# Tracking Coherent Vortices in the Presence of Numerical Diffusion

Dag Feder

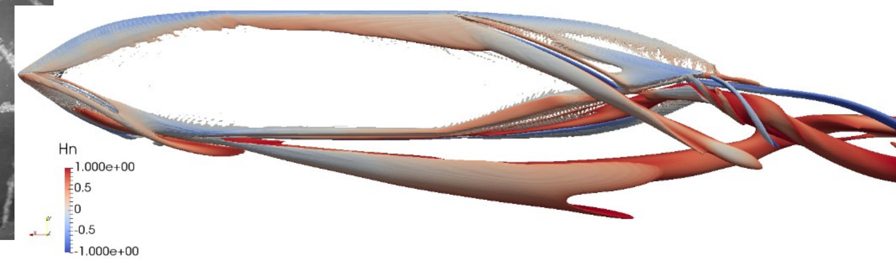
Institute for Fluid Dynamics and Ship Theory
Hamburg University of Technology

# Coherent Vortices

- **Longevity**

  ⇩ Numerics





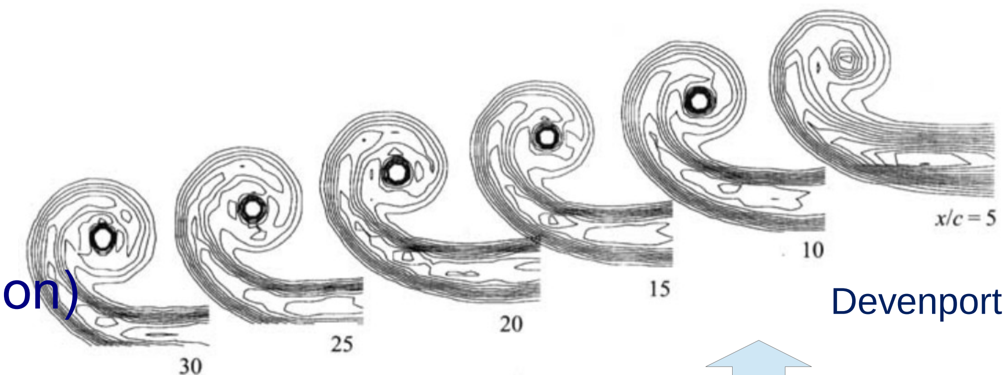

- **Problem:**
  - Huge numerical diffusion

→ **Numerical errors:**

A) Spatial resolution

B) High-order discretisation (convection)

C) Turbulence modelling (curvature)

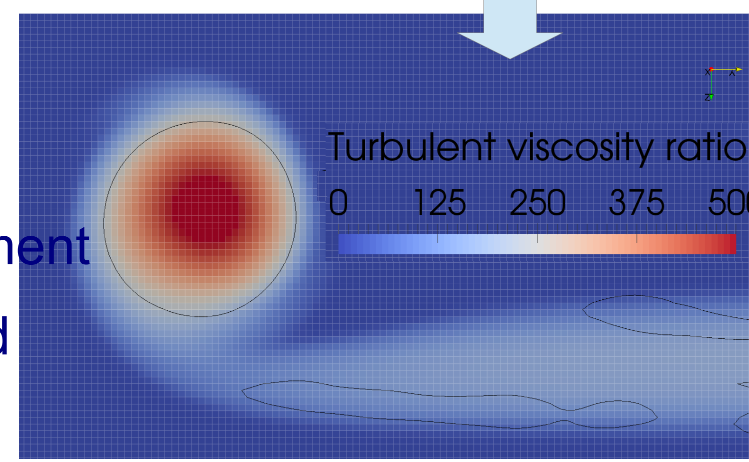



→ **Approach:**

A) AMR (based on e.g. Lambda2)

B) Vorticity Confinement (VC): vortex reinforcement

C) Consider laminar-like vortex core (CC, hybrid RANS-LES)



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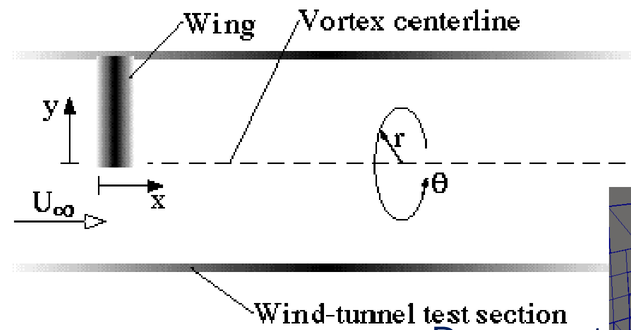
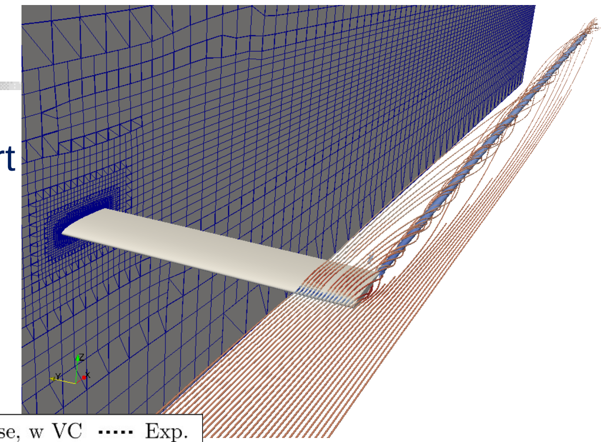
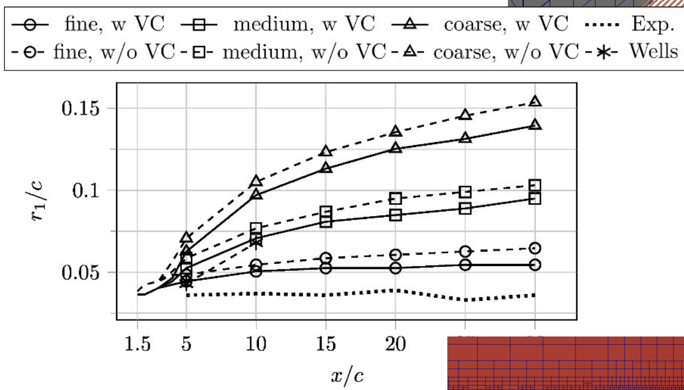
- **AMR**

