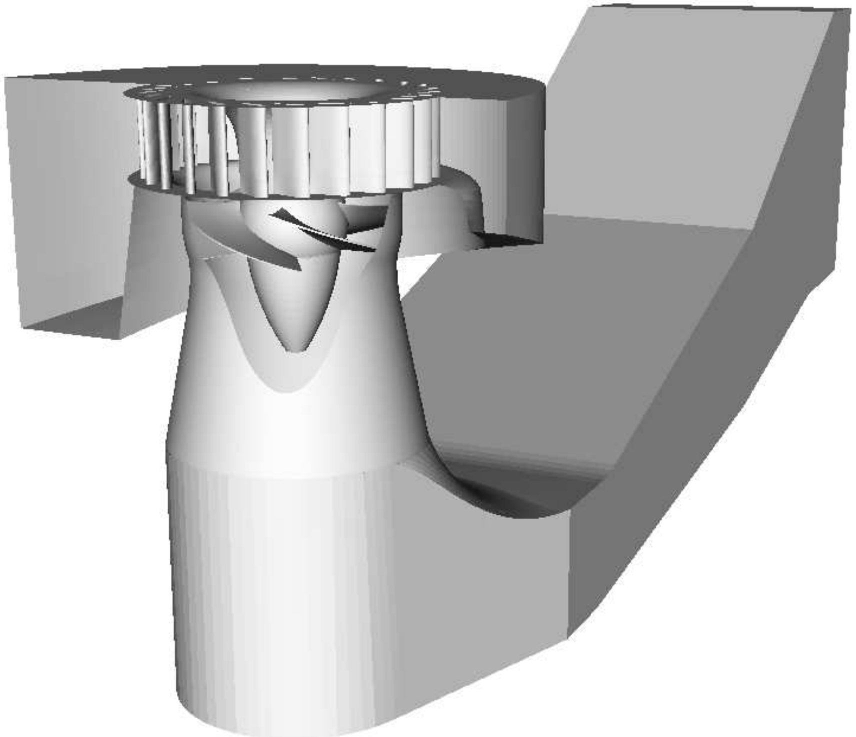
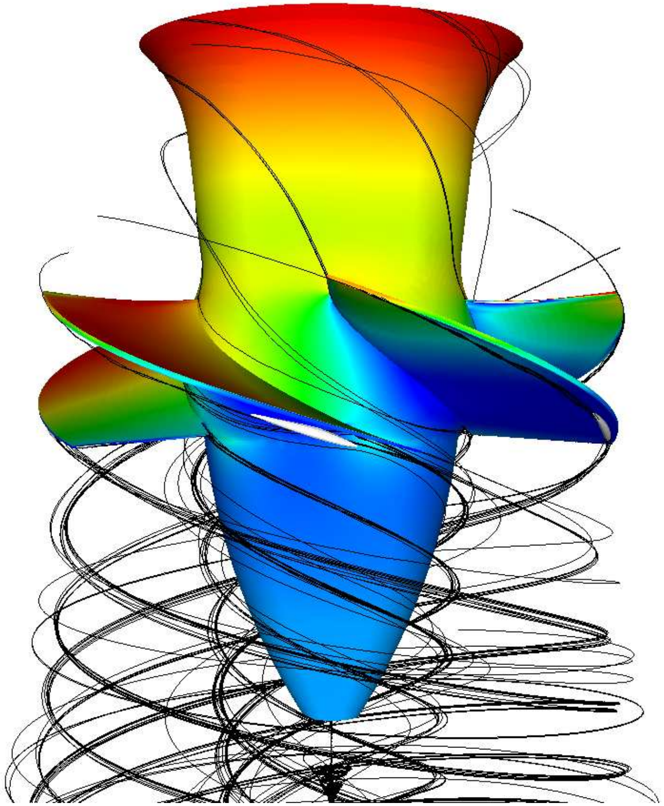
Evaluation of OpenFOAM
for CFD of turbulent flow in water turbines





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Håkan Nilsson, Chalmers / Applied Mechanics / Fluid Dynamics

Purpose of the presentation

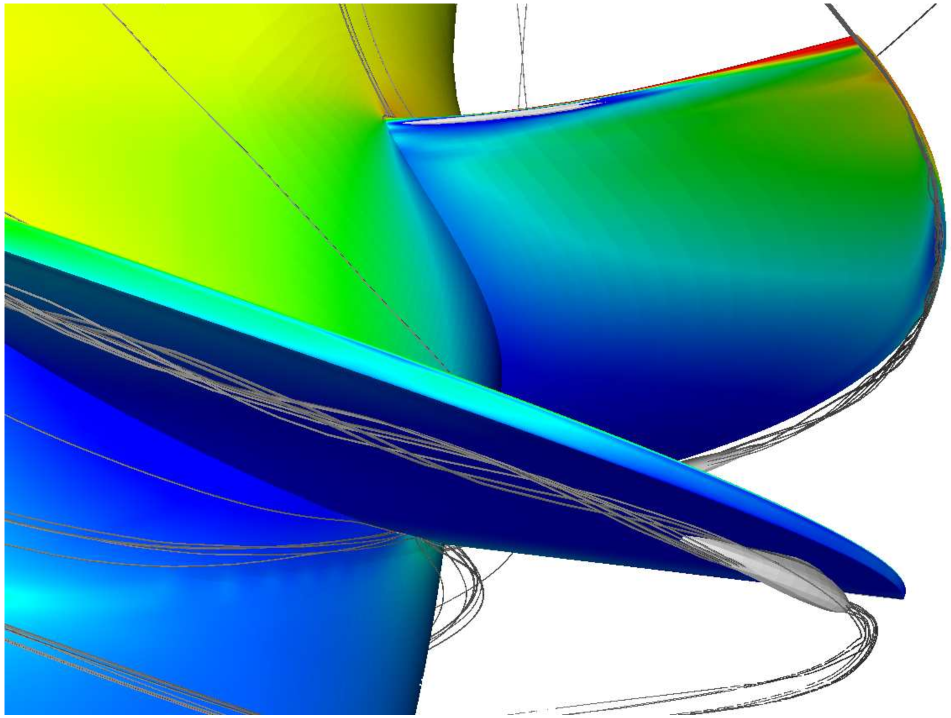
- Presentation of OpenFOAM (www.openfoam.org)
- Validation of OpenFOAM against CFX-5 and measurements
- Visualization of the results

