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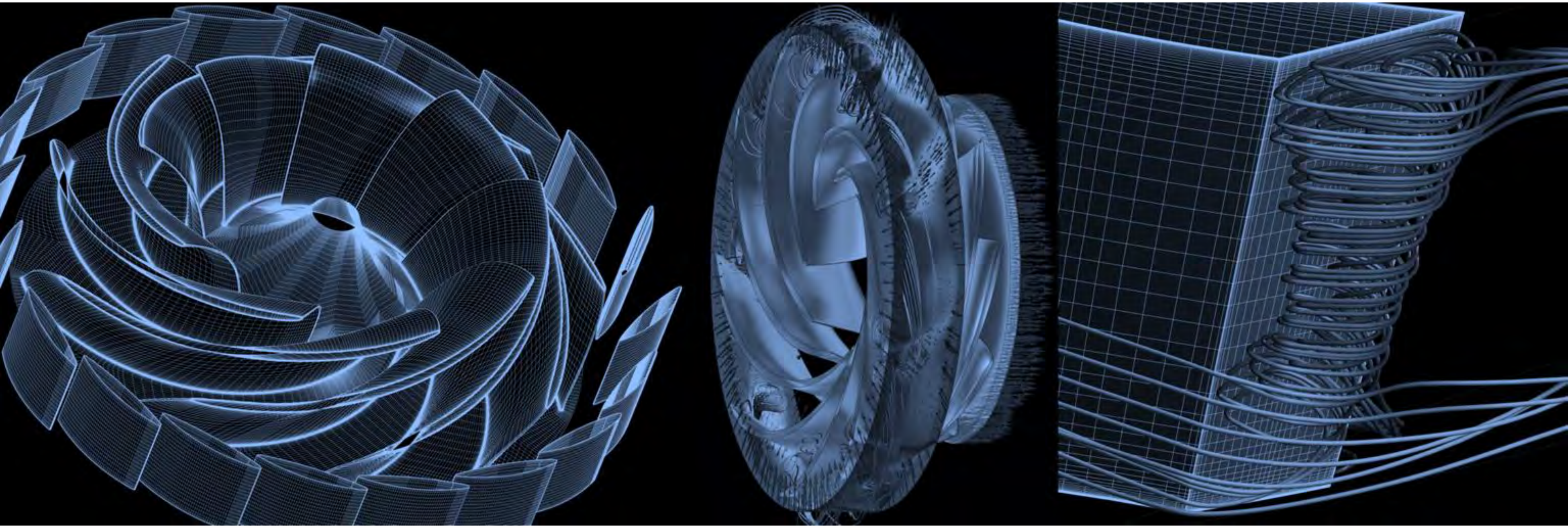

Recent Advances in Numerical Predictions for Off-Design Conditions in Hydraulic Turbomachines

CC Fluid Mechanics and Hydraulic Machines
David Roos Launchbury
13.09.2018

FH Zentralschweiz

EFQM
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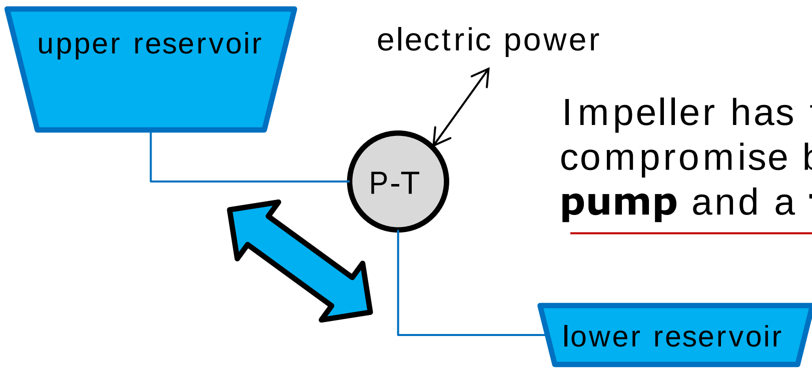
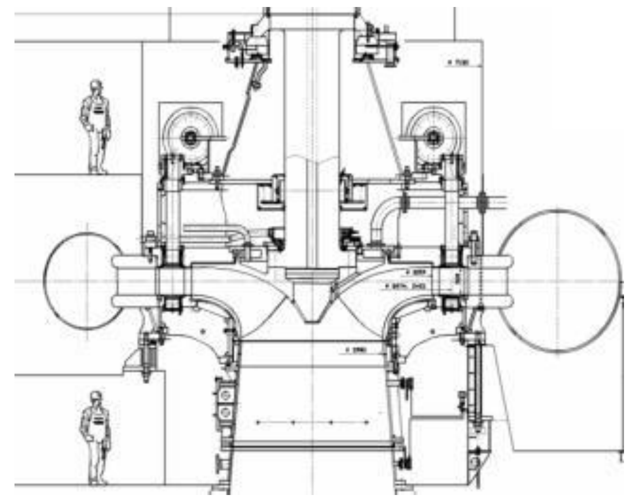
Pump Turbine System