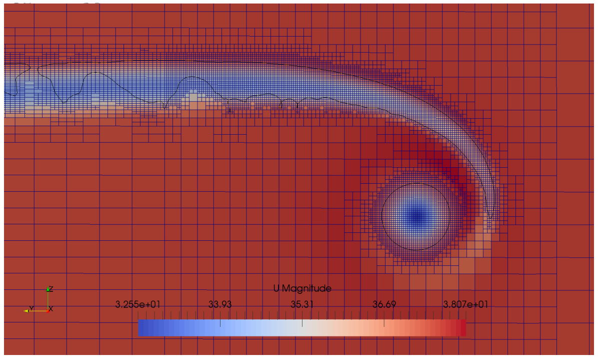



Devenport

$$\boldsymbol{s} = \frac{\nabla|\boldsymbol{\omega}|}{|\nabla|\boldsymbol{\omega}||}\times\boldsymbol{\omega}$$

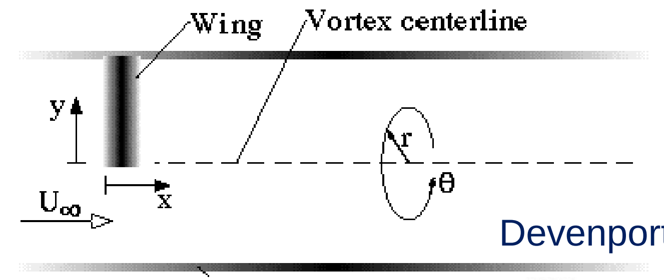


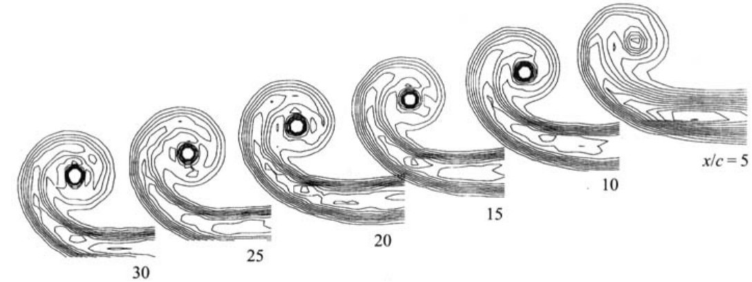


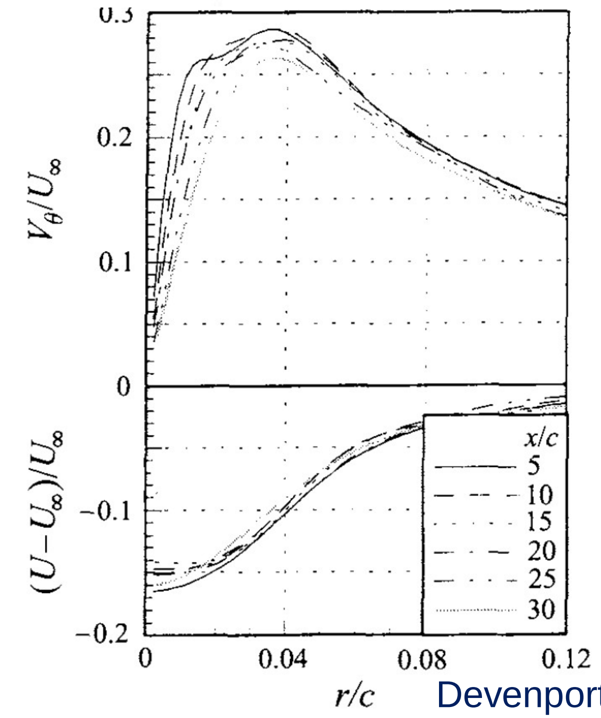



# Devenport-Case

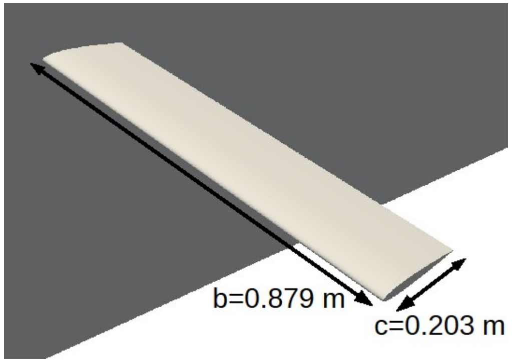
- **Windtunnel experiment: trailing tip vortex**
- **Longevity: vortex core keeps**
- **Laminar flow in core**
- **Devenport et al., 1996**
- **NACA0012, AOA 5°, Re=5e5**
- **Measurements**
  - Velocity profiles: axial, tangential
  - Turbulence stress
- **Wandering motion: correction**



