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Adaptive FEM for Aerospace and Aeroacoustics Applications

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5-7 June, 2013.

About us

What do we do?

- Develop the **open-source** turbulent flow solver **UNICORN**.
  - *FEniCS open-source project.*
  - *MPI-IO, parallel mesh-refinement, dynamic load-balancing.*
  - *Adjoint based mesh adaptivity.*
  - *Linear scalability up to 12,000 cores.*
- Study **turbulent flow** phenomena with several **applications**.
- 1 Professor, 1 senior researcher, 2 post-docs, 5 PhD students.

Who am I?

- 4^{th} year (of 5) **PhD candidate**.
- Use **UNICORN** to study **aerodynamics** and **aeroacoustics**.
  - *Separation, airframe noise (landing gear, slat-noise, etc) and duct-acoustics.*

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Collaboration with **ANSA**

Workflow

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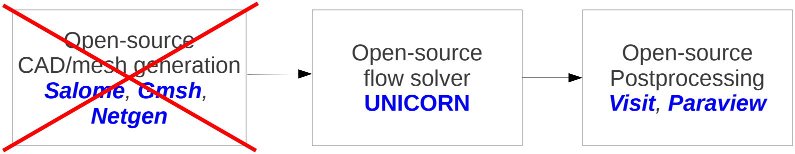
Collaboration with ANSA

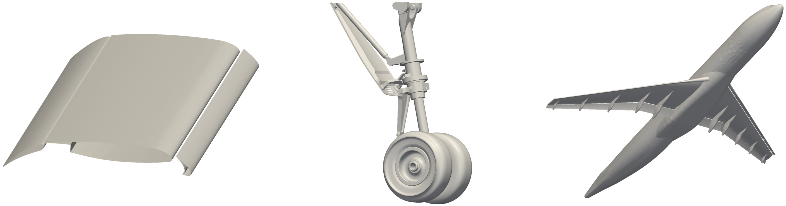
Workflow



Difficult to use for complex geometries...

Collaboration with ANSA

ANSA mesh generation



From left to right...

- 30P30N from NASA, benchmark workshops BANC-I and BANC-II.
- Gulfstream G550 nose landing gear, also BANC-I and BANC-II.
- DLR model airplane, High-Lift Prediction Workshop 2.

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Adaptive FEM for turbulent flows

General Galerkin (G2)

- **FEM** with piecewise linear approximation in space and time.
- Fully **unstructured meshes**.
- Time-resolved method where **numerical stabilization** accounts for unresolved scales.
- **Simple wall shear stress model** based on skin friction, slip velocity boundary condition, in the spirit of simpler models.[1]
- **Adaptive mesh refinement** with respect to output of interest using associated adjoint problem to estimate errors in output.

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[1] U. Schumann, *Subgrid scale model for finite difference simulations of turbulent flows in plane channels and annuli.*

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Adaptive FEM for turbulent flows

Adjoint-based mesh refinement

For $\hat{U} = (U, P)$ a weak solution, $\hat{\varphi} = (\varphi, \theta)$ a solution to a linearized adjoint problem, and $M(\hat{U}) = ((\hat{U}, \hat{\psi}))$ a mean value output, with $\hat{\psi}$ a weight function, we define the error estimate:

$$\boxed{|M(\hat{u}) - M(\hat{U})| = |((\hat{u} - \hat{U}, \hat{\psi}))| \leq \sum_{K \in \mathcal{T}_n} \mathcal{E}_K,}$$

with the error indicator:

$$\mathcal{E}_K \equiv \sum_{n=1}^{N} \left[\int_{I_n} |R_1(\hat{U})|_K \cdot \omega_1 \, dt + \int_{I_n} |R_2(U)|_K \, \omega_2 \, dt + \int_{I_n} |SD_\delta^n(\hat{U}; \hat{\varphi})_K| \, dt \right],$$

for each element K in the mesh $\mathcal{T}_n$, with stability weights ω_i, $i = 1, 2$.

Adaptive FEM for turbulent flows

Adjoint-based mesh refinement

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with the error indicator:

error in M(û) ≡ f(turbulence,adjoint solution)

for each element K in the mesh $\mathcal{T}_n$, with stability weights ω_i, $i = 1, 2$.

Adaptive Mesh Refinement

How do we generate the mesh?

Adaptive algorithm

1. For the mesh $\mathcal{T}_n$: compute primal and adjoint problem.
2. Compute $\mathcal{E}_K$, $K \in \mathcal{T}_n$.
3. Mark 10% of the elements with highest "error indicator" for refinement.
4. Generate the refined mesh $\mathcal{T}_{n+1}$, and goto 1.

Example 30P30N high-lift wing:

Initial mesh: 1M cells.
Mesh after 7 adaptive refinements: 6.6M cells.