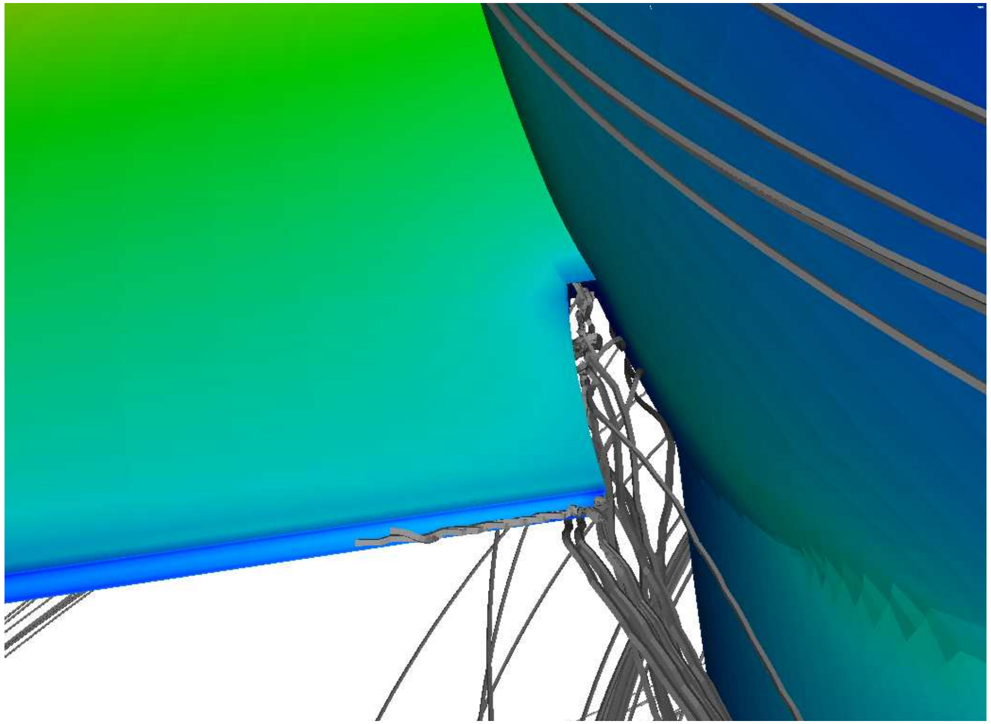
Studied cases:

- Quasi-steady flow in the Hölleforsen draft tube (www.turbine-99.org)
- Unsteady flow in the Hölleforsen draft tube
- Steady flow in the Hölleforsen runner with tip clearance
- Steady flow in the Hölleforsen runner with tip and hub clearances

Runner tip and hub clearances

(and lowest predicted static pressure iso-surface)

