Numerical simulation of pressure oscillations in Francis turbine runners

JASS 2009

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Summary

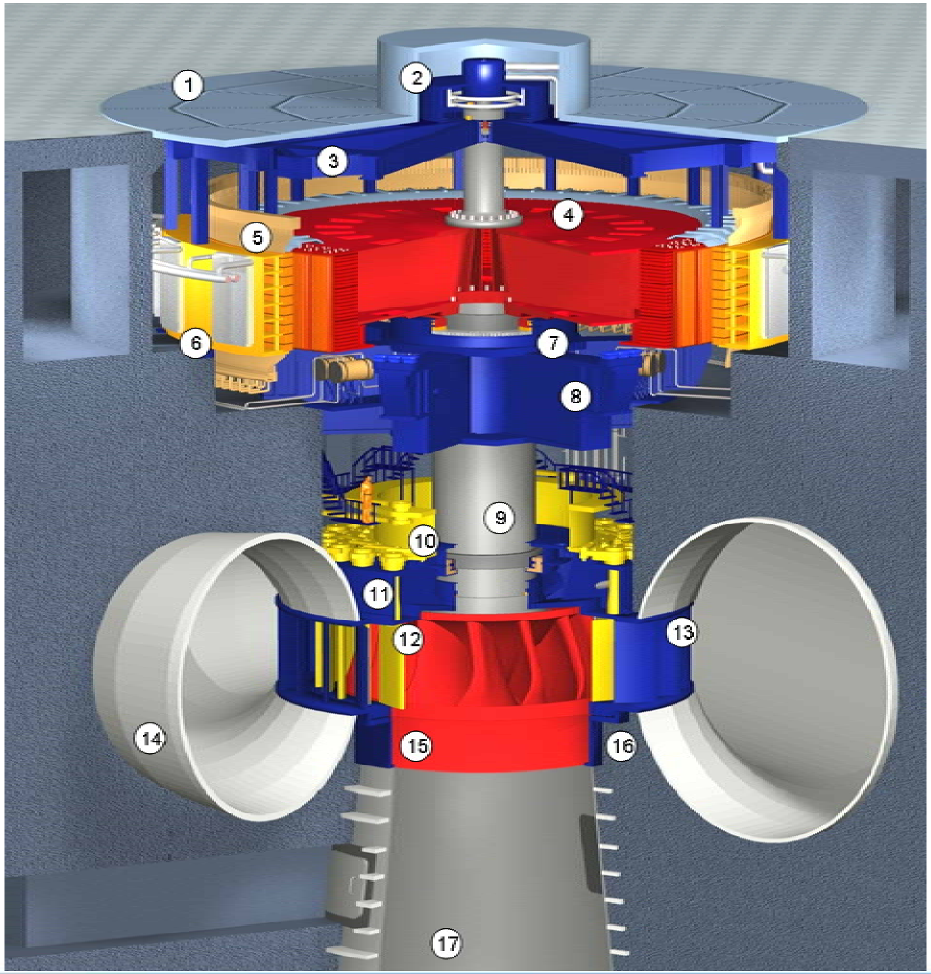
Motivation – General

- Risk of runner cracks, causing energy generation loss, contractual penalties and repair costs.
  - Example:
    - P = 200 MW x 3 Units, Load Factor: 0,70
    - 3 Units down, each for 1 month, due to runner failures
    - Lost energy: ~ 18 Mio €
    - Contractual penalties: ~ 11 Mio €
    - Repair costs: ~ 0,8 Mio € (New runner: ~ 2,0 Mio €/Runner)
- Time and costs involved in a complete model test of a totally new hydraulic design

Motivation – Technical

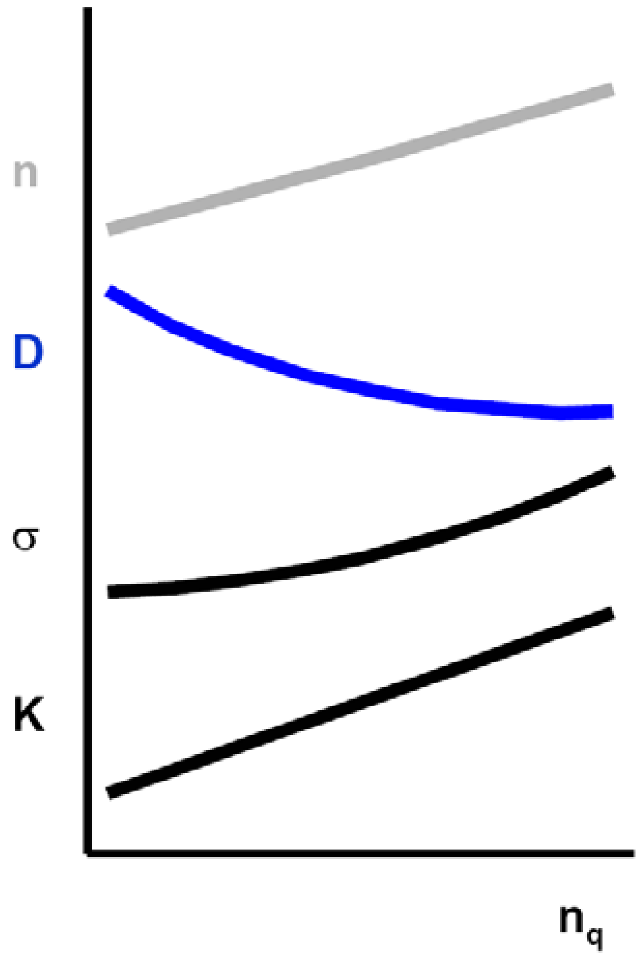
- Numerical prediction of pressure oscillations in hydraulic turbines, specially in Francis runners:
  - Rotor-stator interactions (RSI)
  - Draft tube instabilities (DTI)
  - Vortex shedding effects (VSE)
- Investigation and need of adequate turbulence models for the transient flow simulation
- CFD results as input for:
  - Accurate computational structural analysis (CSA)
  - Runner fatigue strength and fatigue life estimation

Problem description – Definitions



(1) Generator cover
(2) Slip ring
(3) Upper bracket
(4) Generator rotor
(5) Estator
(6) Cooling
(7) Brake
(8) Lower bracket
(9) Shaft
(10) Operating ring
(11) Head cover
(12) Guide vanes
(13) Stay vanes
(14) Spiral case
(15) Turbine runner
(16) Bottom ring
(17) Draft tube

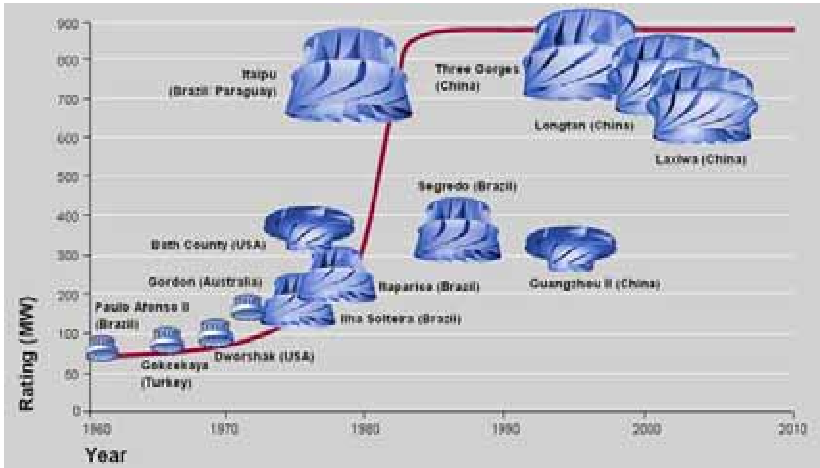
Problem description – Structural loading



Higher specific speed $\left(n_q = n\sqrt{Q}/H^{3/4}\right)$ results in:

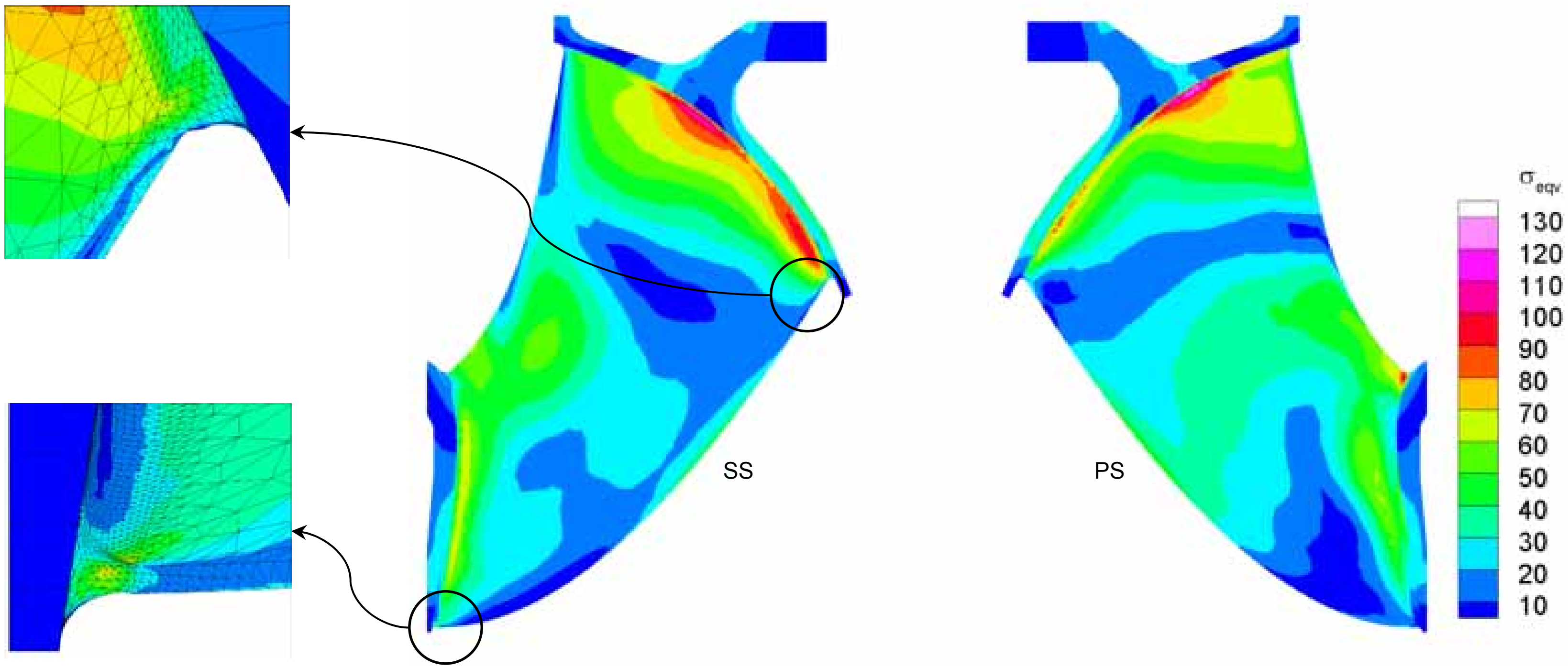
- Higher synchronous speed (n) ⇒ Lower generator cost
- Smaller size (D_{1a}) of turbine runner ⇒ Lower turbine cost
- Higher cavitation factor (σ) ⇒ Higher suction head (h_s) and increase in civil costs
- Increased "specific loading" $\left(K = n_q\sqrt{H}\right)$ of the hydraulic machine ⇒ Increased loads over the turbine structure!

Problem description – Structural loading



- Increase of the specific load (K) over the years:
- Specific load of Three Gorges (2003, 1st Unit) about 10% higher than Itaipu (1984, 1st Unit).
- About 40% increase in the specific load over the last 50 years.

Problem description – Structural problems



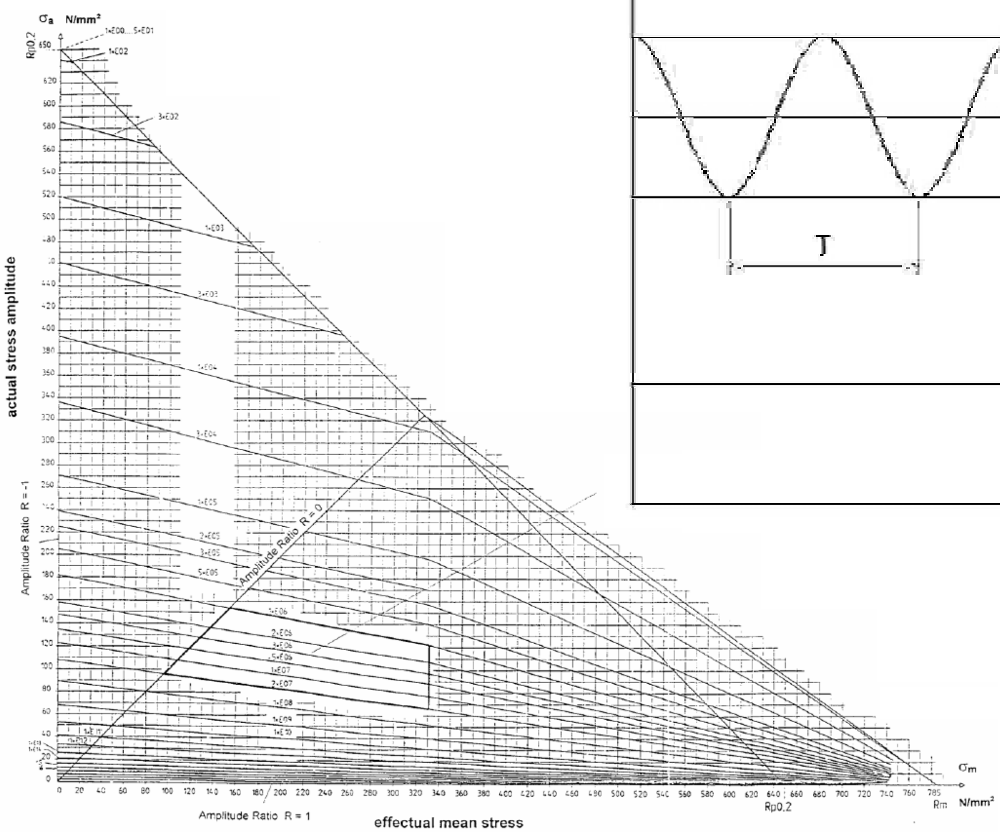
Example of equivalent von Mises structural static stresses

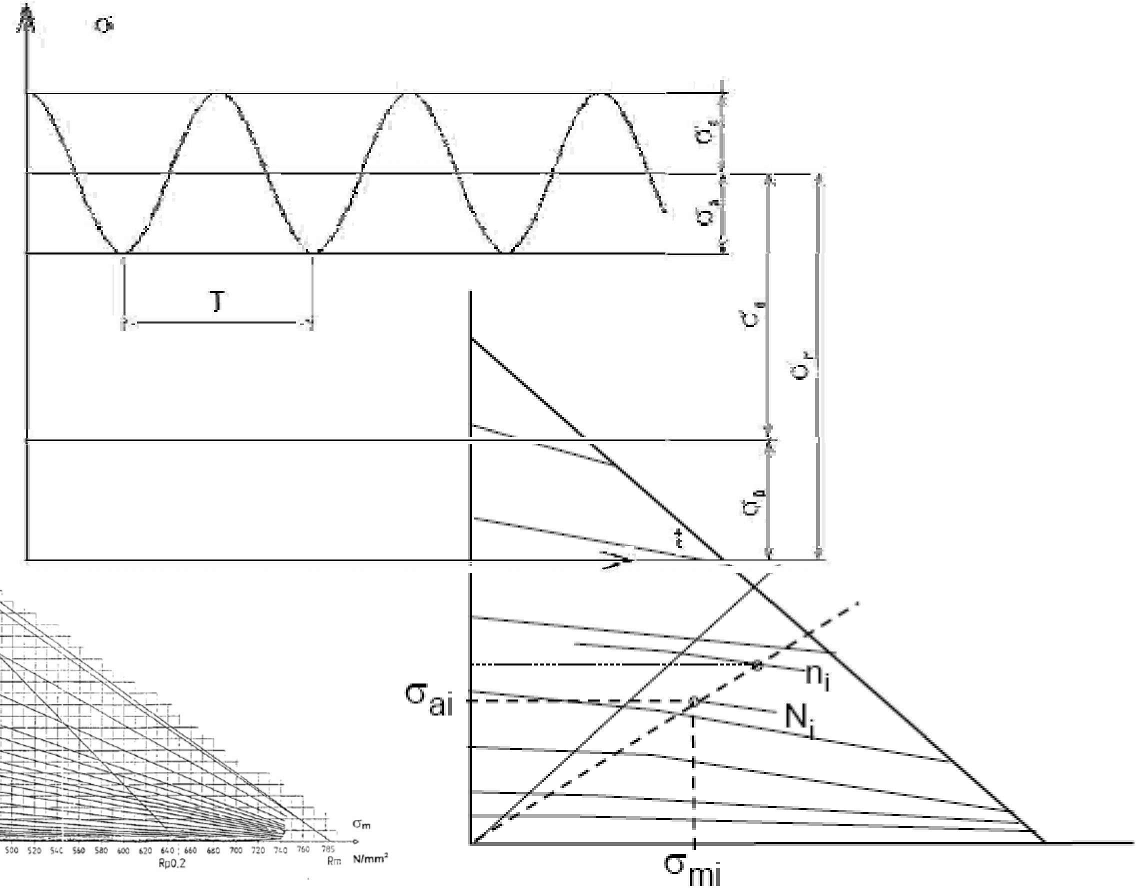
Problem description – Structural problems

