Flow in turbines during new operating procedures

Presenter:

Saeed Salehi

saeed.salehi@chalmers.se

Division of Fluid Dynamics

Department of Mechanics and Maritime Sciences

Chalmers University of Technology

Vattenkraftens FoU-dagar

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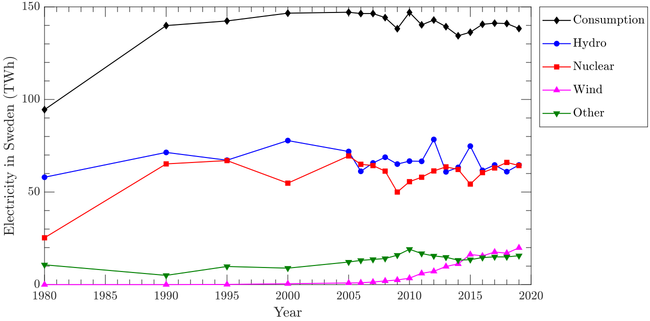
Motivation

- Power production from renewable energy resources are in high demand these days.
- Intermittency of renewable energy resources such as solar and wind
- Hydraulic turbines are designed to work in Best Efficiency Point (BEP)
- Nowadays they are being used more often under varying operating conditions to stabilize the electric grid.
- Significant pressure fluctuations and load variations that could reduce turbine lifetime.



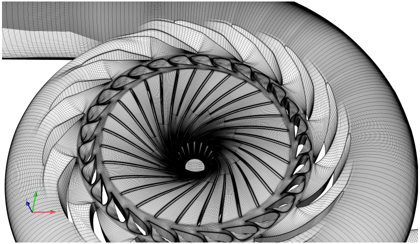
Transient operation

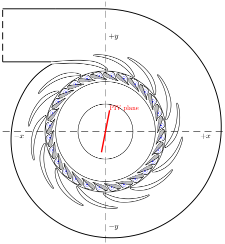
- What is happening during transient?
  - ✓ Changes in turbine load
  - ✓ Changes in flowrate
  - ✓ Changes in guide vanes angles
  - ✓ Changes in runner blades angles
  - ✓ Changes in runner rotational speed
- Different types of transient operations
  - ✓ Load acceptance (BEP to HL)
  - ✓ Load rejection (BEP to PL)
  - ✓ Sudden load removal (Spin-no-load)
  - ✓ Shutdown
  - ✓ Startup

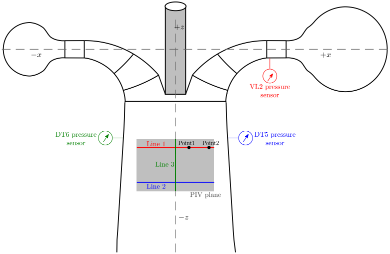
Francis turbine

Francis-99

- High-head Francis turbine model (1:5.1 scale)
- Fully structured hex mesh with 16 million cells
- Transient operations:
  - ✓ Shutdown
  - ✓ Startup
  - ✓ Load acceptance (BEP to HL)
  - ✓ Load rejection (BEP to PL)

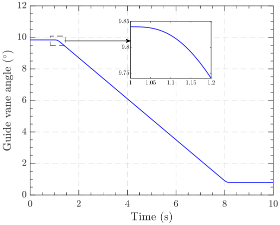




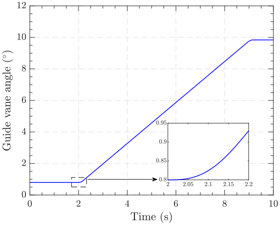


Operational condition

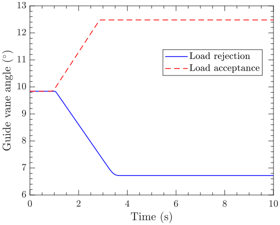
- Turbine shutdown, startup and load change procedures
- CFD code: OpenFOAM-v1912
- Dynamic mesh challenges:
  - ✓ Different mesh motion types at the same time
  - ✓ Severe sensitivity of slipping points on flat surfaces development
  - ✓ Remeshing and mapping the solution
- Simultaneous mesh deformation of the guide vane domain and solid body rotation of runner domain
- Laplacian smoothing mesh morphing, $\nabla \cdot (\Gamma \nabla \boldsymbol{\delta}_{\text{cell}}) = \mathbf{0}$



