World-unique breakthrough: Direct FEM prediction of aerodynamics for design and control

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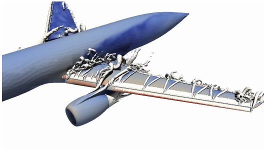
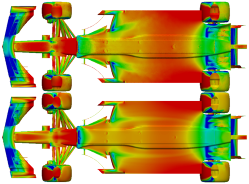




What is Icarus Digital Math?

Open Source spin-off company from academic excellence at KTH, Chalmers and BCAM.

Digital Math - Formulation in FEniCS FEM math notation together with automated computation gives constructive proof, scientific method, reproducible, modifiable, etc.

Direct Finite Element Simulation (DFS) in Digital Math FEniCS offers a unique breakthrough of the main grand challenge in Computational Fluid Dynamics (CFD) of the NASA 2030 Vision: Simulation of 1) **turbulent** 2) **separated flow** in 3) **predictive** quantitative form.

The slip boundary condition is the key to capture the true physics of flow separation as 3d rotational slip separation, shown to be impossible with conventional techniques.

Main message

New methodology and theoretical framework:

- DFS with slip makes CFD computable, because boundary layers don't have to be resolved.
- Gives correct outputs, drag and lift, for basic and advanced benchmarks.

Potential to fundamentally change design, certification and control in aerodynamics.

Recognition and impact at highest echelon of academia and industry

- Recognition from NASA, Fields medalist
- We are elected to IVA Royal Swedish Academy of Engineering Sciences 100-list
- Close partnership Amazon AWS - paradigm shift “elastic supercomputing” with our technology.
- Leading global online course MOOC-HPFEM, 10000+ students, KTHs largest MOOC.
- Pilot project one of the best Formula 1 teams
- Pilot project Norwegian
- ELISE Vinnova project transforming Sweden to electric aviation.
- Client project: Heart Aerospce electric aircraft (Y Combinator)
- Our Open Source FEniCS technology that we founded now de-facto world-standard for mathematical FEM, 300+ developers, 100k+ downloads / year
- Academic and commercial grants, resources, etc. National, EU, Swedish Innovation Agency, etc.

Automated Digital Math - FEniCS

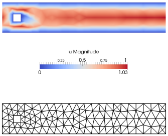
FEniCS(-HPC) open source FEM framework for automated solution of general PDE and Direct FEM Simulation (DFS). We started FEniCS 2003, today de-facto world-standard for mathematical FEM with 100s co-authors at highest level in academia:

Automated discretization (generate code for linear system from PDE):

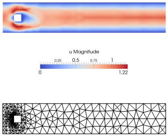
```
r = (inner(grad(u), grad(v)) - inner(f, v))*dx
```

$\Rightarrow$ `Poisson.cpp`

Automated error control (incl. parallel adaptive mesh refinement):



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



with $M(e)$ a goal functional of the computational error $e = u - U$.

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: Autom. generate the solution, mesh and program from PDE (residual) and goal functional $M(e)$ (e.g. drag).

Direct FEM Simulation (DFS)

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

Incompressible Euler as model for high Re flow:

$$\begin{aligned} R(\hat{u}) &= \begin{cases} \partial_t u + (u \cdot \nabla) u + \nabla p = 0 \\ \nabla \cdot u = 0 \end{cases} \\ u \cdot n &= 0, x \in \Gamma \quad \text{(Slip BC)} \\ \hat{u} &= (u, p) \end{aligned}$$

Weak residual $r(\hat{u}, \hat{v}) = (R(\hat{u}), \hat{v})$

Space-time cG(1)cG(1) FEM with Galerkin/least squares stabilization

$$r(\hat{U}, \hat{v}) = (R(\hat{U}), \hat{v}) + (\delta R(\hat{U}), R(\hat{v})) = 0$$

$$\delta = h, \forall \hat{v} \in \hat{V}_h, \; \hat{U} \in \hat{V}_h$$

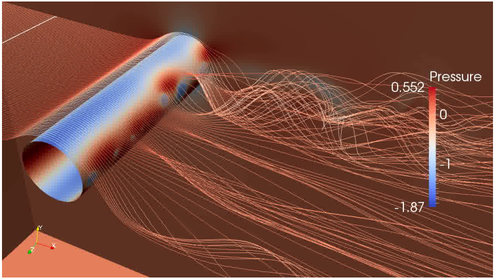
New Direct adaptive error control method