Runner cracks at the trailing edge at the crown and band

Problem description – Fatigue analysis

- Haigh diagram:



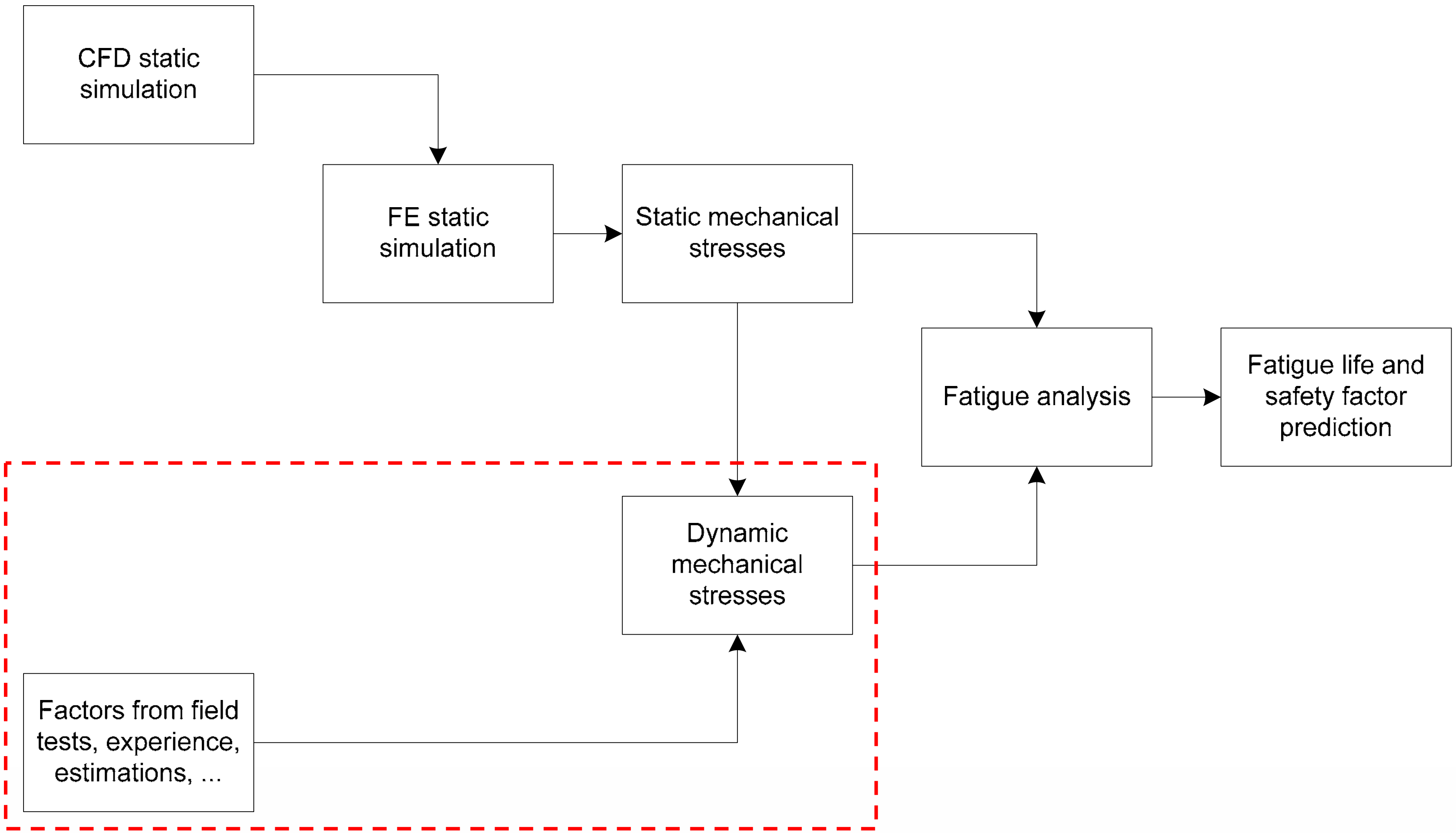


Problem description – Measuring

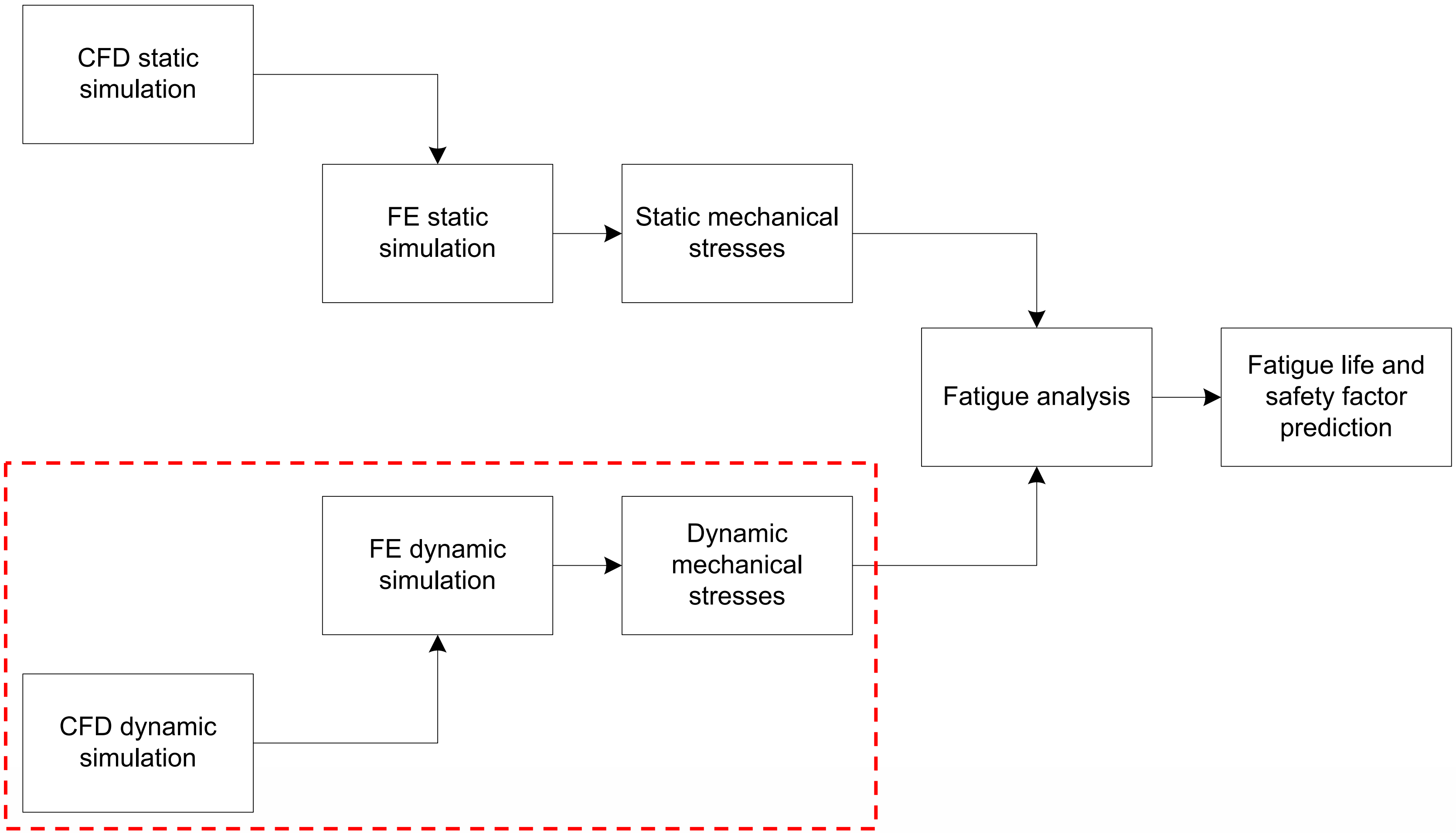
Model

Prototype

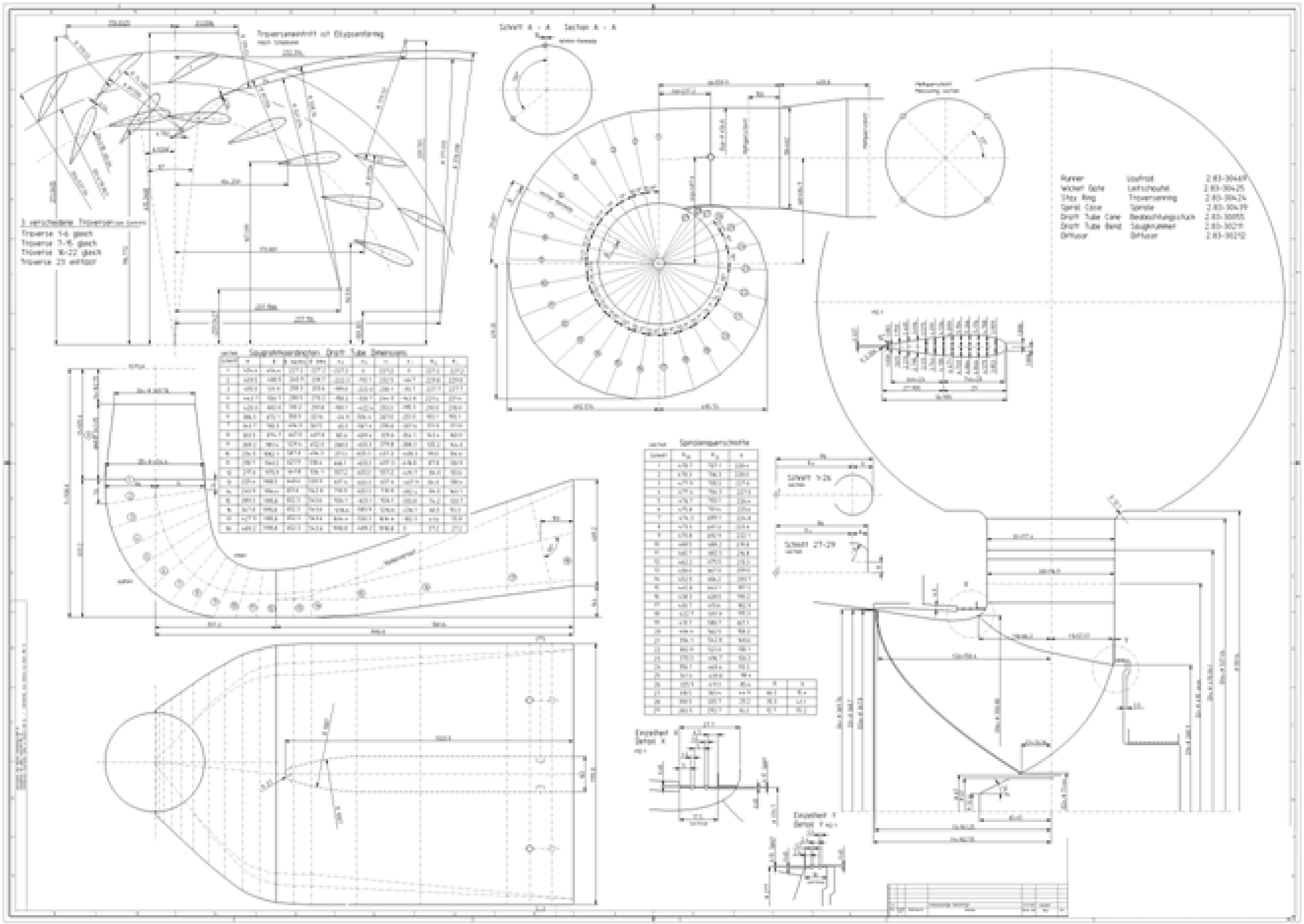
Problem description – Current procedure



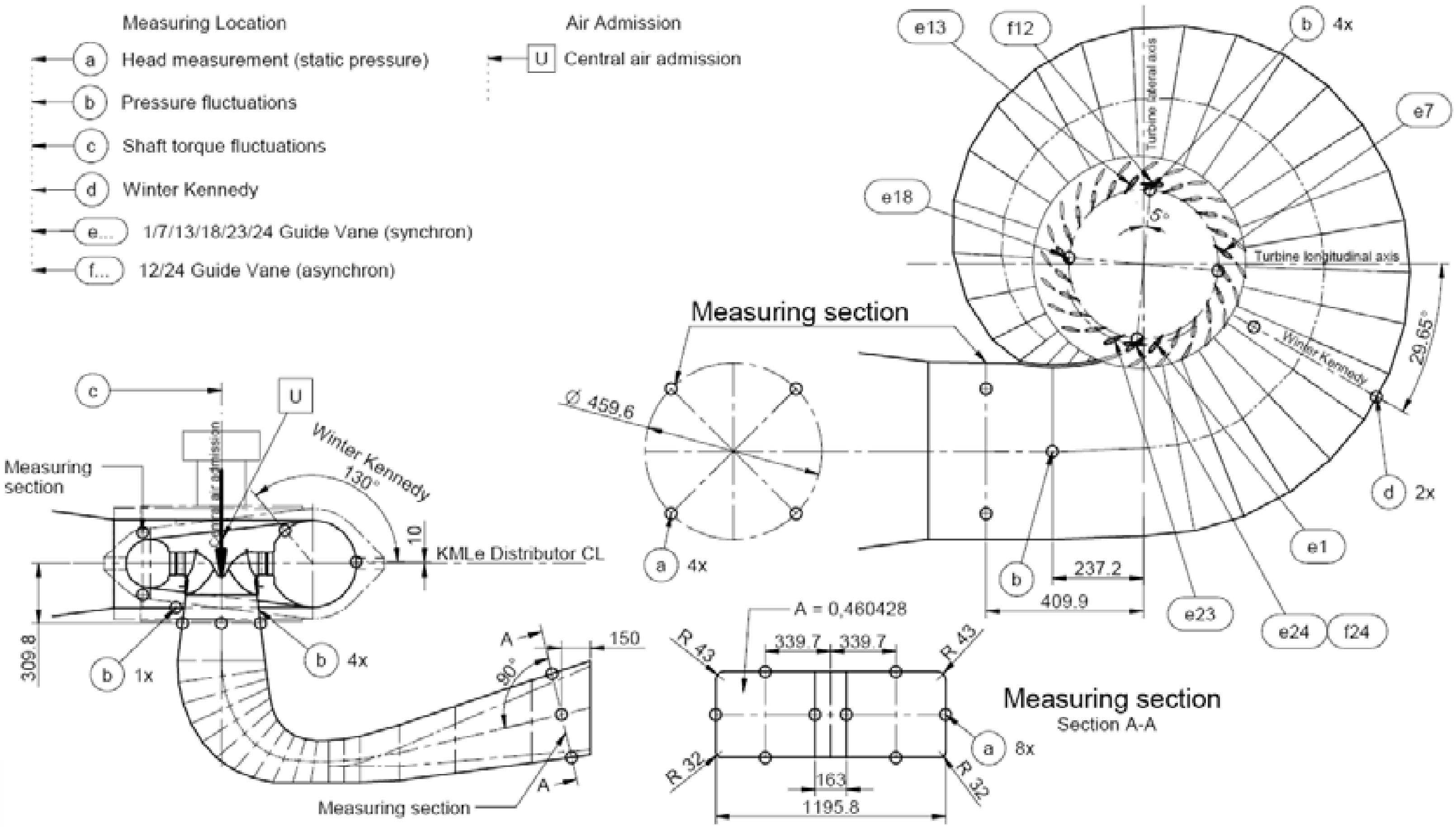
Problem description – Proposed procedure