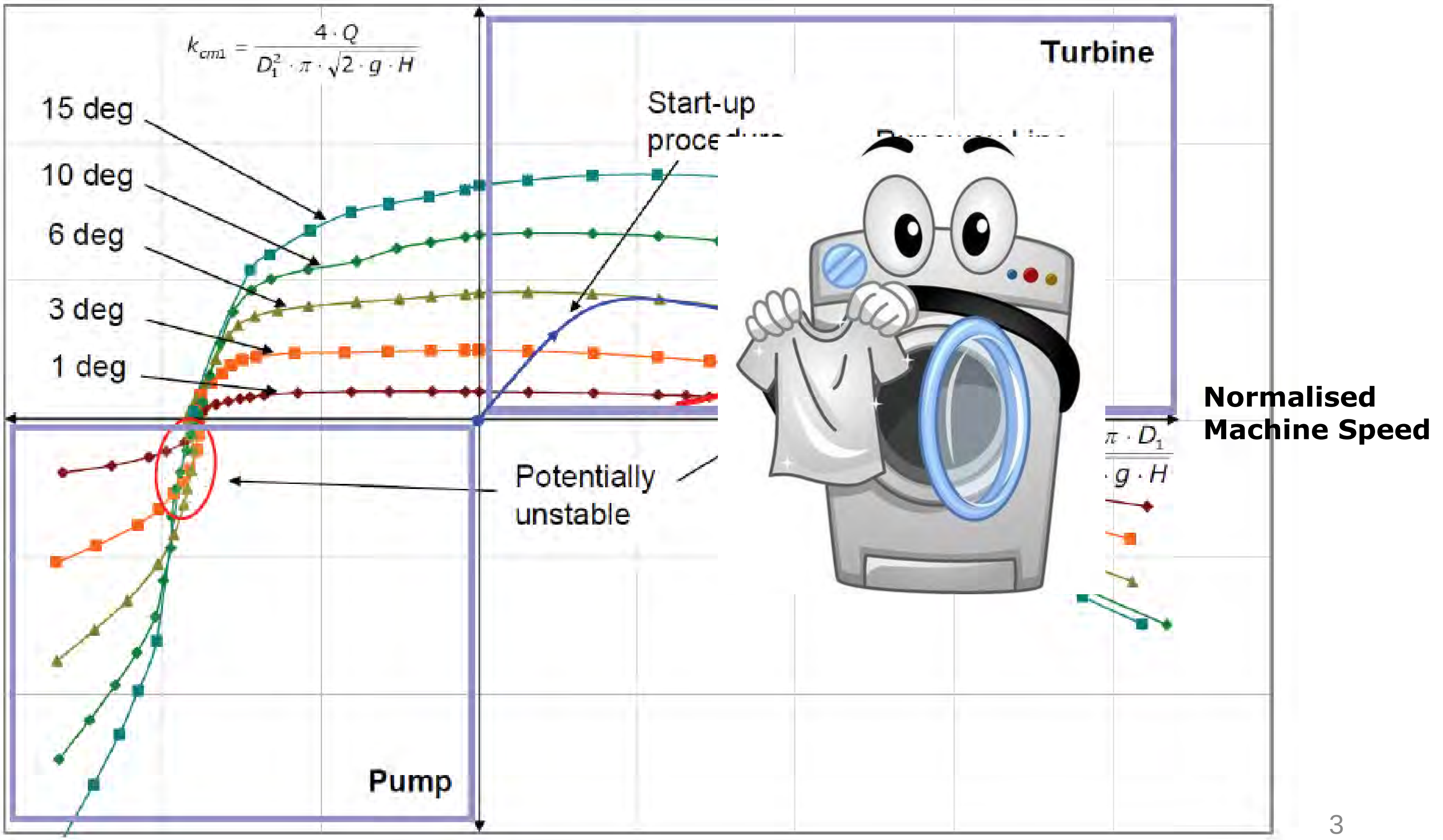
Impeller has to be a compromise between a **pump** and a **turbine**



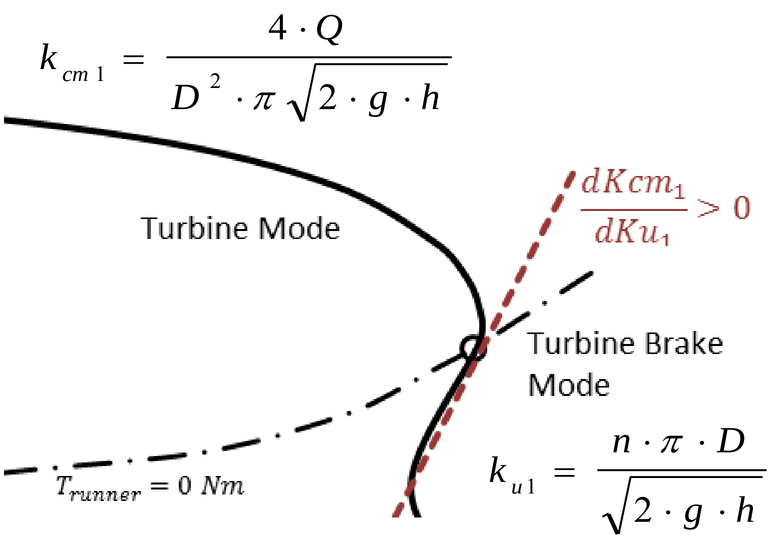
C. Gentner, Challenges in the Design of Pump Turbine, 2012

- The special geometry of the pump turbine has a negative impact on the stability of the hydraulic system

Pump Turbine Start-up Procedure



Instabilities in Pump Turbines



- The instabilities can lead to:
  - Additional dynamic stresses
  - Restrictions in the operating range
  - Unfavourable dynamic behaviour
  - Difficulties to synchronize the turbine with the power grid