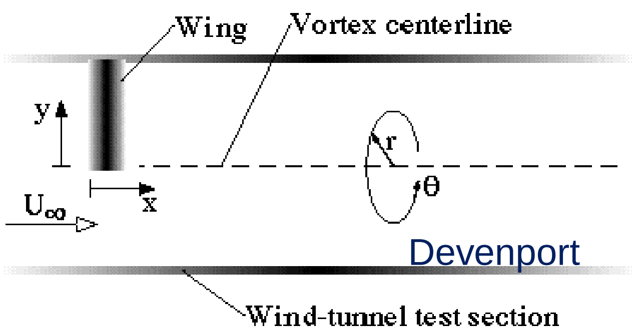



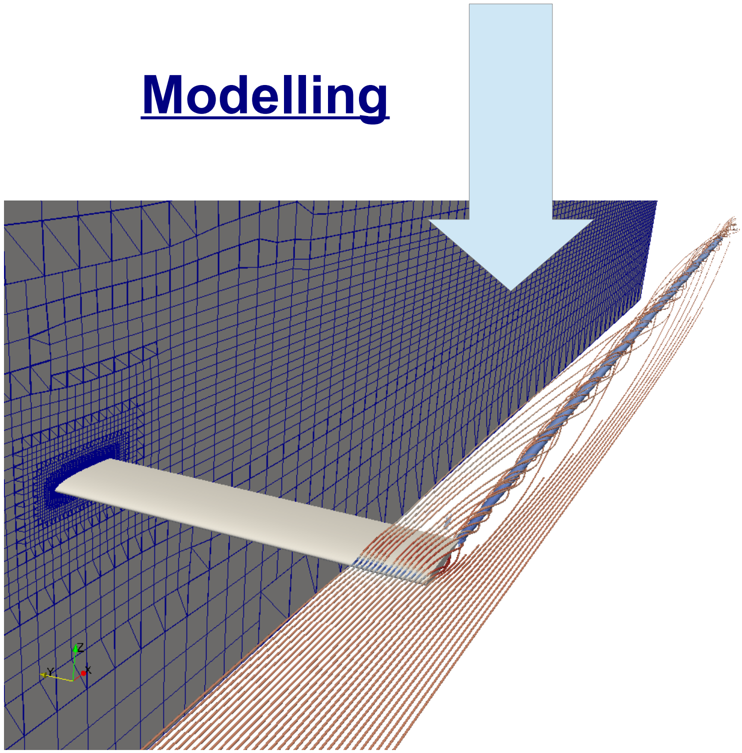

Devenport



# Modelling Approach




**Modelling**



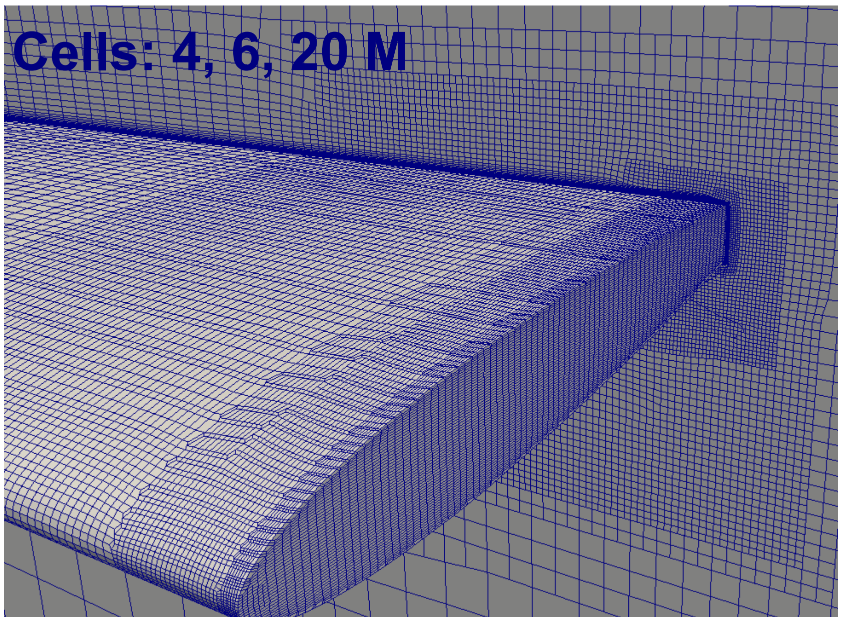
- **Domain scale 1:1**
- **Mesh:**
  - Static refinement around tip vortex
- **Apply Vorticity Confinement**
  - Evaluate method's potential
- **Turbulence modelling:**
  - RANS & Hybrid RANS-LES
  - → laminar vortex core