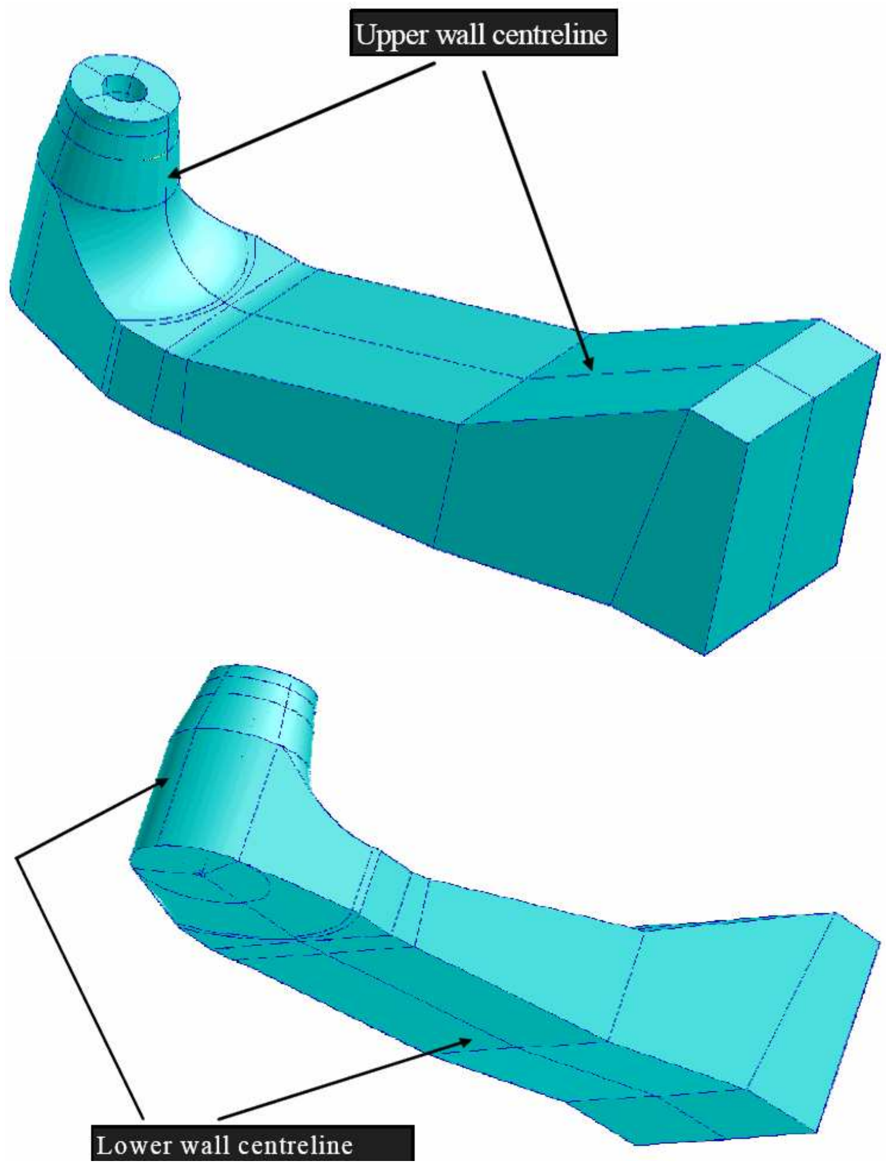


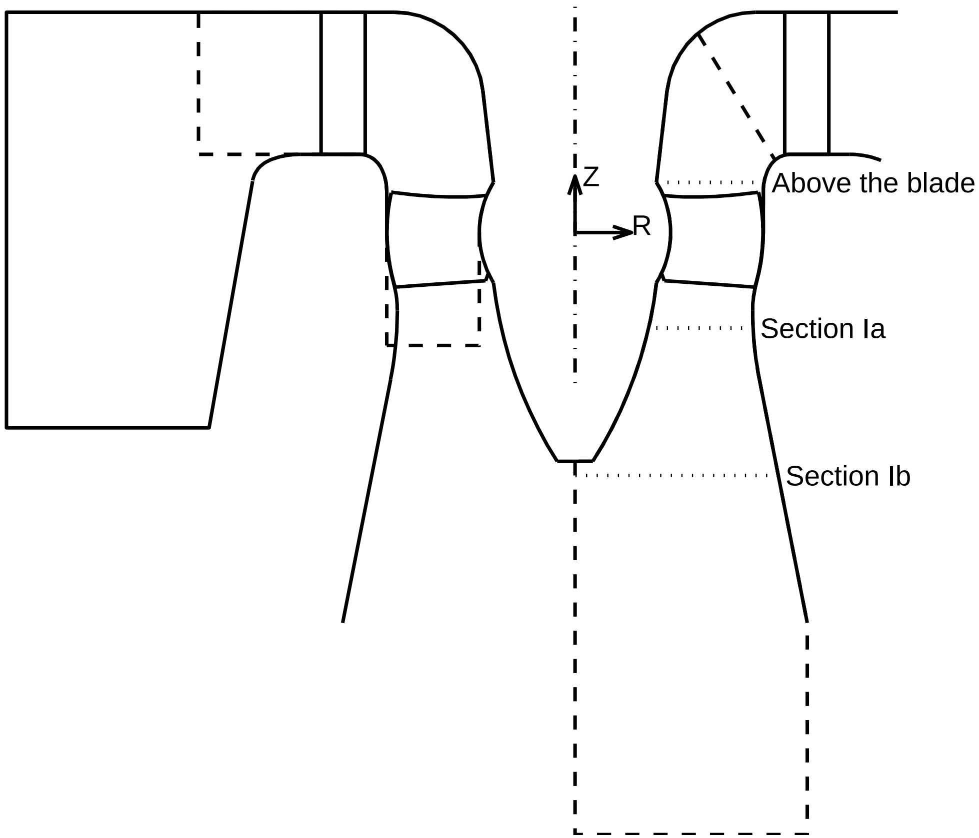


The OpenSource OpenFOAM CFD solver

- OpenFOAM = Open Field Operation and Manipulation, www.openfoam.org
  An OpenSource object oriented C++ tool for solving PDE's
- Preprocessing (grid generator, converters, manipulators, case setup)
- Postprocessing (using OpenSource Paraview)
- Many specialized CFD solvers implemented, e.g.
  - simpleFoam: A finite volume steady-state solver for incompressible, turbulent flow of non-Newtonian fluids, using the SIMPLE algorithm
  - turbFoam: A finite volume solver for unsteady incompressible, turbulent flow of non-Newtonian fluids, using the PISO algorithm
  - icoDyMFoam: Sliding/moving grid
- OpenSource = possibility to have insight into the code
  - * Makes development and tailor-made solvers possible
    - simpleUnsteadyRotatingFoam: Unsteady SIMPLE solver with Coriolis and centrifugal terms
    - cavInterFoam: Cavitation using VOF and the Kunz' cavitation model
  - * Makes research implementations available and results reproducable.
- Access to an international community of OpenFOAM users
- Runs in parallel using automatic/manual domain decomposition.

