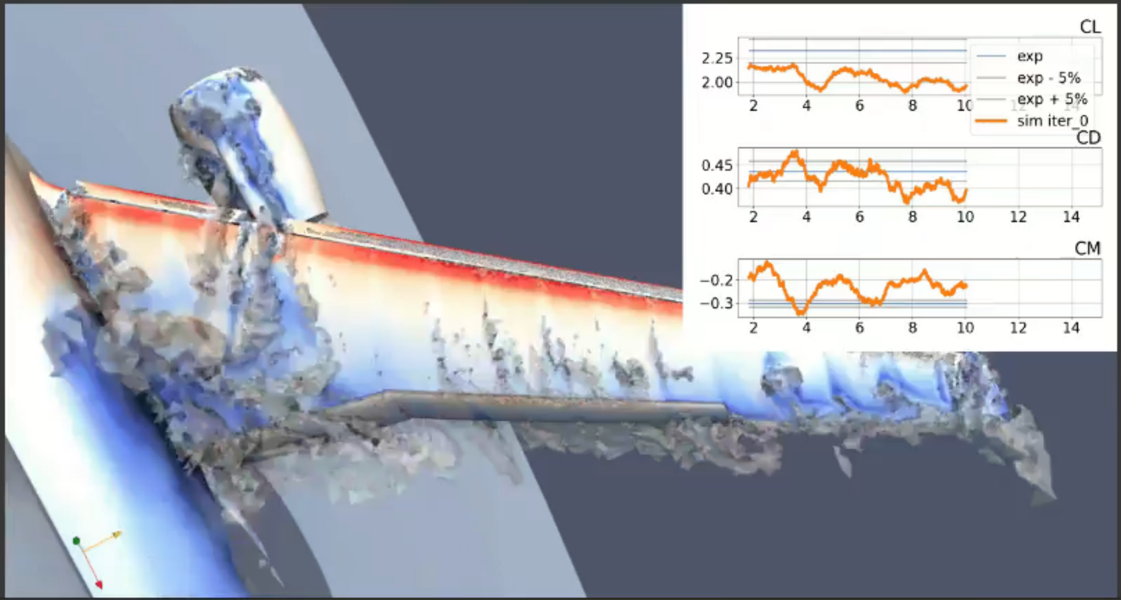
```
# Weak residual of stabilized Direct FEM for Euler
rs_m = inner(grad(p) + grad(um)*um + f_noise, v)*dx
rs_c = (inner(div(um), q))*dx
r_m = (inner(u - u0, v)/kf)*dx + rs_m + wgammas*nm*inner(um, n)*inner(v, n)*ds + LS_u
r_c = (2*kf*inner(grad(p - p0), grad(q)))*dx + rs_c + r_c_unique + LS_p
```

Overwriting file_part02.py

Show code

...

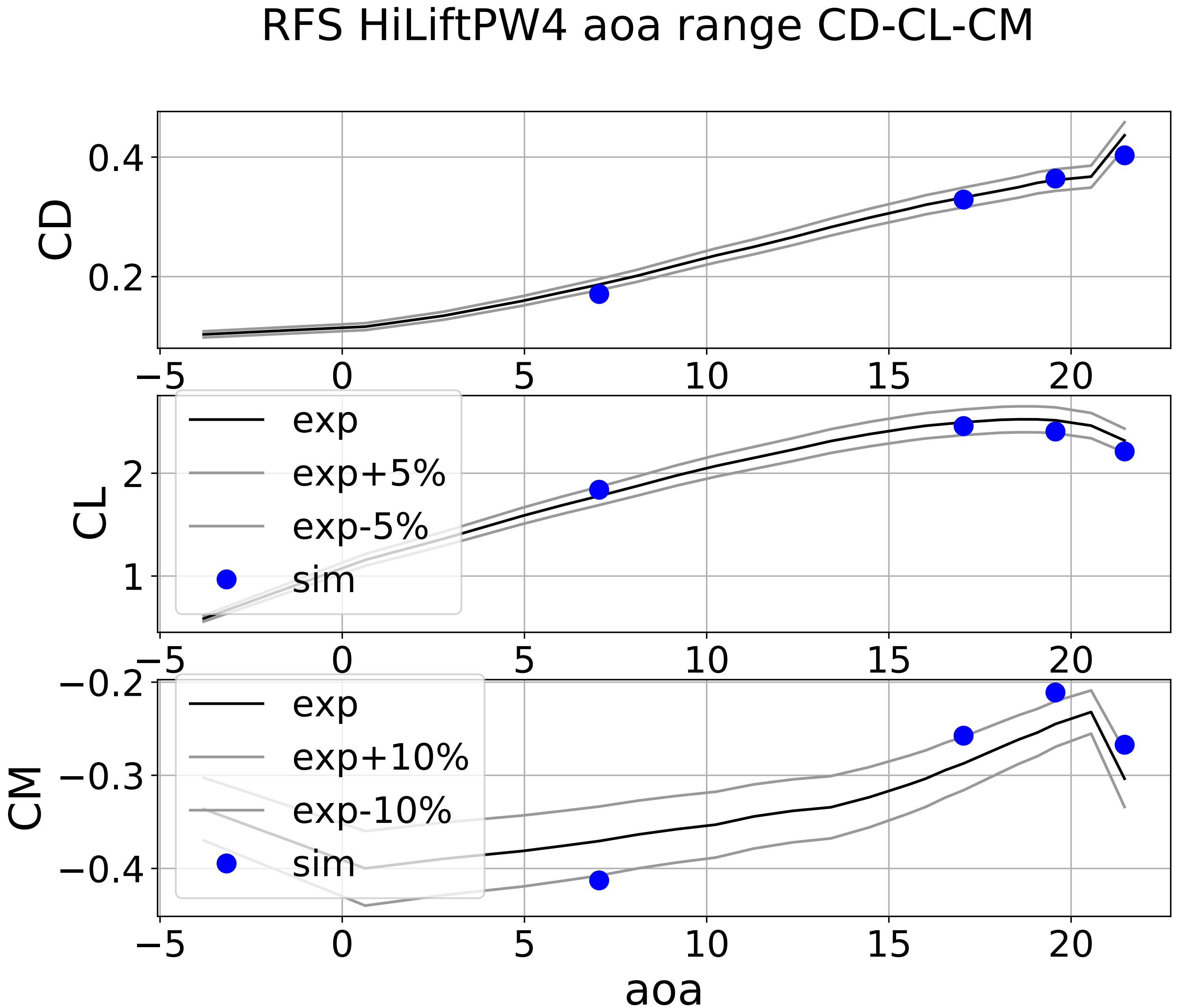
Visualization of Adaptive Euler HiLiftPW4 jjan@kth.se