Shutdown



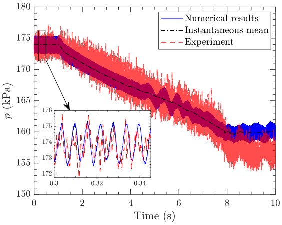
Startup



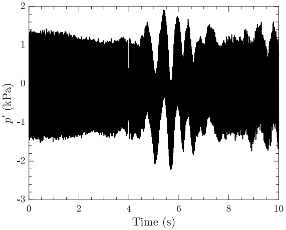
Load change

Mesh motion

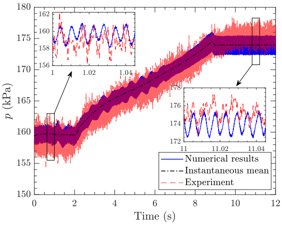
Vaneless space pressure



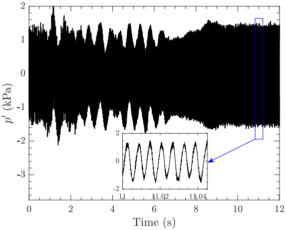
Shutdown, Pressure variation



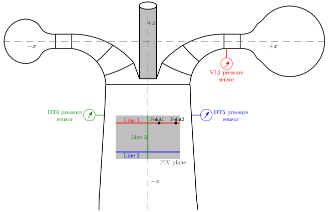
Shutdown, Fluctuating pressure



Startup, Pressure variation

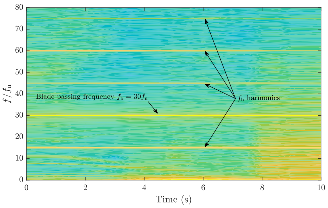


Startup, Fluctuating pressure

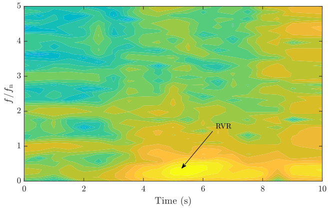


- Very good agreement with experimental data
- Maximum relative error for the VL2 sensor is 4.9%
- Captured pulsations due to the Rotor-Stator Interaction (RSI)
- Low-frequency and high-amplitude oscillations due to Rotating Vortex Rope (RVR)

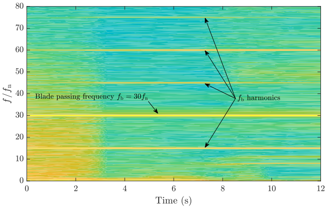
Pressure STFT



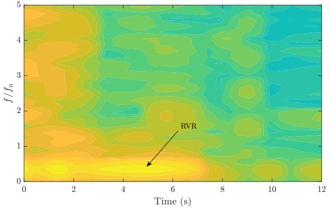
Shutdown, VL2



Shutdown, VL2 (zoomed)



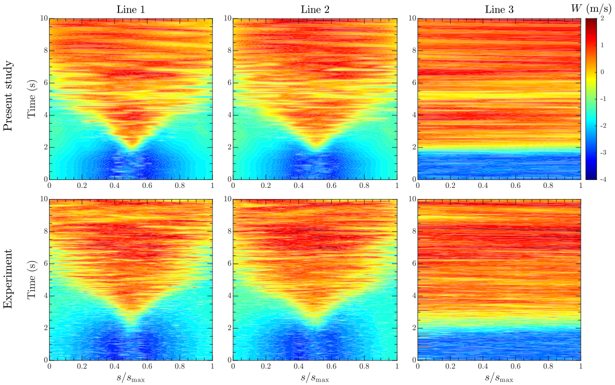
Startup, VL2

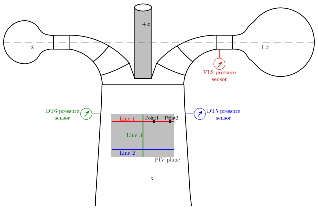


Startup, VL2 (zoomed)