Geometry and measurement sections





Settings

- 60% load, close to the best efficiency for the system
- Standard $k - \varepsilon$ turbulence model with wall-functions
- Inlet BC: Steady axi-symmetric U, k, ε
  Draft tube: from experiments, Runner: from separate guide vane computations
- Velocity BC: Wall functions at walls and Neumann at outlet
- k and ε BC: Wall functions at walls and Neumann at outlet
  Draft tube: Backflow values derived from the average at the inlet
- Pressure BC: Neumann pressure at all boundaries except at the outlet:
  Runner: Neumann, Draft tube: Constant
- Draft tube grid: Block-structured, $1,002,360$ grid points.
- Runner grid: Block-structured, $\sim 2,200,000$ grid points.
- Gamma discretization scheme. A smooth and bounded blend between the second-order central scheme and the first-order upwind scheme.

Validation of engineering quantities, definitions

Normalization factor (dynamic pressure at Ia):

$$P_{dyn,Ia} = \rho Q^2/(2A_{Ia}^2)$$

The pressure coefficient

$$C_p = \frac{P}{P_{dyn,Ia}}$$

The mean pressure recovery

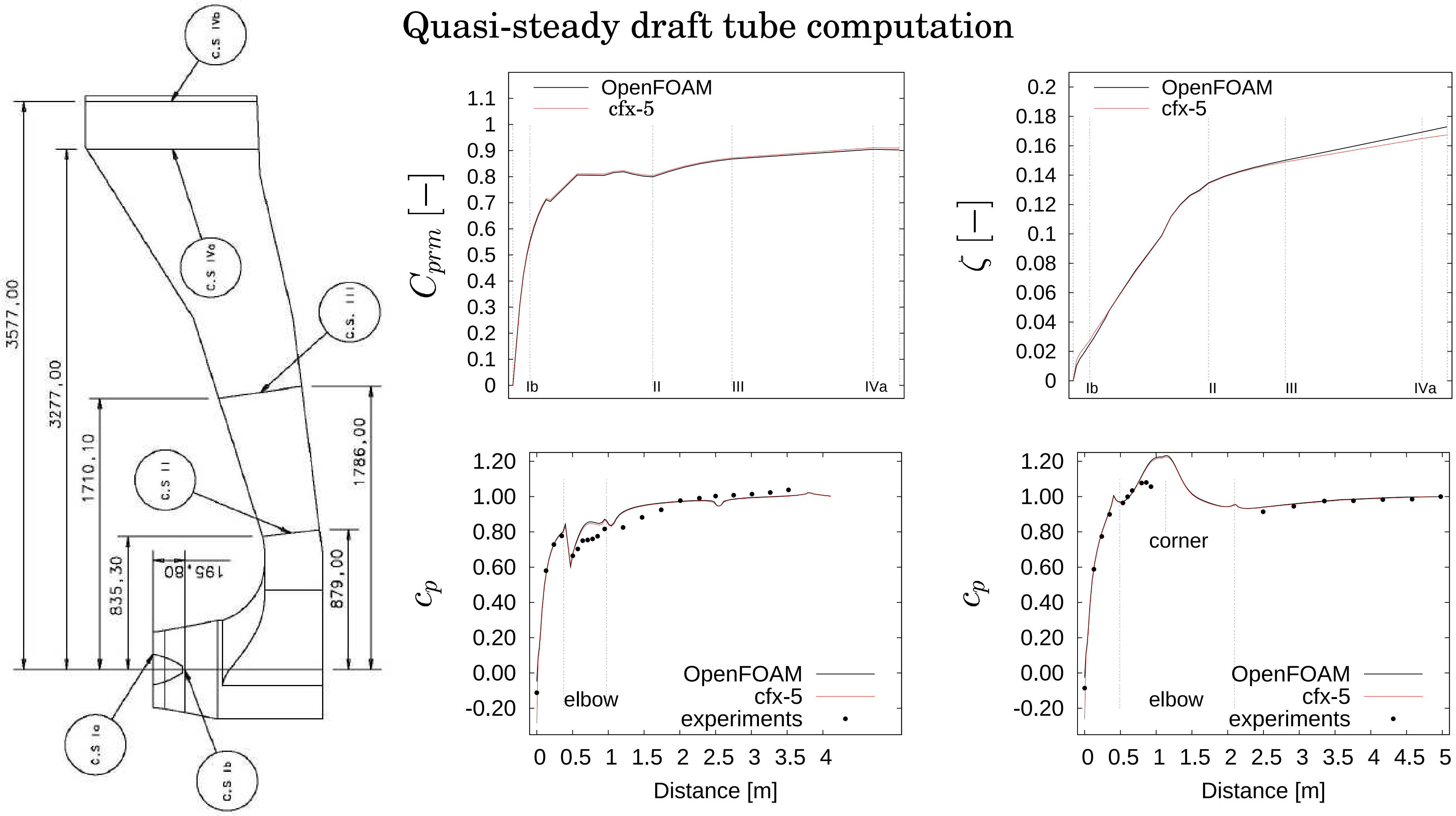
$$C_{prm} = \frac{\frac{1}{A_{CS}}\int\int_{A_{CS}} PdA - \frac{1}{A_{Ia}}\int\int_{A_{Ia}} PdA}{P_{dyn,Ia}}$$