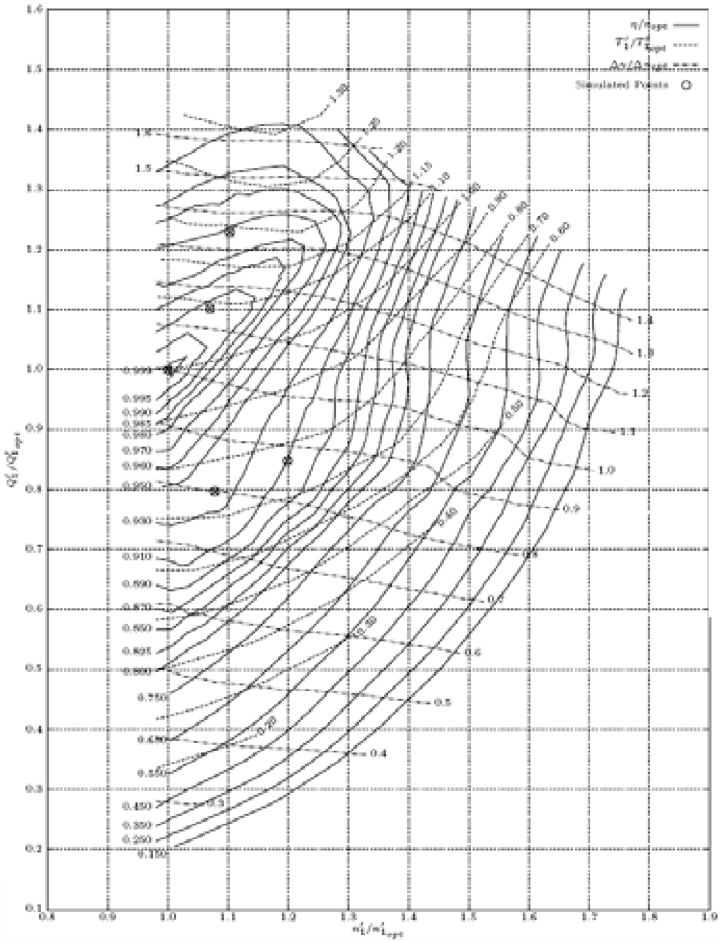
Machine description – Hydraulic contour

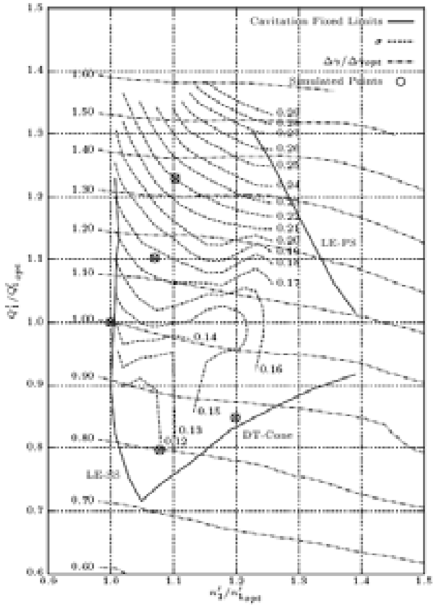


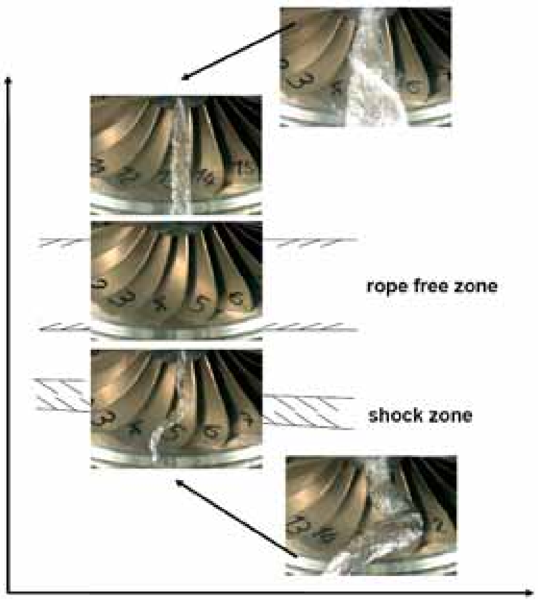
Machine description – Measuring points



Machine description – Model hill chart







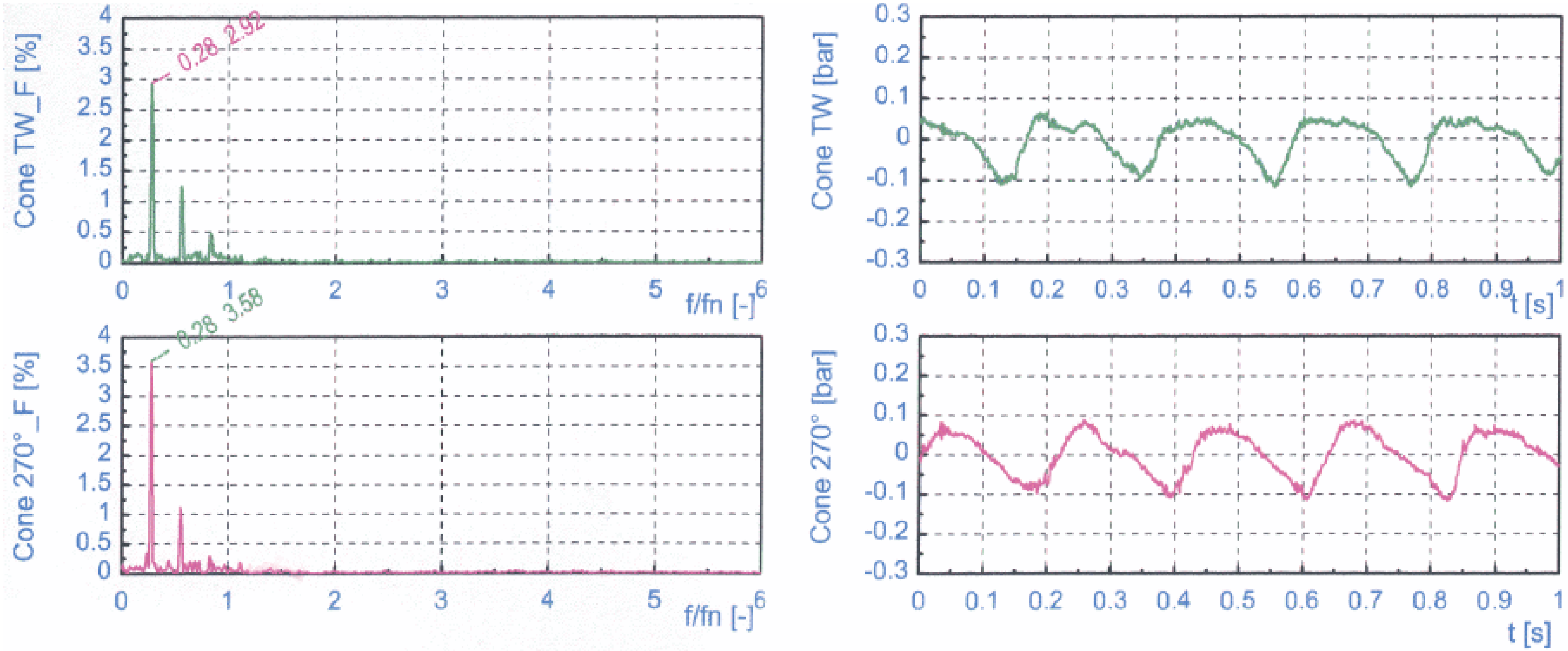
$$n'_1 = nD/\sqrt{H}$$

$$Q'_1 = Q/D^2\sqrt{H}$$

$$T'_1 = T/D^3H$$

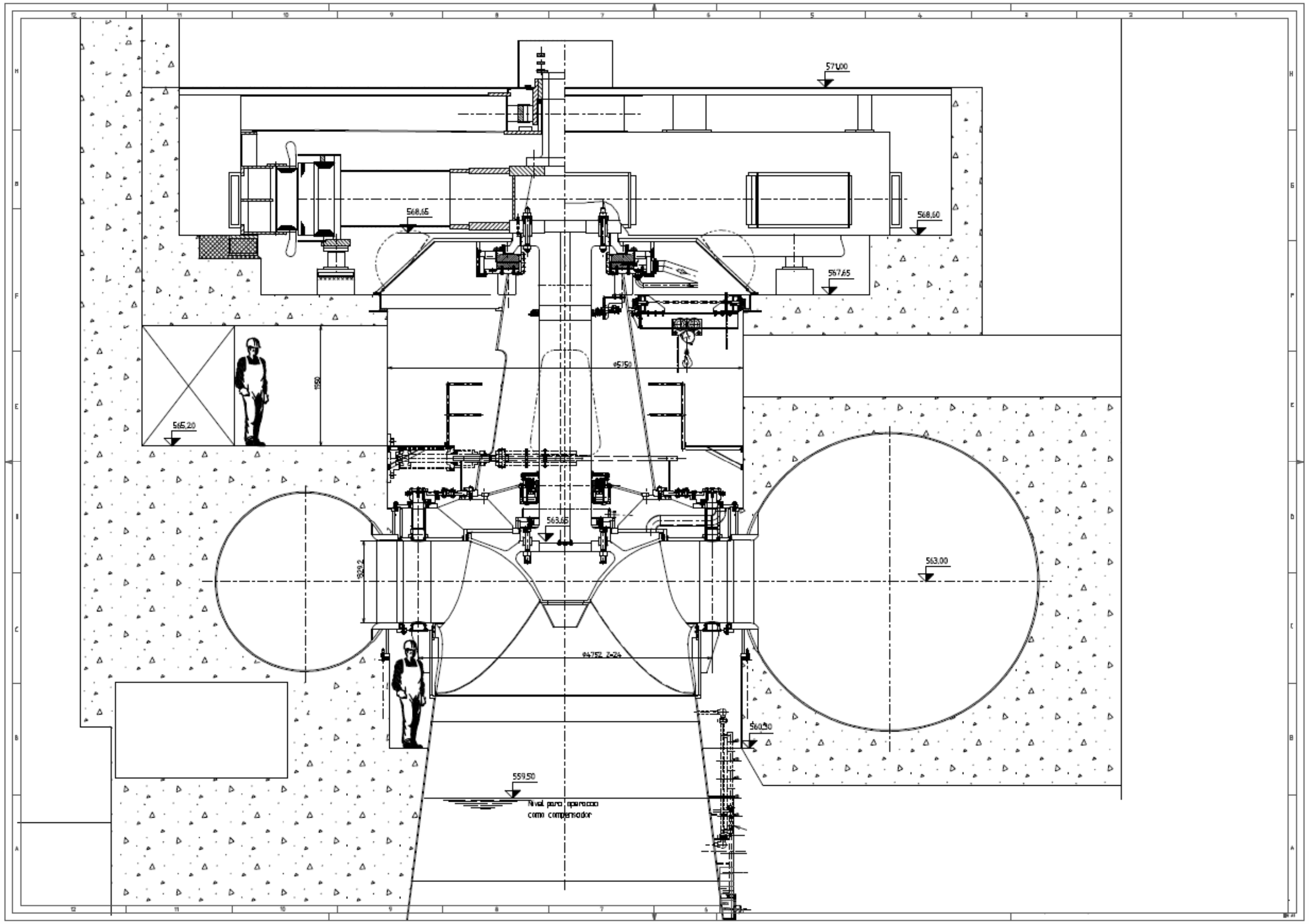
$$\sigma = \left(h_{amb} - h_{va} - h_s\right)/H$$

Machine description – Draft tube oscillations



- Example of pressure fluctuations in the draft tube at part load, measured during the model test: $(p - \overline{p})/\rho g H$
- Used for calibrating the CFD transient simulation.

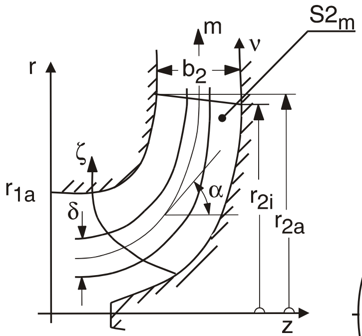
Machine description – Cross-section

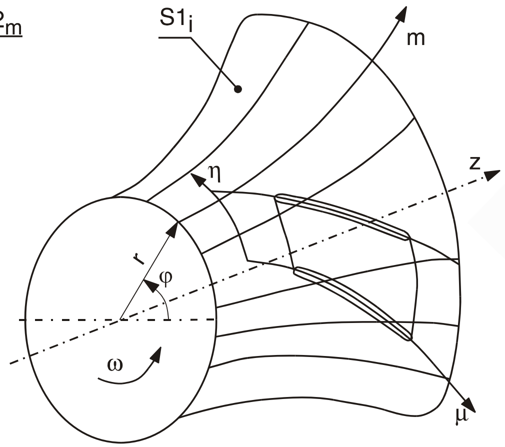


Machine description – Prototype runner

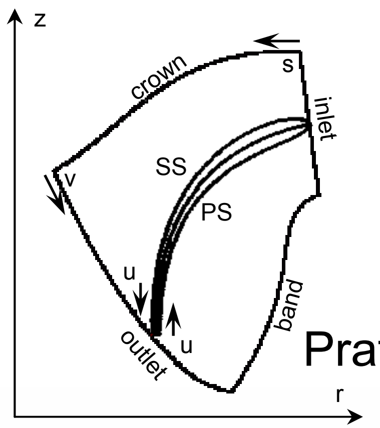
Prototype runner at the manufacturing shop.