$\Rightarrow$ Compare, e.g., with Imamura et al, 16.3M points![2]

[2]Imamura, T., Murayama, M., Hirai, T., and Yamamoto, K., *Aeroacoustic Simulations around 30P30N, JAXA's Result,"* *Proceedings for BANC-II*, 2012.

Adaptive Mesh Refinement

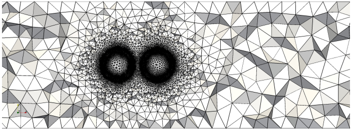
How to choose the refinement target $M(\hat{u})$?

It depends on the application...

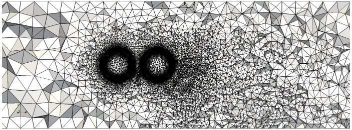
- For aerodynamics, drag, lift or drag+lift.
- For external aeroacoustics, Lighthill's analogy.
- Duct acoustics, pressure drop.
- ...

Adaptive Mesh Refinement

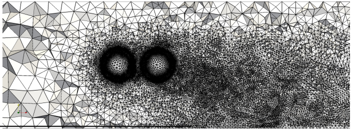
Initial mesh[3]:



3 refinements:



9 refinements:



[3] Vilela de Abreu et at, Adaptive computation of aeroacoustic sources for a rudimentary landing gear using Lighthill's analogy, Proceedings for the 17th AIAA/CEAS Aeroacoustics Conference, 2011.

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Adaptive Mesh Refinement

What are the advantages of an adaptively generated mesh?

- Mesh captures the relevant flow features.
- No need for *ad hoc* meshing.
- No need for a “mesh study” [4].
- Final mesh has “optimal” size.

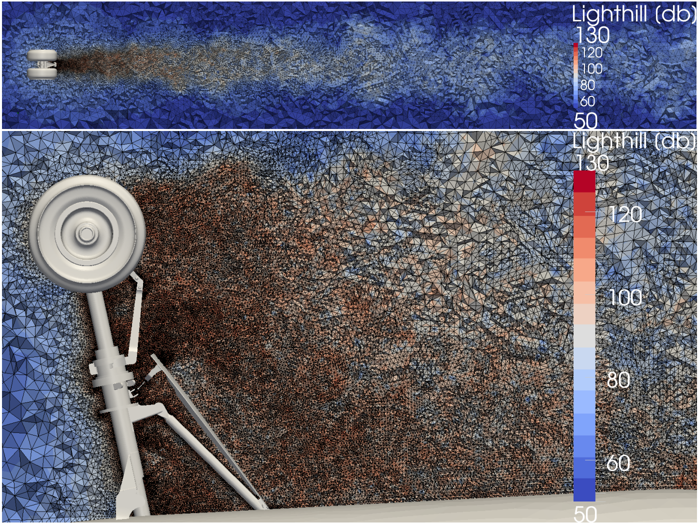
[4] A hierarchy of meshes is automatically generated by the adaptive algorithm and flow solutions are available for all meshes. Moreover, a stop criterion for the algorithm should be chosen to ensure “mesh convergence”.

Adaptive Mesh Refinement

Mesh captures the relevant flow features...

Adaptive Mesh Refinement

Mesh captures the relevant flow features...



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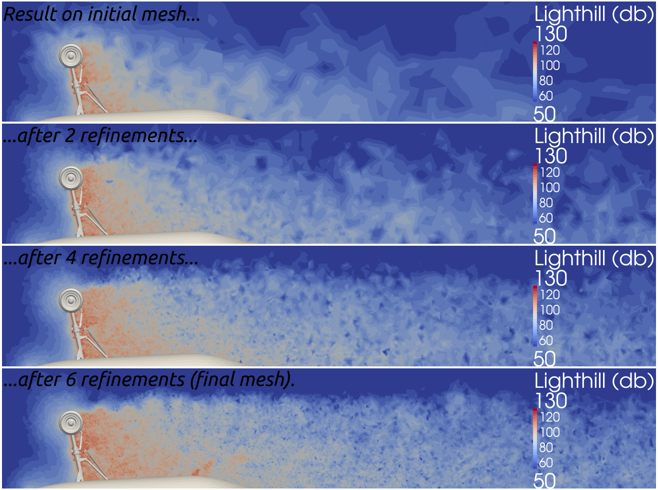
Adaptive Mesh Refinement

Solution on different meshes...