Directly use error representation: $M(\hat{e}) = r(\hat{U}, \hat{\phi})$
Error indicator: $\mathcal{E}_K = r(\hat{U}, \hat{\phi})_K$
Adjoint prob. autom. gen.: $r'(\hat{\phi}, \hat{v}) = M(\hat{v})$
Iteratively solve primal and dual problem, refine marked cells.

[Hoffman, Jansson, et. al., 2012 C&F], [Hoffman, Jansson, et. al. 2016, Encyclopedia of Computational Mechanics]

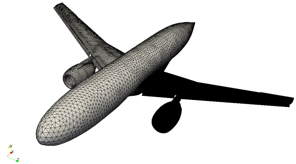
New Theory of Flight

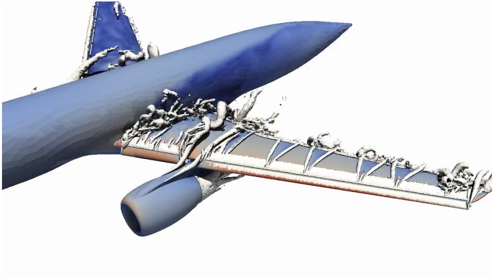
The new theory is based on our new resolution of d'Alembert's paradox showing that slightly viscous bluff body flow can be viewed as zero-drag/lift potential flow modified by 3d rotational slip separation arising from a specific separation instability of potential flow, into turbulent flow with nonzero drag/lift. Detailed Direct FEM Simulation (DFS) of incompressible Euler with slip BC validating the theory for full aircraft, NACA0012 airfoil, cylinder, car, etc. with adaptive error control.



3D slip separation

Validation: Time-resolved adaptive simulation of aircraft



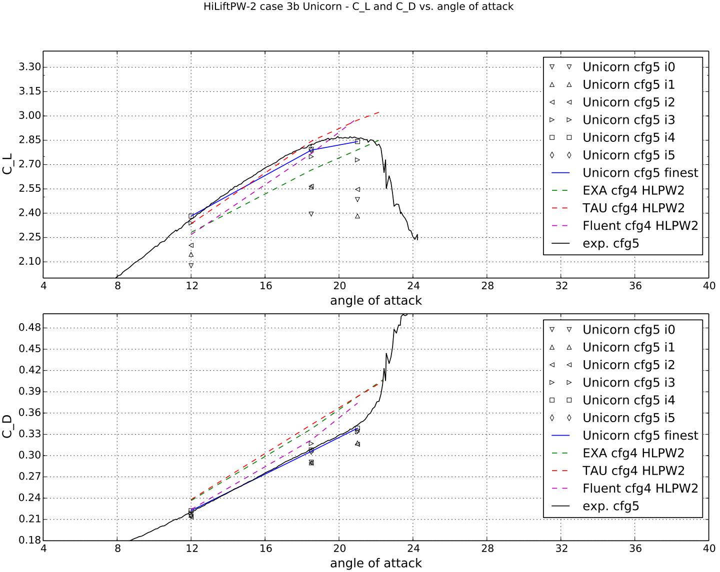


HiLiftPW 2 and 3 benchmark challenges. Participated with good results, and our adaptive methodology was highlighted in summary. Invited to provide reference results for High Order CFD Workshop 2017 [Hoffman, Jansson, Johnson, JMFM, 2015] [Hoffman et. al., CMAME, 2015], [Jansson et. al., Hilift Springer brief, 2017]

Our computational results capture phenomena including the key stall mechanism well quantitatively at $Re \approx 10^6 - 10^7$.