Executing (5h 9m 32s) Cell > system() > _system_compat() > _run_command() > _monitor_process() > _poll_proces

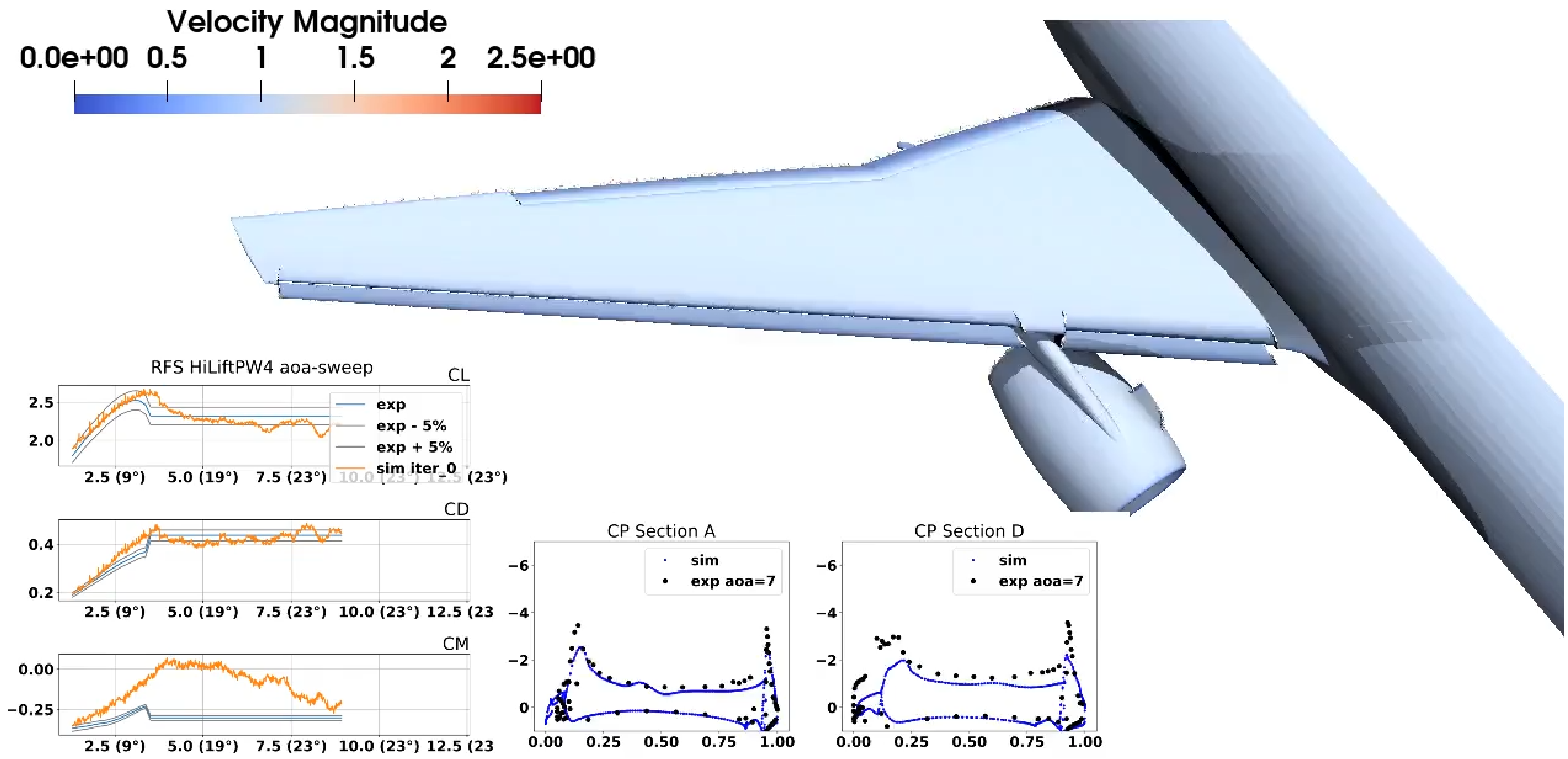
Prediction of CL and CD pre-stall within 5%, and CM for all angles and CL and CD at stall within 10%, spefically also predicts pitch-break.