Machine description – Coordinate system





Classic coordinate system



Pratical coordinate system

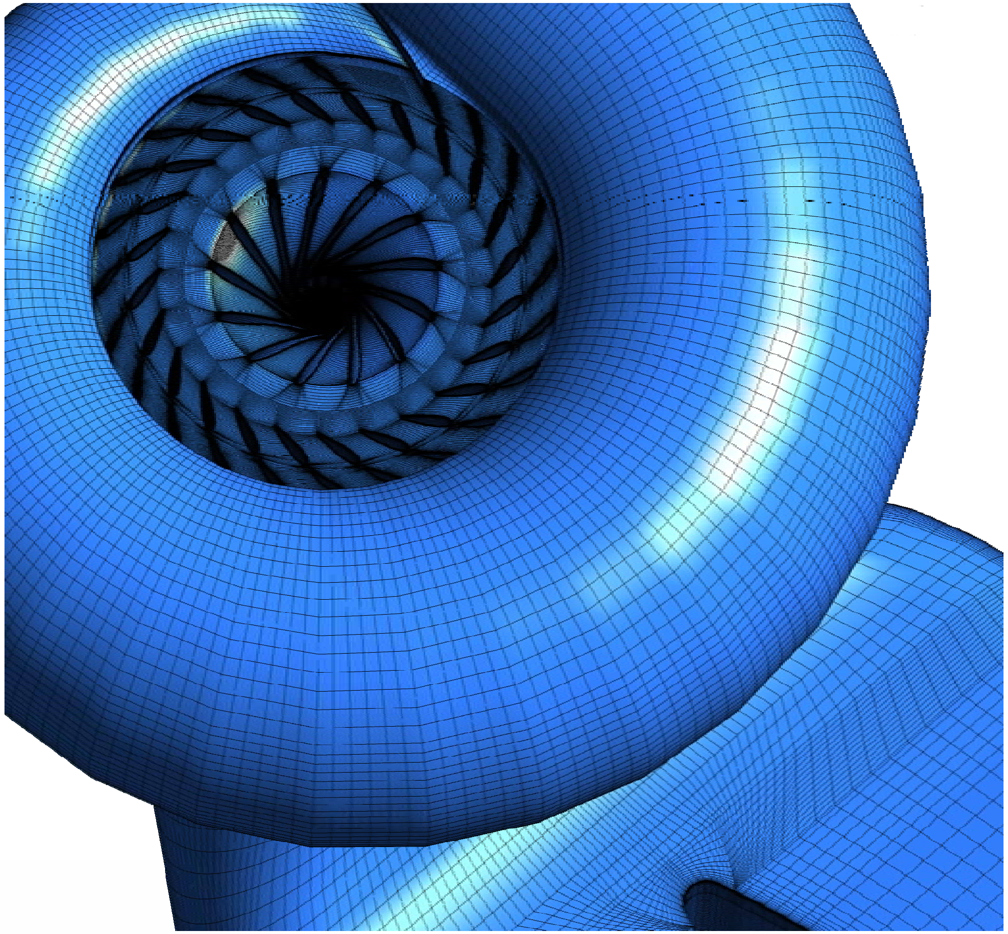
Numerical set-up – Overview

- Simulation of real Francis turbine: n_q = 80 min^{-1}
- Transient CFD simulation
- Complete turbine simulation
- Coupled simulation of all components
- Rotating and non-matching interfaces
- Blading meshed with IDS
- SC and DT meshed with ICEM
- Compared solvers : NS3D, CFX

Numerical set-up – Tested parameters

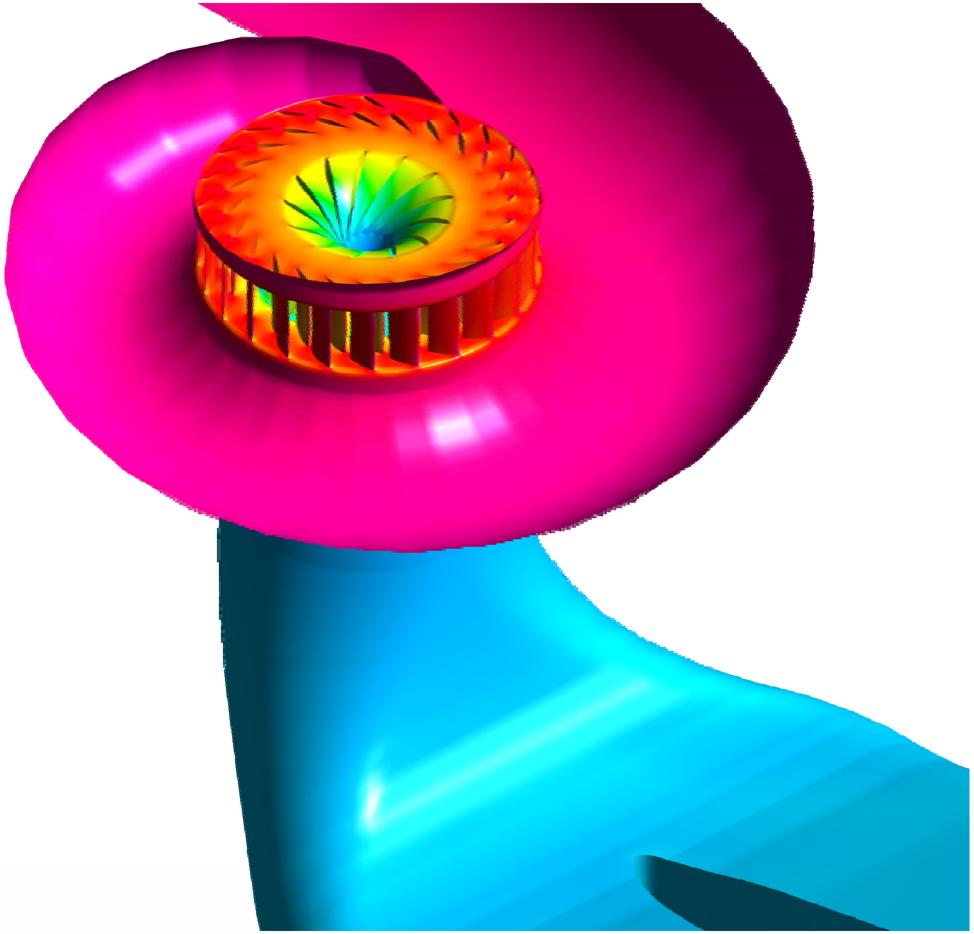
- Mesh density: from ~ 3,8 up to ~ 6,0 million cells
- Interpolation schemes: UDS, CDS, QUICK, MINMOD
- Turbulence models: k-ε, k-ε LCL, k-ω, k-ω SST
- Turbulence models: URANS, SAS, DES
- Turbulence inlet content: from 1% up to 10%
- Wall treatment: with wall function, $30 < y^+ < 300$
- Outlet domain extension and BC type

Numerical set-up – Computational model



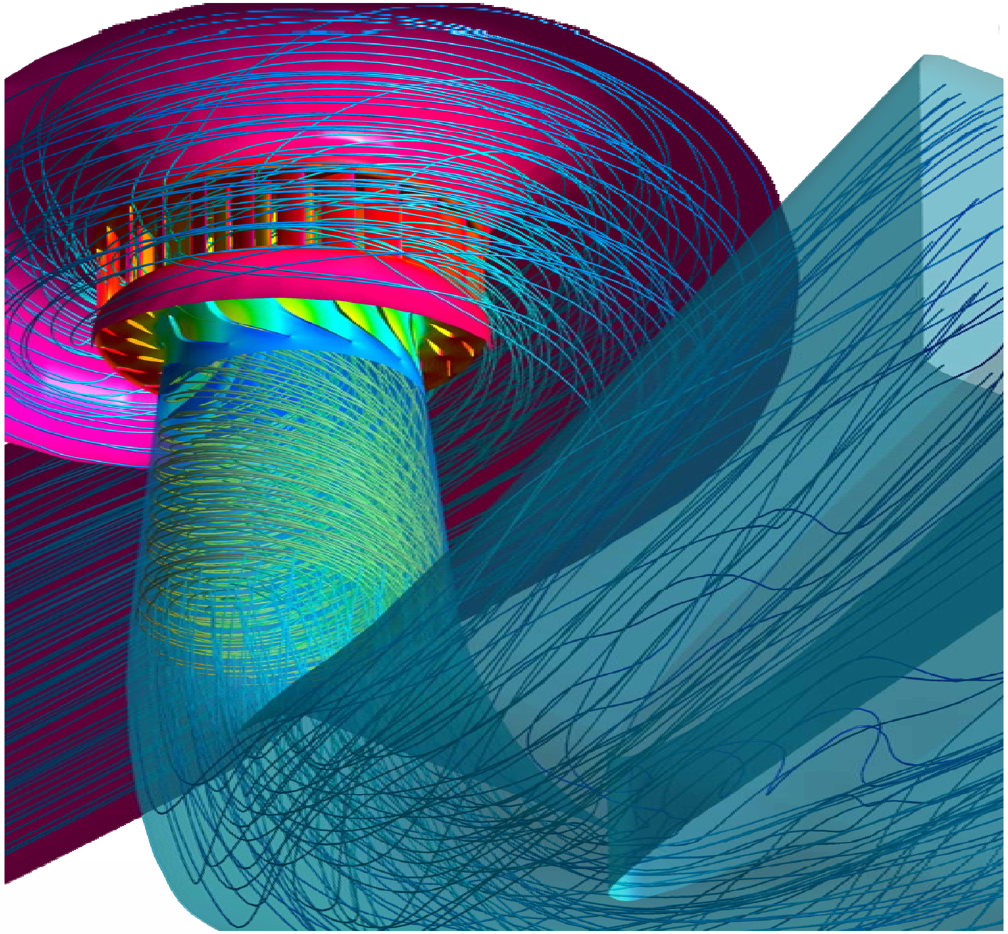
Francis turbine
mesh containing
~ 6.000.000 cells

Numerical set-up – Computational model



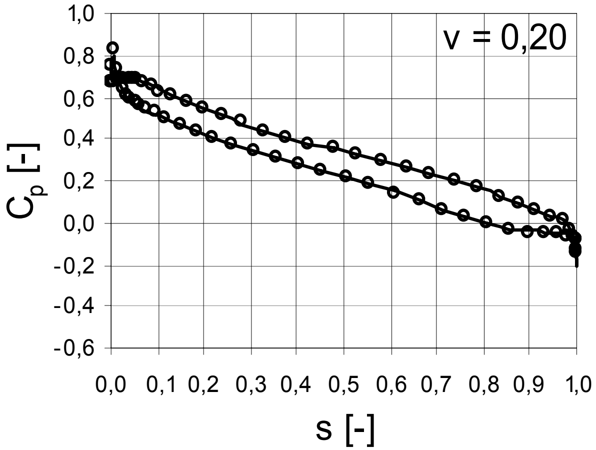
Time averaged pressure distribution at the rated point

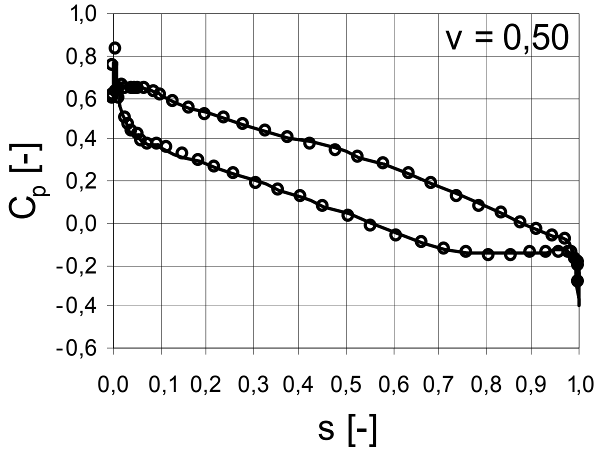
Numerical set-up – Computational model

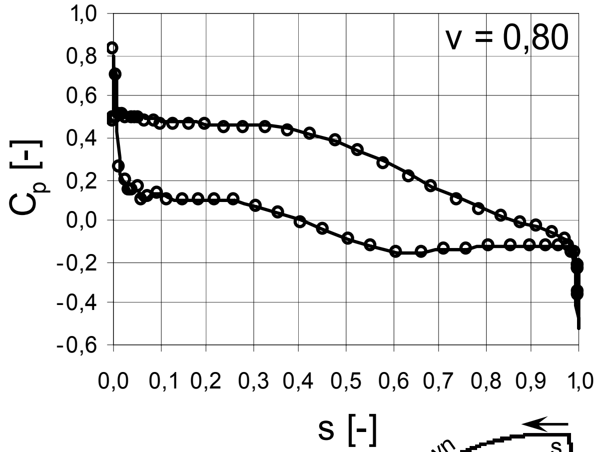


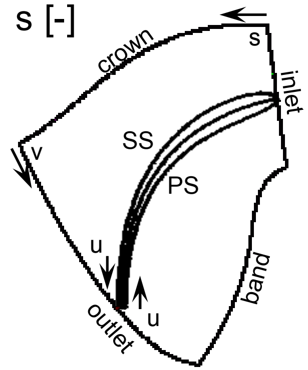
Time averaged stream lines at the rated point

Numerical set-up – Codes: NS3D & CFX









Calculated with NS3D (–) and CFX (○)

C_p : Pressure coefficient

s : Normalized blade length, measured from blade nose

v : Conformal plane coordinate, measured from crown to band

Numerical set-up – Validation

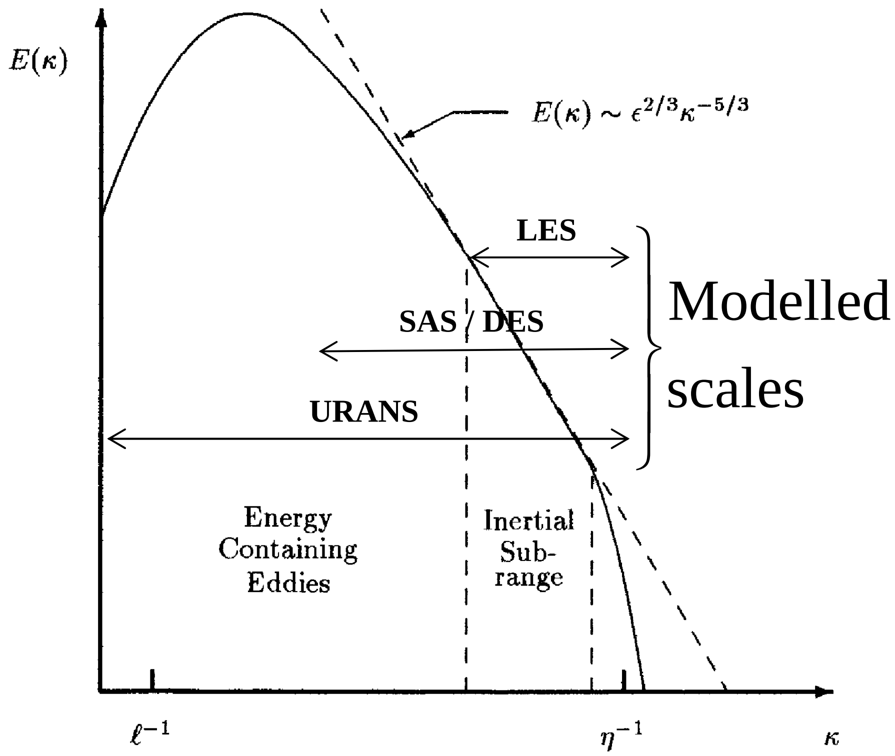
	Model Test				Simulation				**Deviation**			
Operating Point	$n_1'/n_{1\,opt}'$ [%]	$Q_1'/Q_{1\,opt}'$ [%]	$T_1'/T_{1\,opt}'$ [%]	η/η_{opt} [%]	$n_1'/n_{1\,opt}'$ [%]	$Q_1'/Q_{1\,opt}'$ [%]	$T_1'/T_{1\,opt}'$ [%]	η/η_{opt} [%]	$\delta n_1'$ **[%]**	$\delta Q_1'$ **[%]**	$\delta T_1'$ **[%]**	$\delta\eta$ **[%]**
Optimum	100,0	100,0	100,0	100,0	99,4	100,0	100,3	100,2	**-0,6**	**< 0,1**	**0,3**	**0,2**
Rated (design pt.)	110,3	111,5	108,3	97,2	109,6	111,5	110,0	98,7	**-0,6**	**< 0,1**	**1,6**	**1,5**
Normal	107,0	103,0	102,2	99,3	106,0	103,0	102,4	99,4	**-1,0**	**< 0,1**	**0,2**	**0,1**
Part load at high head	107,8	73,9	69,3	93,8	106,7	73,9	69,3	93,8	**-1,0**	**< 0,1**	**0,0**	**0,0**
Part load at low head	119,9	70,8	64,4	91,0	119,0	70,8	65,1	91,9	**-0,7**	**< 0,1**	**1,0**	**1,0**

Transient simulation set-up – Parameters

- Number of time steps (TS) for capturing:
  - DTI: ~ 120 TS / Revolution (Courant number ≤ 30)
  - RSI: ~ 400 TS / Revolution (Courant number ≤ 1,5)
  - VSE: ~ 6000 TS / Revolution (Courant number ≤ 0,2)
- Required number of revolutions until stabilization:

  ~ 35 at the rated operating point
- Cluster: 8 quad-core Intel Q6600 2,4GHz, 2GB RAM
- Computation speed: ~ 2 revolutions / day (for RSI)
- Solver: BCGSTAB without multigrid approach

Transient simulation set-up – Turbulence



- Kolmogorov length scale:
  - In URANS, all the eddies are modelled.
  - In DNS, all the eddies are numerically computed.
  - In LES, the biggest eddies, i.e. the most energetic, are computed, and the smallest are modelled.
  - DES and SAS represent a compromise between URANS and LES.