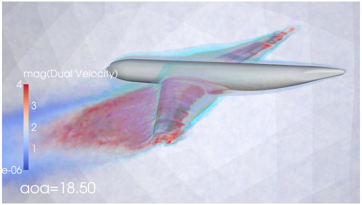
HiLiftPW-2: our results

Unicorn/FEniCS-HPC (our) results from NASA/Boeing HiLiftPW-2 workshop for full aircraft:

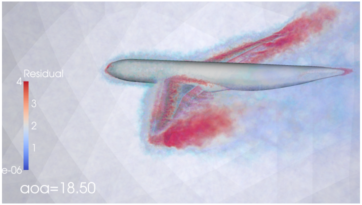


Adaptive mesh refinement - adjoint velocity

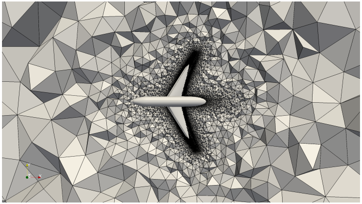
Goal quantity: drag and lift
Recall: $M(\hat{e}) = (-R(\hat{U}), \hat{\phi})$



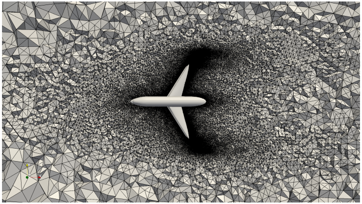
Dual velocity $\hat{\phi}$



Residual $R(\hat{U})$



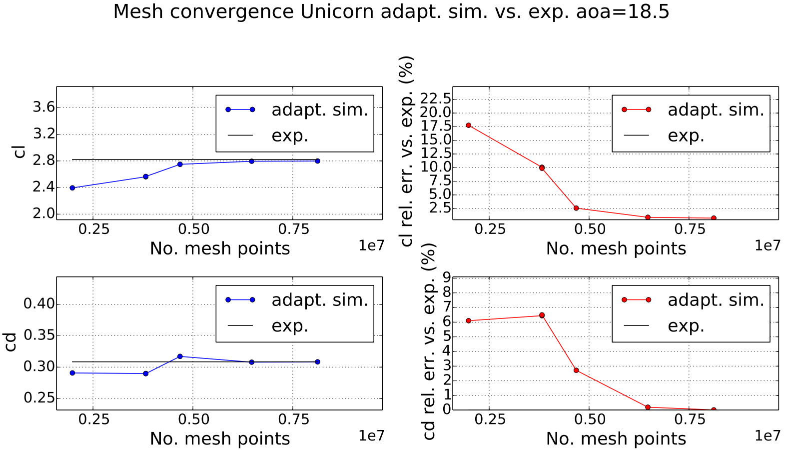
Coarse starting mesh



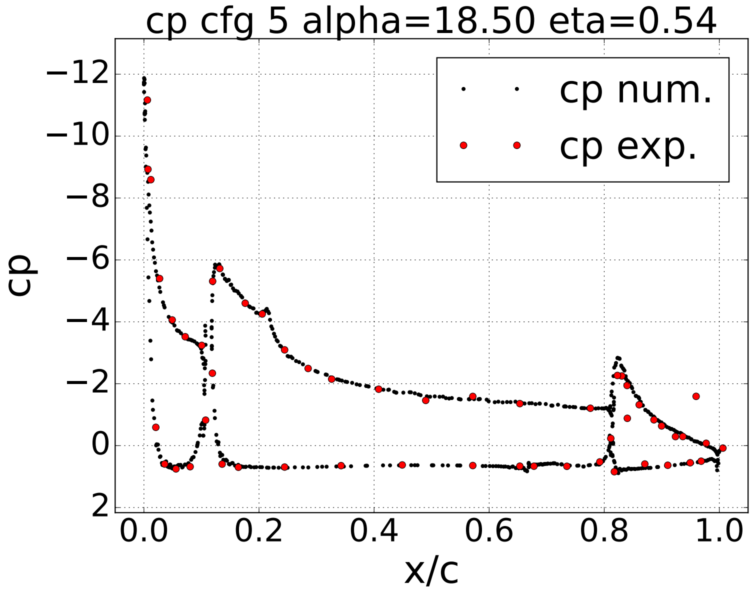
Refined mesh 5 adapt. it.