The energy loss coefficient

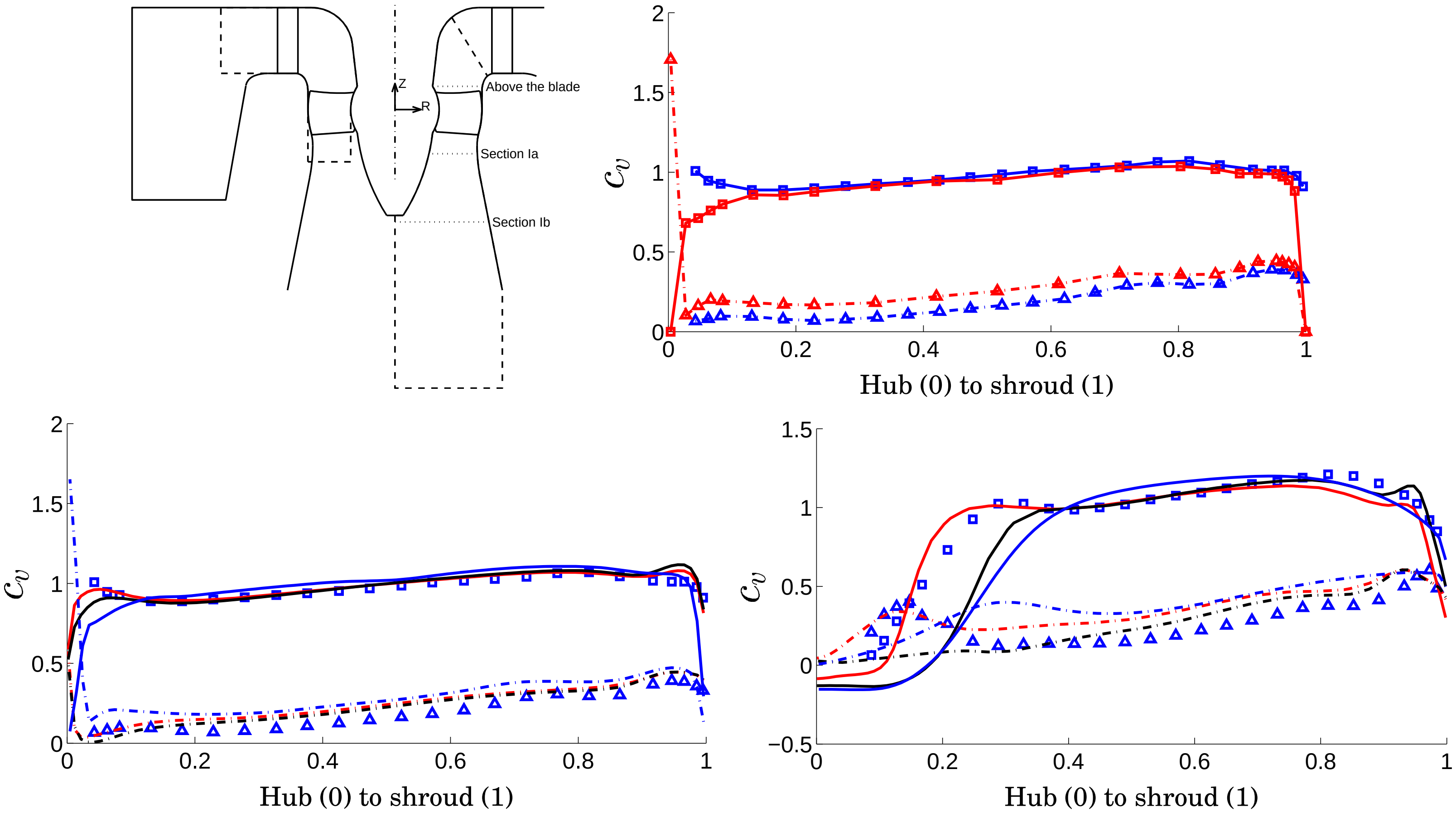
$$\zeta = \frac{\int\int_{A_{Ia}}\left(P+\rho\frac{|\vec{U}|^2}{2}\right)\vec{U}\cdot\hat{n}dA - \int\int_{A_{CS}}\left(P+\rho\frac{|\vec{U}|^2}{2}\right)\vec{U}\cdot\hat{n}dA}{\left|\int\int_{A_{Ia}}\rho\frac{|\vec{U}|^2}{2}\vec{U}\cdot\hat{n}dA\right|}$$