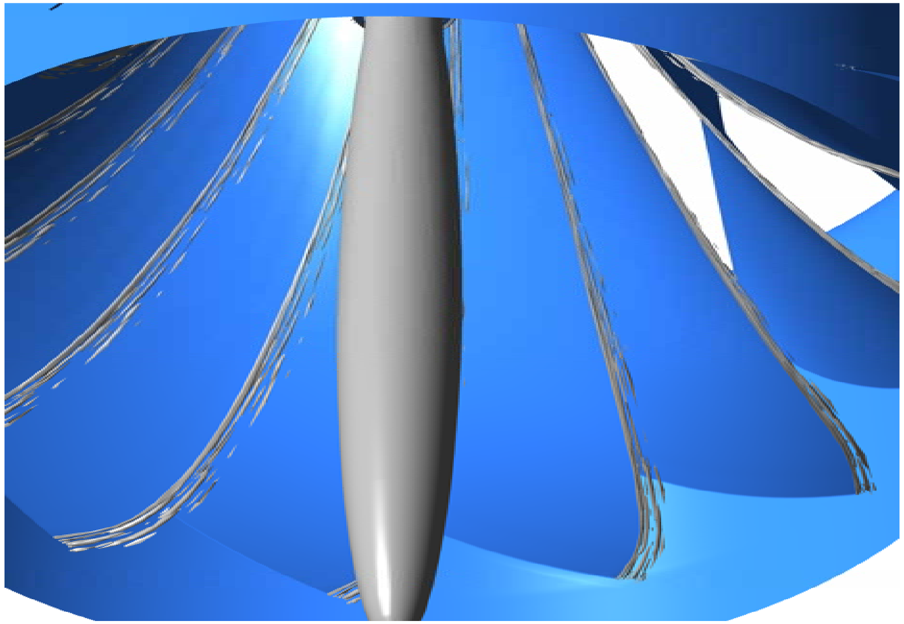
Transient simulation set-up – Validation

- Peak to peak pressure oscillation at the draft tube cone: $\left(\Delta p = p - \bar{p},\ \Delta p_{P2P} = \Delta p_{max} - \Delta p_{min}\right)$

Part load at low head	$\frac{\Delta p_{P2P}^{HW}}{\rho g H}$ [%]	$\frac{\Delta p_{P2P}^{90°}}{\rho g H}$ [%]	$\frac{\Delta p_{P2P}^{TW}}{\rho g H}$ [%]	$\frac{\Delta p_{P2P}^{270°}}{\rho g H}$ [%]	$\frac{f}{f_n}$ [-]
Model Test	10,58	9,02	11,42	13,56	0,295
Simulation	10,08	8,60	11,88	13,10	0,315
Deviation	**-0,50**	**-0,42**	**0,46**	**-0,46**	**6,8%**

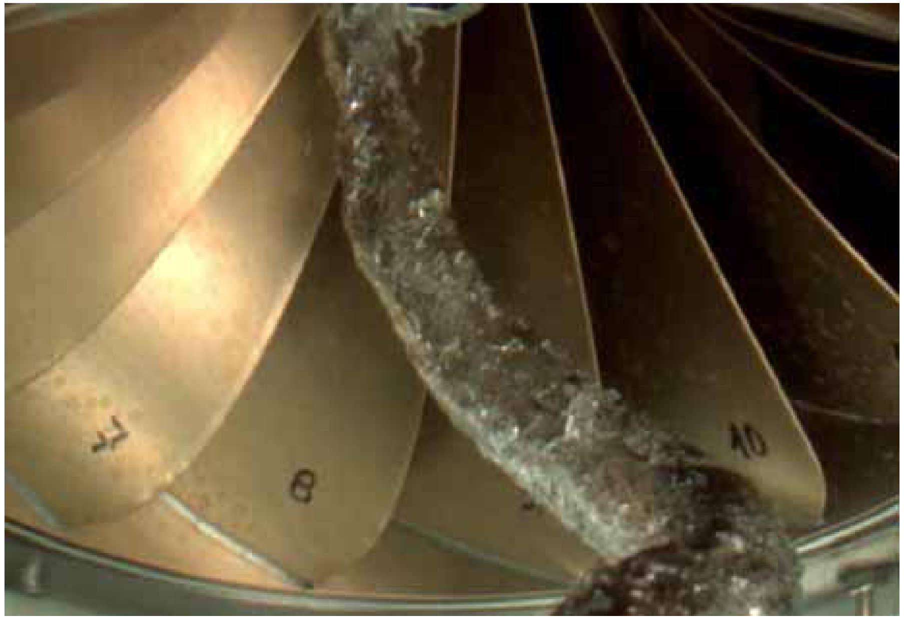
Transient simulation – Validation

Observed at the model test for the rated operating point



Numerically simulated for the rated operating point (vapour pressure isosurface)

Transient simulation – Validation

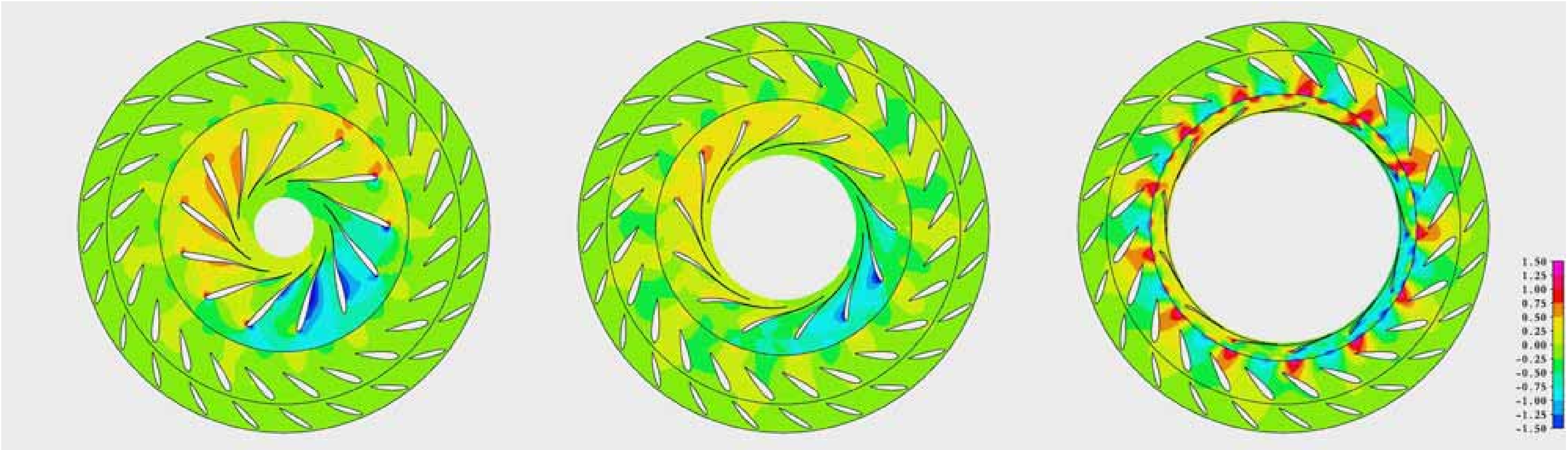


Observed at the model test for part load at low head

Numerically simulated for part load at low head
(vapour pressure isosurface)

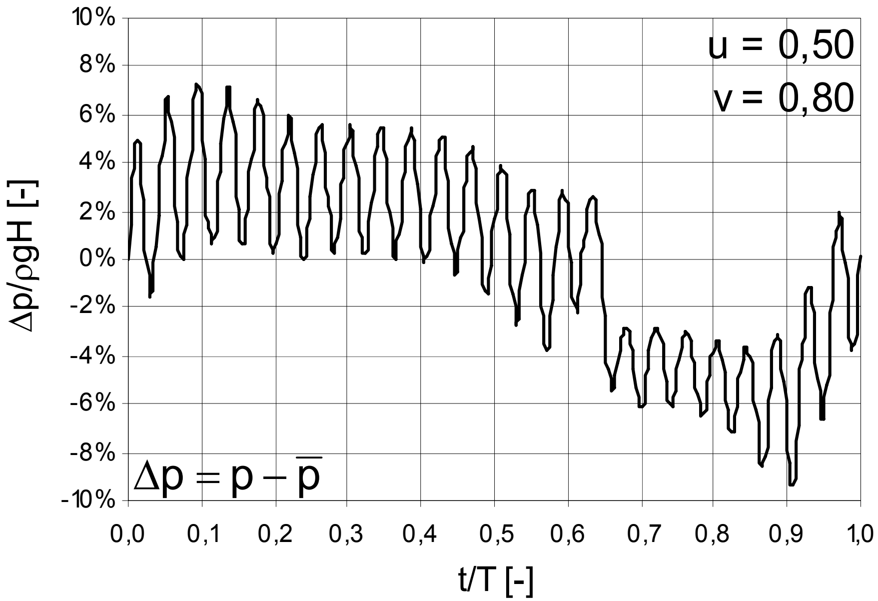
Rated point results – Pressure oscillation

- Pressure oscillation, $\Delta p/\rho gH$ [%], at conformal planes:
  $(\Delta p = p - \overline{p})$

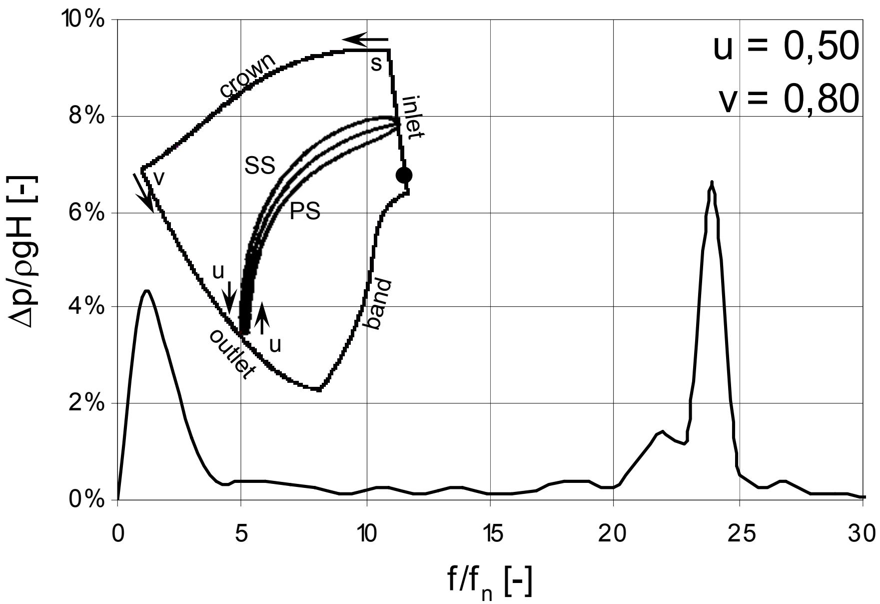


v = 0,20 v = 0,50 v = 0,80

Rated point results – Time history

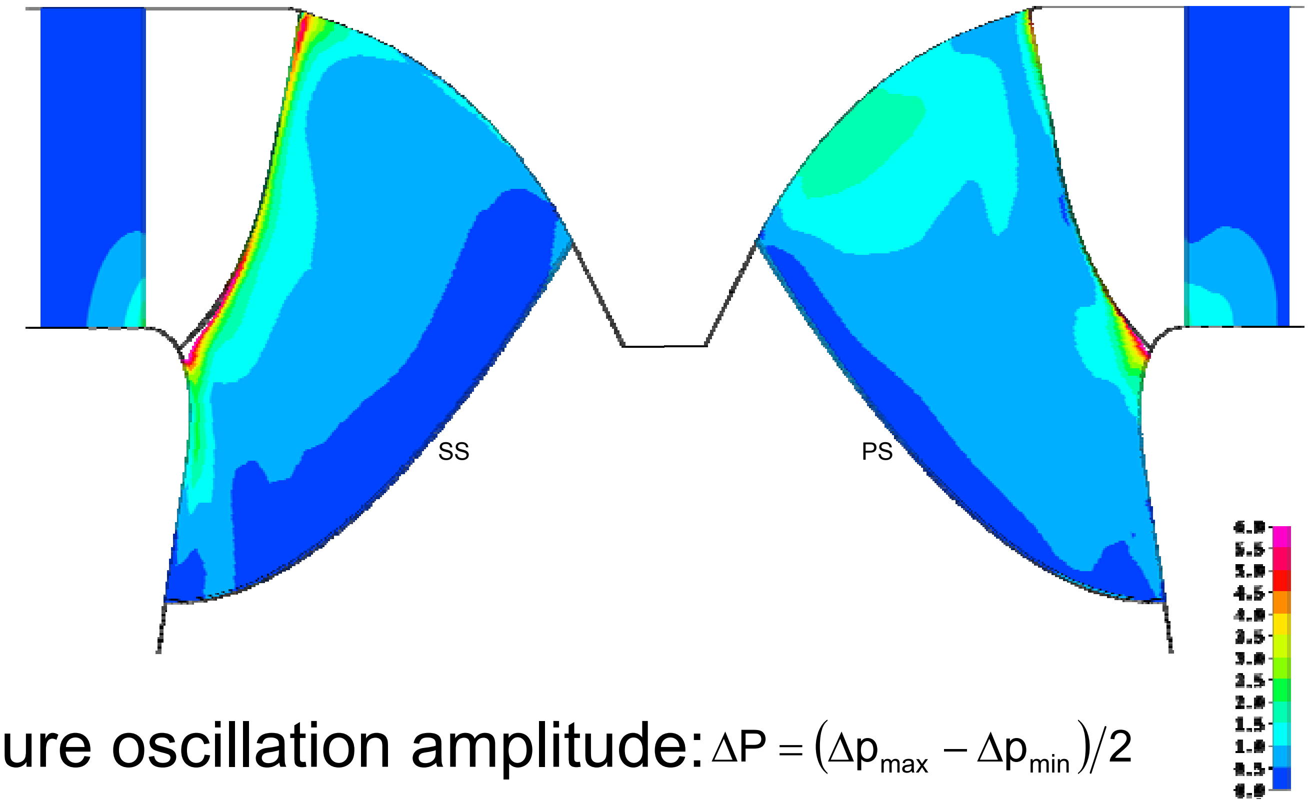


Time history at blade leading edge near to the band



Fourier transform at blade leading edge near to the band

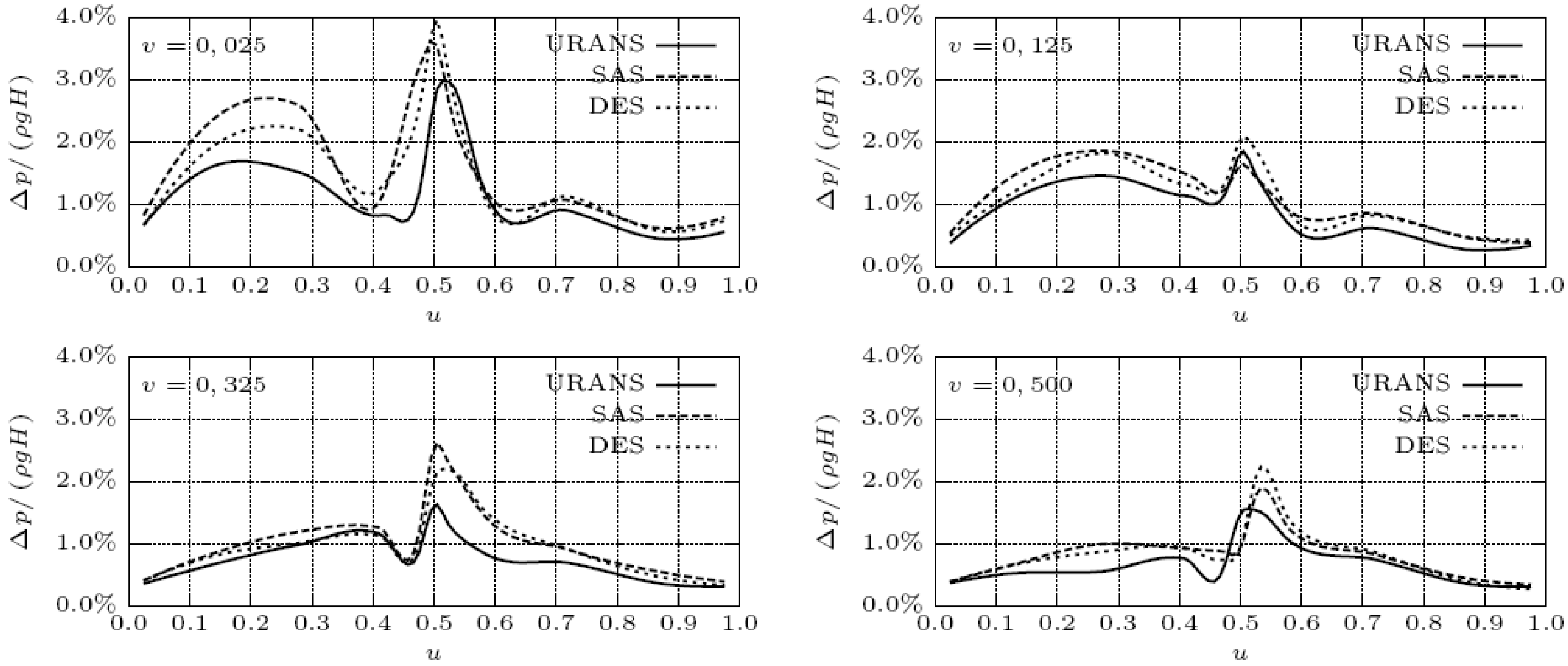
Rated point results – Oscillation amplitude



Pressure oscillation amplitude: $\Delta P = (\Delta p_{max} - \Delta p_{min})/2$

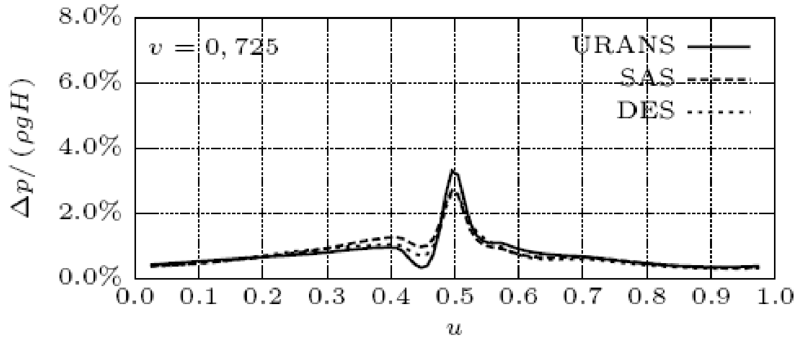
Meridian view. Values above 6,0% not coloured.