Mesh-independent under adjoint-based adaptive error control



aoa sweep 7-23 with animated CP

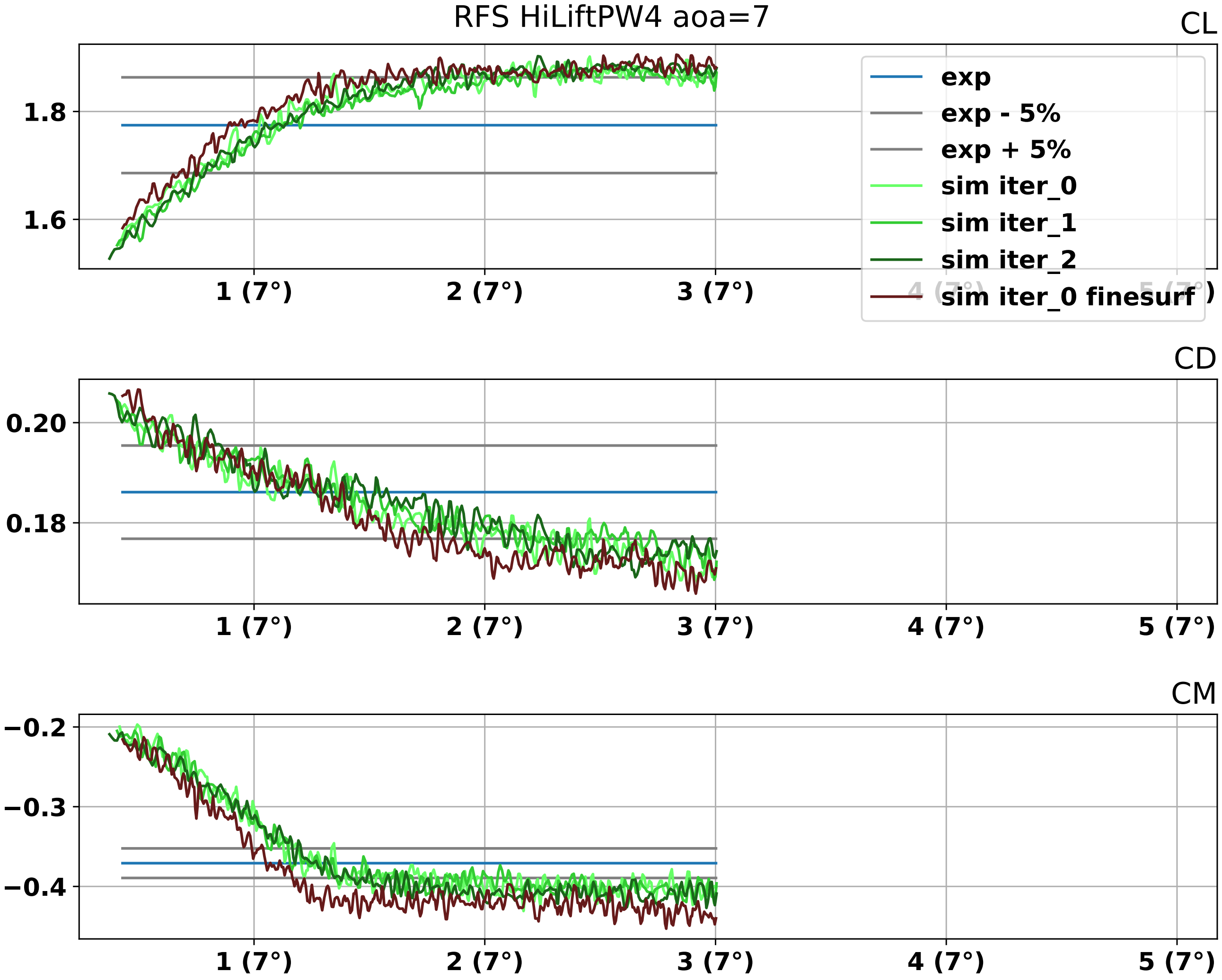
Digital Math RFS HiLiftPW4 jjan@kth.se aoa: 07.00°



- Coarsest starting mesh ~500k vertices (from ANSA).
- Both CD and CL within 5% of exp, mesh-independent under adaptive refinement.
- First principles and very cheap+fast: 10-100 core hours
- Euler equations - slip boundary condition

