Modeling of Swirling Flow in a Conical Diffuser

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Outline

Introduction

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Background

- Hydro power
- Water turbines
- Draft tubes and diffusers
- Vortex ropes

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Numerical Considerations

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- Boundary conditions
- CALC-PMB
- Geometry
- Mesh

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- Analogies to confined swirling flow
- CAD imperfections

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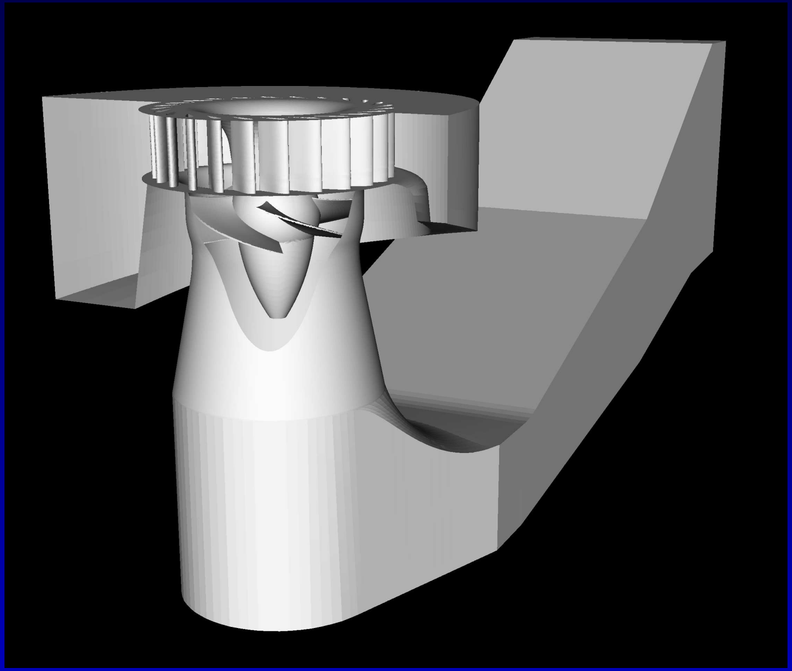
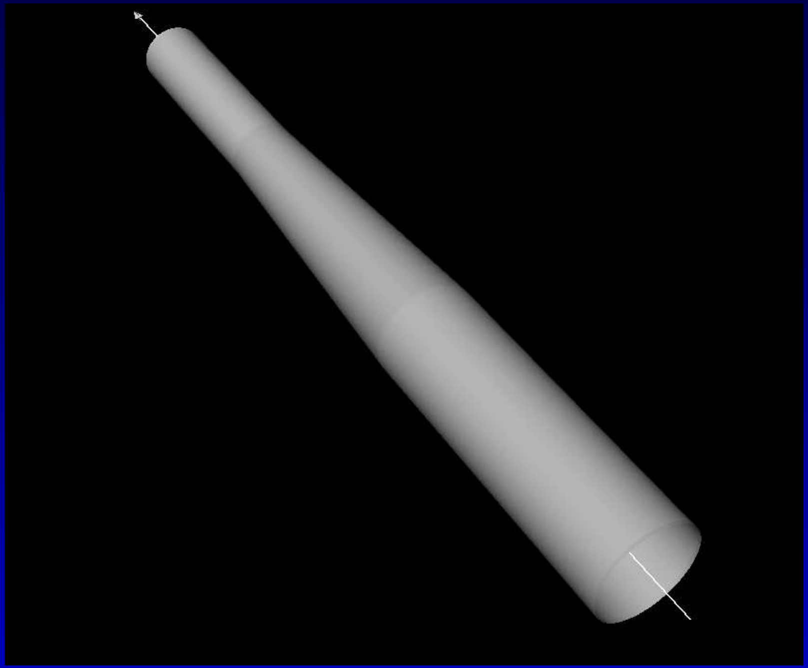
- Results
- Conclusions
- Future Work

