Numerical Simulation of Hydraulic Turbine During Transient Operation Using OpenFOAM

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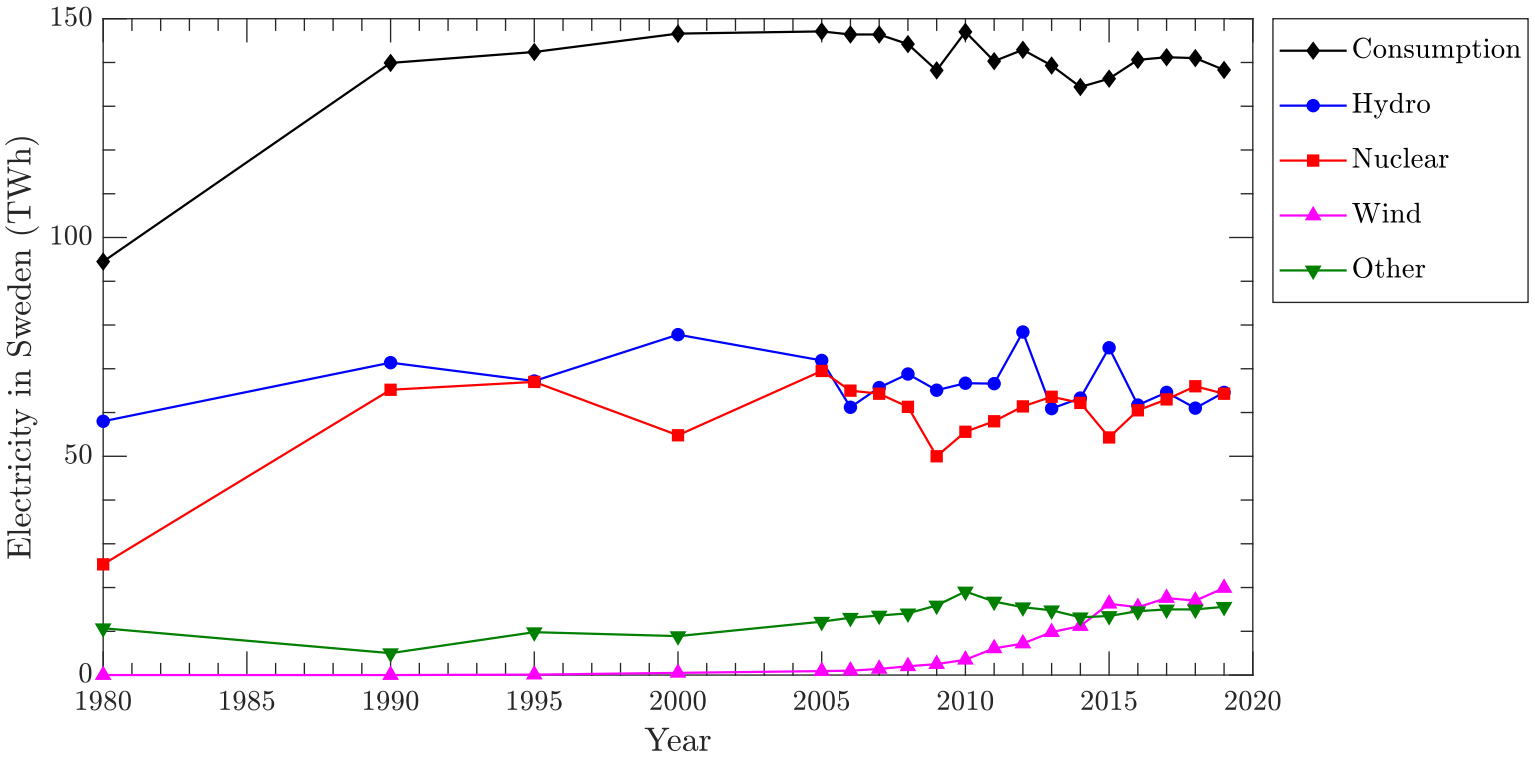
VATTENFALL