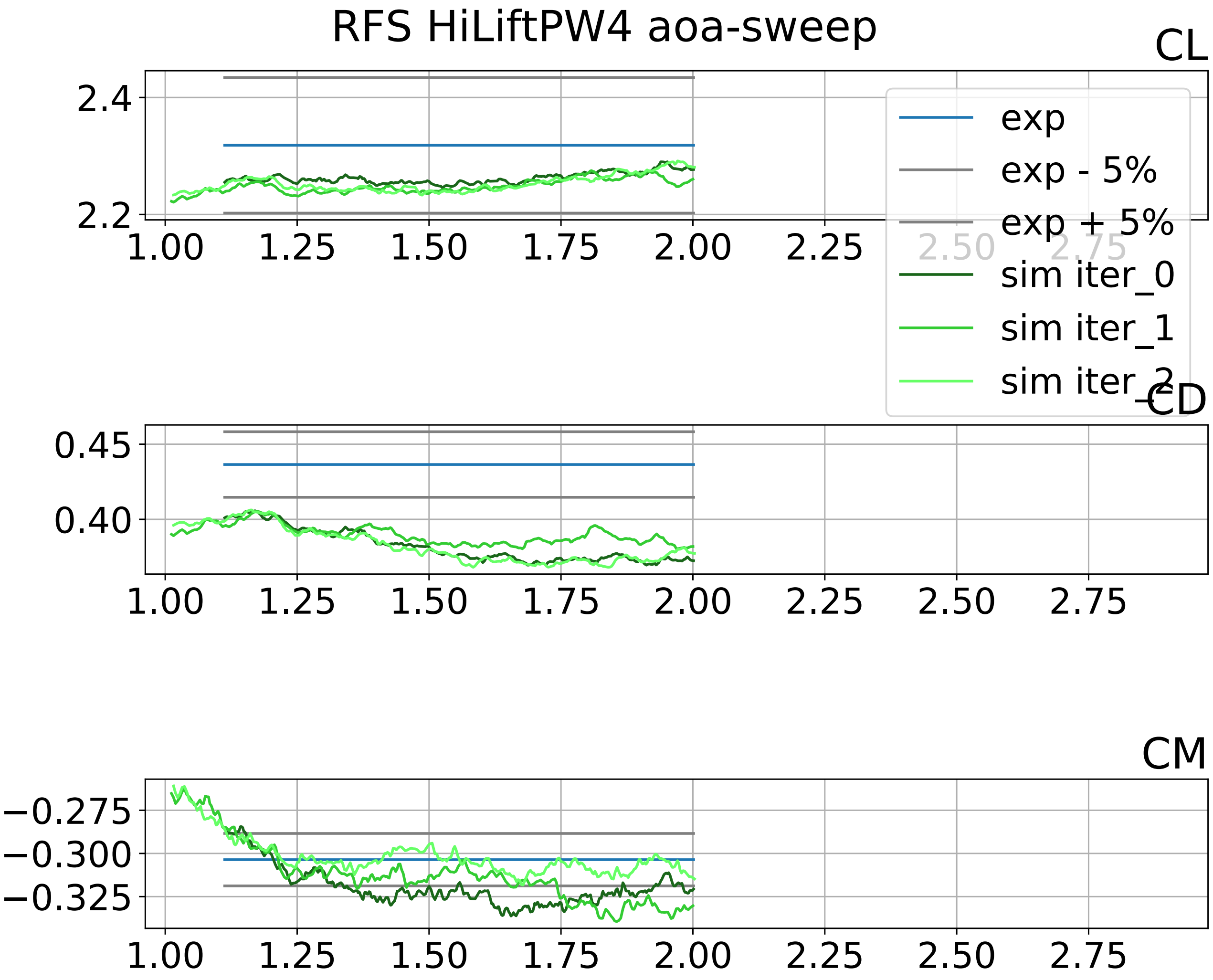
Adaptive error control for fixed aoa=7

Both CD and CL within 5% of exp, CM within 10%, mesh-independent

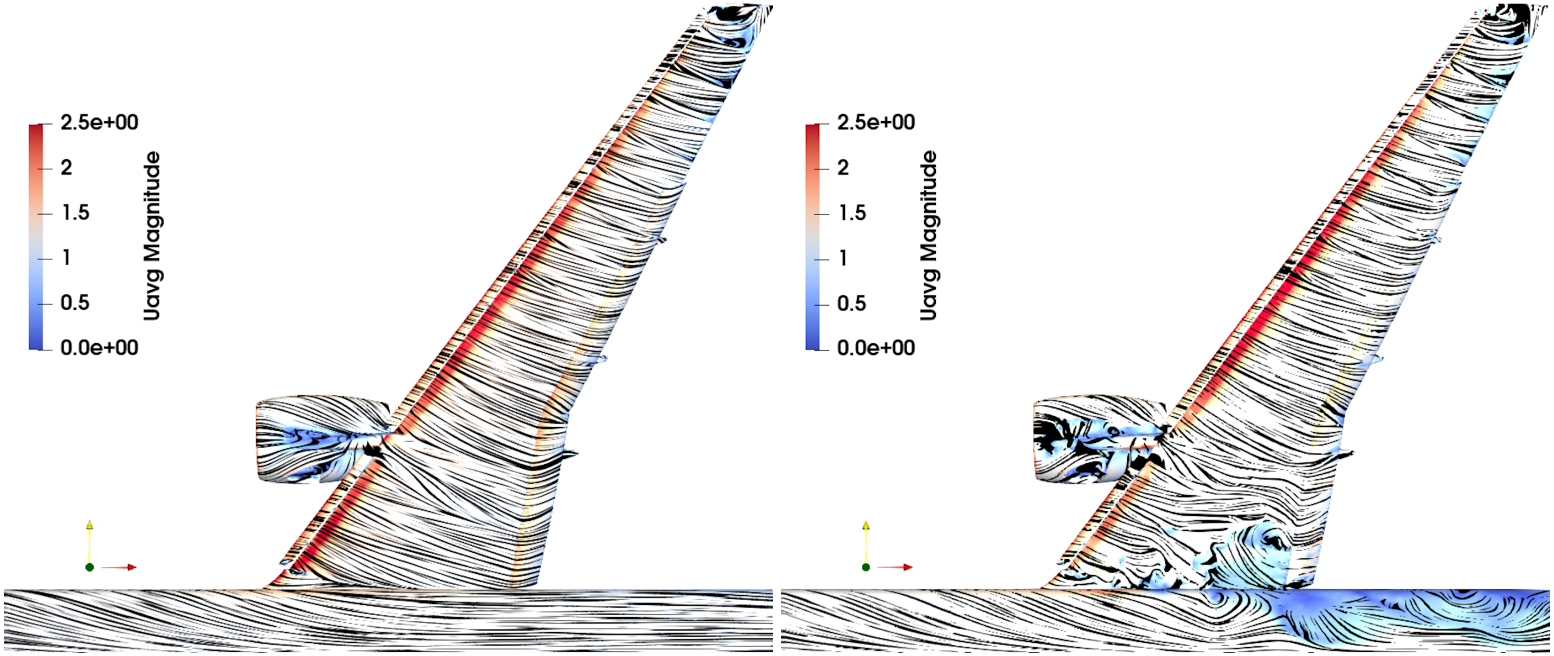


Adaptive error control for fixed aoa=21.5 (fine surface mesh)

CD, CL and CM within 10% of exp, mesh-independent

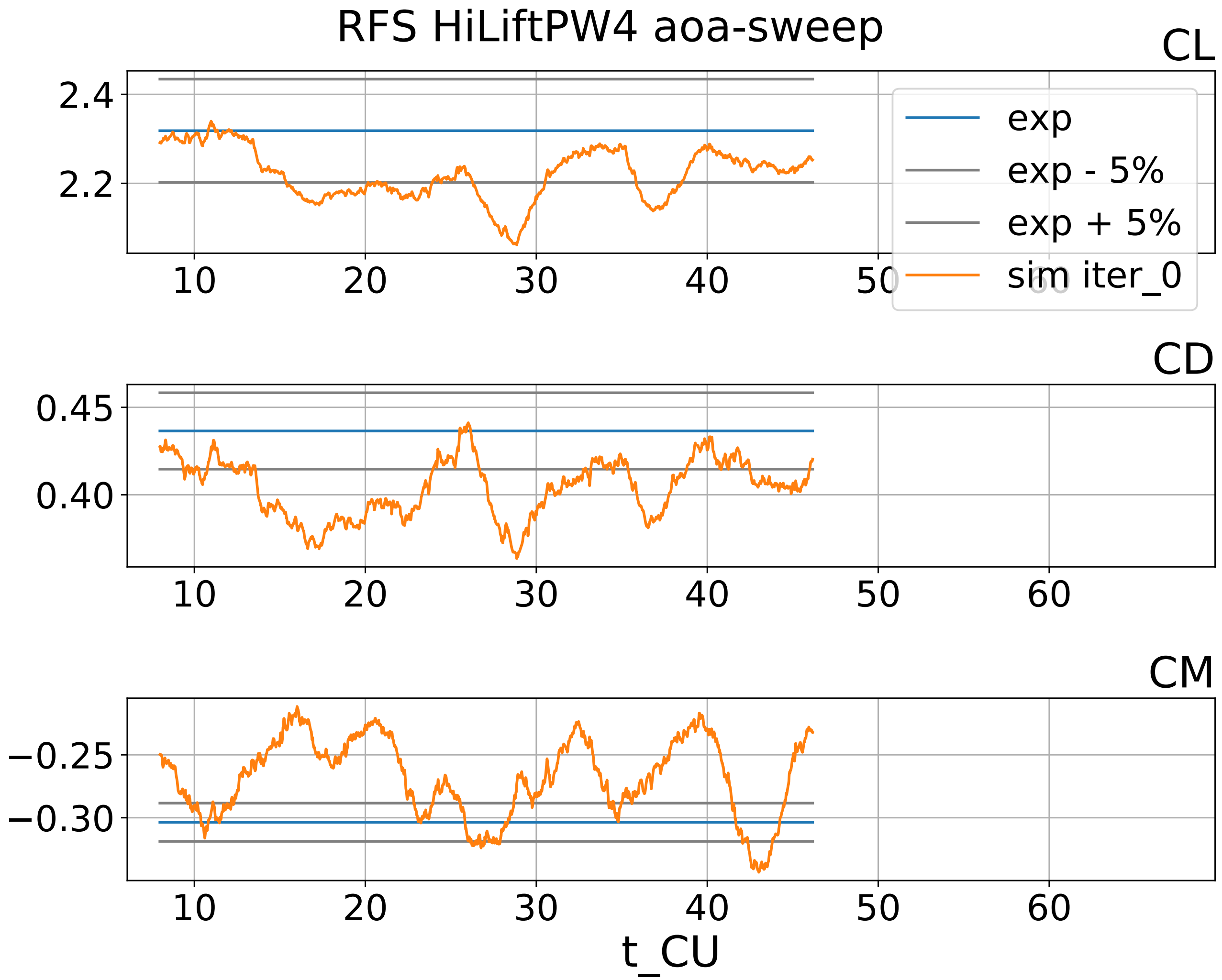


Surface streamline for aoa=17 (left) and aoa=21.5 (right) (fine surface mesh)