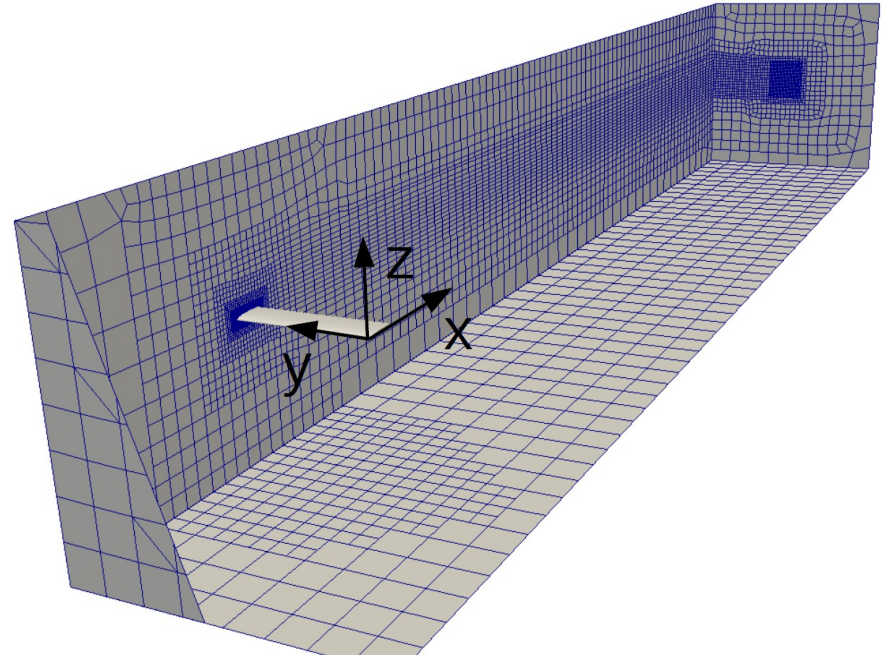
# Numerical Setup: Settings & Models

- **Solver**
  - pimpleFoam, v3.0.1
  - Outer correctors: 20, under-relaxation: 0.3
  - Same for all calculations → comparability
- **Schemes** (divSchemes)**:**
  - U: upwind, linearUpwindV
  - nut: limitedLinear
- **Turbulence modelling**
  - RANS: SpalartAllmaras
  - Hybrid RANS-LES: SpalartAllmaras-DDES
  - Wall treatment: low-Re

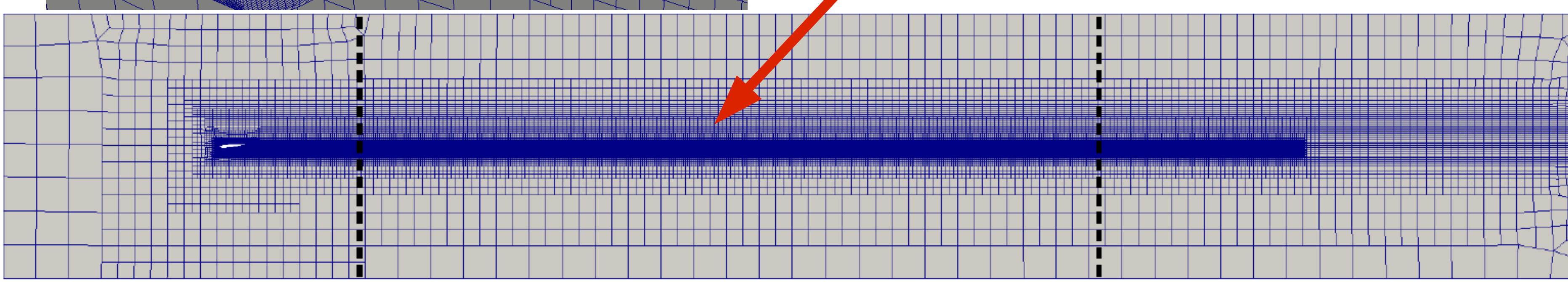
# Numerical Setup: Grid

- **Unstructured**
- **Hexahedral**
- **Numeca: Hexpress 5.1**
- **Cells: 4, 6, 20 M**






**4/ 8/ 16 cells per vortex core**



$x = 5c$ $x = 30c$

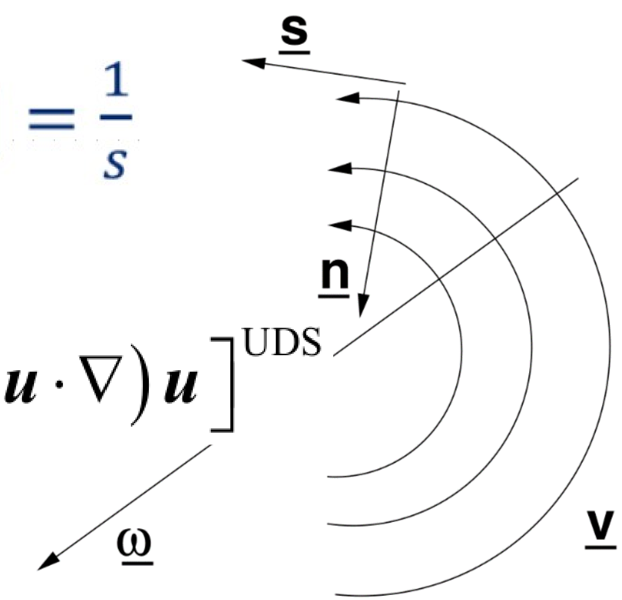
# Vorticity Confinement: Method

- **Target: reduce the effect of numerical diffusion on vortices**
- **Steinhoff (1994), further methods**
- **Insert momentum source S**