Validation of engineering quantities, results

Quasi-steady draft tube computation



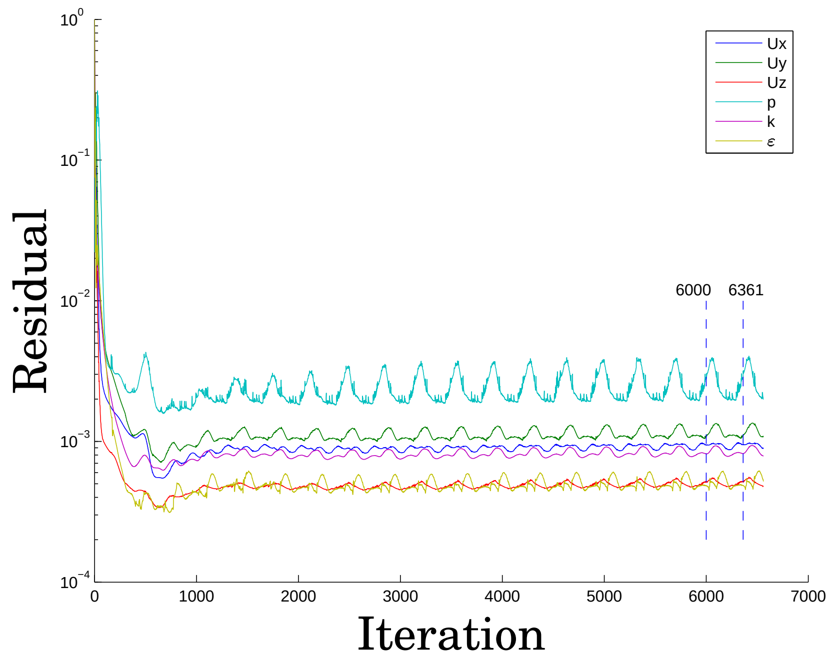
Validation of velocity profiles at section Ia



Squares: measured axial velocity. Triangles: measured tangential velocity. In (a) the colors correspond to two different measurements. In (b) and (c): Blue curve: quasi-steady draft tube, Black curve: runner without hub clearance, Red curve: runner with hub clearance.

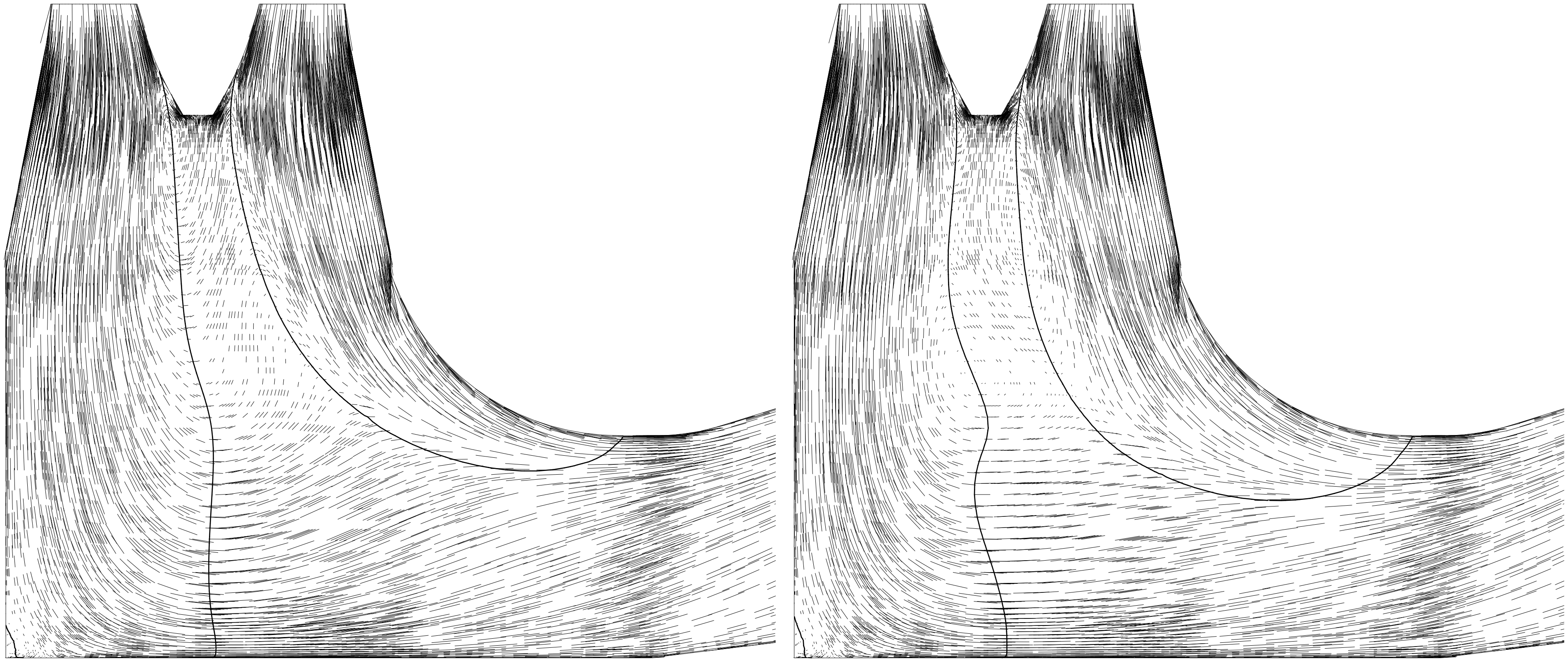
Convergence of the quasi-steady draft tube computation

- The residuals drop rapidly in the initial phase of the computation, but are then oscillating in a periodic fashion about a mean level.
- Inherent unsteadiness in the flow makes a steady solution impossible with the present level of diffusion (turbulence and numerical).
- One period in the fluctuating residuals correspond to one period in the vortex rope.
- Chosen averaging interval shown with dashed lines, yielding the 'quasi-steady' solution that is presented in the present work.