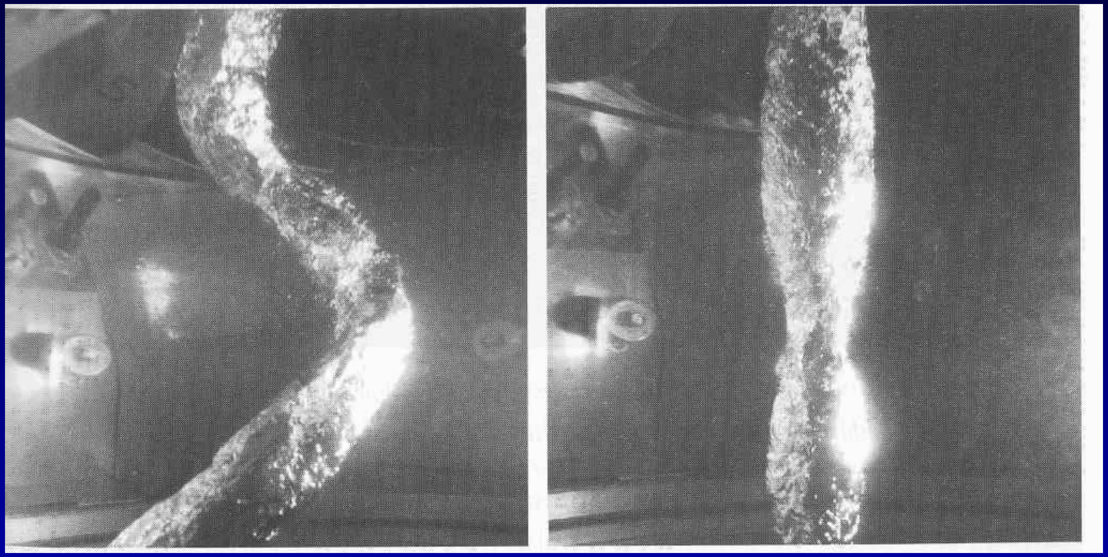
Background and Motivation





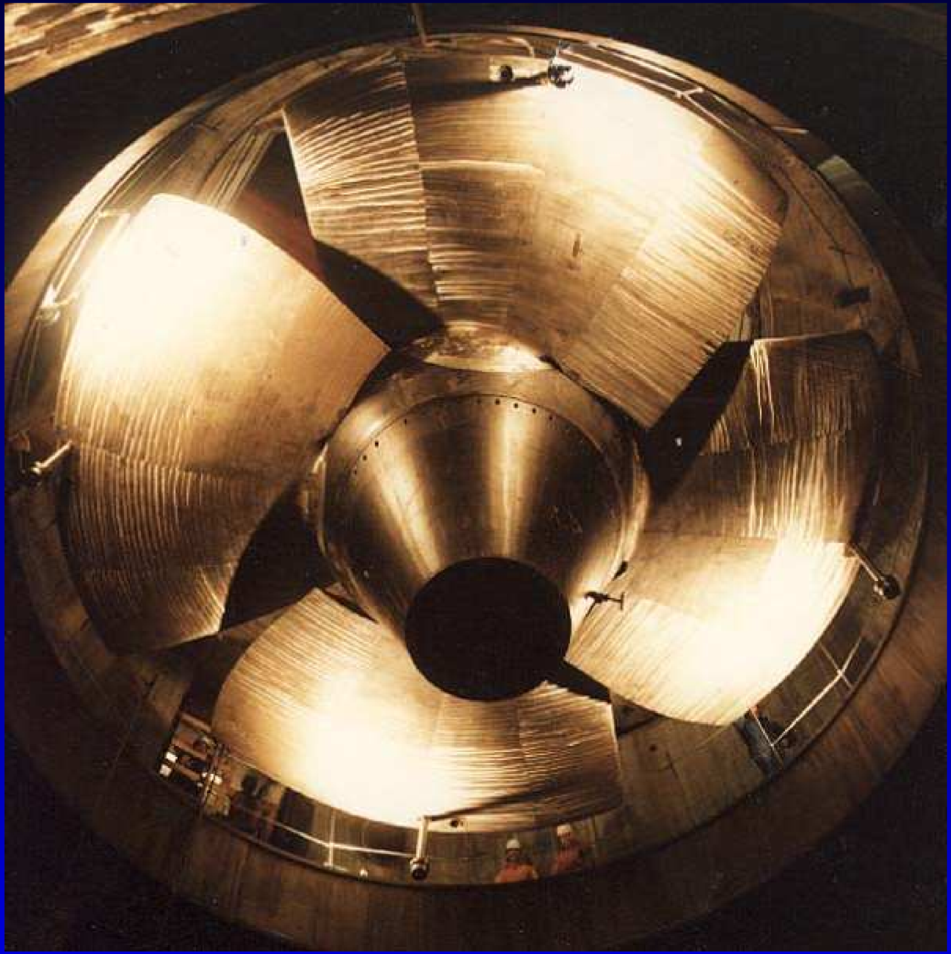
Kaplan turbine of Hölleforsen and a slightly simplified model

Background and Motivation



Cavitation in unsteady vortex ropes

Background and Motivation



Project

Supervisor/Examinator: Dr. Håkan Nilsson

Numerical Considerations

(U)RANS, continuity & Boussinesq assumption

$$\begin{aligned}
\partial_0 U_i + U_j \partial_j U_i &= -\frac{1}{\rho}\partial_i P + \nu\, \partial_j \partial_j U_i - \partial_j < u_i' u_j' > \\
\partial_i U_i &= 0 \\
- < u_i u_j > &= 2\nu_t S_{ij} - \frac{2}{3} k \delta_{ij} \\
S_{ij} &= \frac{1}{2}\left(\partial_j U_i + \partial_i U_j\right)
\end{aligned}$$

Numerical Considerations

Wilcox $k-\omega$ turbulence model

$$
\begin{aligned}
\nu_t &= k/\omega \\
\partial_0 k + U_j\partial_j k &= P_k + \partial_j\left((\nu + \nu_t/\sigma_k)\partial_j k\right) - \varepsilon \\
\partial_0 \omega + U_j\partial_j \omega &= \partial_j\left((\nu + \nu_t/\sigma_\omega)\partial_j \omega\right) - \\
&\quad \frac{\omega}{k}(c_{\omega 1}P_k + c_{\omega 2}k\omega) \\
P_k &= \nu_t\left(\partial_j U_i + \partial_i U_j\right)\partial_j U_i \\
\varepsilon &= \beta\omega k
\end{aligned}
$$

$$\beta = 0.09,\ c_{\omega 1} = 5/9,\ c_{\omega 2} = 3/40,\ \sigma_k = \sigma_\omega = 2$$

Numerical Considerations

Boundary conditions

$$Walls: \quad U_i = \mathbf{0}\,, k = 0,\ \omega = \frac{6\nu}{C_{\omega 2} r^2}$$

$$Inlet: \quad U_i = U_i^{exp}\,, k = f(r)(\partial_r U_{axial})^2$$

$$\omega = \frac{\sqrt{k}}{g(r)}$$

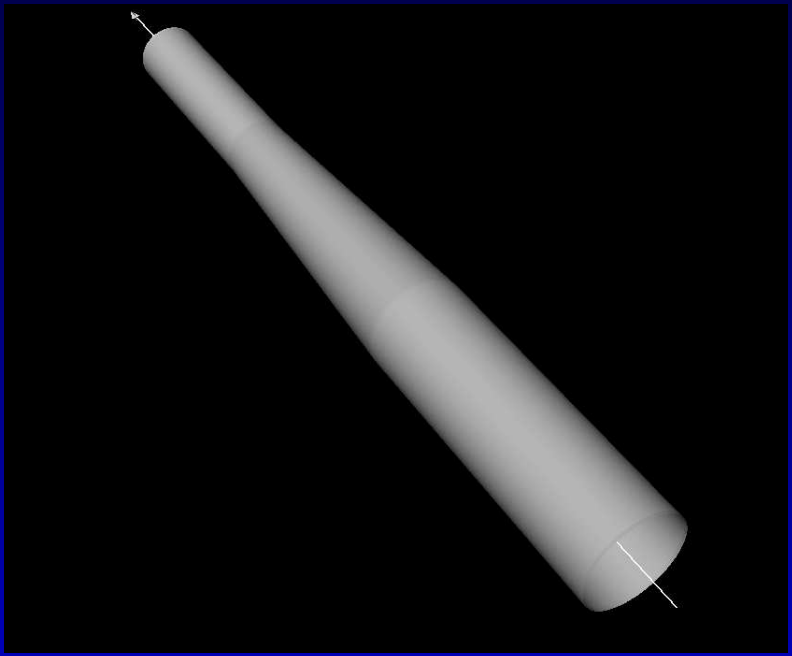
$$Outlet: \quad \partial_0 U_i + U_b \partial_n U_i = \mathbf{0},\ \partial_n(\cdot) = 0$$