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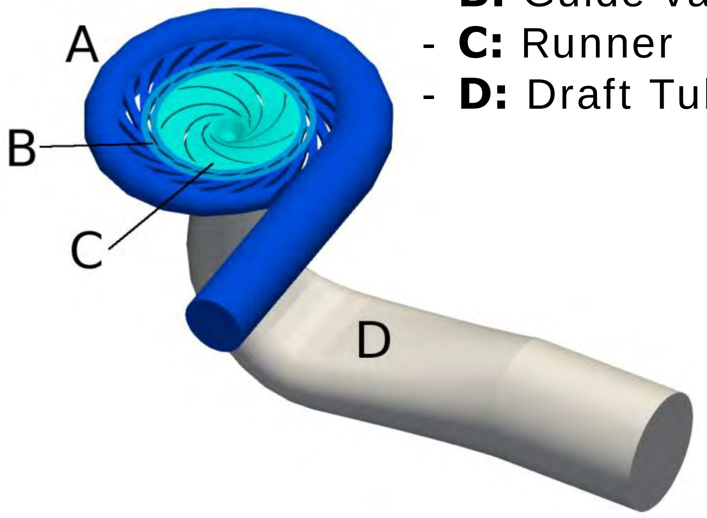
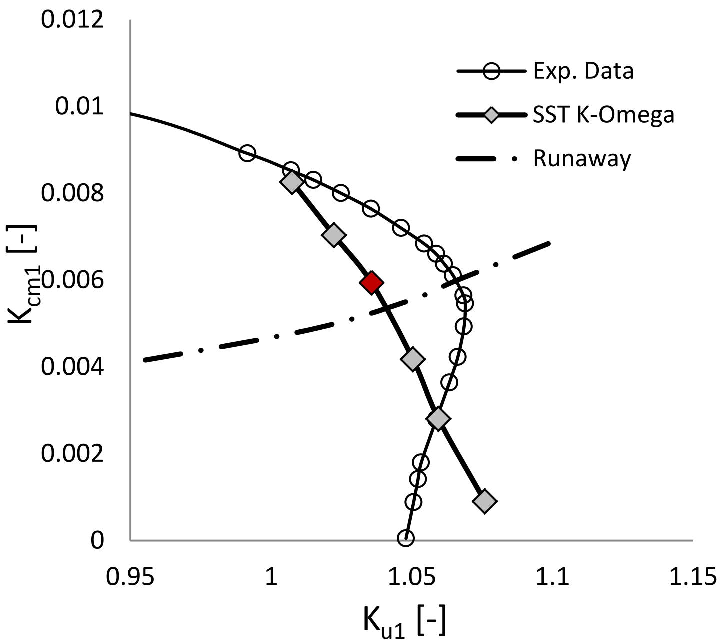
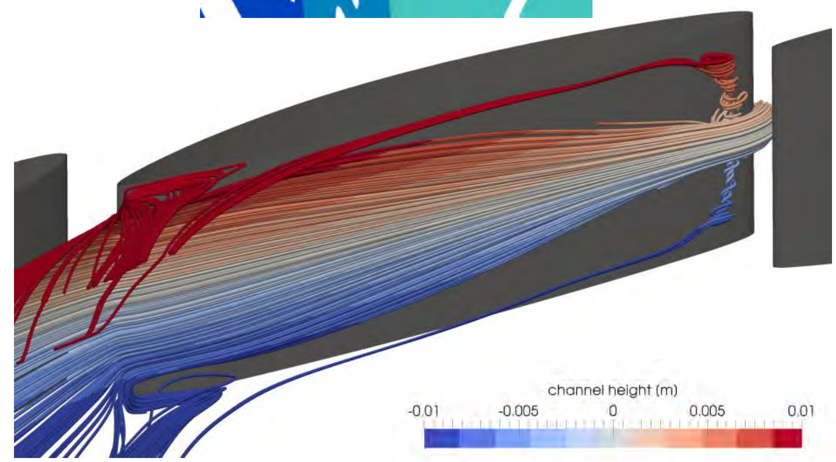
Simulation of Synchronisation Conditions

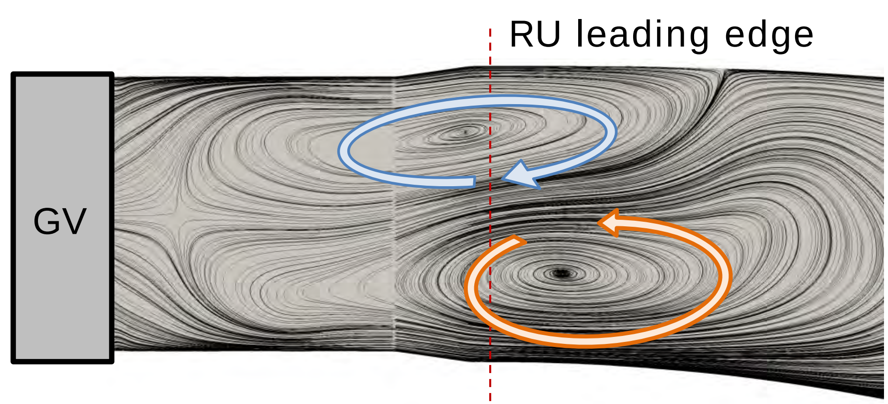
- The dominant flow features vary in **space** and **time**
- Computational domain:
  - Full-size pump-turbine (periodicity not valid)
  - Transient simulation with sufficiently small time-step
- Full Geometry
  - **A:** Spiral casing + Stay vanes
  - **B:** Guide vanes
  - **C:** Runner
  - **D:** Draft Tube



Simulation of Synchronisation Conditions







Simulation with SST k-ω is **unable** to capture the instability

Turbulence models have a large influence on the **vortex formation** in the **vaneless space**, and therefore determine the stability of the characteristic

Eddy Viscosity Turbulence Models

- Reynolds averaging of momentum equation leads to additional stress terms (divergence of a symmetric tensor, "Reynolds stress tensor")

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial(\bar{u}_i \bar{u}_j)}{\partial x_j} = \bar{f}_i - \frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\nu\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right)\right) - \frac{\partial \tau_{ij}}{\partial x_j}$$

- Usually turbulence models use the Boussinesq hypothesis to model the effect of the Reynolds stress tensor.

$$\tau_{ij} - \frac{1}{3}\tau_{kk}\delta_{ij} = \nu_t\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right) = 2\nu_t \bar{S}_{ij}$$