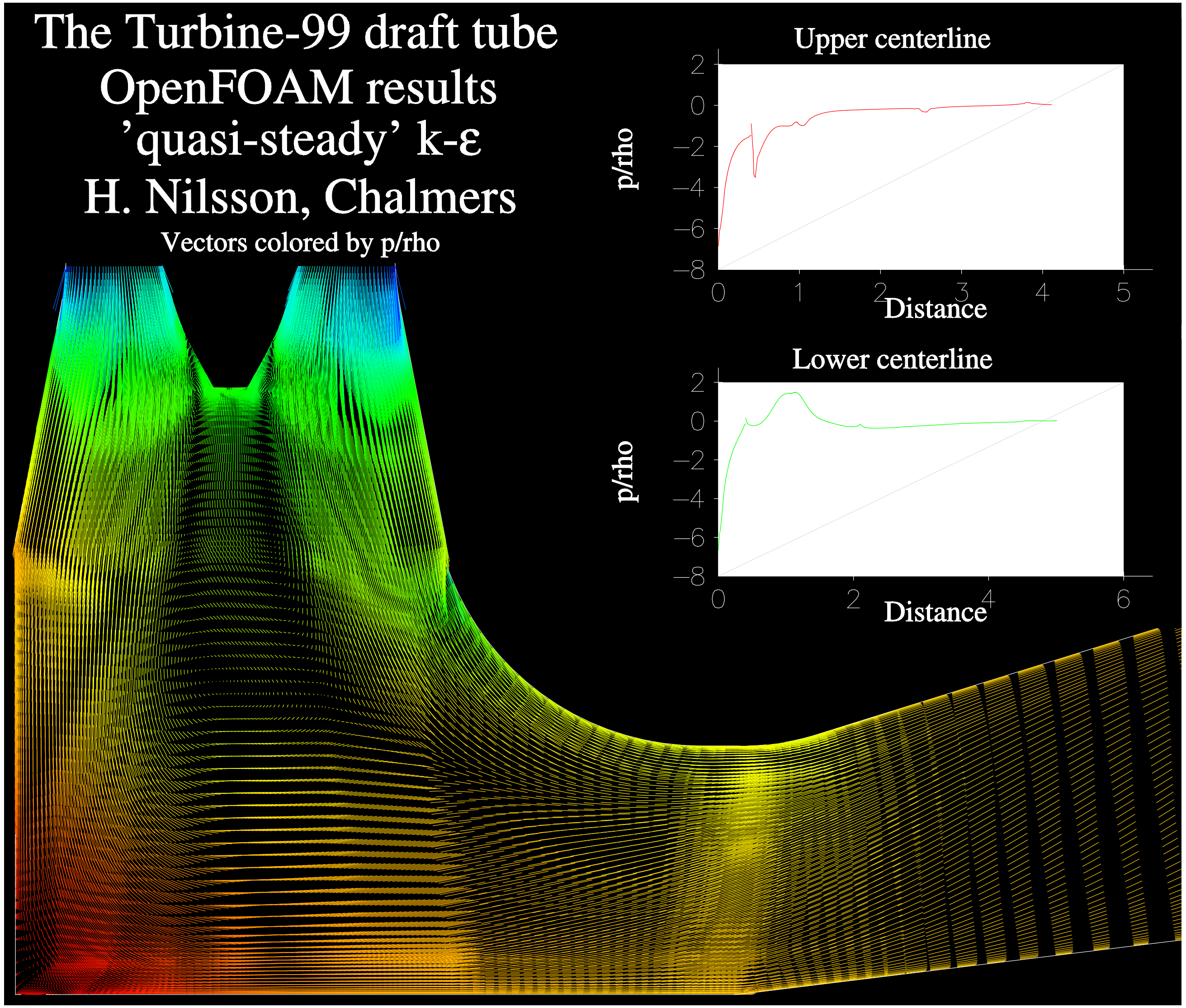


Unsteadiness in the quasi-steady draft tube computation

- Two snapshots of the flow to show the magnitude of the flow oscillations. The solid lines are where the vertical velocity is zero.