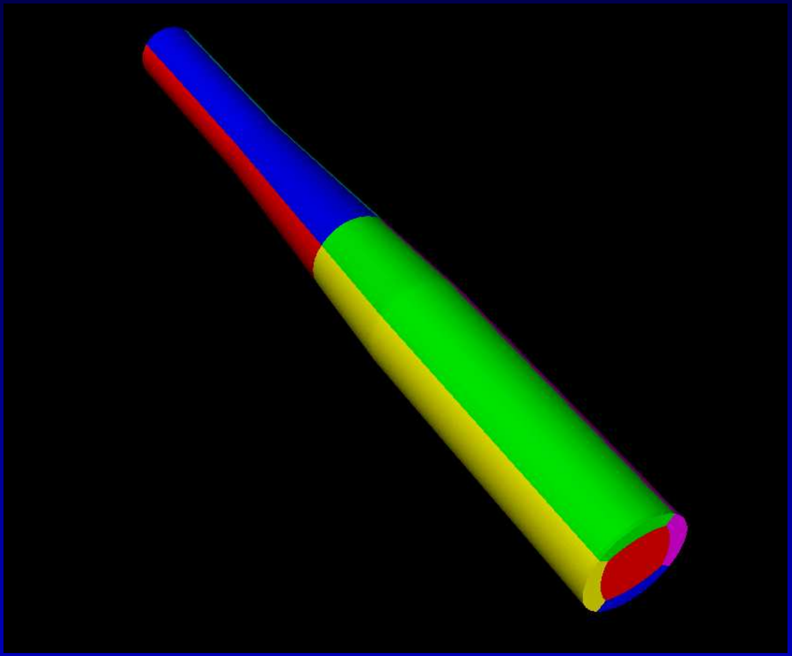
Numerical Considerations

Parallel multiblock code: CALC-PMB

- Finite volume method
- Block structured hexahedral grid
- MPI
- Rhie-Chow interpolation
- Simplec algorithm
- TDMA