- Effects of the Reynolds stresses cause increased mixing and dissipation
  → Artificial "turbulent" viscosity (added to laminar viscosity)

$(\nu + \nu_t)$

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial(\bar{u}_i \bar{u}_j)}{\partial x_j} = \bar{f}_i - \frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\nu\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right)\right) - \frac{\partial \tau_{ij}}{\partial x_j}$$

Eddy Viscosity Turbulence Models

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- Problem: Eddy viscosity is a scalar quantity, i. e. added diffusion is isotropic

- Turbulence is hardly ever isotropic, especially not in fully formed vortices

- Isotropic eddy viscosity models have trouble reproducing the flow field in the vaneless spaces of a pump turbine

- The vortex structures strongly affect the incoming flow into the runner

Eddy Viscosity Turbulence Models

$(\nu + \nu_t)$

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial(\bar{u}_i \bar{u}_j)}{\partial x_j} = \bar{f}_i - \frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\nu\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right)\right) - \frac{\partial \tau_{ij}}{\partial x_j}$$

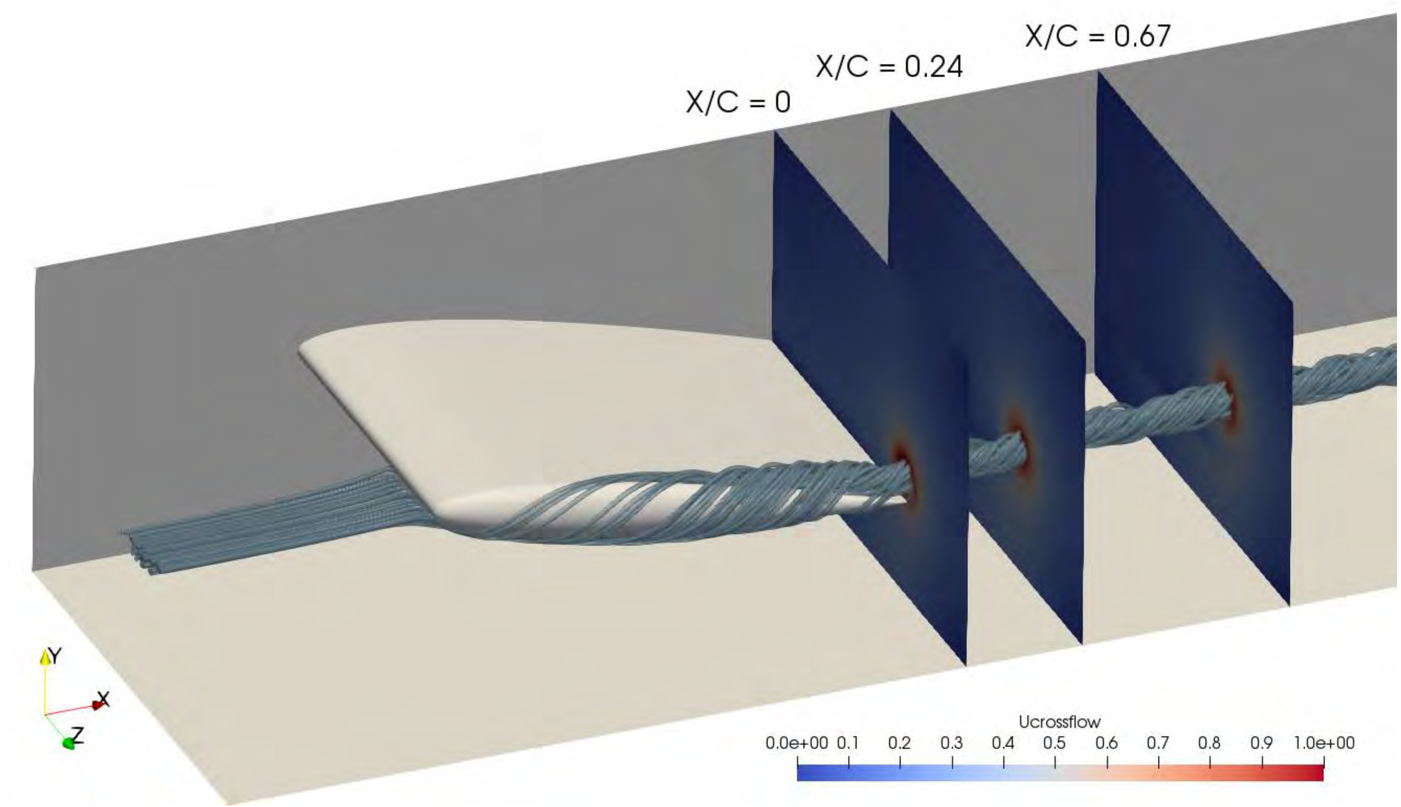
- Solution: Use turbulence models that allow anisotropy and model the full Reynolds stress tensor

- Explicit Algbraic Reynolds Stress Models (EARSM)
  - Based on standard 2-equation models
  - Try to reconstruct the stress tensor algebraically from the velocity gradients

- Full Reynolds Stress Models
  - Solve transport equations for all 6 components + scale equation