KTH VETENSKAP OCH KONST

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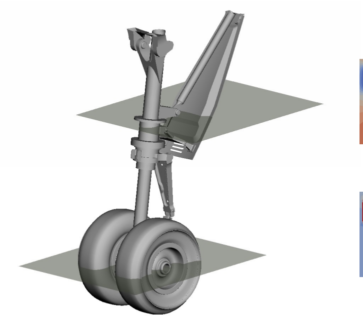
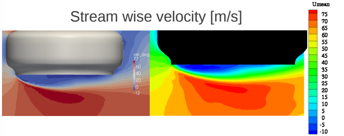
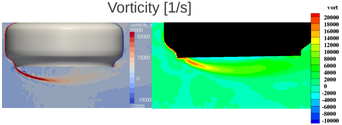
Benchmark results, BANC-II



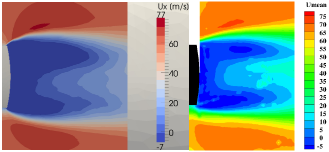
Stream wise velocity [m/s]



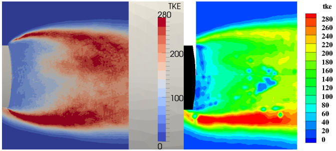
Vorticity [1/s]



Stream wise velocity [m/s]

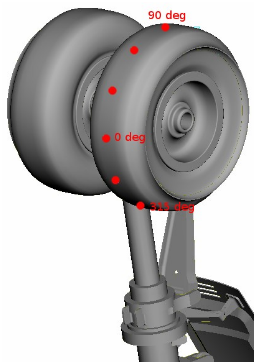


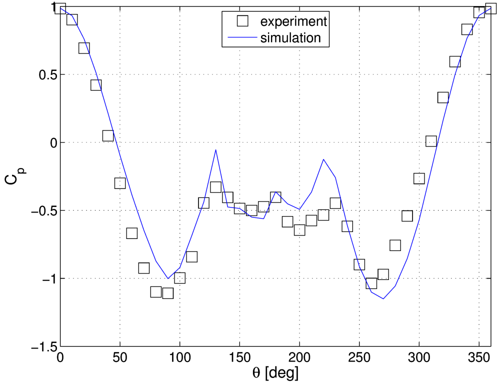
TKE [m2/s2]



In *all* figures: left, *sim*; right, *exp*.

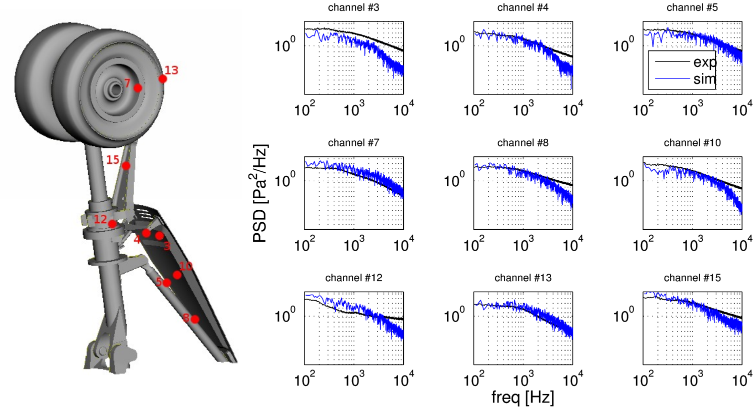
Benchmark results, BANC-II





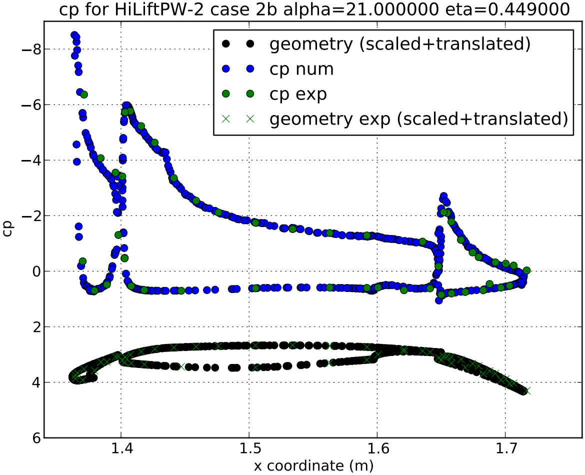
Mean static pressure coefficient distribution.

Benchmark results, BANC-II



Power Spectral Density unsteady pressure.

Benchmark results, HiLiPW-2



Mean static pressure coefficient distribution.

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Why **ANSA**?

Enabling features

- Easy to clean-up geometries, even for new users.
- Batch mesh generation.
- Precise control of parameters (*e.g. leading edge curvature, growth rate, min-max cell sizes, quality*).
- High quality volume mesh (highly required in our framework for refinement).
- ...

⇒ *Very knowledgeable, efficient and helpful support! Thanks Vangelis!*

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Unicorn and DOLFIN, open source

`http://launchpad.net/unicorn`

Acknowledgement

All initial meshes were generated with **ANSA** by Beta CAE Systems.

The code **Saaz** was used in "offline mode" for post-processing.[5]

Financial support from

- Swedish Foundation for Strategic Research
- European Research Council
- Swedish Research Council, Swedish Energy Agency

This work was performed on resources provided by the Swedish National Infrastructure for Computing (**SNIC**) at the Center for High-Performance Computing (**PDC**) at KTH.

[5]Alden King, Eric Arobone, Scott B. Baden and Sutanu Sarkar, *The Saaz Framework for Turbulent Flow Queries, 2011.*