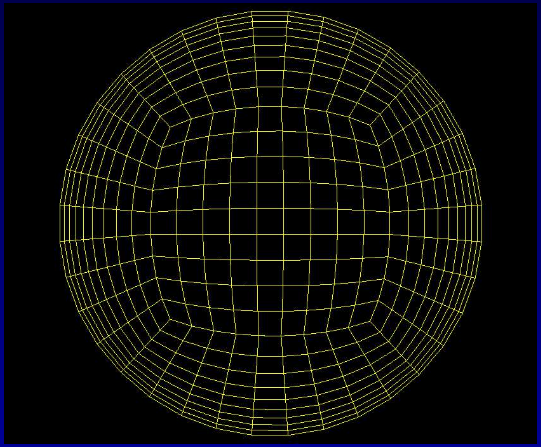
Numerical Considerations

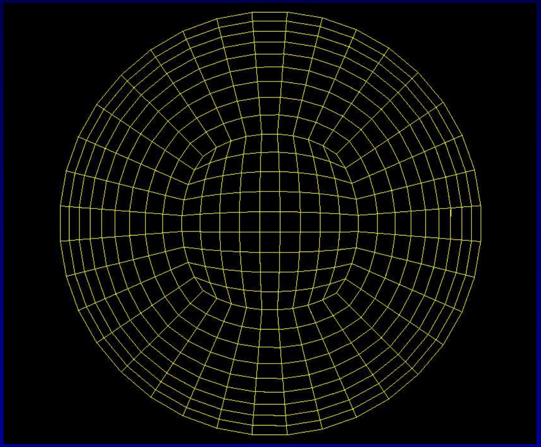


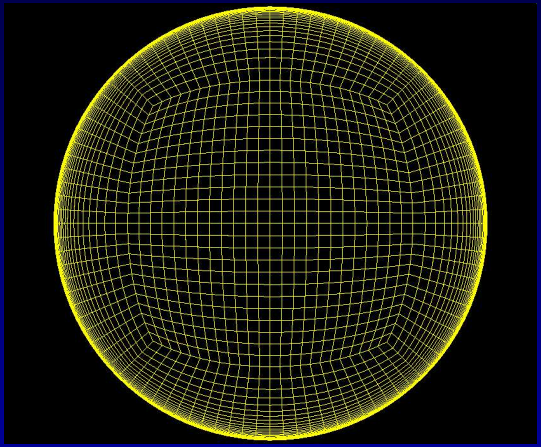


Geometry and block structures

Numerical Considerations







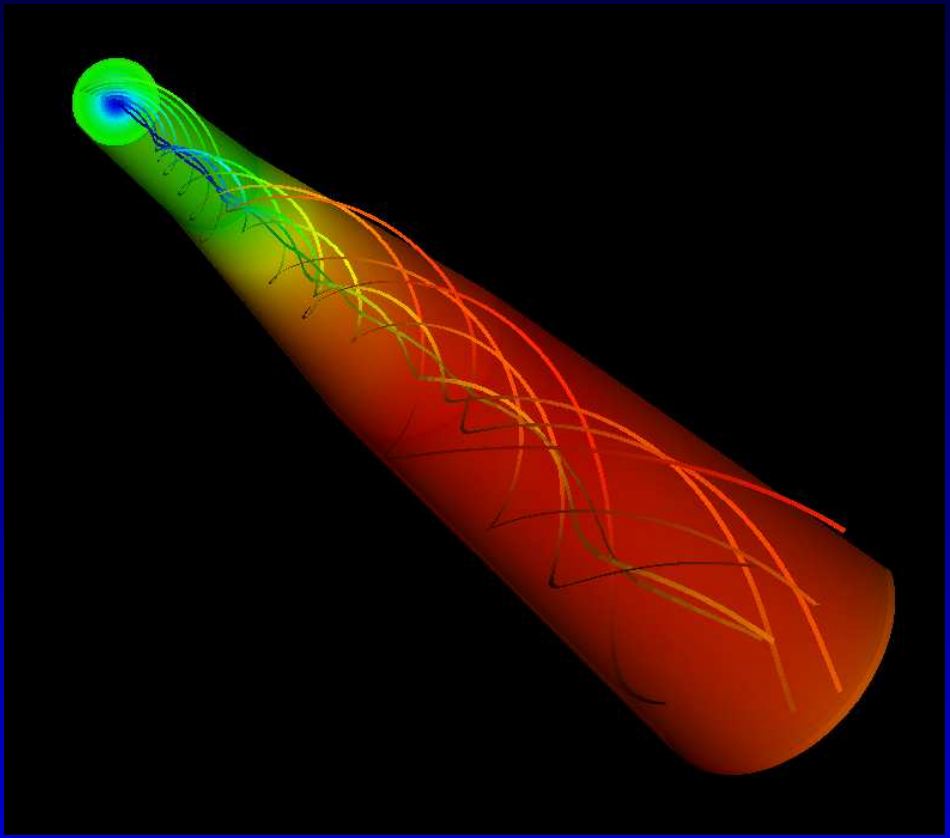
Computational grids

Numerical Considerations

$Case$	$Grid$	Re	$Steady/Unsteady$	$Grid\,Size$	HRN/LRN
1:1	1	Re_0	Steady	100,000	HRN
1:2	1	Re_0	Unsteady	100,000	HRN
2:1	2	$Re_0/10$	Steady	100,000	HRN
2:2	2	$Re_0/10$	Unsteady	100,000	HRN
3:1	3	$Re_0/10$	Steady	781,250	LRN
3:2	3	$Re_0/10$	Unsteady	781,250	LRN

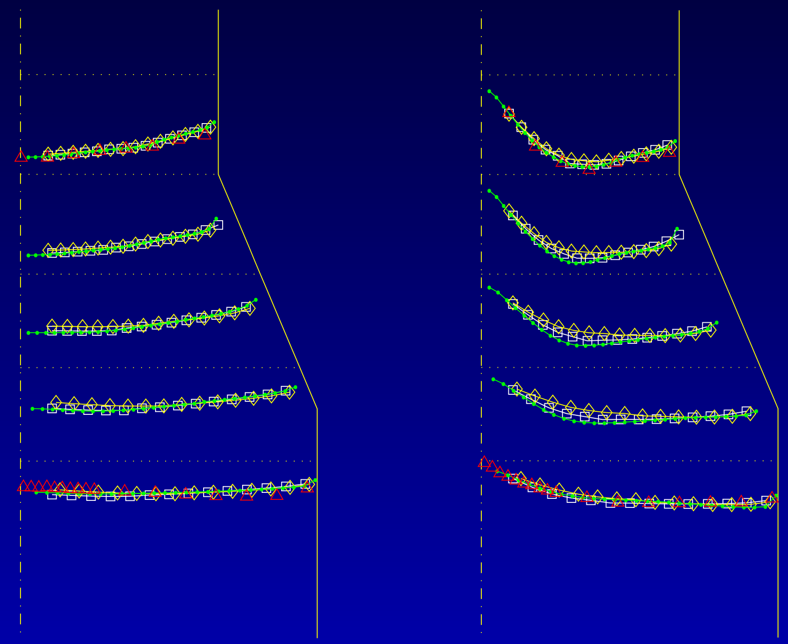
Six cases, $Re_0 = 2.8 \cdot 10^6$

Results



Streamlines and wall pressure distribution

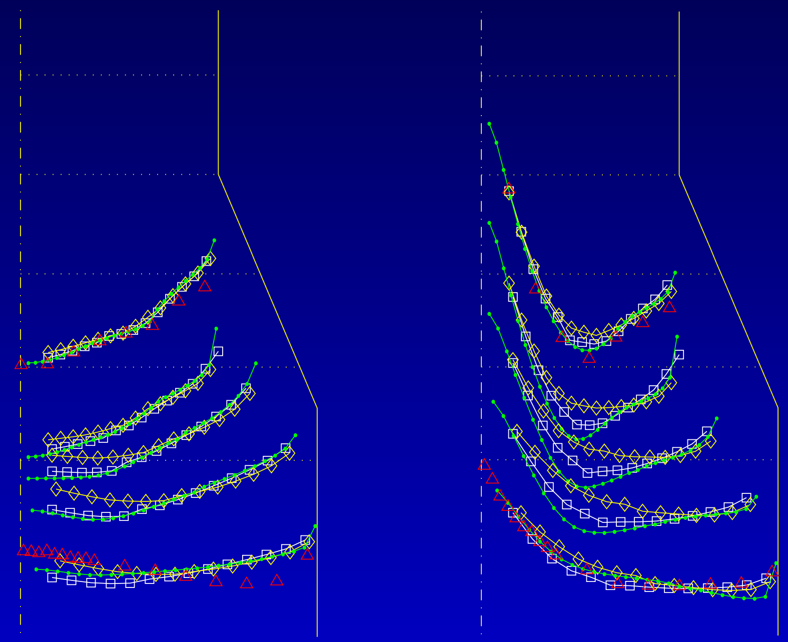
Results



In excellent agreement with experimental data...