NACA0012 Tip Vortex Flow Comparison

- Evaluation of crossflow velocity in NACA0012 profile tip vortex



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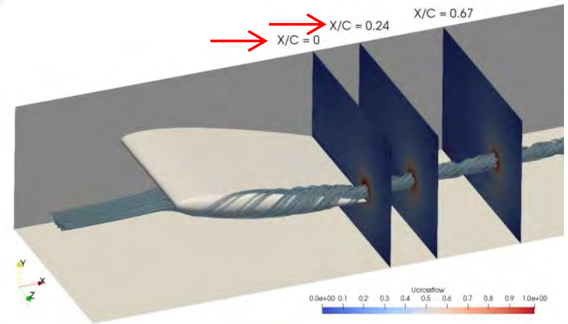
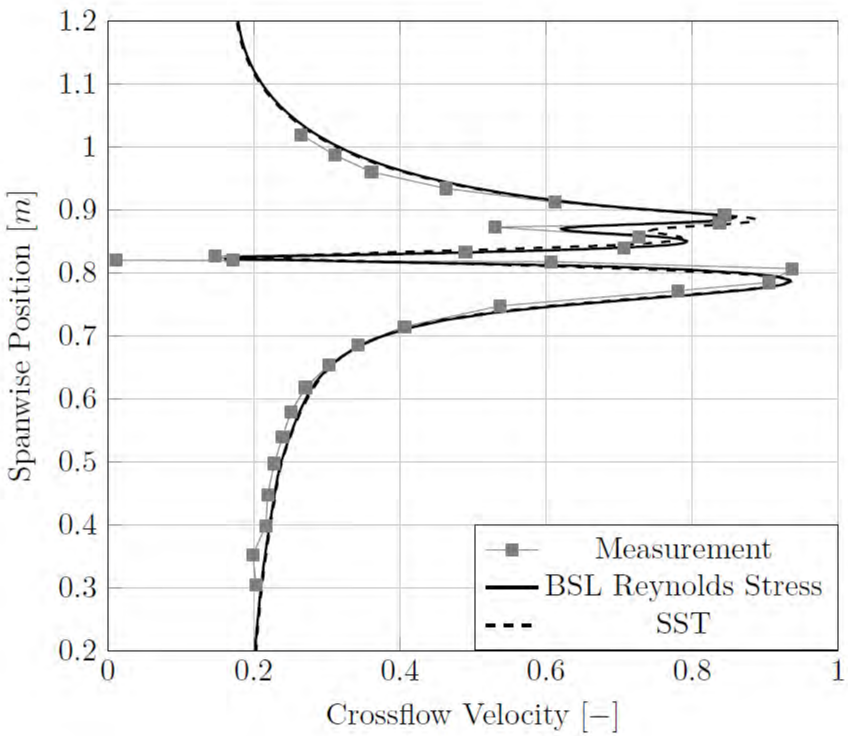
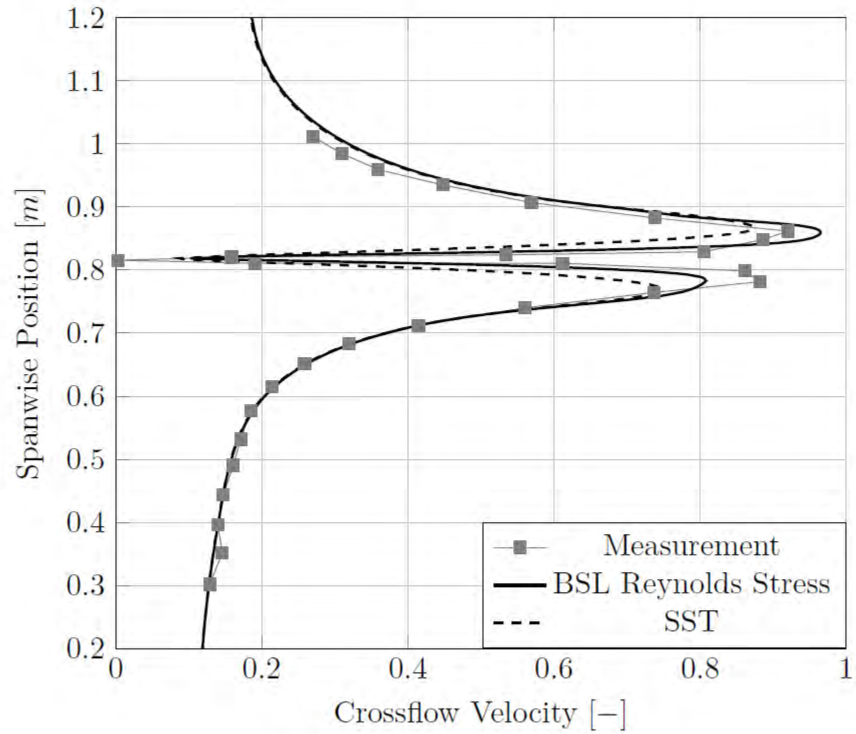
NACA0012 Tip Vortex Flow Comparison



- Evaluation of crossflow velocity in NACA0012 profile tip vortex (0%, 24%)