- Blade passing frequency ($f_\mathrm{b} = 30f_\mathrm{n}$) is dominant
- $f_\mathrm{b} = 30f_\mathrm{n}$ harmonics (e.g. $60f_\mathrm{n}$) are also excited.
- low-frequency pulsation caused by Rotating Vortex Rope (RVR)

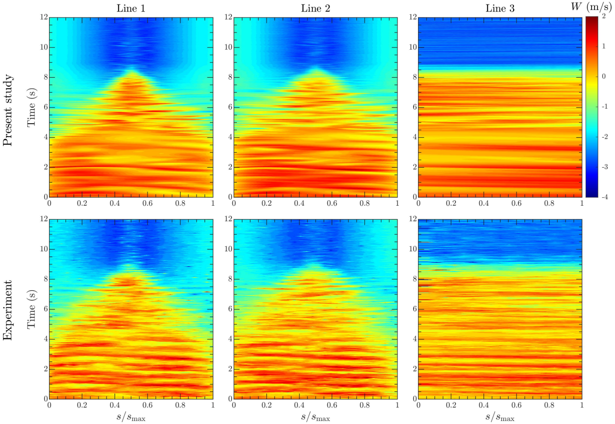
Shutdown velocity field

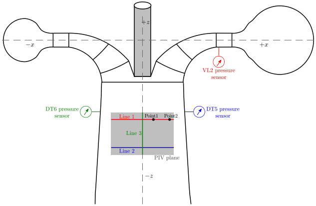




- Very good agreement with experiments
- Inception and expansion of a reversed flow region at the center
- Large oscillations due to the RVR between

Startup velocity field





- Very good agreement with experiments
- Large oscillations due to the RVR between

Shutdown: vortical structures at draft tube

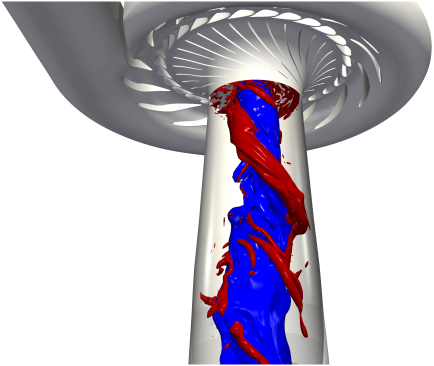
Startup: vortical structures at draft tube

Load change: vortical structures at draft tube

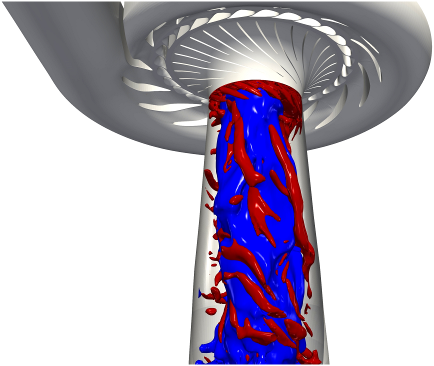
BEP to PL

BEP to HL

Rotating vortex rope



$\alpha = 5.32^{\circ}$, 55.5% load (Part load)



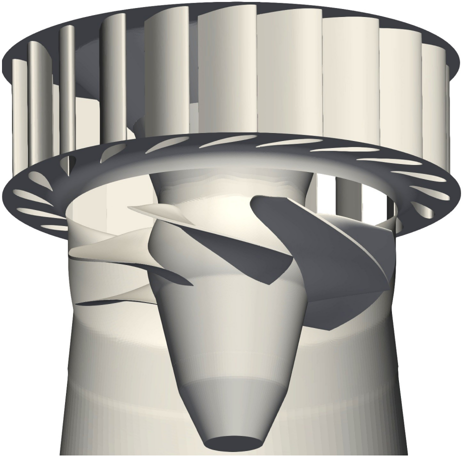
$\alpha = 2.72^{\circ}$, 29.9% load (Deep part load)