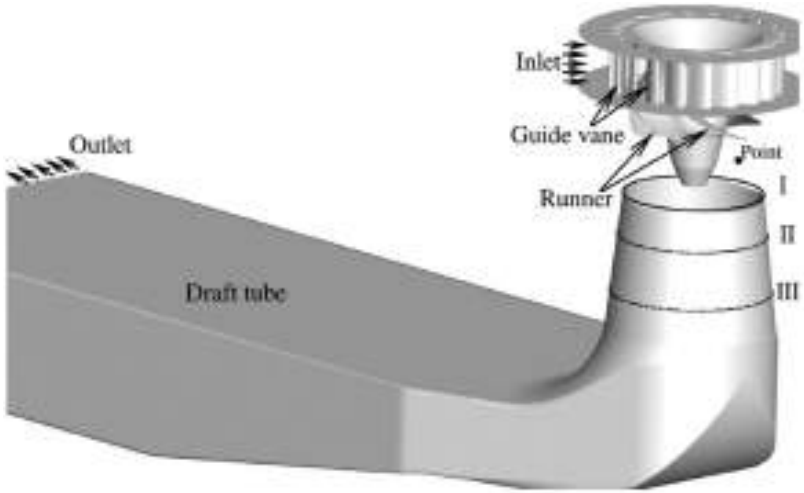
Motivation

- Power production from renewable energy resources are in high demand these days.
- Intermittency of such resources
- Requirement for regulation of the electric grid.



Hydraulic Turbines

- 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.
- Varying conditions can cause hazardous flow-induced instabilities
- Significant pressure fluctuations and load variations
- Negative effects on the turbine lifetime.



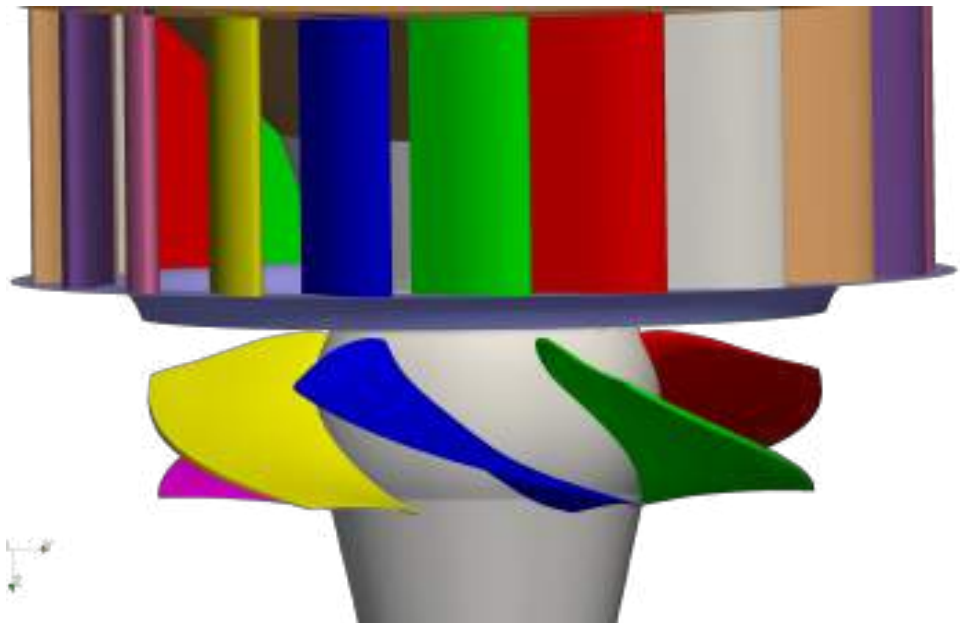
Transient Operation

- 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 transient operating modes
  - ✓ Load acceptance (BEP to HL)
  - ✓ Load rejection (BEP to PL)
  - ✓ Sudden load removal (Spin-no-load)
  - ✓ Shutdown
  - ✓ Startup

Challenges

Dynamic Mesh Challenges

- Mesh motion types:
  - ✓ Runner rotation
  - ✓ Opening/closing guide vanes
  - ✓ Changing runner blades angles
  - ✓ Flow driven rotation of runner using 6DOF solver
- Different mesh motion types at the same time
  - ✓ On the same domain
  - ✓ On different domains
- Approaches for dynamic mesh treatment:
  - ✓ **Mesh morphing**
  - ✓ Overset
  - ✓ Immersed boundary