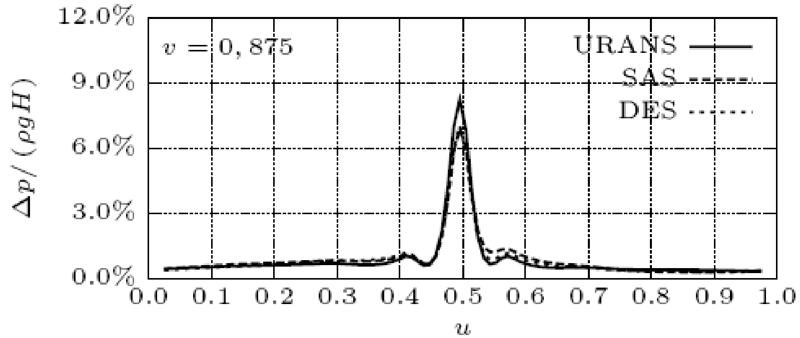
Rated point results – Oscillation amplitude

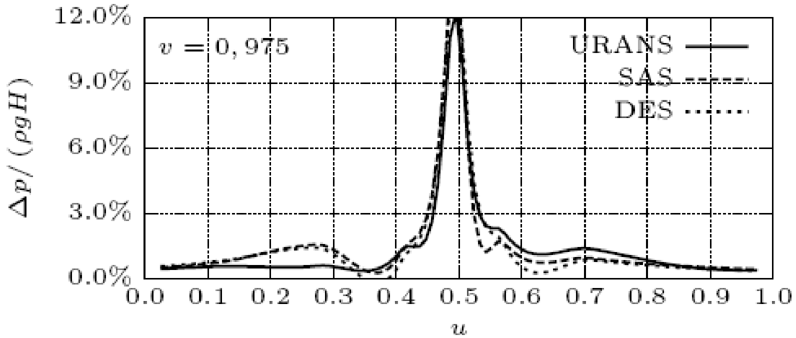


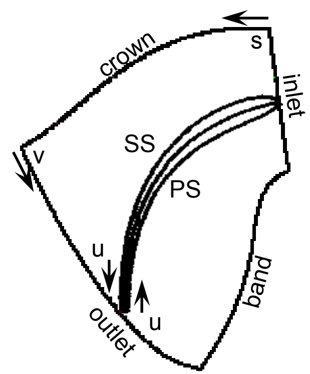
Pressure oscillation amplitude and the turbulence models

Rated point results – Oscillation amplitude









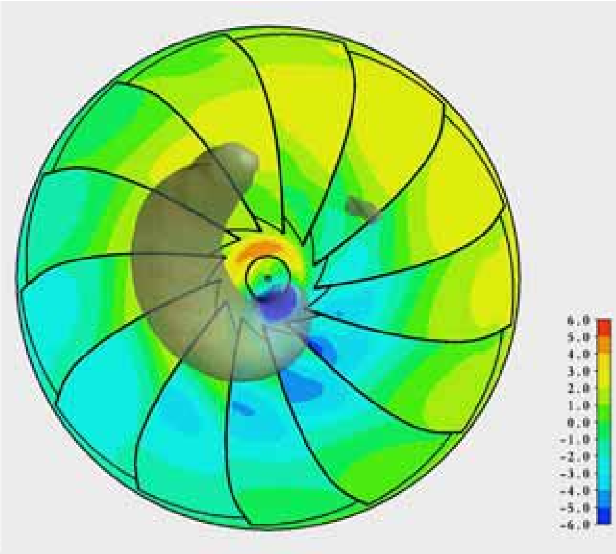
Pressure oscillation amplitude and the turbulence models

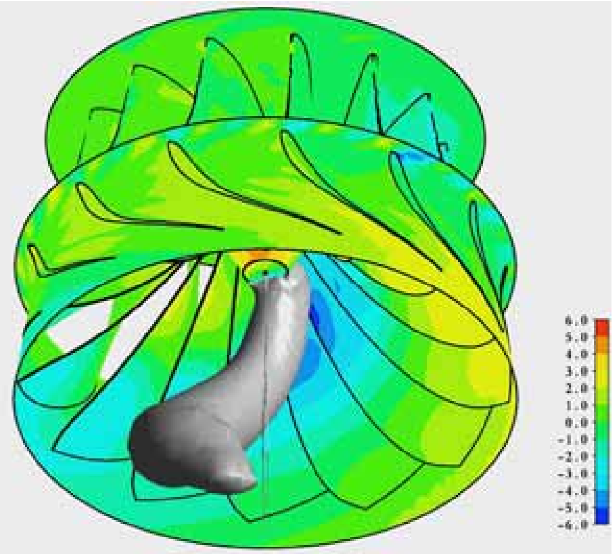
Rated point results – Comments

- Flow dominated by kinematic effects from RSI
- Limited influence from turbulence models on results
- Pressure oscillation amplitude:
  - Maximum: 12,4% at the leading edge near to band
  - Overall: 0,3%-2,1% in most part of the blade
- Dominating frequencies:
  - f_n: Rotation, nose vane passing frequency
  - f_n x z_0: Guide vanes passing frequency

Part load results – Pressure oscillation

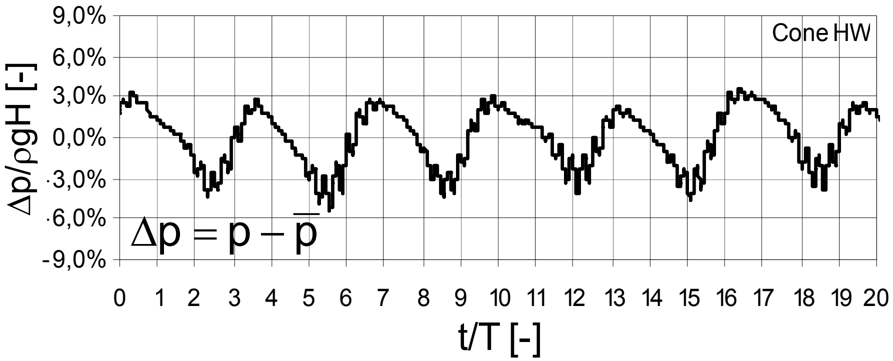
- Pressure oscillation, $\Delta p/\rho gH$ [%]: $(\Delta p = p - \overline{p})$

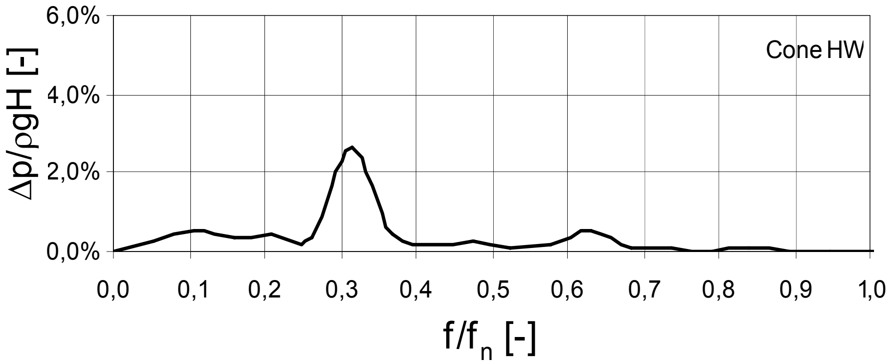


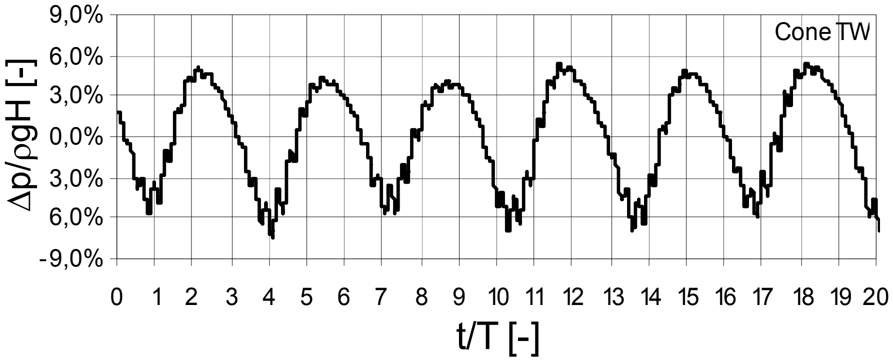


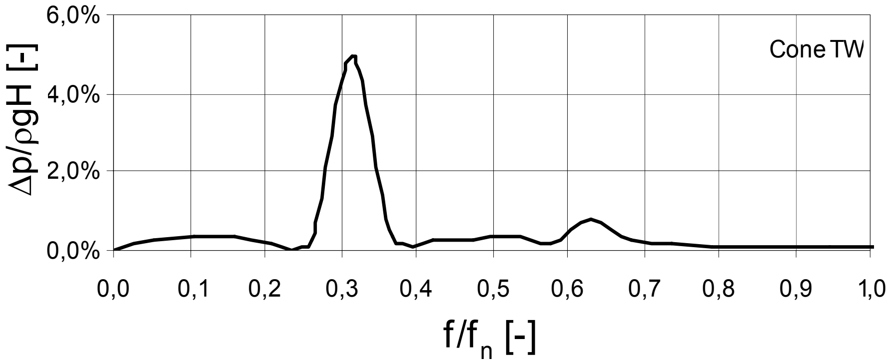
Stationary reference | Bottom view | Runner reference

Part load results – Time history





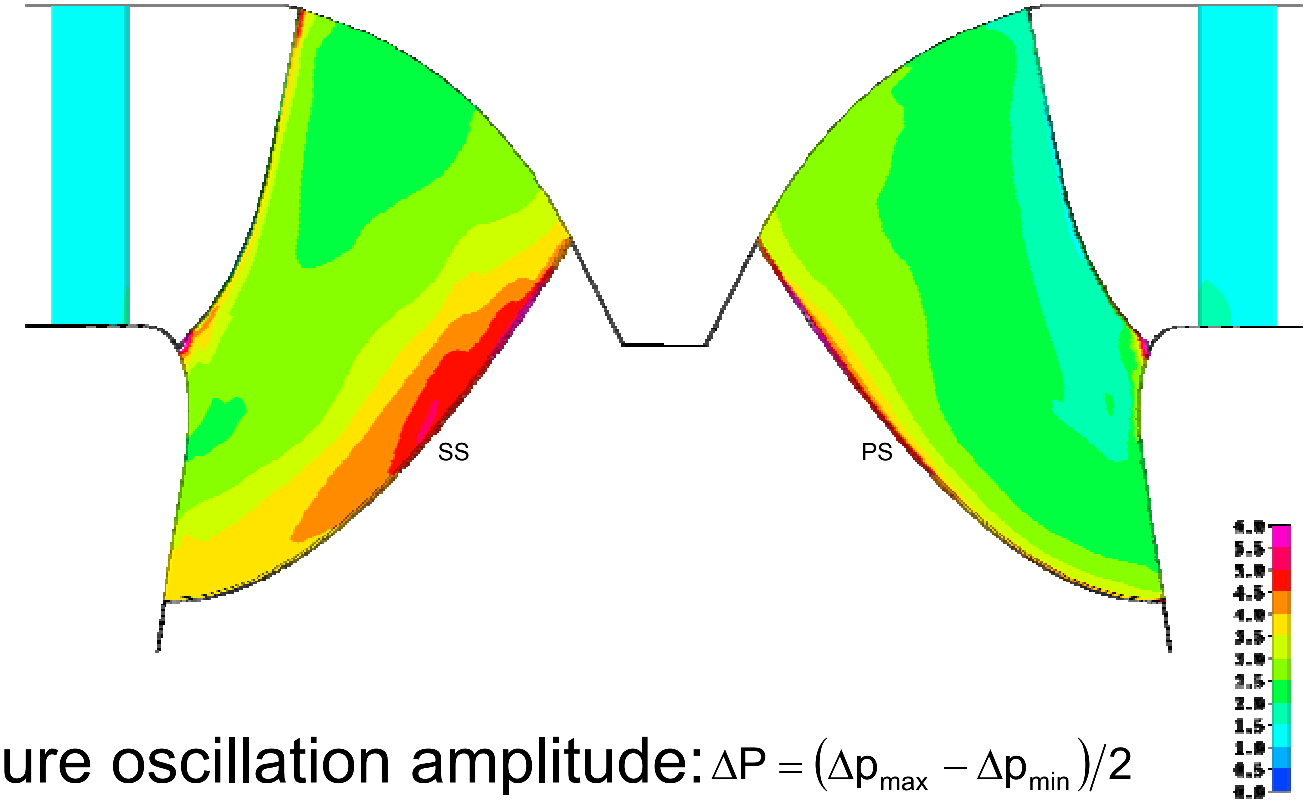




Time history at draft tube cone

Fourier transform at DT cone

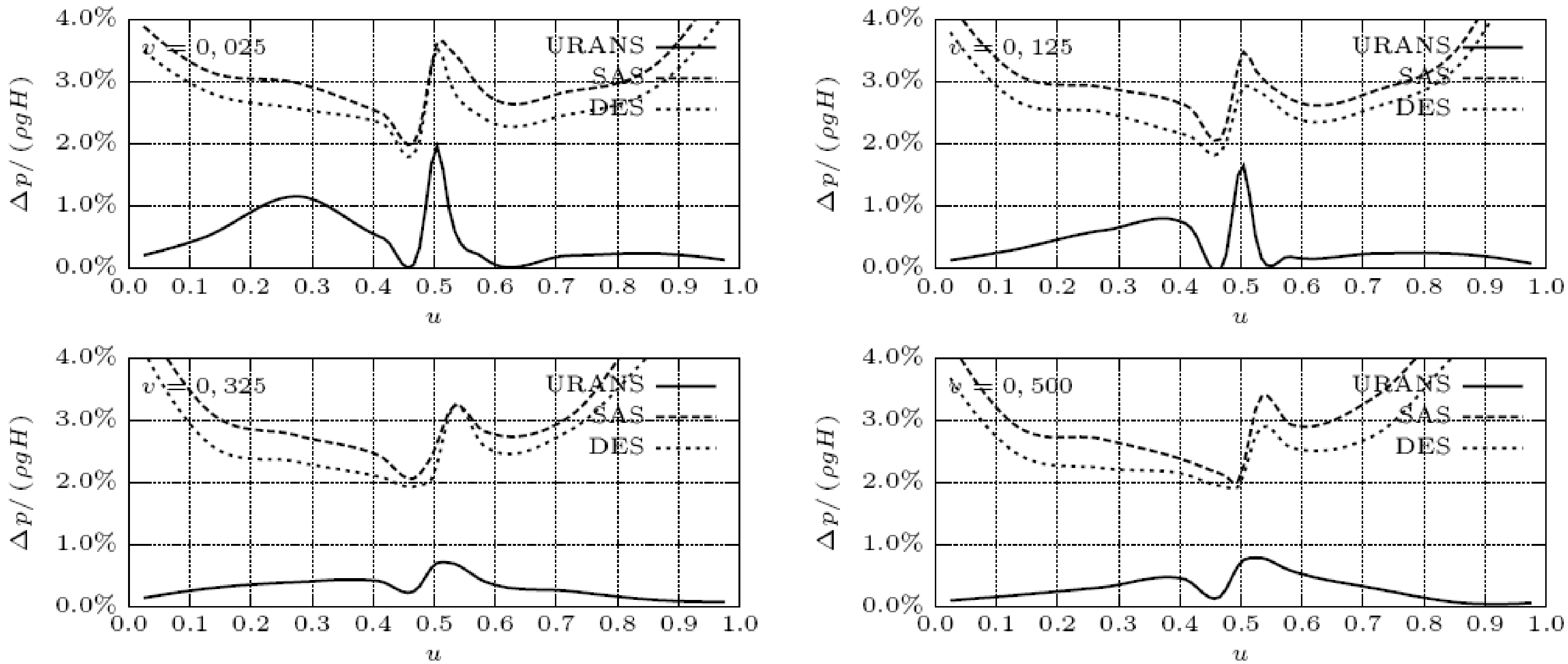
Part load results – Oscillation amplitude