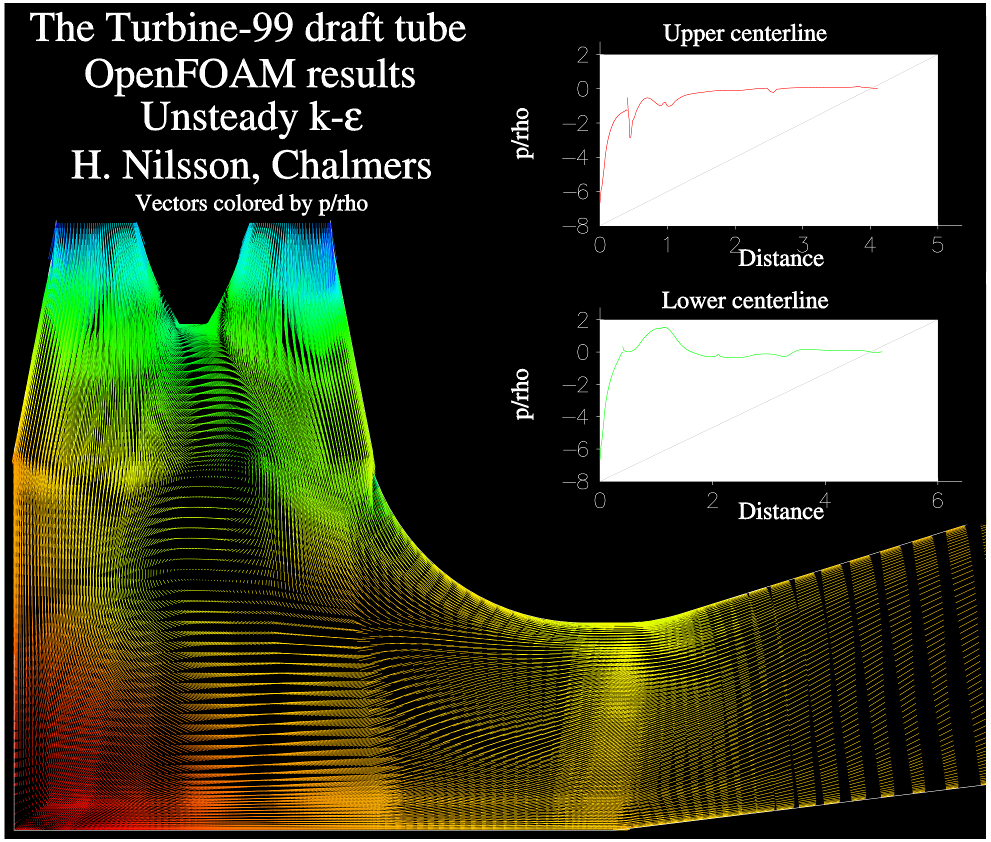


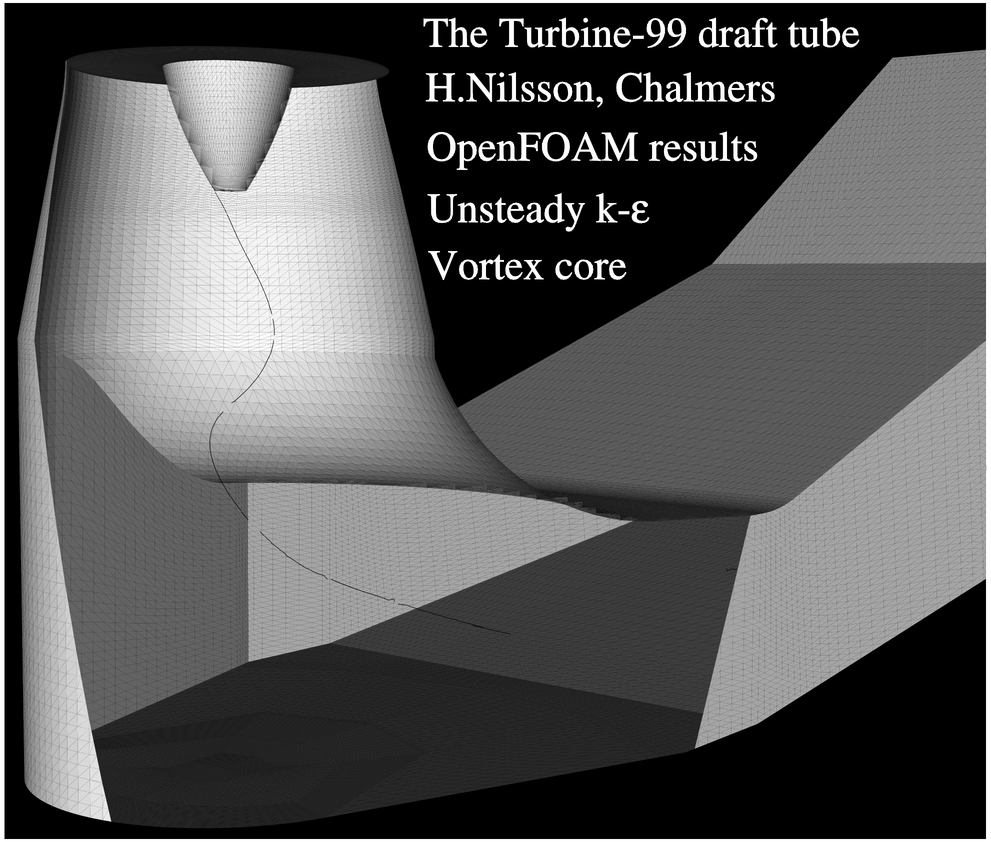
Unsteadiness, the movie



Vortex rope of the unsteady draft tube computation

Periodicity in time: $\sim 0.48s$ (same as CFX-5)





Conclusions

- The steady draft tube computation was unable to dampen the physical unsteadiness of the vortex rope, i.e. neither the $k-\varepsilon$ turbulence model nor the numerical schemes were diffusive enough to yield a fully steady solution.
- The averaged 'quasi-steady' solution yields results very similar to those of CFX-5 and the experiments
- An unsteady computation yields a highly unsteady vortex rope with a period of 0.48s, similar to CFX-5
- The steady runner computations compare well with the experimental results at sections Ia and Ib.
- The inclusion of the runner blade hub clearance is important for the correct flow to develop downstream the runner and in the draft tube.
- OpenFOAM is able to generate good computational results in an efficient way.
- The free OpenFOAM common platform facilitates international collaboration.

Thank you for your attention!

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