- Shear layer instability (Kelvin–Helmholtz)
- RVR is helically wrapped around the central stagnant region
- Stagnant region inflates and RVR vanishes
- It is possible to reduce or remove the RVR by diminishing the central wake region

Kaplan turbine

Mesh motion requirement

- Kaplan turbines transients: variation of both guide vane and runner blade angles at the same time as runner rotation
- Mesh motion types:
  - ✓ Runner solid body rotation
  - ✓ Runner mesh deformation due to change in runner blades angles
  - ✓ Guide vane mesh deformation due to change in guide vanes angles
  - ✓ Flow driven rotation of runner (variable rotational speed)
- The methodology is not available in standard OpenFOAM.



Dynamic mesh challenges in Kaplan turbine

- To have a smooth mesh deformation, points should slip on arbitrarily shaped (curved) boundary surfaces (e.g.runner hub and shroud).
- General slip condition is very sensitive (i.e., points do not follow the surface geometry)
- General slip removes the normal component (only tangential components is kept)

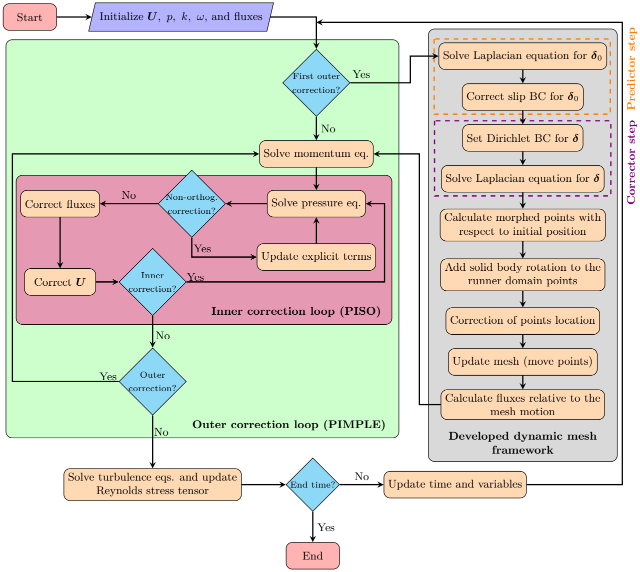
$$\boldsymbol{\delta}_{\|} = \boldsymbol{\delta} - (\boldsymbol{\delta} \cdot \hat{n}) \cdot \hat{n},$$

- Explicit implementation has convergence issues
- Inside point does not *feel* movements on the slip BCs.
- Mesh deformation instability in small clearances (hub and shroud clearances)
- Simultaneous mesh deformation and solid body rotation
- Many developments and bug fixes are required for this complex mesh motion.

Novel mesh morphing approach

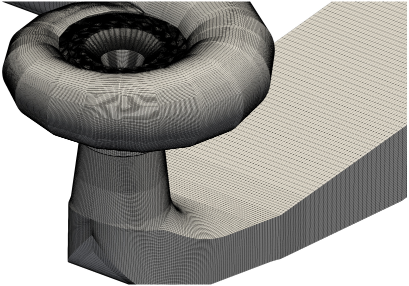
- The main idea is to have two different displacement fields ($\boldsymbol{\delta}_0$ and $\boldsymbol{\delta}$)
- Solve the Laplacian equation for each of those fields.
- **Predictor step**:
  - ✓ Laplacian solution gives intermediate displacement field ($\boldsymbol{\delta}_0$)
  - ✓ Conventional explicit slip is imposed on the surfaces
- **Corrector step**:
  - ✓ Tangential component of $\boldsymbol{\delta}_0$ is set as Dirichlet boundary condition for the main displacement field ($\boldsymbol{\delta}$)
  - ✓ Laplacian equation is solved for $\boldsymbol{\delta}$
- Now the inside points *feel* the slip boundary surface and move with the same curvature.
- Finally a solid body rotation around turbine axis on the runner morphed mesh