$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u} \cdot \nabla)\boldsymbol{u} = -\frac{1}{\rho}\nabla p + \nu \Delta \boldsymbol{u} + \boldsymbol{S}$$

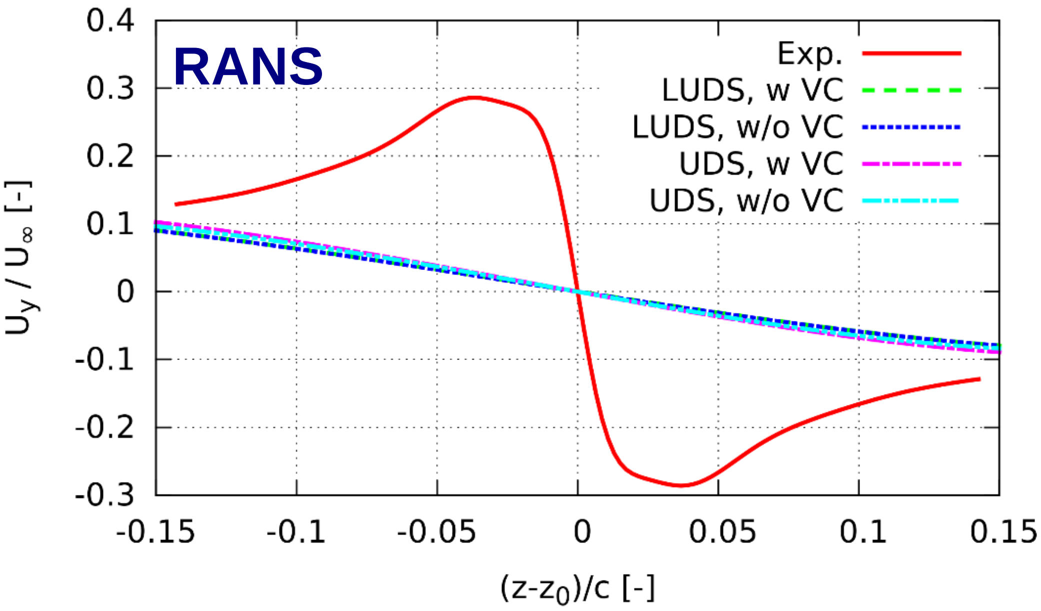
$$\boldsymbol{S} = \epsilon \boldsymbol{s} \qquad \boldsymbol{s} = \frac{\nabla|\boldsymbol{\omega}|}{\left|\nabla|\boldsymbol{\omega}|\right|} \times \boldsymbol{\omega}$$

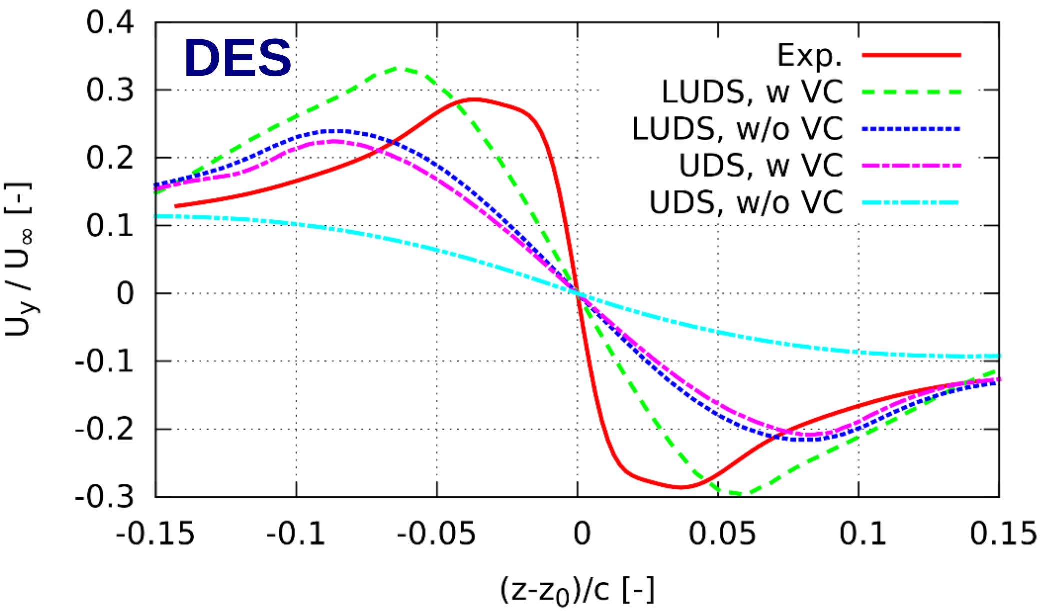
- **Methods**
  - $\varepsilon = f(0.04, h, |\boldsymbol{v} \cdot \boldsymbol{\omega}|, \ldots),\ [\varepsilon] = \frac{m}{s},\ [s] = \frac{1}{s}$
  - Adaptive: no arbitrary user-defined coeff. (0.04)
    - Hahn and Iaccarino (2008)
    - $\epsilon$ prop. to $\nu_n \Delta \boldsymbol{u} \equiv \boldsymbol{D} \approx \left[(\boldsymbol{u} \cdot \nabla)\boldsymbol{u}\right]^{\mathrm{CDS}} - \left[(\boldsymbol{u} \cdot \nabla)\boldsymbol{u}\right]^{\mathrm{UDS}}$