Aerodynamic forces $\alpha = 18.5^\circ$

Lift and drag within 1.5% of exp.
Use 1280 cores on SuperMUC supercomputer

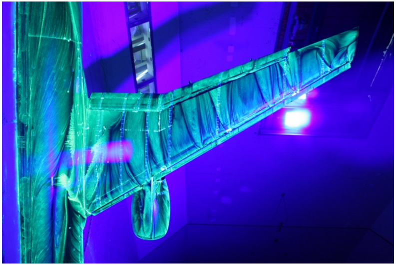


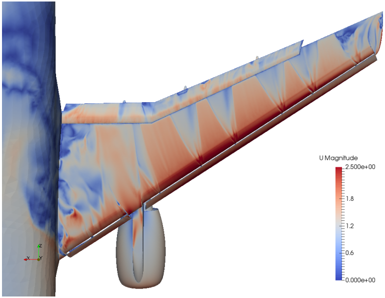
Pressure distribution

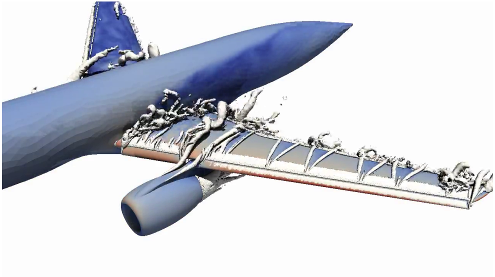


HiLiftPW-3: Surface velocity pylon-on

Stall: $\alpha = 21.57$ and $\alpha = 22.56$



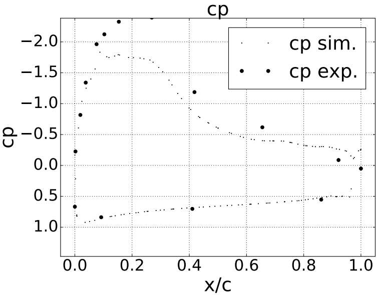




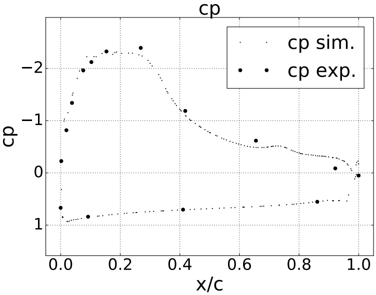
Illustrative cp ex.: adaptivity

JSM pylon-on, $\alpha = 4.36$, flap D-D
NB: Adaptivity targets mean quantity, not pointwise pressure

Adaptive iteration 0 (starting mesh)