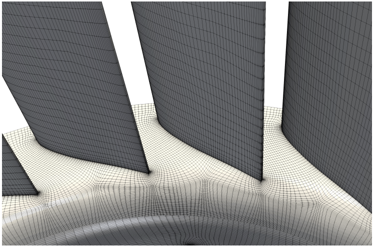
Flowchart

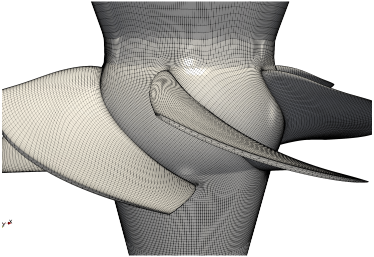

Start
Initialize $\boldsymbol{U}$, p, k, ω, and fluxes
First outer correction?
Yes
No
Solve momentum eq.
Solve pressure eq.
Non-orthog. correction?
No
Yes
Correct fluxes
Update explicit terms
Correct $\boldsymbol{U}$
Inner correction?
Yes
No
Inner correction loop (PISO)
Outer correction?
Yes
No
Outer correction loop (PIMPLE)
Solve Laplacian equation for $\boldsymbol{\delta}_0$
Correct slip BC for $\boldsymbol{\delta}_0$
Predictor step
Set Dirichlet BC for $\boldsymbol{\delta}$
Solve Laplacian equation for $\boldsymbol{\delta}$
Corrector step
Calculate morphed points with respect to initial position
Add solid body rotation to the runner domain points
Correction of points location
Update mesh (move points)
Calculate fluxes relative to the mesh motion
Developed dynamic mesh framework
Solve turbulence eqs. and update Reynolds stress tensor
End time?
No
Update time and variables
Yes
End

U9 Model

- Kaplan turbine model
- 1:3.875 scale model of a Porjus U9 prototype
- 6 runner blades and 20 guide vanes
- No experimental data during transient operating modes (Setup is under construction)
- 13 million cells in total

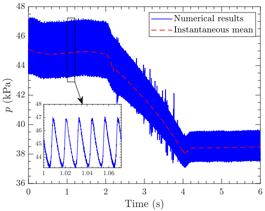




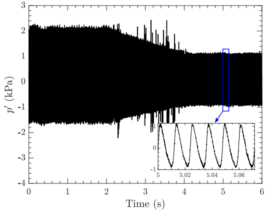


Mesh motion (full domain)