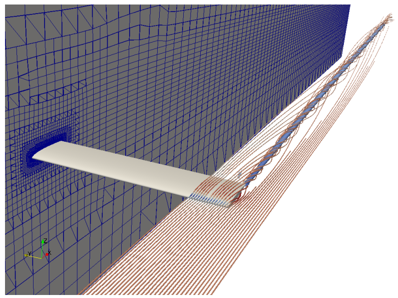


Löhner 2009

# Potential of VC in RANS and DES



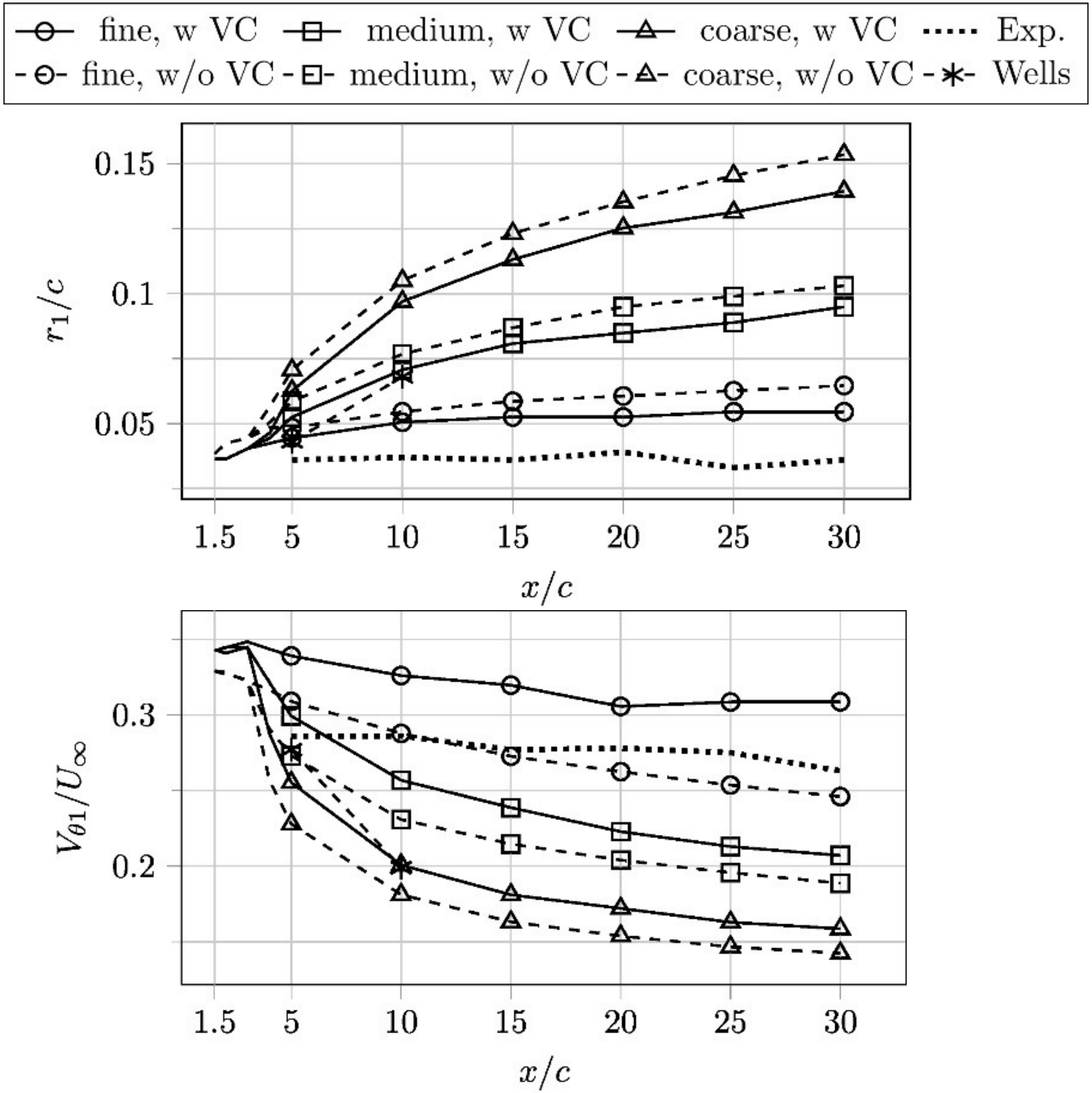



- **Tip vortex, tang. Velocity (x=5c)**
- **upwind (Hahn and Iaccarino) and linearUpwind**
- **RANS**
  - Weak vortex
  - Turbulent viscosity due to rotational flow
  - Effect of VC negligible
- **DES**
  - Stronger vortex
  - High potential of VC