Results

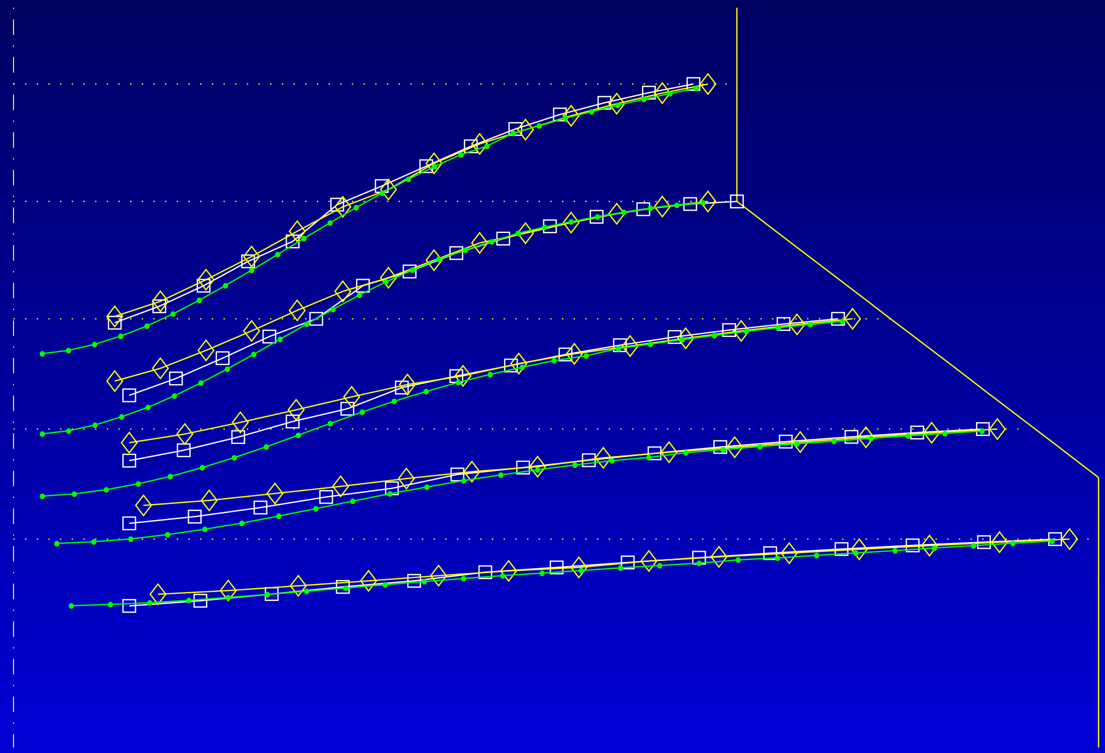
Not really.



●: Case 3:1; □: Case 2:1; ◇: Case 1:1; △: Experimental data

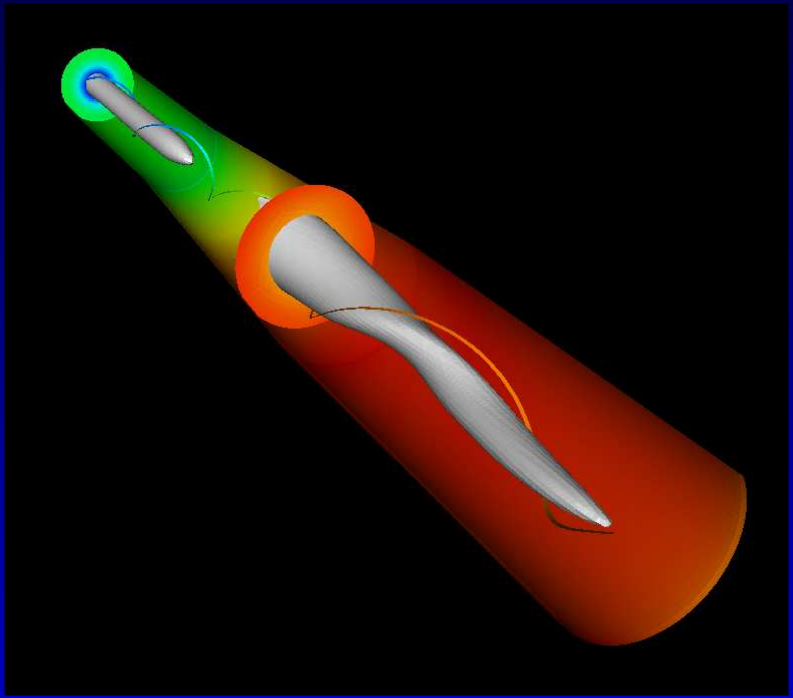
Results

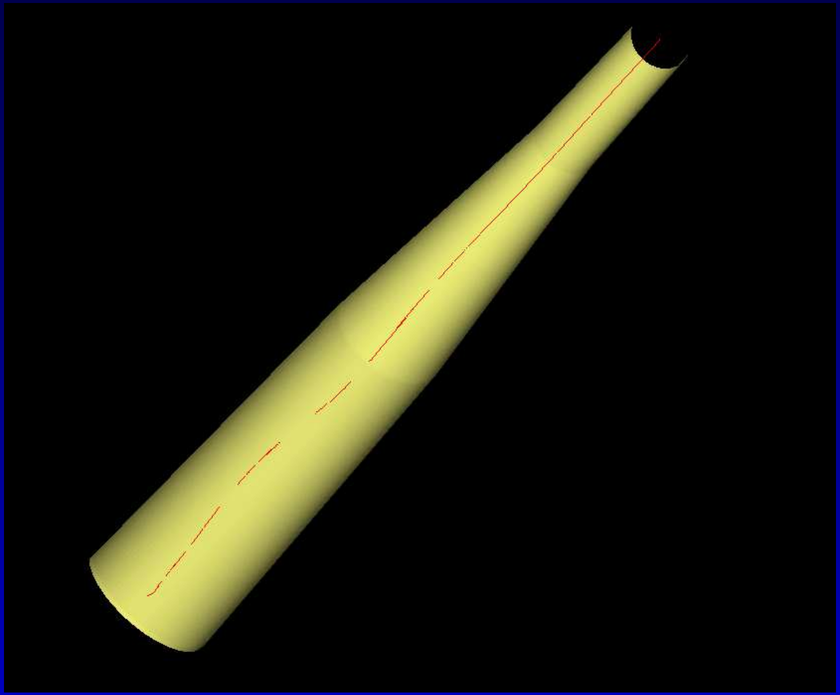
Mean pressure profiles



●: Case 3:1; □: Case 2:1; ◇: Case 1:1.