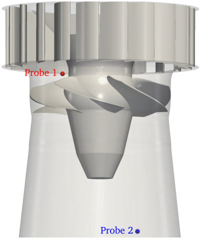
Pressure probes

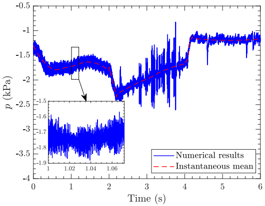


Static pressure for Probe 1

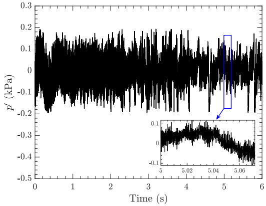


Pressure fluctuations for Probe 1





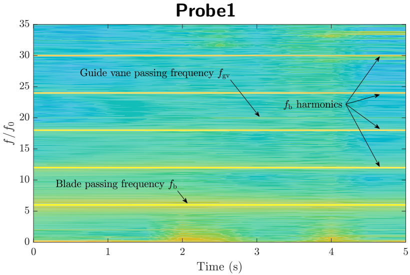
Static pressure for Probe 2

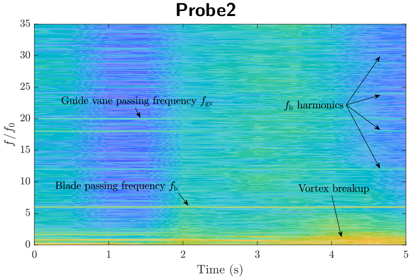


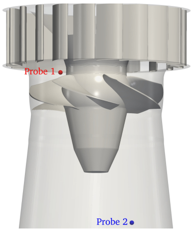
Pressure fluctuations for Probe 2

- Constant mean during the stationary BEP* and PL
- Linear change during transient
- Pressure fluctuations at Probe 1 are mostly affected by the Rotor-Stator Interaction (RSI)

Pressure STFT







$$f_\mathsf{b} = f_0 \cdot Z_\mathsf{b}$$

$$f_\mathsf{gv} = f_0 \cdot Z_\mathsf{gv}$$

- Runner blade frequency and its harmonics are the dominant frequencies for Probe 1
- The guide vane passing frequency is also slightly excited
- Spectrogram of Probe 2 signifies the dominance of low frequencies due to rotating vortex rope and its breakup.

Vortical structures at draft tube

Conclusions

Concluding remarks

- Francis turbine:
  - ✓ Simultaneous mesh deformation of the guide vane domain and solid body rotation of runner domain
  - ✓ Severe sensitivity of points slipping on flat surfaces.
  - ✓ High frequency RSI fluctuations as well as Low-frequency oscillations due to Rotating Vortex Rope (RVR) are well captured.
  - ✓ OpenFOAM provides a trustworthy CFD tool for prediction of transient operation of hydraulic turbines.
- Kaplan turbine:
  - ✓ Kaplan turbine transients involve an elaborate mesh motion, including mesh deformation, solid body rotation and slipping on curved surfaces.
  - ✓ Explicit slip boundary condition is not numerically stable and inside points cannot *feel* it.
  - ✓ A novel numerical framework in OpenFOAM is introduced to address this complex dynamic mesh phenomenon.
  - ✓ Current framework make inside points aware of slipped surfaces.
  - ✓ The developed methodology was successfully tested on a Kaplan turbine model (U9).
- All the cases and codes will be available through the TurboWG in near future

Publications

- Saeed Salehi, Håkan Nilsson, Eric Lillberg and Nicolas Edh; "Numerical Simulation of Hydraulic Turbine During Transient Operation Using OpenFOAM", IOP Conf. Ser.: Earth Environ. Sci. 774 012058, 2021
- Saeed Salehi, Håkan Nilsson, Eric Lillberg and Nicolas Edh; "Development of a novel numerical framework in OpenFOAM to simulate Kaplan turbine transients", IOP Conf. Ser.: Earth Environ. Sci. 774 012058, 2021
- Saeed Salehi, Håkan Nilsson, Eric Lillberg and Nicolas Edh; "An in-depth numerical analysis of the transient flow field of a Francis turbine during shutdown", Renewable Energy 179 (2021) 2322–2347.
- Saeed Salehi, Håkan Nilsson; "Effects of uncertainties in positioning of PIV plane on validation of CFD results of a high-head Francis turbine model", Renewable Energy, 2021 (**Revision submitted**)
- Saeed Salehi, Håkan Nilsson; "OpenFOAM for Francis Turbine transients", OpenFOAM Journal 2021 (**Revision submitted**).
- Saeed Salehi, Håkan Nilsson; "Startup of a high-head Francis turbine: A detailed numerical study", To be submitted to Renewable Energy.

Future works

- Understanding flow structures during off-design and transient operation using machine learning and dimensionality reduction algorithms.
- In-depth analysis of pulsating forces during load variation of Francis turbines
- Detailed analysis flow field inside Kaplan turbine during load change, shutdown, startup, etc.
- Improve the mesh deformation framework
- Add flow driven rotation of runner capability (6DOF solver) to the developed framework
- Validation of numerical results with experimental data (as soon as they are available)

Acknowledgments

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Thank you