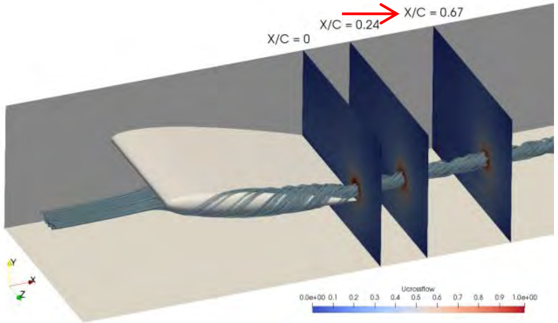


Crossflow Velocity in Wing Tip Vortex of NACA0012 at X/C = 0.0

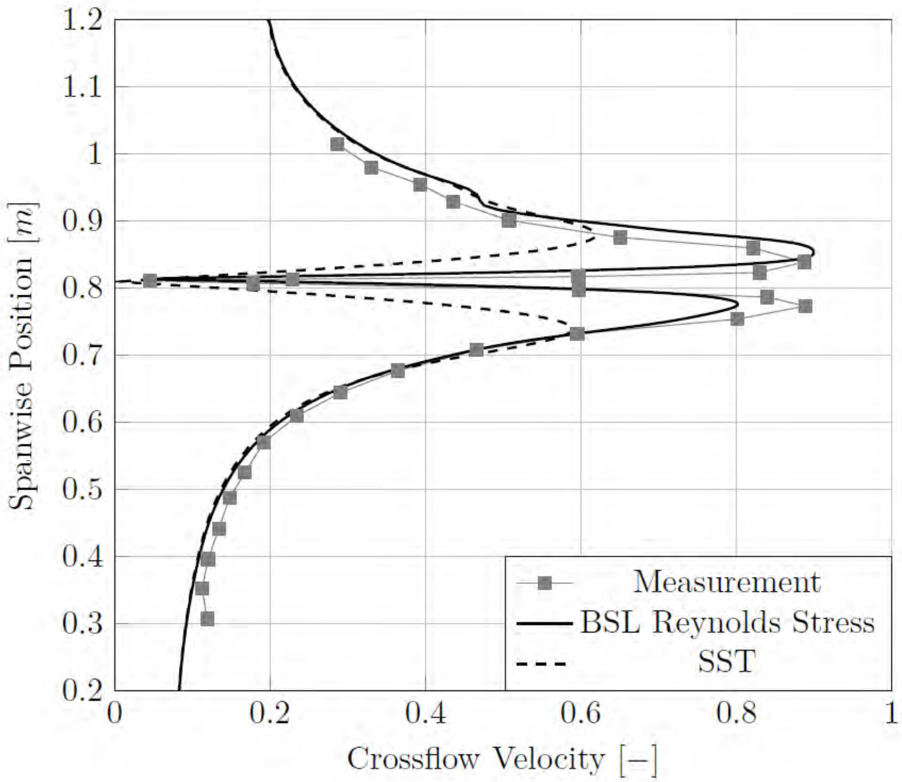


Crossflow Velocity in Wing Tip Vortex of NACA0012 at X/C = 0.24

NACA0012 Tip Vortex Flow Comparison



- Evaluation of crossflow velocity in NACA0012 profile tip vortex (67%)



Crossflow Velocity in Wing Tip Vortex of NACA0012 at X/C = 0.67

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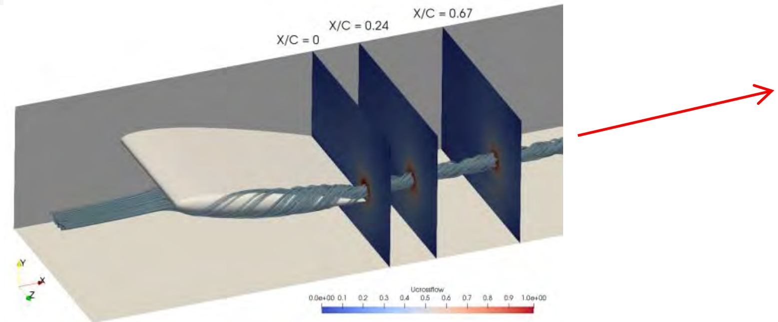
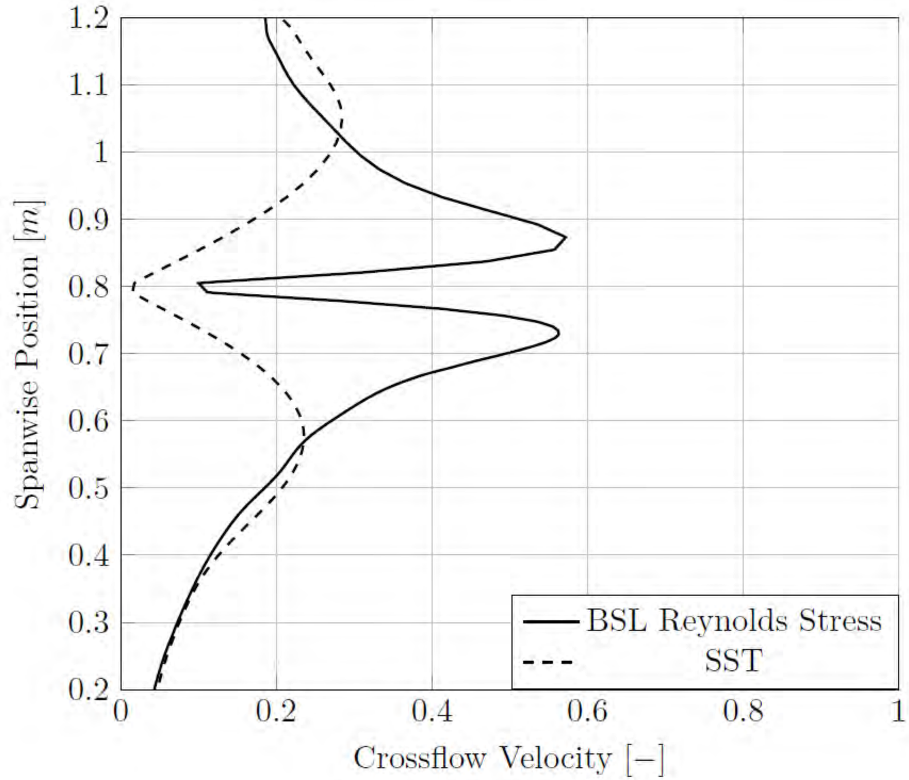
NACA0012 Tip Vortex Flow Comparison