Pressure oscillation amplitude: $\Delta P = \left(\Delta p_{max} - \Delta p_{min}\right)/2$

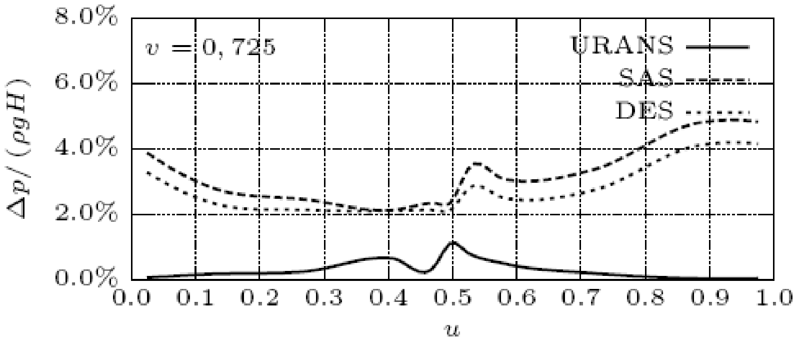
Meridian view

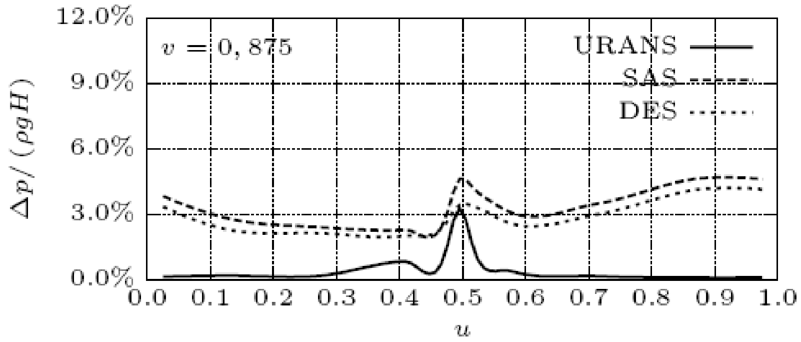
Part load results – Turbulence models

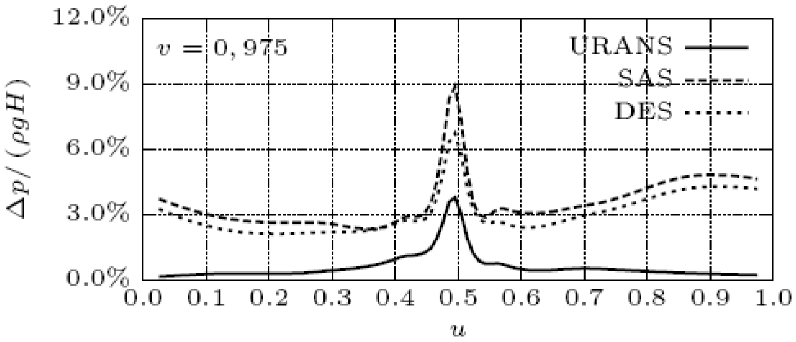


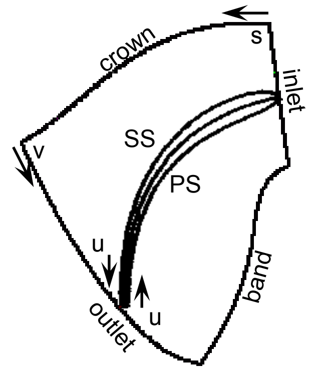
Pressure oscillation amplitude and the turbulence models

Part load results – Turbulence models



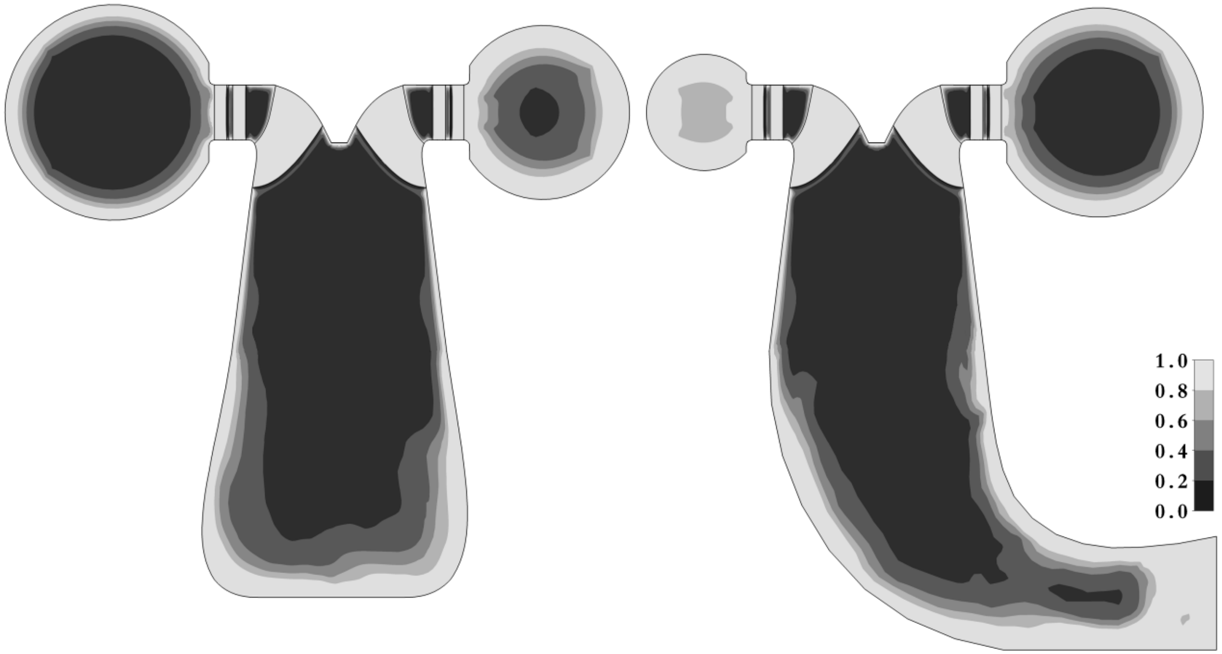






Pressure oscillation amplitude and the turbulence models

Part load results – Blending Function



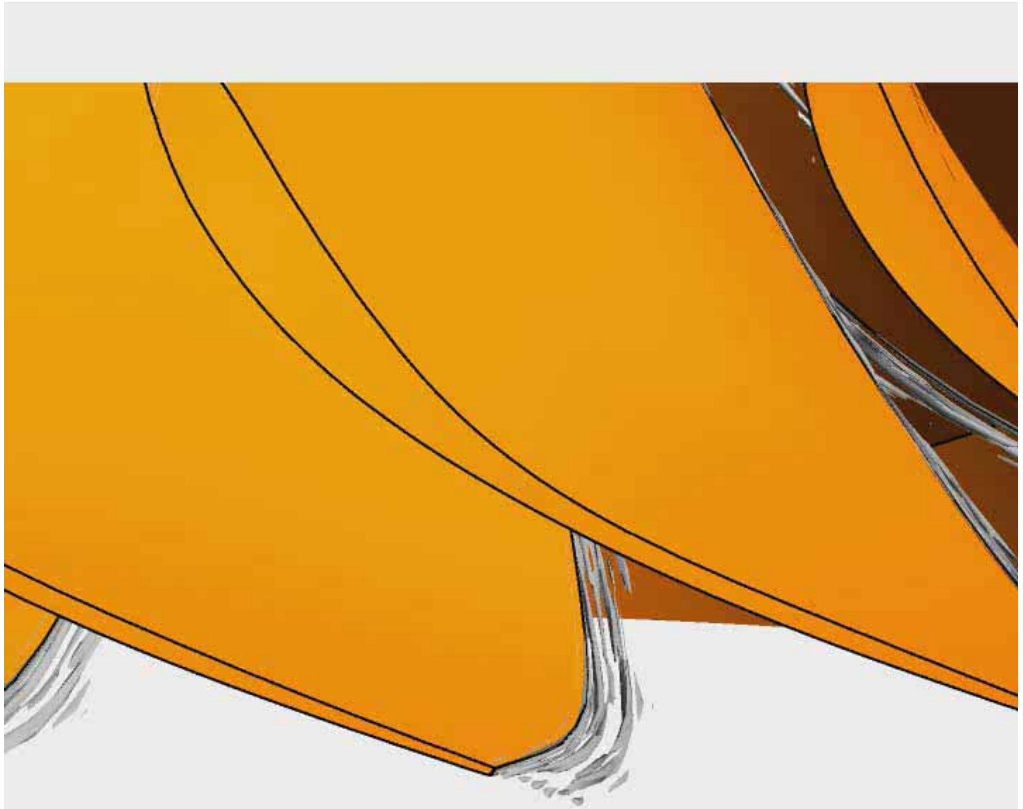
Blending function for DES and SAS

Transversal and longitudinal views

Part load results – Comments

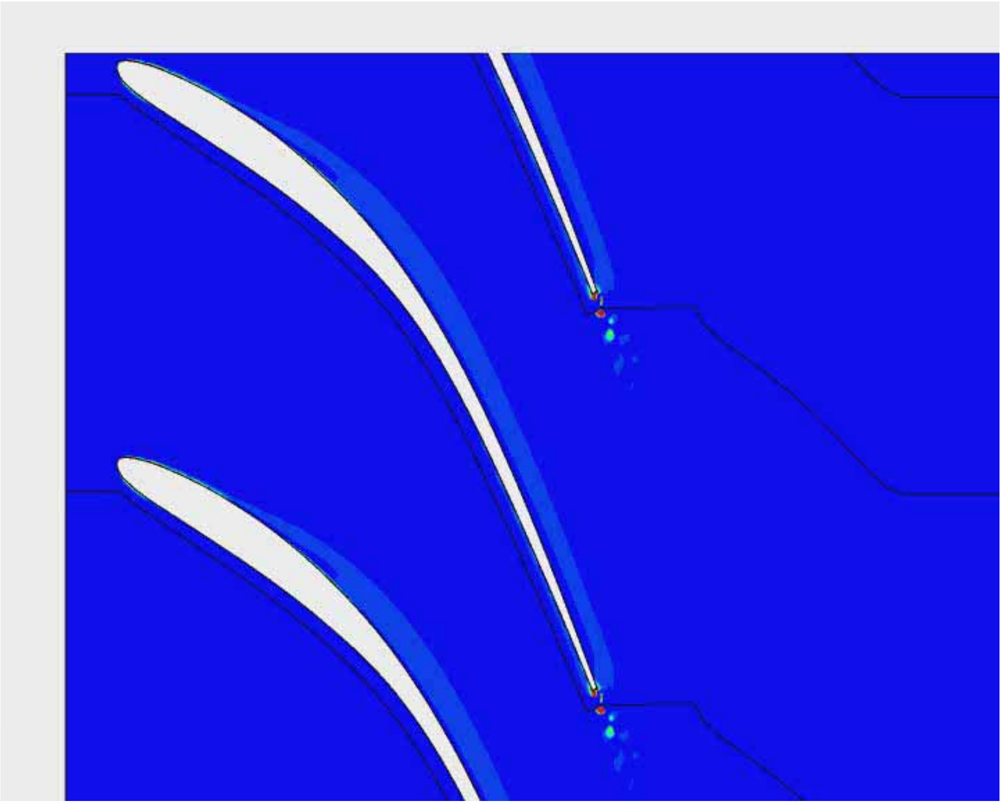
- URANS cannot capture the DTI effects
- Turbulence models such as SAS, DES or LES are needed
- Pressure oscillation amplitude:
  - URANS: 3,9% (leading edge) / 0,1%-1,2% (blade)
  - SAS: 5,0% (leading edge) / 0,6%-5,0% (blade)
- Dominating frequency:
  - 0,32·f_n: Draft tube vortex rope rotating frequency