Results

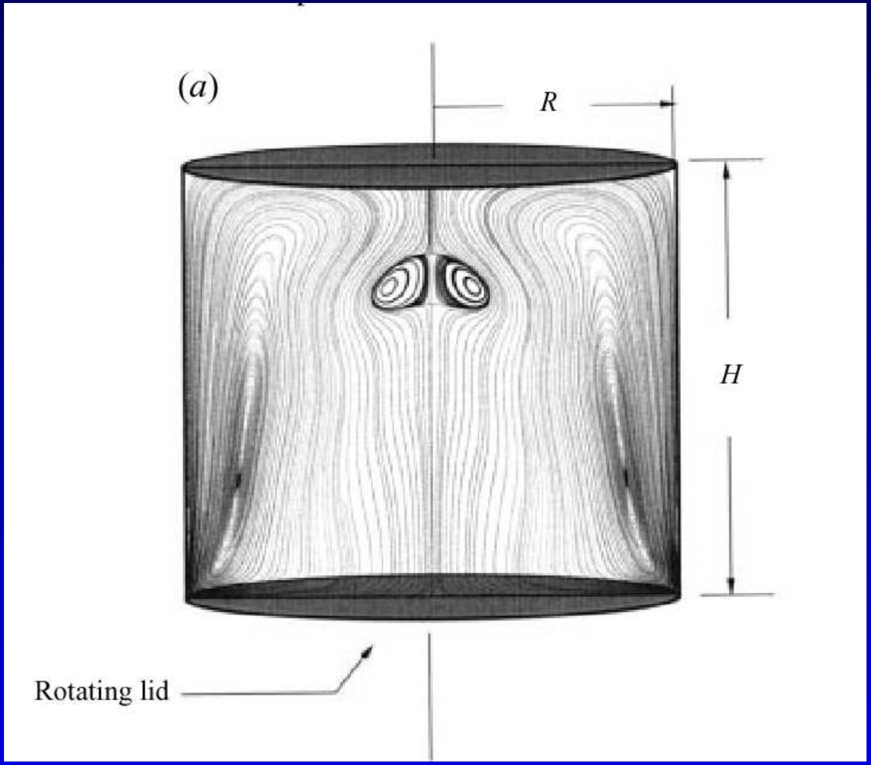




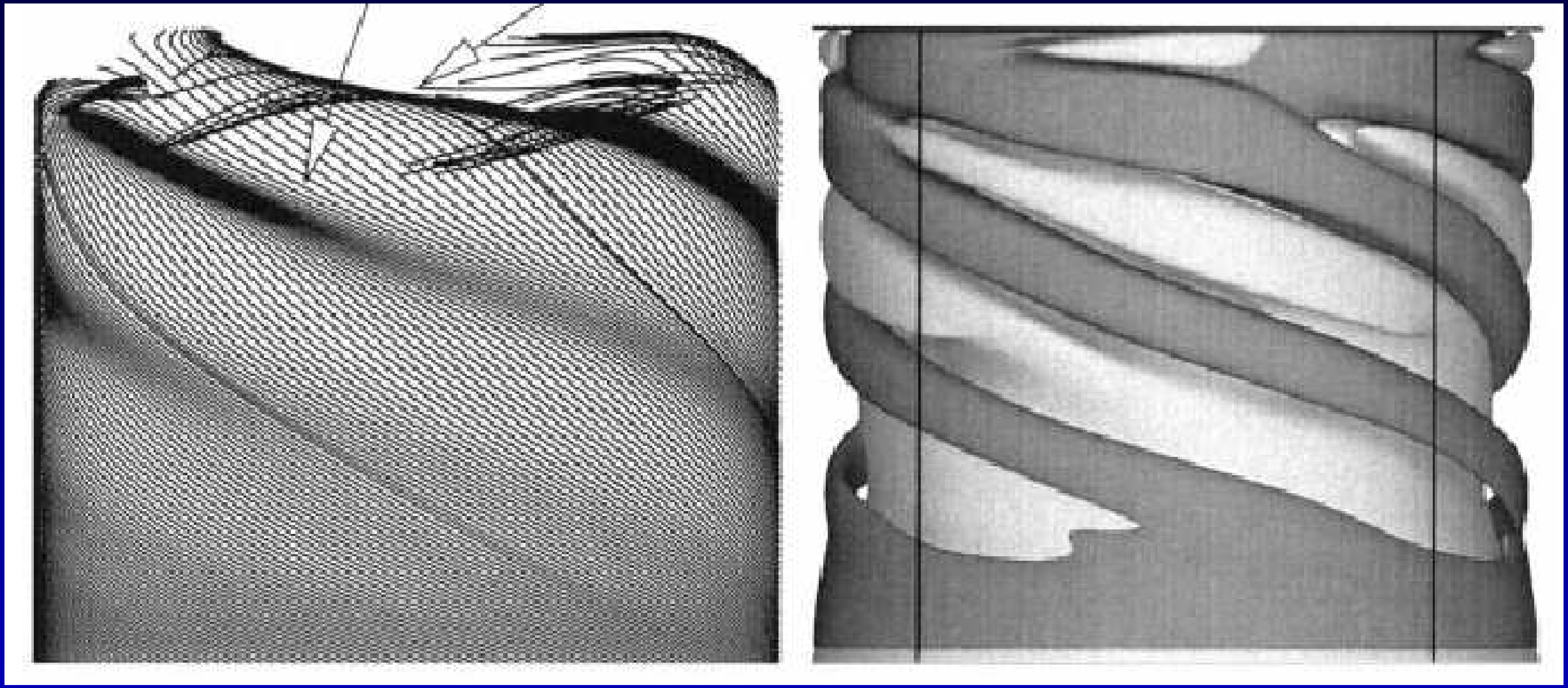
Iso-pressure surfaces, planes of pressure distribution and vortex core