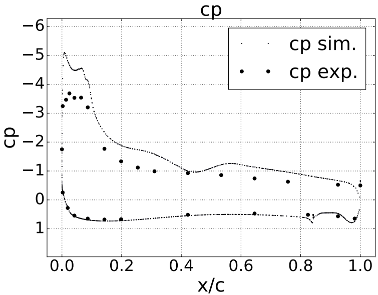


Adaptive iteration 3

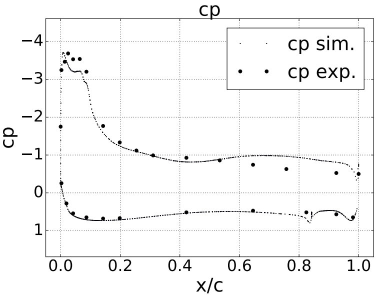


Illustrative cp ex.: stall

JSM pylon-on, $\alpha = 22.56$, wing B-B

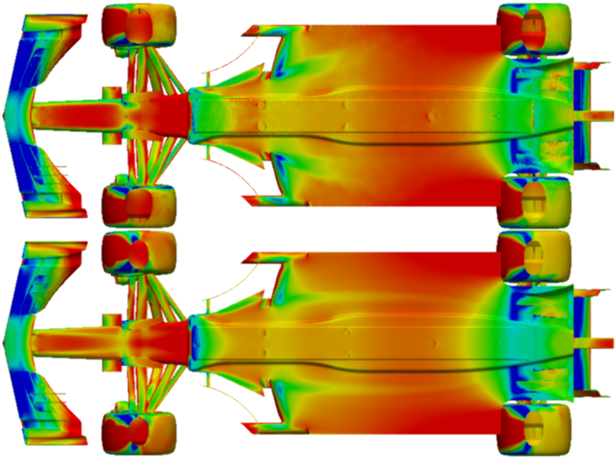


No trip-force



With trip-force

CP Perrinn F1 DFS/Unicorn/FEniCS (top) vs. Fluent (bottom)



CD and CL within 4% . 20x more cells in Fluent mesh.

In collaboration with Torbjörn Larsson (previous head of CFD in F1), Creo Dynamics.

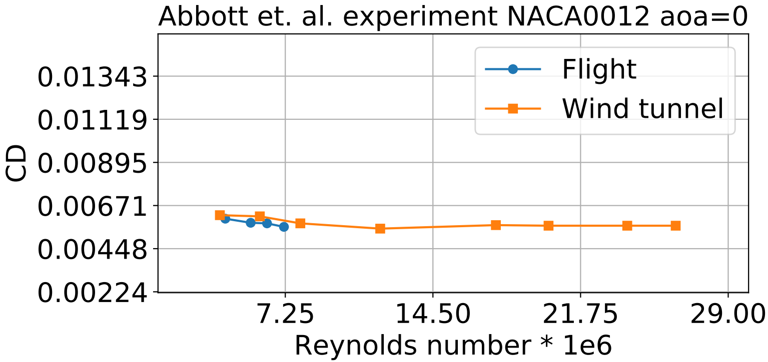
More results: F1 cases, landing gear, etc. available

Drag prediction with DFS - no skin friction

Based on the Digital Math framework and the Unicorn/FEniCS realization, we show that our Direct FEM Simulation (DFS) predictions of drag without skin friction are consistent with advanced untripped benchmarks. This changes the design process to focus on form, where large gains from increasing lift/drag may be possible.

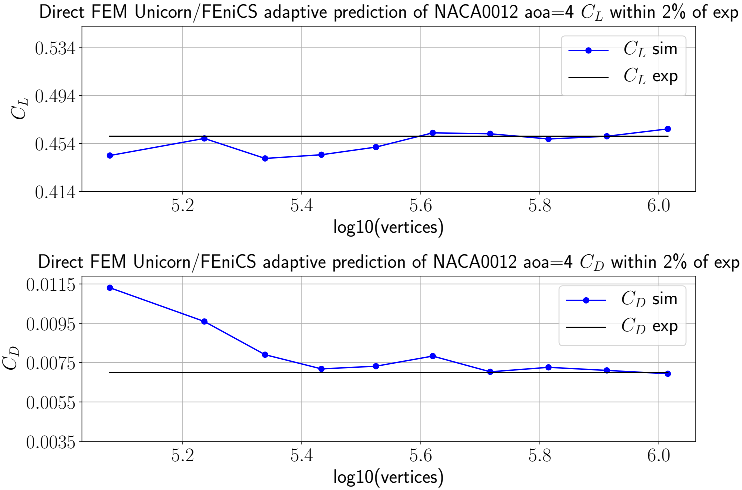
Drag prediction with DFS - untripped experiments

Untripped experiments ([Abbott, 1945], [Ladson, 1988], [Rivers, 2019]) show drag does not depend on Reynolds number, for high Reynolds number,