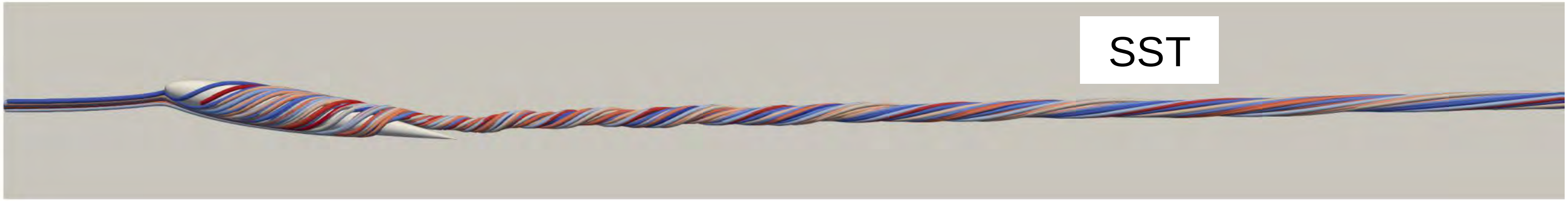


- Evaluation of crossflow velocity in NACA0012 profile tip vortex (582%)



Crossflow Velocity in Wing Tip Vortex of NACA0012 at X/C = 5.82

NACA0012 Tip Vortex Flow Comparison



What's the catch?

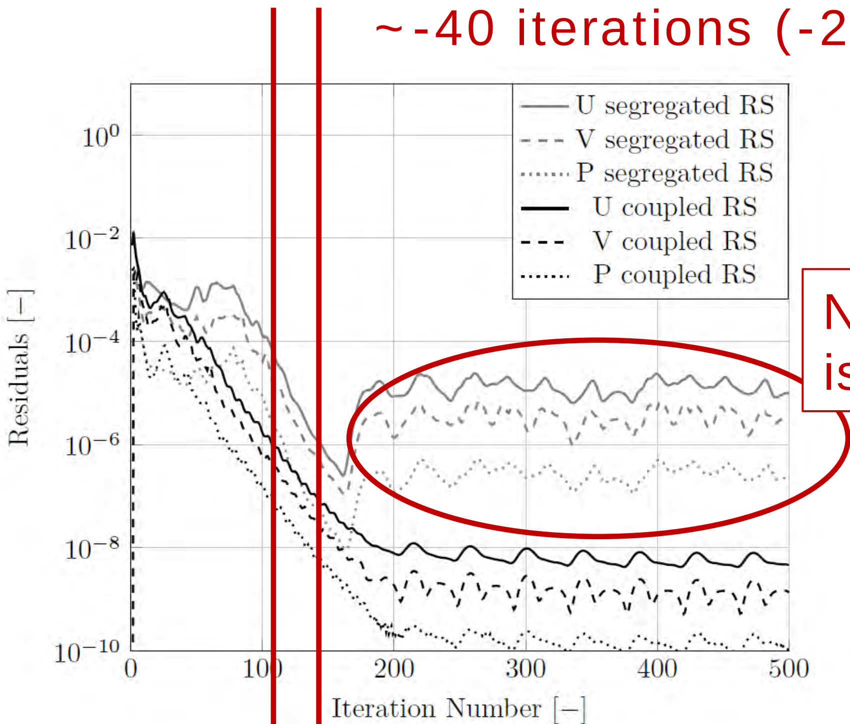
- Reynolds stress models improve the results significantly for vortex dominated flows
- Drawbacks of these models?
  - Decoupling of stress and velocity fields → checkerboarding
  - Stability and convergence issues
  - Increased computational effort (7 equations for full RSM)
- Goal: reduce/eliminate these drawbacks

Efforts to Reduce Disadvantages of Reynolds Stress Models

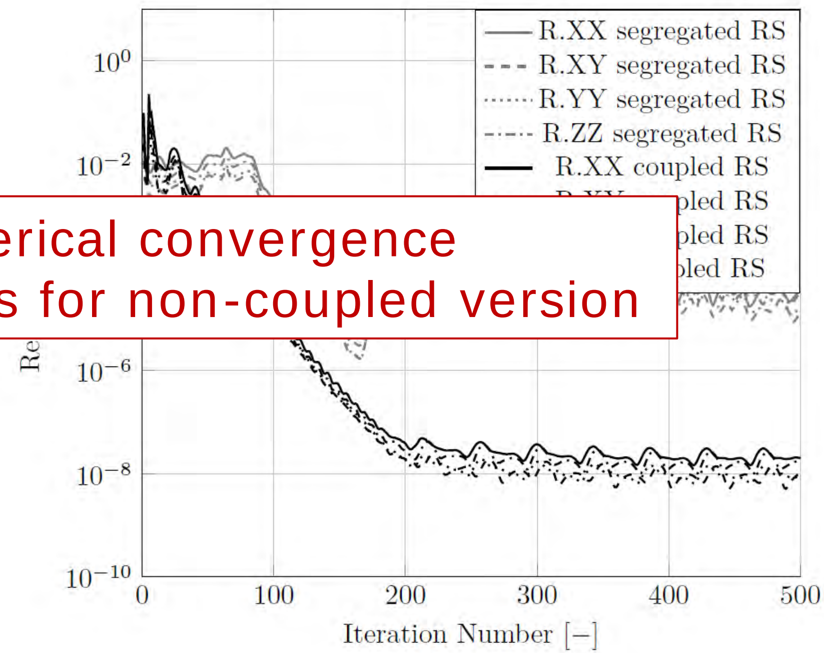
- Checkerboarding solutions:
  - Replace normal components of interpolated Reynolds stresses using a smaller stencil, leading to tight coupling and disappearance of decoupling.
- Computational effort and stability
  - Couple Reynolds stress equations (only applicable to full RSM)