Results

Analogies to confined swirling flow

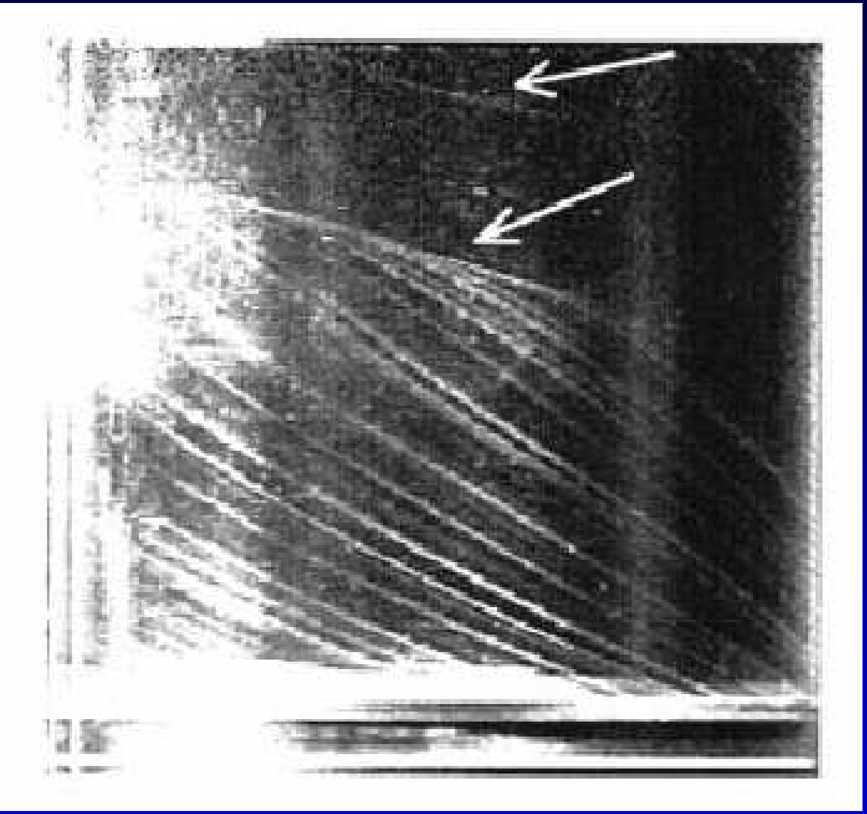


Results



Analogies to confined swirling flow: Calculation

Results



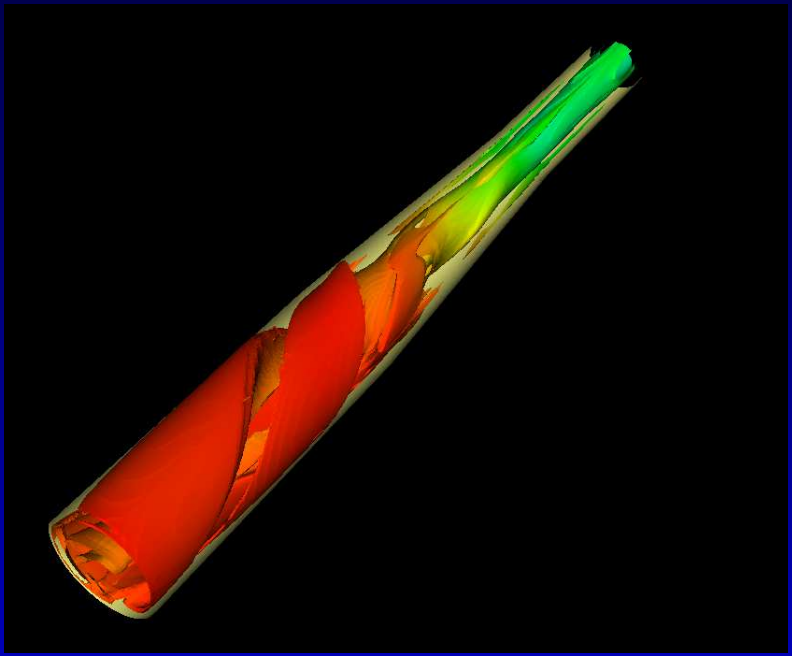
Analogies to confined swirling flow: Experiment

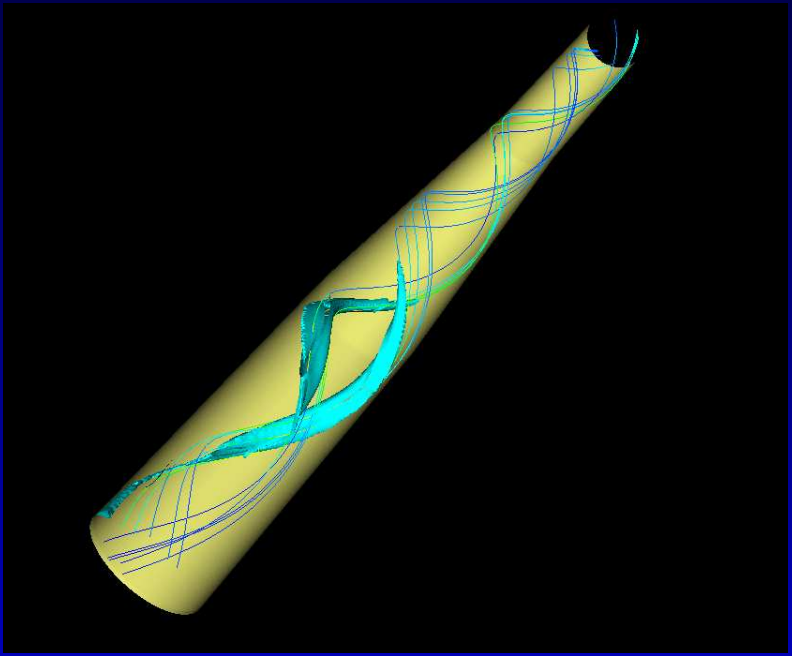
Results

Analogies to confined swirling flow

- Smearlines and velocity magnitude gradient, $(\partial_r |U_i|)$

Results





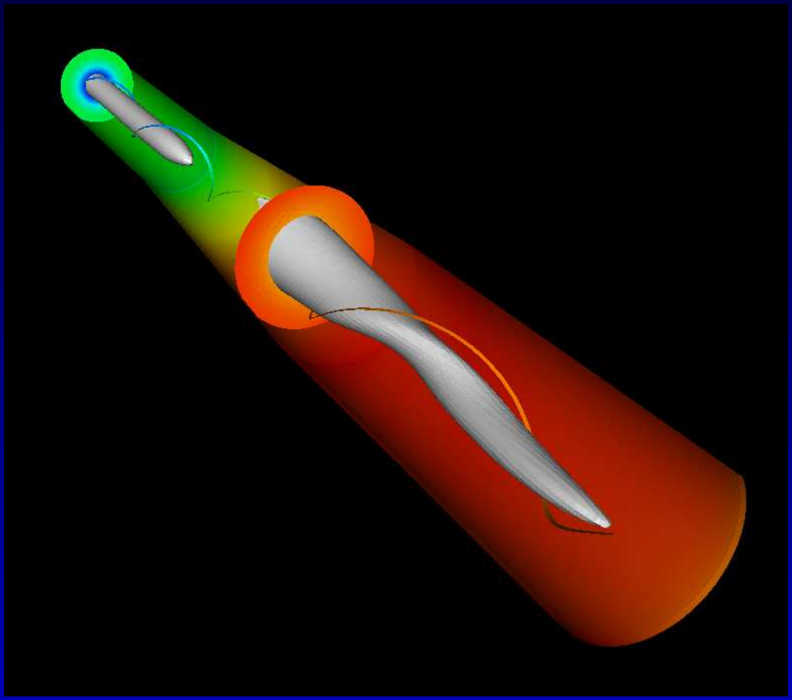
Normalized helicity, $\varphi = \frac{\Omega_i U_i}{|\Omega_i||U_i|}$