Time history for Free-air alpha=21.5

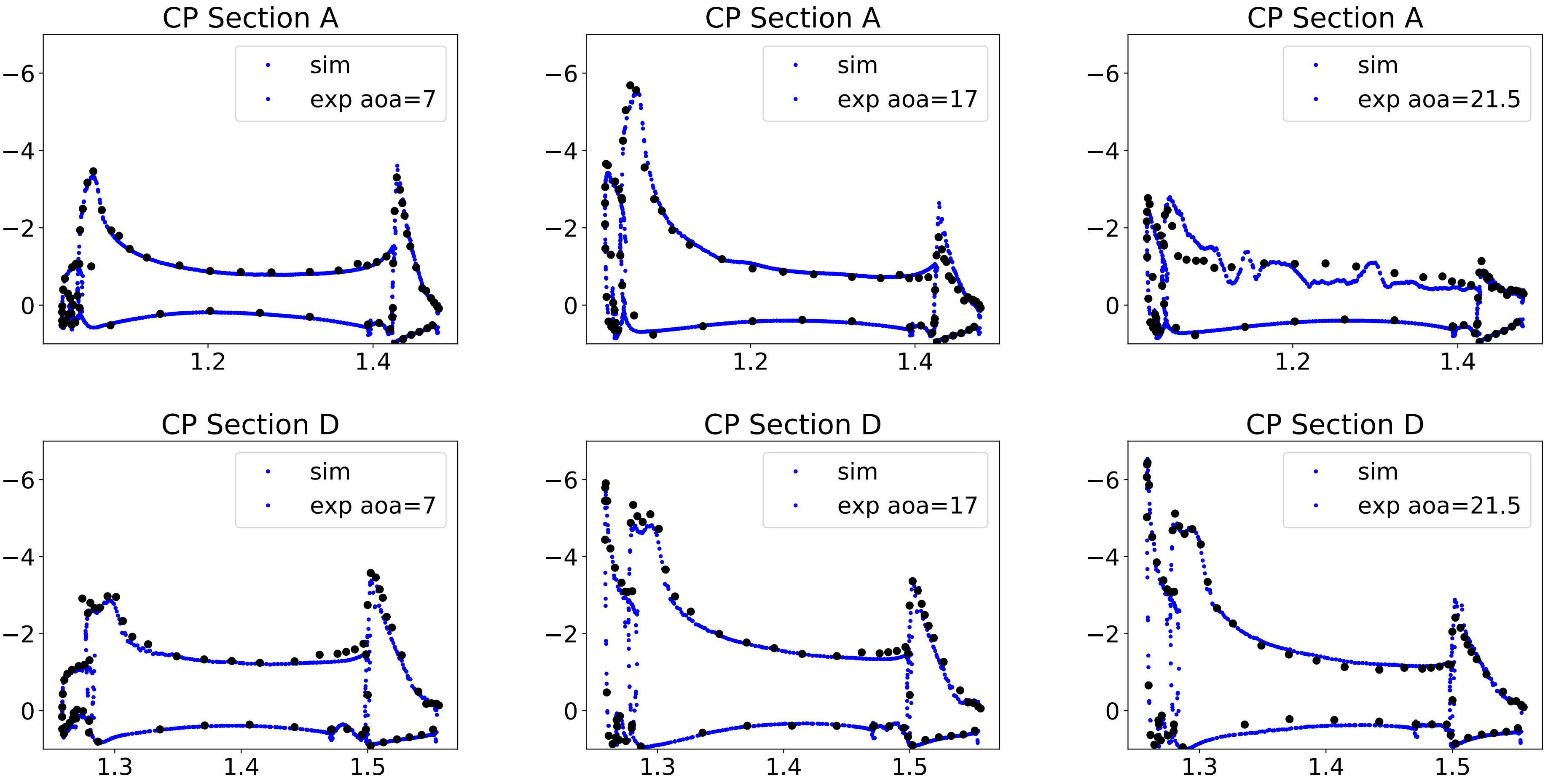
50 CU | 4 core hours / CU | Total cost: 2 USD