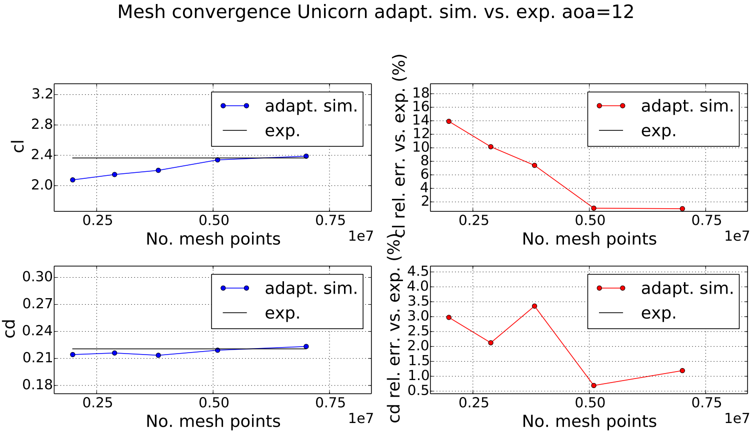
DFS drag prediction - good match with no skin friction

NACA0012 aoa=4 :



DFS drag prediction - good match with no skin friction

HiLiftPW-2 :



DFS drag prediction - good match with no skin friction

Skin friction experiments appear to use tripping to match (questionable) no-slip, which acts like a form of tripping.

Tripped experiments appear to give inflated skin friction coefficients to which standard wall models are calibrated.

Standard CFD: skin friction drag 50% of total drag = form/pressure + skin friction drag

DFS: Form/pressure drag $\geq$ 90% + skin friction $\leq$ 10%

Major impact on design: Form is everything!

DFS computes lift drag from form only. Skin friction small!

Team: Spin-off from academic excellence at KTH+BCAM

- Johan Jansson, Associate Professor KTH+BCAM, CEO+Chair
- Rahul Kumar, Post-doc JJ, PhD Houston
- Ezhilmathi Krishnasamy, PhD student JJ, MSc LTH
- Massimiliano Leoni, PhD student JJ, MSc Politecnico Milano
- Tamara Dancheva, PhD student JJ, MSc Strasbourg+KTH
- Claes Johnson, Professor emeritus KTH+Chalmers
- Ridgway Scott, Professor emeritus Univ. of Chicago

BCAM (Bilbao)

EXCELENCIA
SEVERO
OCHOA

KTH (Stockholm)

MOOC - online course on adaptive FEM, DFS, FEniCS

High Performance Finite Element Modeling MOOC supported by KTH MOOC committee on edX

10000+ participants, largest MOOC at KTH.

New round planned for January/February 2020.

Easy “elastic supercomputing” interface with Amazon AWS

We have verified large scale industrial cases both on traditional supercomputers, and now also on Amazon AWS, where we show better performance than the Cray supercomputer at KTH, and which represents a paradigm shift, allowing easy ”elastic supercomputing” in a web browser.

Possibility to run, reproduce, modify our simulations in an easy “one-click” AWS supercomputer web interface. Please let me know if you’re interested!

References

1. Jansson et. al., Hilift Springer brief, 2017
2. Hoffman, Jansson, Johnson, JMFM, 2015
3. Hoffman et. al., CMAME, 2015

Main message

New methodology and theoretical framework:

- DFS with slip makes CFD computable, because boundary layers don't have to be resolved.
- Gives correct outputs, drag and lift, for basic and advanced benchmarks.

Potential to fundamentally change design, certification and control in aerodynamics.