Results: Backward Facing Step with Coupled and Segregated RS Eqns

~-40 iterations (-25%) to target 1e-6



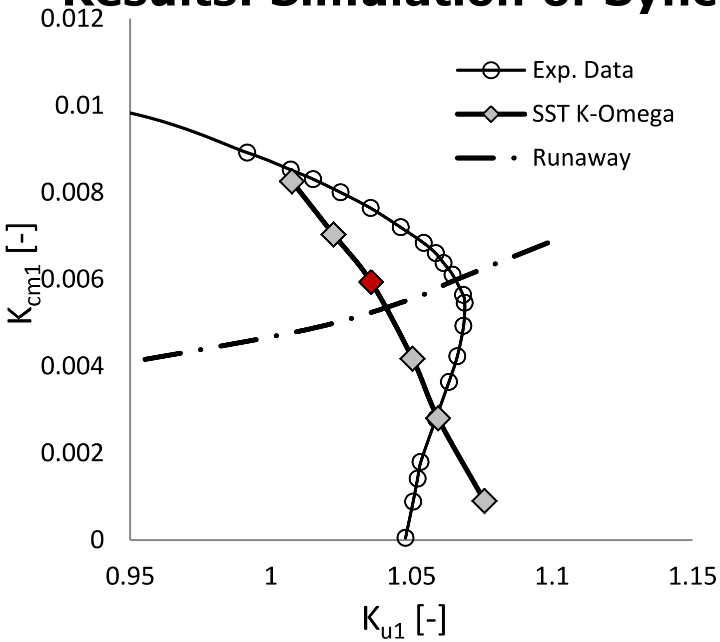
Pressure/Momentum Convergence Behaviour in 2D Backward Facing Step Simulation

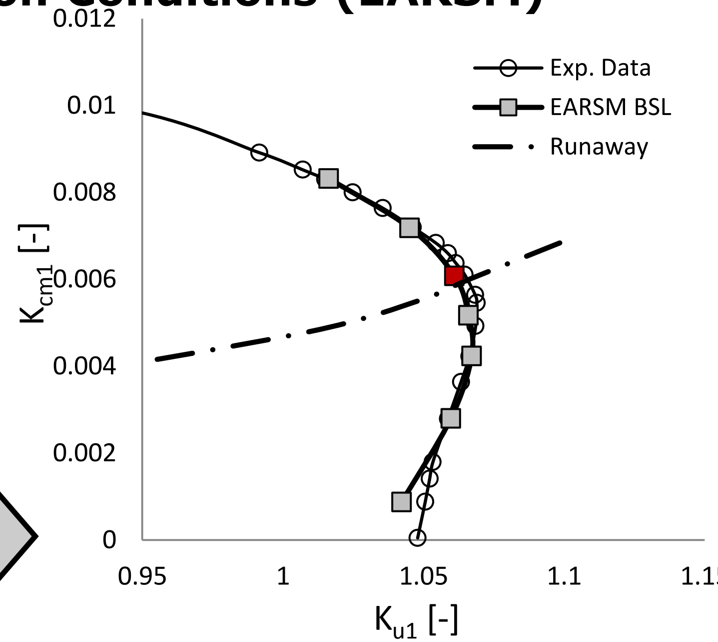


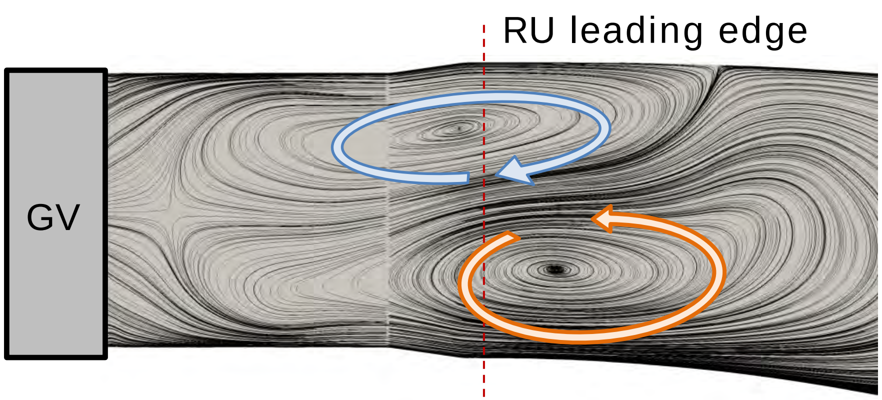
Numerical convergence issues for non-coupled version

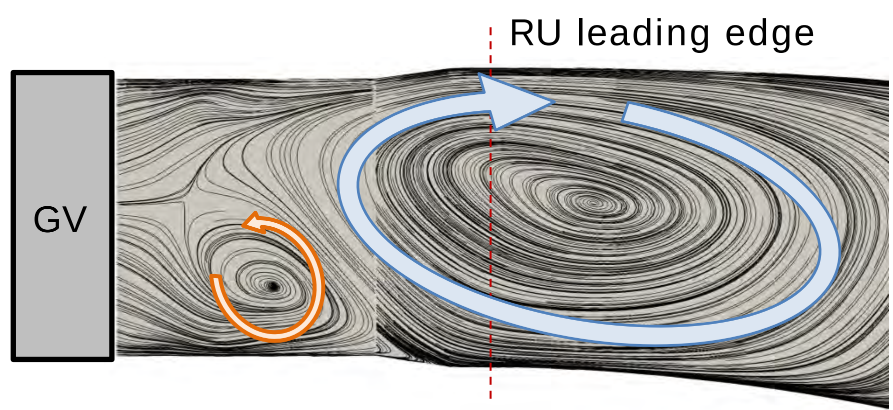
Reynolds Stress Convergence Behaviour in 2D Backward Facing Step Simulation

Results: Simulation of Synchronisation Conditions (EARSM)









Conclusion & Outlook

- Turbulent structures in vaneless space have a strong influence on the characteristics in regions of instability

- Using non-isotropic turbulence models leads to an improved prediction of pump turbine instability

- Inter-equation coupling of the full Reynolds stress models shows promising preliminary results

- Models not yet optimised for efficiency

- Coupling can lead to badly conditioned linear systems in more complicated cases