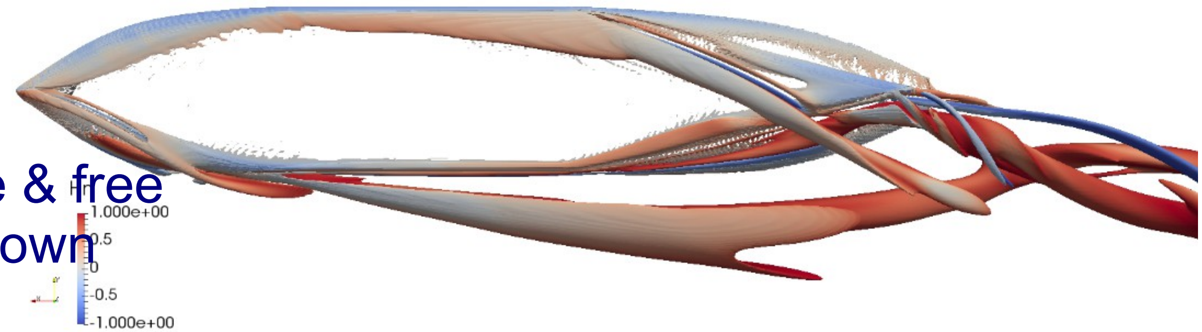
# Grid Convergence Study

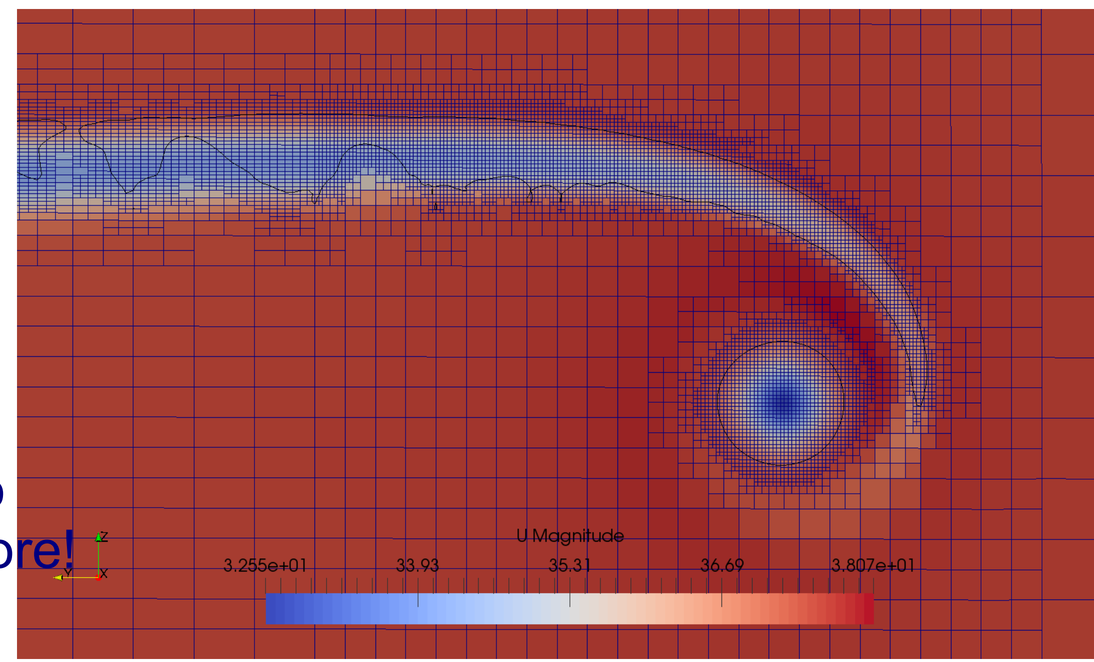
- **Turb.: SA-DDES**
- **Cell size**
  - Fine: 16 cells/ core
  - Medium: 8 cells/ core
  - Coarse: 4 cells/ core
- **Core radius**
  - Exp.: constant
  - Sim.: convergence
- **Peak tangential velocity**
  - Exp.: slight decrease
  - Sim.: finer → stronger
- **VC: r ⇩ & V ⇧**



# Adaptive Mesh Refinement (AMR)

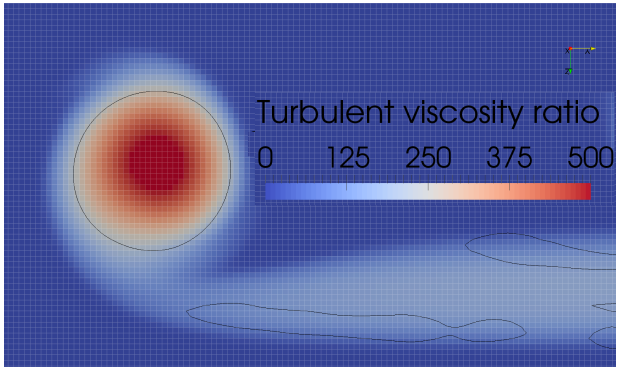
- **Motivation:**
  - Location of the vortex core & free shear layer previously unkown
  - Transient
  - ➔ AMR
- **Criterion:**
  - Vortex identification
  - e.g. Lambda2 < 0
- **Tip vortex and free shear layer**
- **Important:**
  - turbulence modelling needs to consider laminar-like vortex core!