Summary/Conclusions

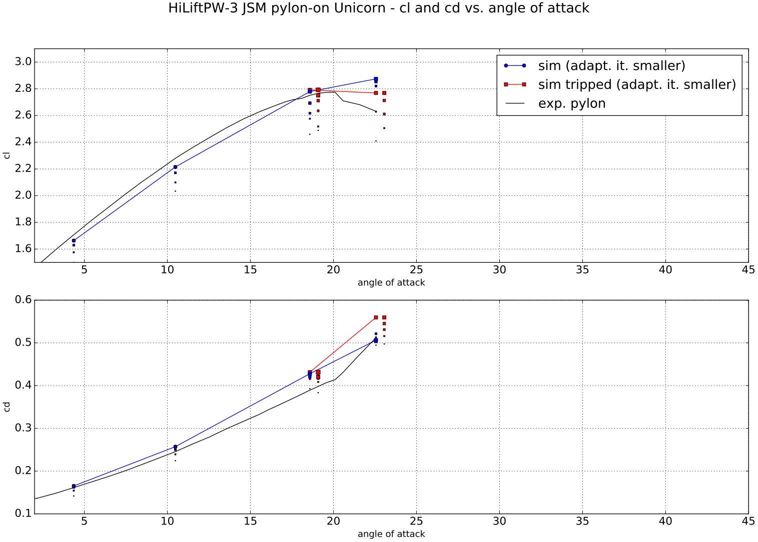
Overall summary:

- The power of general Direct FEM methodology and the FEniCS high-level modeling language and automation including code generation allows reliable, general, PDE modeling on HPC systems.
- Advanced "grand challenge" applications using HPC resources with optimal strong scaling up to at least 10000 cores: full aircraft simulation with novel results (adaptivity, stall prediction) and multiphysics applications.
- DFS enables prediction of turbulent flow cheaply, order of magnitude faster than RANS, and capturing more phenomena (stall, time-resolved). Several orders of magnitude faster than standard LES.

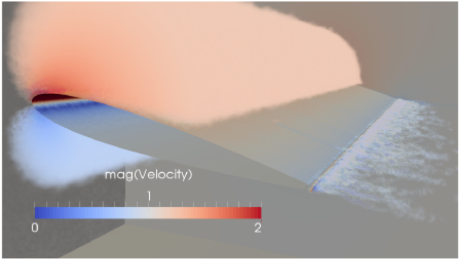
Acknowledgements:

Appendix

HiLiftPW-3 (pylon-on) our results



Streamwise vortices on trailing edge



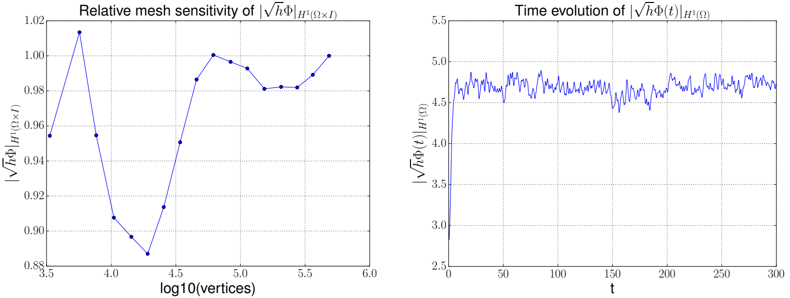
DFS computability of turbulent flow by adjoint stability

We demonstrate computability of 3D turbulent flow by stability of the 3D adjoint problem. We describe this in the invited chapter "Computability and Adaptivity in CFD" in Encyclopedia of Computational Mechanics.

We can bound the global error by:

$$|M(\hat{u}) - M(\hat{U})| \leq C_U h \|R(\hat{U})\| |\hat{\psi}|_{H^1} \tag{1}$$

We show that $\|\sqrt{h}R(\hat{U})\|$ and $|\sqrt{h}\hat{\psi}|_{H^1}$ are bounded, which gives computability.



Stability of H1-seminorm of adjoint velocity wrt. mesh refinement and time

Drag prediction with DFS - no skin friction

Rivers et. al. [Rivers, 2019] perform experiments of a full aircraft - the NASA Common Research Model. The experiments show that the drag does not depend on the Reynolds number. They say: “Typically, as Reynolds number increases, the skin friction drag decreases, which in turn means the total drag should decrease and effective camber increases. This typically results in an increase in lift at a given angle-of-attack, and at a given CL, the pitching moment should be more negative. None of the data at any of the three temperatures presented follow these trends. This break in trend may be explained by a greater extent of laminar flow at the lower Reynolds numbers, which in turn could cause a thinner boundary layer at the trailing edge of the upper surface than the higher Reynolds numbers. This behavior is being investigated further. “