Results

Generation of asymmetric modes

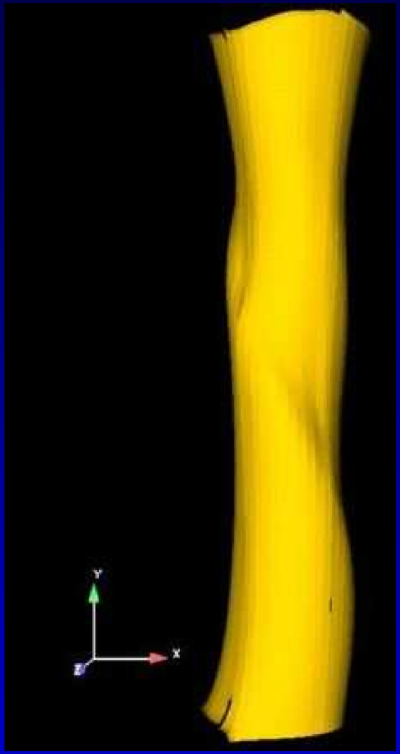
- Grid topology?
- Asymmetric boundary conditions?
- Order of indices?
- CAD-geometry?

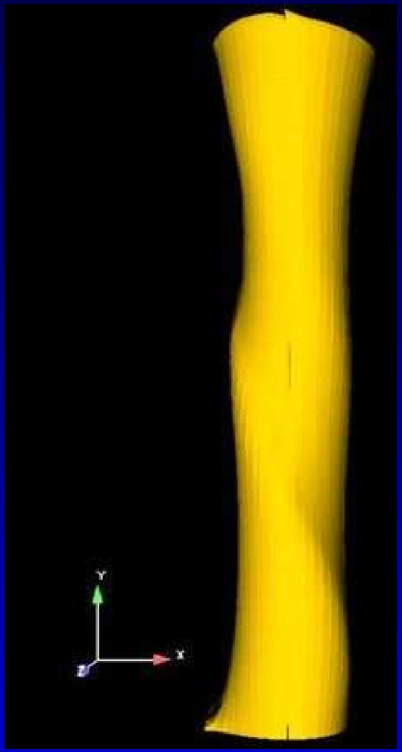
Results

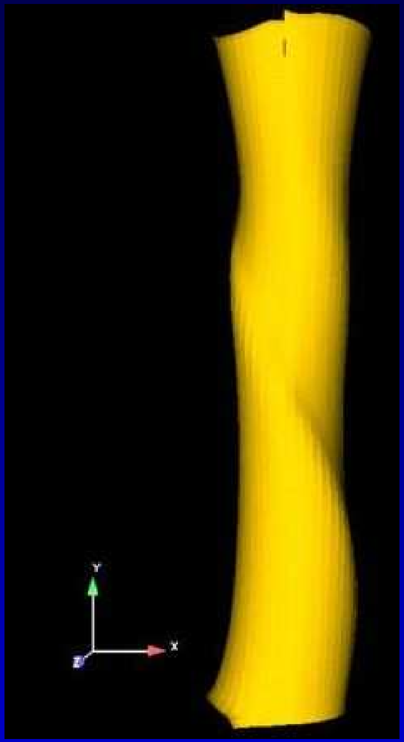


Iso-pressure surfaces as indicator of asymmetry

Results

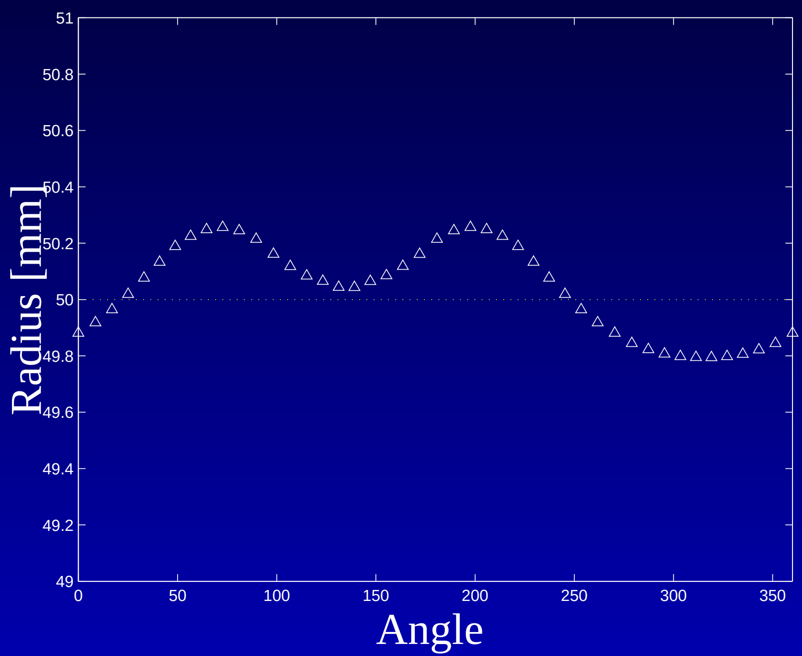






Asymmetry is geometrically induced

Results



CAD-imperfection → Forced symmetry breaking disturbance

Conclusions

Instability
- The mean flow is very sensitive to disturbances

ICEM spline conversion
- Do we get what we ask for?

Steady solutions
- Due to turbulence model or asymmetric geometry?

Turbulence model
- Overestimates radial mixing in the forced vortex region

Future Work

LES - Large Eddy Simulation

- Resolve large turbulent scales
- No need for boundary conditions for k and ε
- Weaker dependence on turbulence model