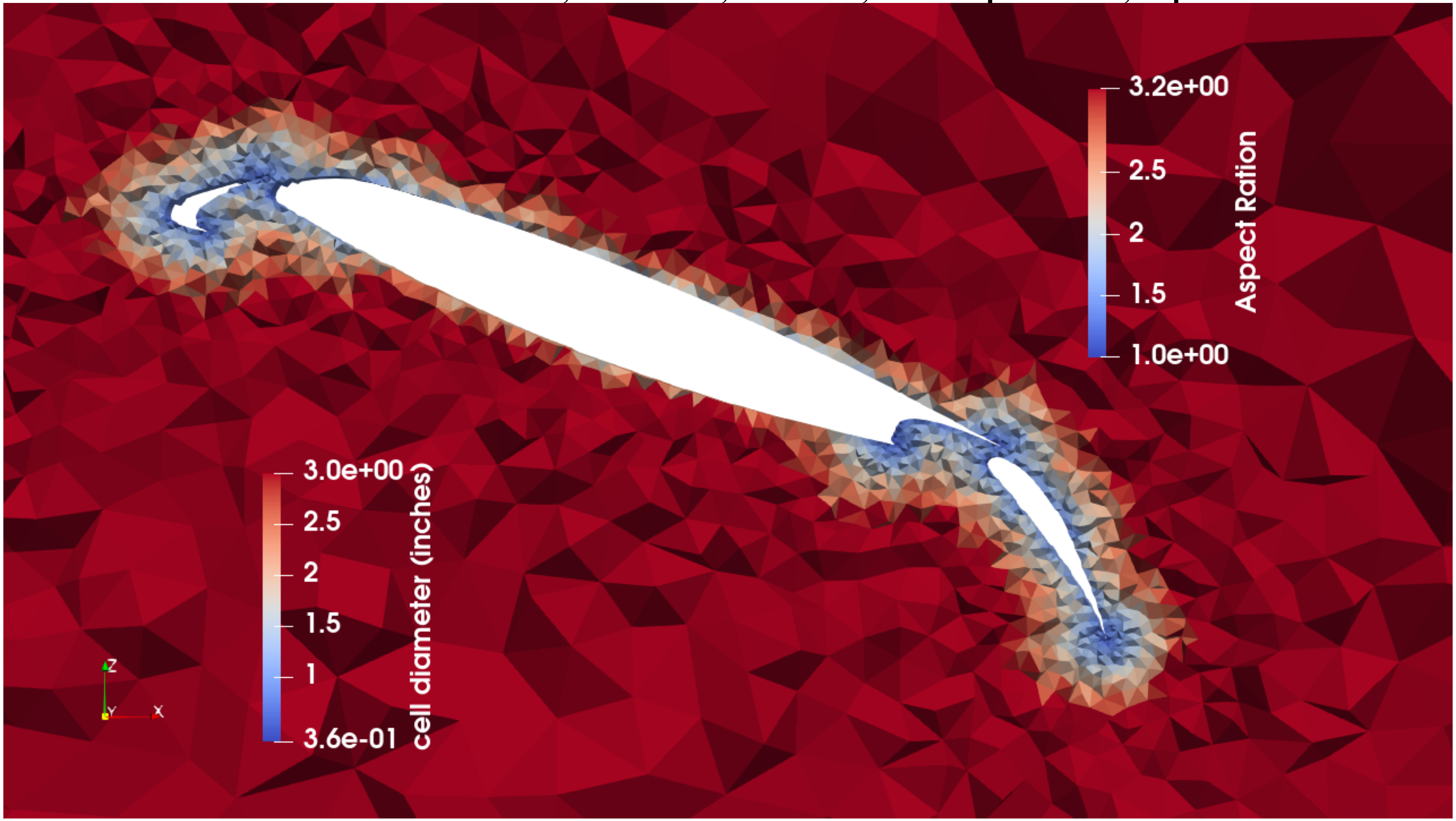
CP plot for 21.5deg

Consistent with 5% accuracy vs. exp in forces, which are simply integrated CP.

Note oscillatory CP in in-board separation wake at A.

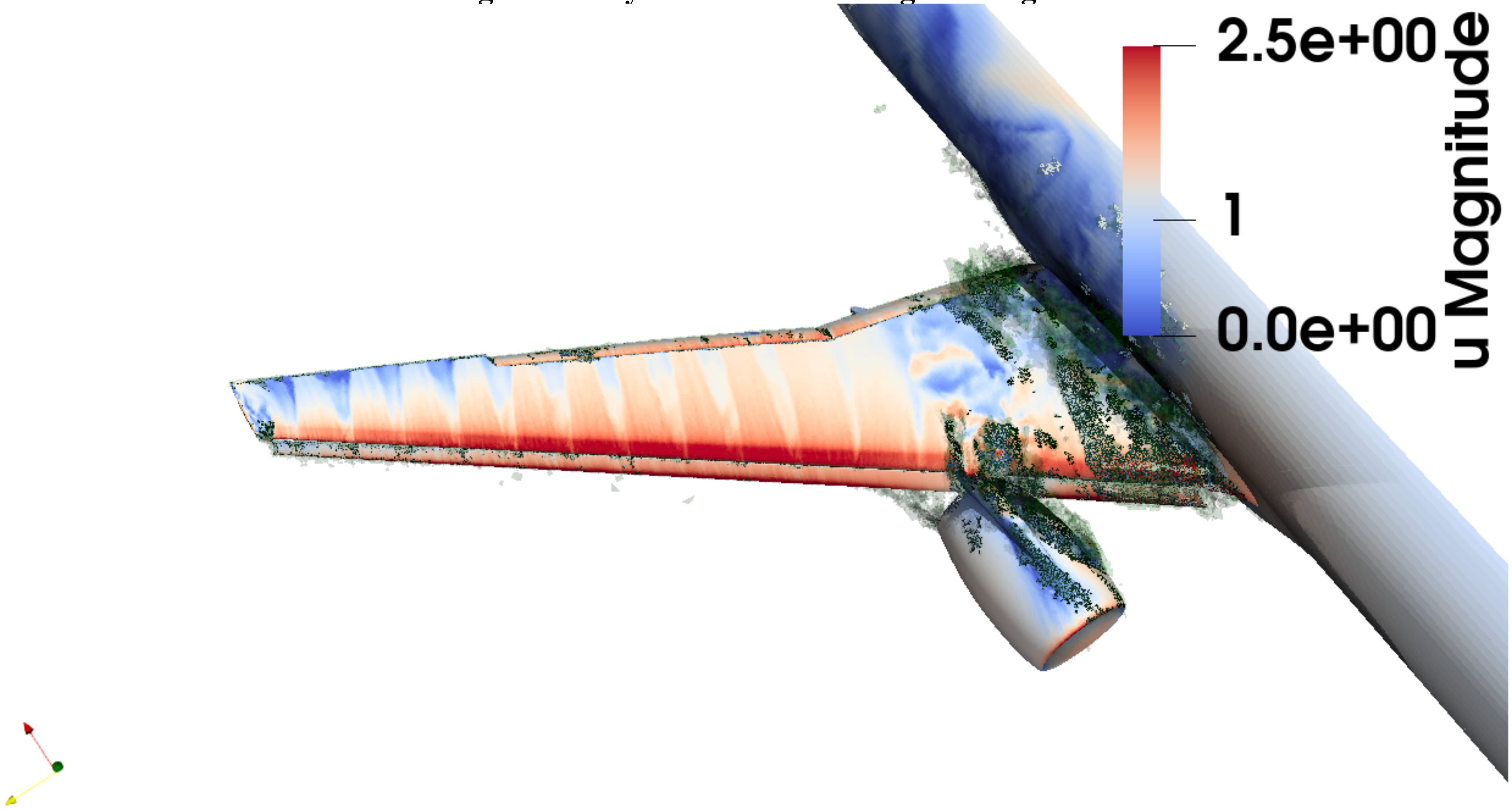


Cell diameters: 10% chord: 1 inches, 50% chord, 1.5 inches, Slat+Flap: 1 inches, Aspect Ratio: 1-3