Rated point results – Vortex shedding



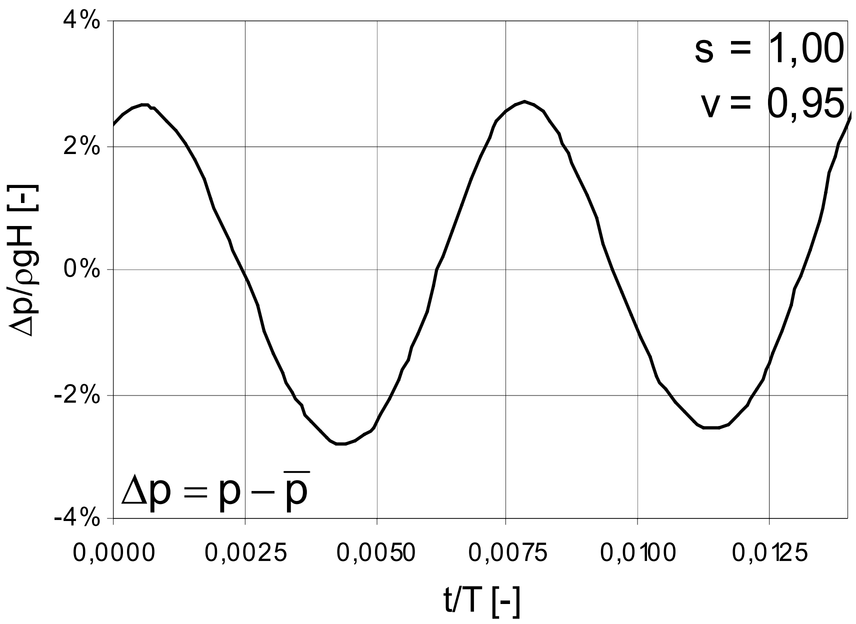
Vortex shedding at runner trailing edge

Rated point results – Vortex shedding

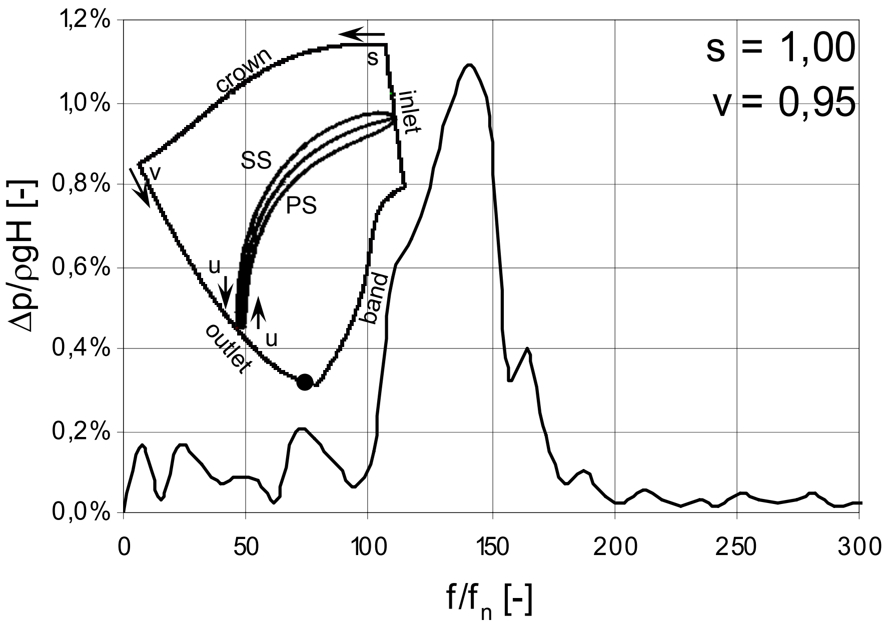


Vortex shedding at conformal view near to the band

Vortex shedding – Time history

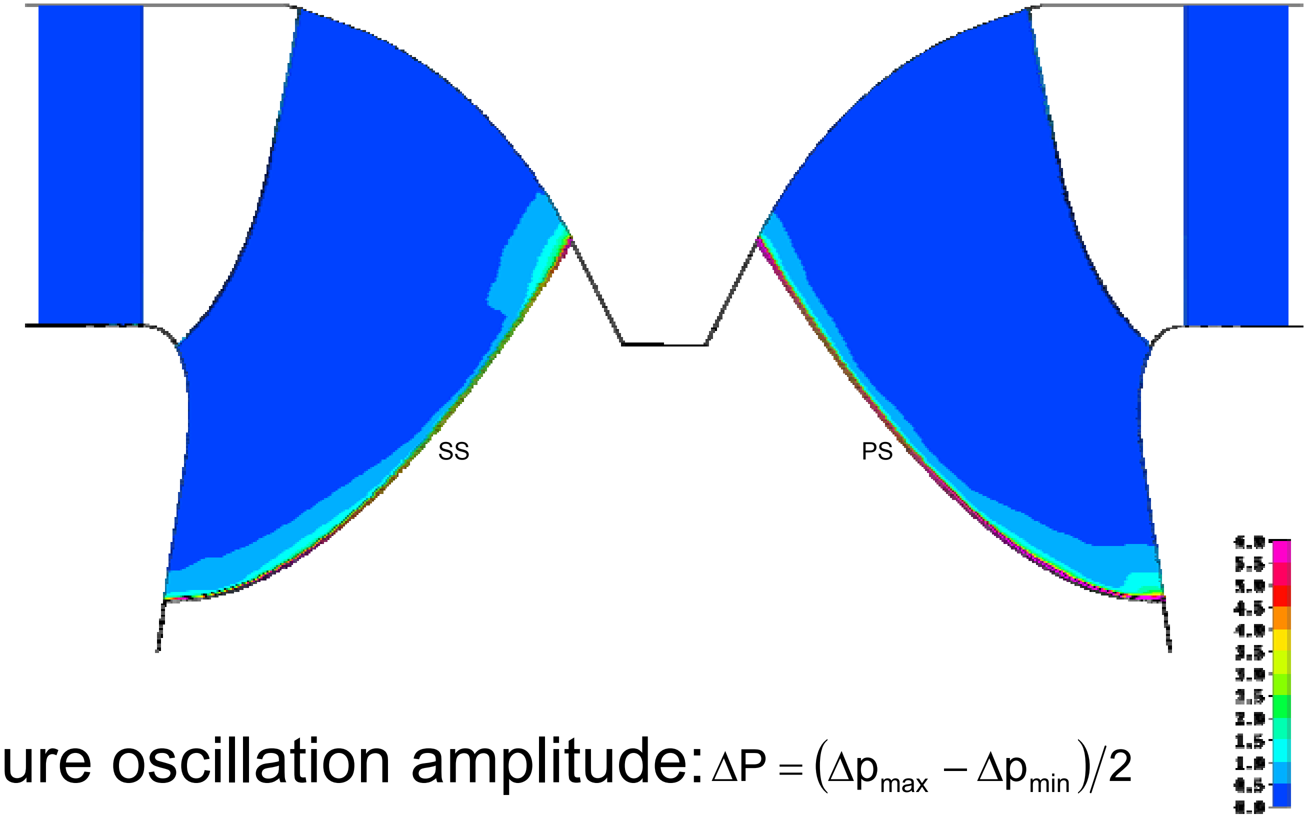


Time history at blade trailing edge near to the band



Fourier transform at blade trailing edge near to the band

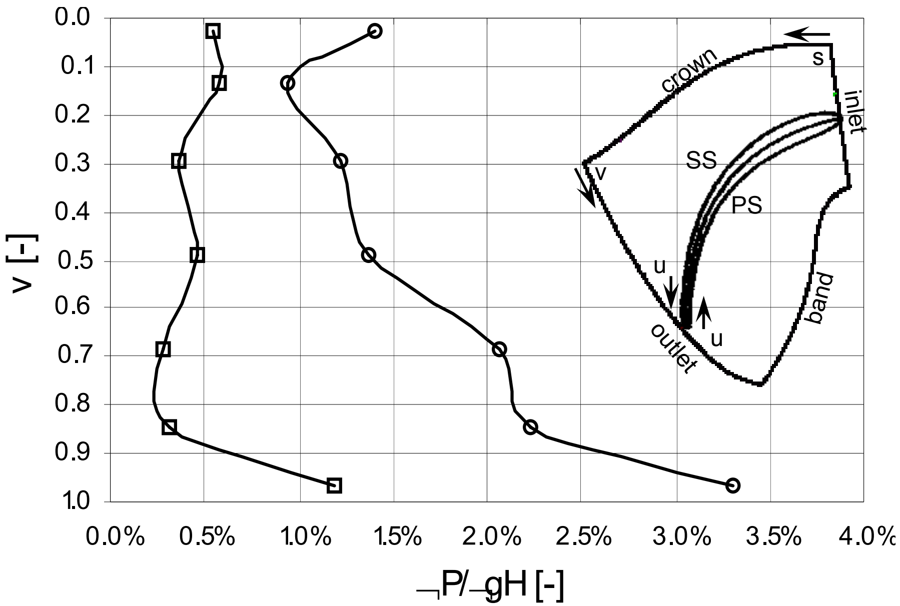
Vortex shedding – Oscillation amplitude



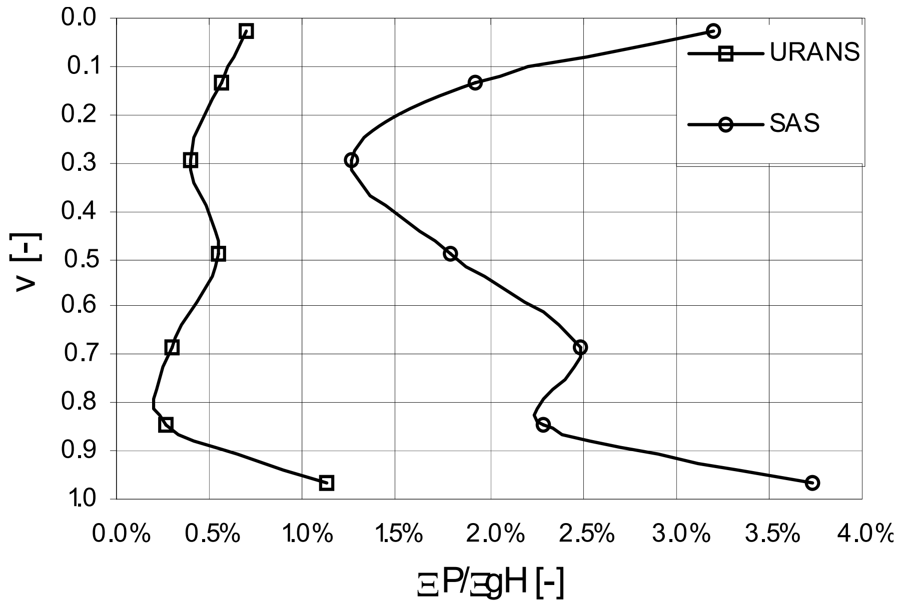
Pressure oscillation amplitude: $\Delta P = (\Delta p_{max} - \Delta p_{min})/2$

Meridian view

Vortex shedding – Oscillation amplitude

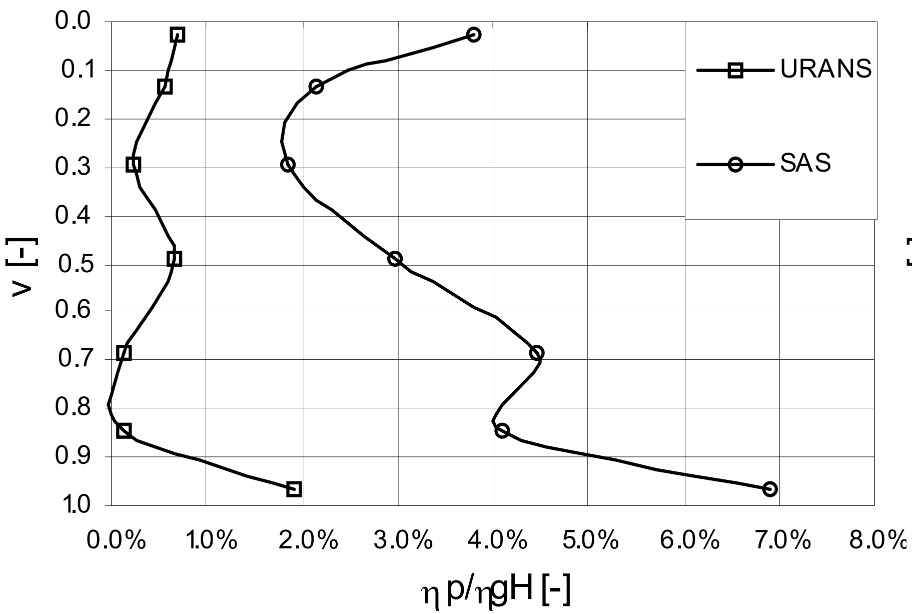


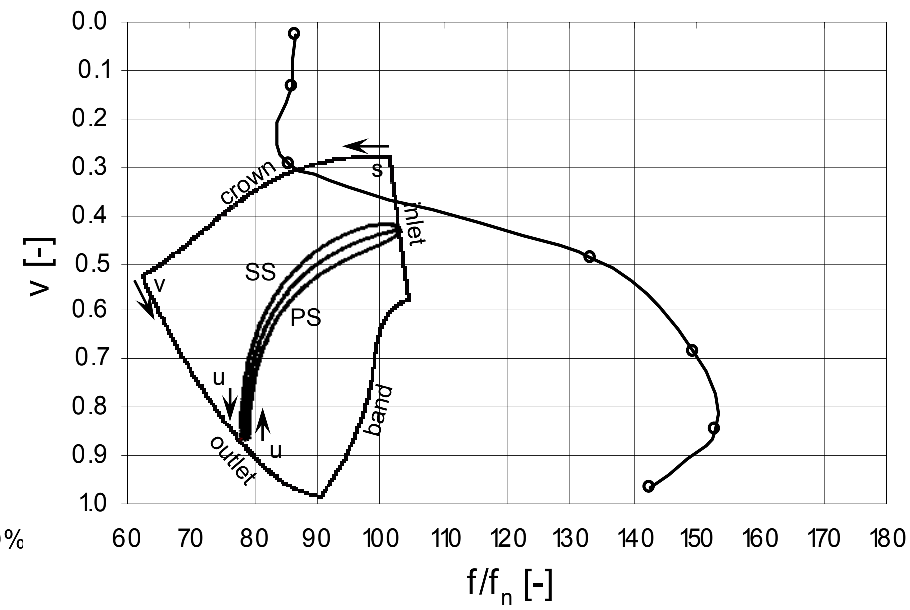
Turbulence models results at trailing edge at pressure side



Turbulence models results at trailing edge at suction side

Vortex shedding – Oscillation amplitude

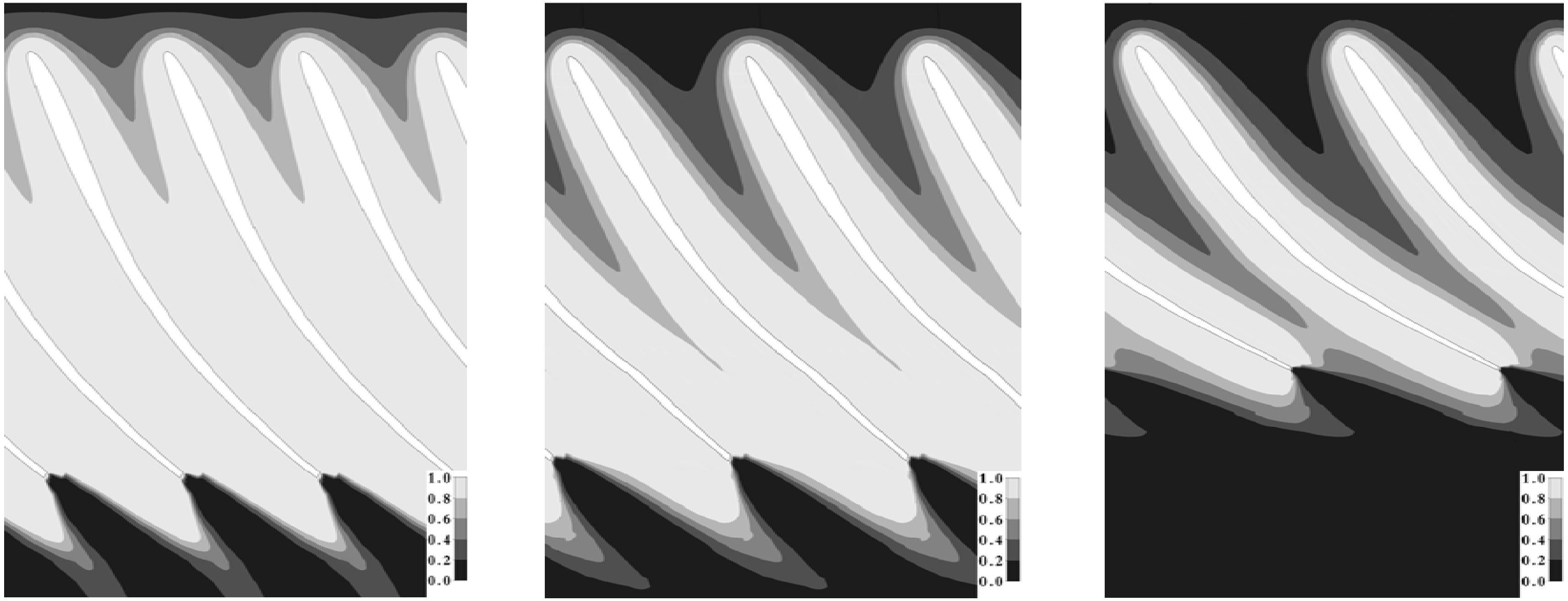




Turbulence models results at trailing edge: differential pressure between PS-SS

Turbulence models results at trailing edge: vortex shedding frequency

Vortex shedding – Blending Function



Blending function for DES and SAS

Conformal planes v = 0,20, v = 0,50, v = 0,80

Vortex shedding – Comments

- Turbulence models:
  - Tested: URANS, SAS, DES
  - Best agreement with model test observed pattern: SAS and DES
- Pressure oscillation amplitude:
  - From 0,9%, in the vicinity of the crown
  - Up to 3,7%, in the vicinity of the band
- No synchronous frequency along the blade:
  - ~ $150 \cdot f_n$ in the vicinity of the crown
  - ~ $85 \cdot f_n$ in the vicinity of the band

Vortex shedding – Comments

- Importance to the runner structural analysis:
  - Considerable amplitudes compared to RSI & DTI:
    - RSI: 0,3%-2,1% (excluding the leading edge region)
    - DTI: 0,6%-5,0% (excluding the leading edge region)
    - VSE: 0,9%-3,7%
  - The VSE pressure oscillation is applied at the runner structure weakest region:

    Along the trailing edge, from the crown up to the band
  - High oscillating frequency:

    $\sim 85 \cdot f_n - 150 \cdot f_n$

Conclusions

- Ability to numerically predict pressure oscillations in Francis turbines
- Tight agreement between simulation and model test results
- No deviations between NS3D and CFX results
- Dynamic flow through the Francis turbine dominated by RSI, DTI and VSE

Conclusions

- Importance of VSE for the pressure oscillations
- Need of adequate turbulence models such as SAS, DES and LES
- URANS not suited for part load and vortex shedding
- Accurate input available from the transient CFD results for the runner CSA
- Possibility to estimate the runner fatigue strength

Next Steps

- Simulation of additional operating points in severe part load and overload conditions.
- Deeper investigation of the model constants in SAS and DES turbulence models.
- Evaluation of the fluid structure interaction.
- Assessment of the pressure oscillation effect on the structure strength and fatigue life.

Thank you for your attention!