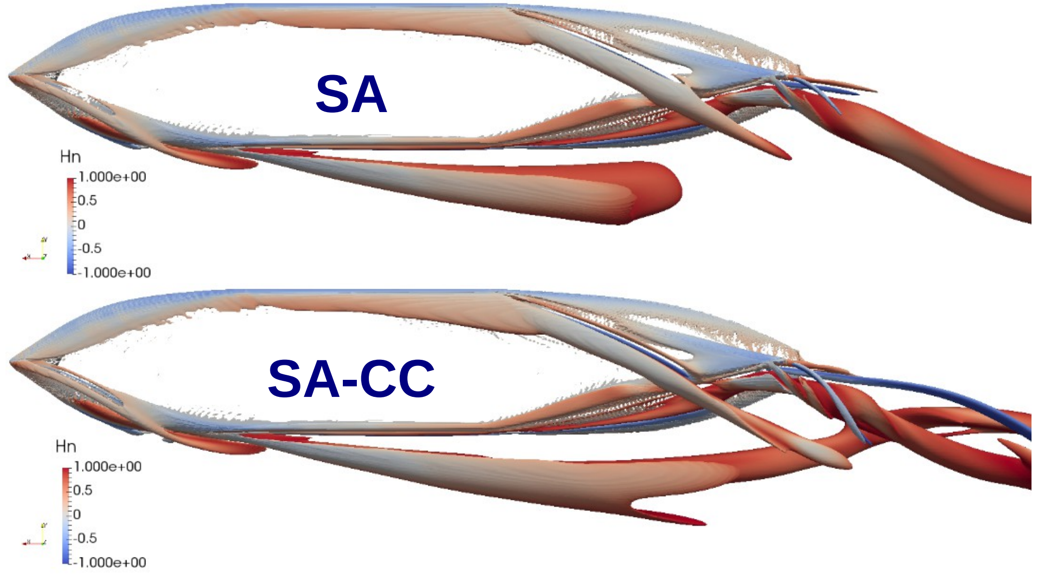
# Conclusions

- **Problem:**
  - High numerical diffusion smears out coherent vortices
- **Reasons:**
  - Discretisation (spatial, equations)
  - Turbulence modelling
- **Target:**
  - Reduce numerical diffusion
- **Approach:**
  - Mesh:
    - fine (>10 cells/ core)
    - adaptive (AMR)
  - Turbulence: consider laminar-like vortex core
  - VC: reinforces vortex



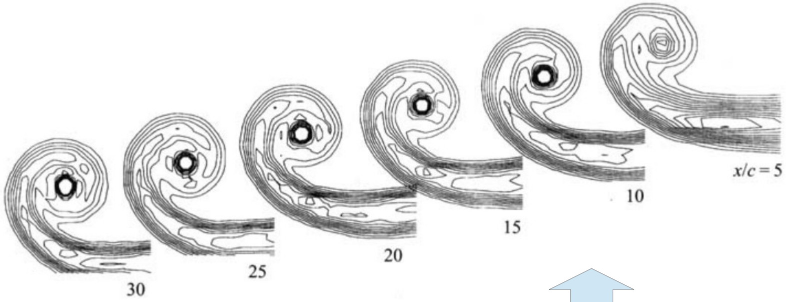
# Outlook

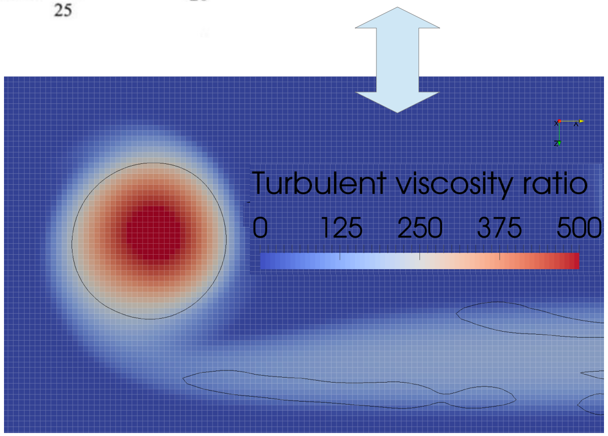
- **Vortex evolution**
  - Massless tracer particles
- **Turbulence modelling**
  - Anisotropic EVMs, with CC, e.g. v2f – CC
  - SA/SST – IDDES – CC → reduce overprediction in RANS-region
- **VC method:**
  - Coupling with Computational Vortex Method (→ LEMOS, Rostock)
- **Complex geometries**
  - Ships in manoeuvring conditions
  - e.g. KVLCC2 at 30° drift angle



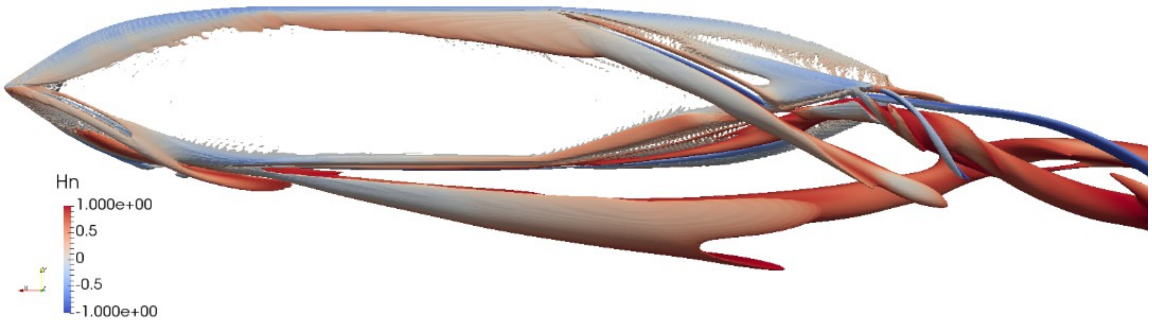

NASA


Krüger


30
25
20
15
10
$x/c = 5$


Turbulent viscosity ratio
0 125 250 375 500

# Thank you!


Hn
1.000e+00
0.5
0
-0.5
-1.000e+00