Snapshot of adjoint solution (green) for aoa=21.5

Showing sensitivity in nacelle and wing-root region



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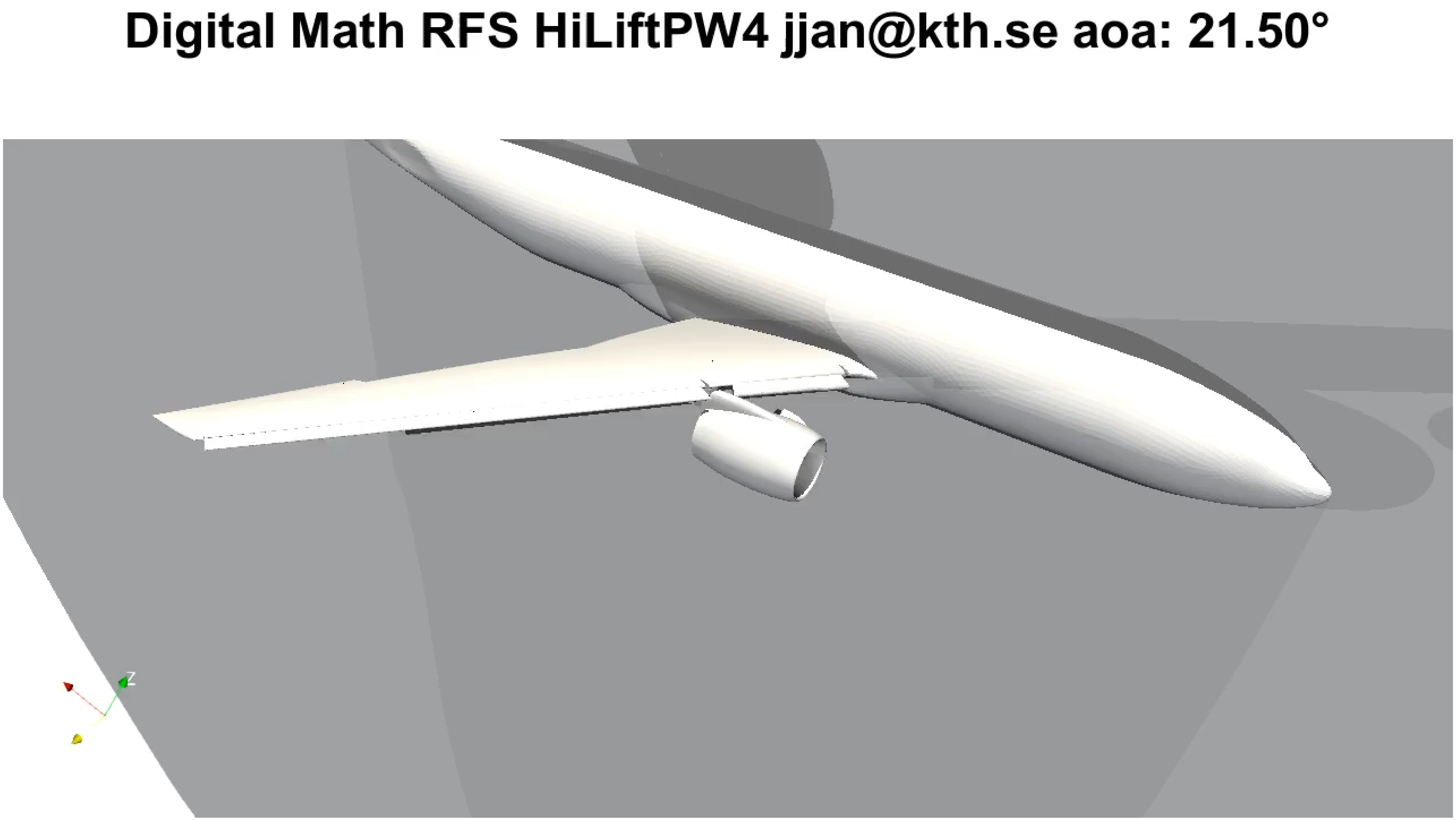


Euler overview paper

http://digimat.tech/paper-euler-short/

Euler CFD as a solution to NASA Vision 2030

1. Emphasis on physics-based, predictive modeling:
Predictive - first-principles, parameter-free, adjoint-based adaptivity

2. Management of errors and uncertainties resulting from all possible sources:
Same as 1, additionally automatically generates low-level source code from math notation

3. A much higher degree of automation in all steps of the analysis process:
Same as 1 and 2

4. Ability to effectively utilize massively parallel, heterogeneous, and fault-tolerant HPC architectures:
Extremely cheap and fast performance (less than 200 core hours),

5. Flexibility to tackle capability- and capacity-computing tasks in both industrial and research environments
Same as 4

6. Seamless integration with multidisciplinary analyses that will be the norm in 2030
Digital Math general framework for PDE (FSI etc.)

Key questions

1)- How sensitive are the integrated forces and moments (e.g. lift, drag, pitching moment coefficients) to the computational grid? (a) Will we be able to show convincing convergence with respect to the grid? (b) Can we define a credible process for verifying that the results are sufficiently converged, and what exactly would that process be?
Yes to all. 5% of experiment (10% for moments and at stall angle) under adjoint-based adaptive error control.

How do we handle the very thin boundary layer at the leading edge in a sufficiently accurate yet affordable manner?
Euler - slip boundary condition is enormously fast and cheap.

Will some kind of implicit time-stepping be necessary at realistic Reynolds and Mach numbers?
To be able to do adaptive error control, we need FEM in space-time - cG(1)cG(1) - which is implicit.

What are the factors limiting accuracy and/or computational cost, and what is the estimated gain (in accuracy and/or cost) from improvements to each factor?
With Euler we do not see anything limiting accuracy and/or computational cost. Accuracy: 5% . Computational cost: 5 USD.

Relevance of tripping used on the wing. Does tripping need to be explicitly represented, or numerical transition is sufficient?
We do not have tripping anywhere.

With the fuselage mounted on the tunnel wall, how important is it to characterize the tunnel boundary layer?
With first-principles Euler, we can predict the experimental results without any tunnel geometry or boundary layers from the tunnel.

Discussion

- Proposed Euler CFD/RFS as solution to the NASA Vision 2030 challenges.
- Predictive incompressible unsteady Euler - first principles - no modeling parameters.
- Extremely fast and cheap: < 100 core hours - "zero" computational cost
- Coarse mesh from ANSA: 500k vertices giving good validation.
- Vision: Design and certification of aircraft and engineering systems should be done by simulation (e.g. Digital Math Euler Real Flight Simulator) within 5 years.
- Collaboration activity on Euler with ZJ Wang in TFG, replicates fundamental result.
- Slip BC: models the very small skin friction beyond drag crisis at Re ~500000
- Compressible formulation showing similar promising results, on-going validation.

Conclusion

- We can with first principles predictive Euler CFD/RFS predict the forces for the sweep of aoa=7 through aoa=21.5, and moments, within 5% of experiment (10% for moments and at stall angle) under adjoint-based adaptive error control.

Perspectives

- The Euler approach represents a paradigm shift in fluid mechanics, giving a first-principles approach, and resolving the challenges described in NASA Vision 2030
- The Euler approach matches the experiments to expected accuracy, and gives comparable validation results to other WMLES results, but 1000x faster and cheaper, with adaptive error control, and with no manual/explicit parameters to tune.

You're welcome to get involved!
Try yourself, modify, extend!
http://digitalmath.tech/hiliftpw4-aiaa

Commercial cooperation:
http://icarusmath.com

Any questions, ideas, comments:
jjan@kth.se

Appendix: Predagogic overview of Euler and HiLiftPW2 and 3 results

Online course DigiMat Pro (30000+ participants):

http://digimat.tech/digimat/#digimat-Pro
("Real Flight Simulation" and "Adaptivity")

Appendix: Collaboration activity on Euler in HiLiftPW4

Basic statement:

Johan Jansson and ZJ Wang are driving forward an activity on first-principles Euler in HiLiftPW4, and can now make a basic statement that:

1. Unsteady Euler equations with free slip can generate unsteady vortices and produce separation.

The working assumptions in the activity are:

1. The solution of the unsteady Euler equations is a good approximation of the Navier-Stokes equations at very high Reynolds numbers (Re) . 2. We also need to assume that when Re is high enough, the forces converge under (adaptive) mesh refinement to a well-determined value.

The plan is to carry out further verification and development together.

Appendix: Solving the reproducibility crisis - Digital Math

One important aspect that we're driving forward is reproducibility, there is a reproducibility crisis in science today, and we see that we have a solution with our Digital Math framework, which in principle means to also publish the runnable source code in a web environment with data, and leveraging a high-level mathematical notation as we have in our Open Source FEniCS framework. This is described in a Panel Debate I organized with the EU Commission, Swedish Parliament and Lorena Barba, who was part of developing guidelines for this in the National Academies of Sciences in the US.

Lorena Barba says in Physics World:

> What we are calling for is changing those norms to give importance to the full set of digital objects that are part of a scientific study and acknowledging that the scientific paper is insufficient today in its methods section to include all of the information needed for another researcher to confirm the results or build from those results.

Panel debate and references in: http://digimat.tech/paneldebate-kth/

Appendix: NASA Vision 2030:

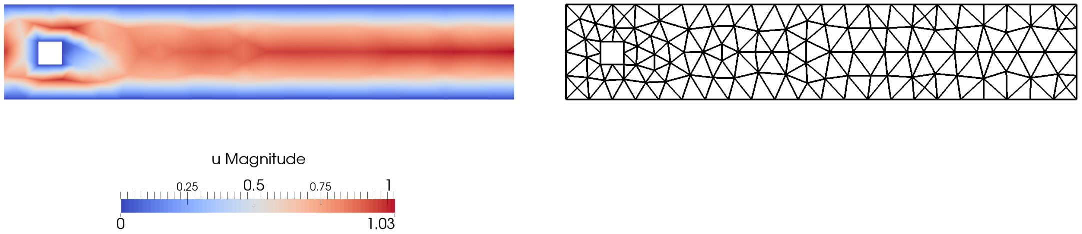
The basic set of capabilities for Vision 2030 CFD **must include, at a minimum**
...
3. A much higher degree of automation in all steps of the analysis process is needed including geometry creation, mesh generation and **adaptation**, the creation of large databases of simulation results, the extraction and understanding of the vast amounts of information generated, and the ability to computationally steer the process. Inherent to all these improvements is the requirement that every step of the solution chain executes high levels of reliability/robustness to minimize user intervention.
...
Although grid refinement is often seen as a panacea to addressing grid resolution issues, it is seldom done in practice (with the exception of a few workshop test cases) **because uniform refinement is impractical in 3D**. **Adaptive mesh refinement strategies offer the potential for superior accuracy at reduced cost, but have not seen widespread use due to robustness, error estimation, and software complexity issues.**

Appendix: Automated Digital Math- realized in FEniCS

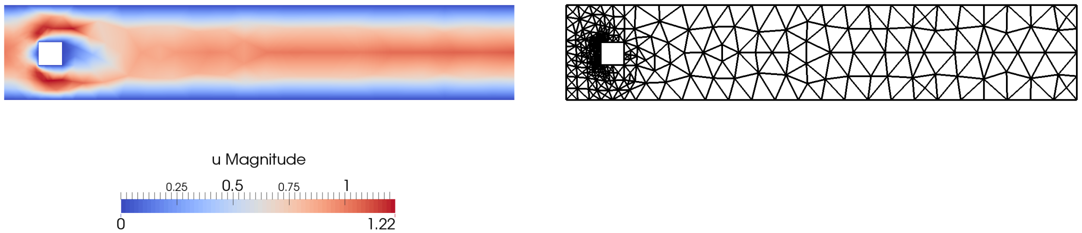
- **Automated discretization:** (generate code for linear system from PDE/model.)

  `r = (inner(grad(u), grad(v)) - inner(f, v))*dx` $\Rightarrow$ `Poisson.cpp`

- **Automated error control:** (including parallel adaptive mesh refinement.)
  Direct duality-based error control: $M(\hat{e}) = r(\hat{U}, \hat{\phi})$



$|M(e)| \leq TOL \Rightarrow$



  with $M(e)$ a goal functional of the computational error $e = u - U$, and $\hat{\phi}$ the adjoint.

- **Automated modeling of unresolved subscales:** (i.e. turbulence)
  $(R(U), v) + h(R(U), R(v)) = 0, \forall v \in V_h$ (residual-based stabilization/dissipation)

Goal: Automatically generate the **program**, **mesh** and **solution** from PDE/model (residual) and goal functional $M(U)$ (e.g. drag).

First principles - Euler equations for fluid - slip boundary condition