Dynamic Mesh Challenges

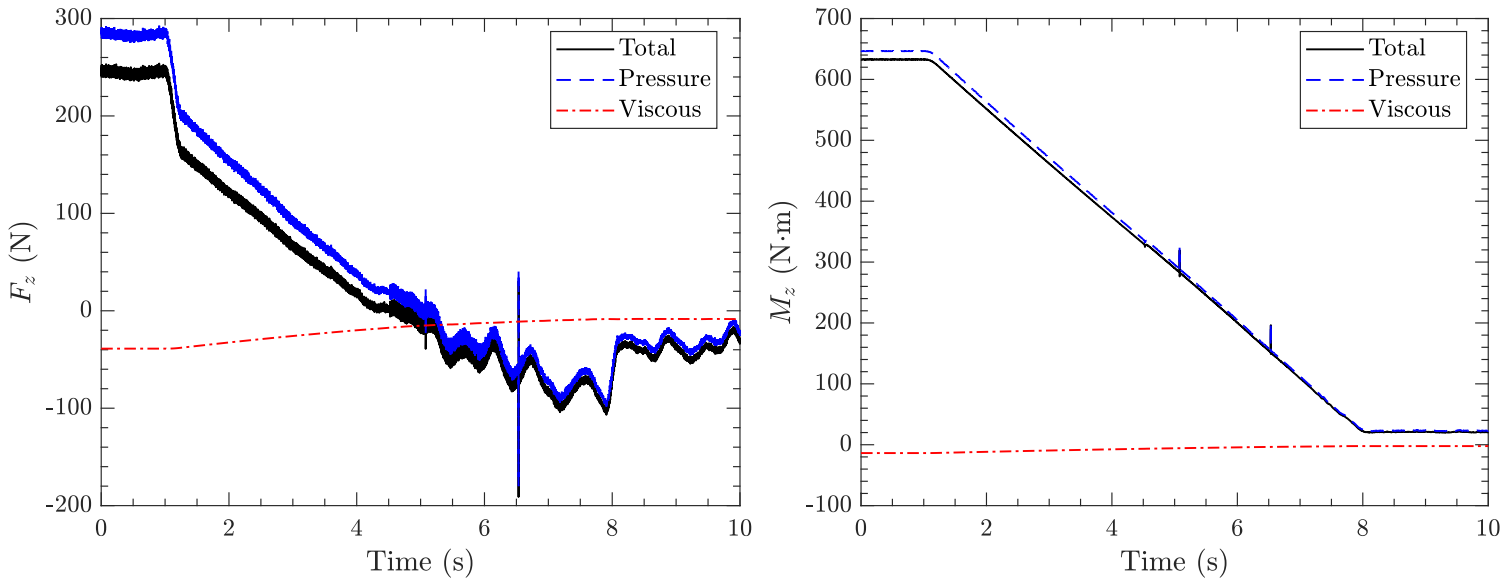
- Sensitivity of slipping points on surfaces
- Slipping points on a curved surface
- Small clearances
- `surfaceSlipDisplacement` BC: explicit correction
- `pointDisplacement` and `cellDisplacement`
- Overset and Immeresed boundary methods need further development



Many developments and bug fixes are needed to make this complex phenomena happen in OpenFOAM.

Numerical Challenges

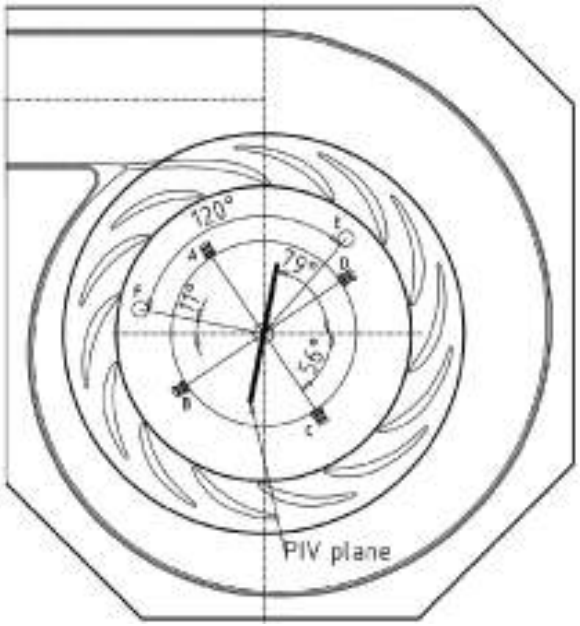
- Small time-step, large flow time ($dt = \mathcal{O}(10^{-5})$, $T = 12 \sim 20$s)
- Remeshing and mapping the solution (Fluxes are not conserved, spikes in the flow field)
- Smooth time varying boundary conditions
- Convergence issues in minimum load conditions

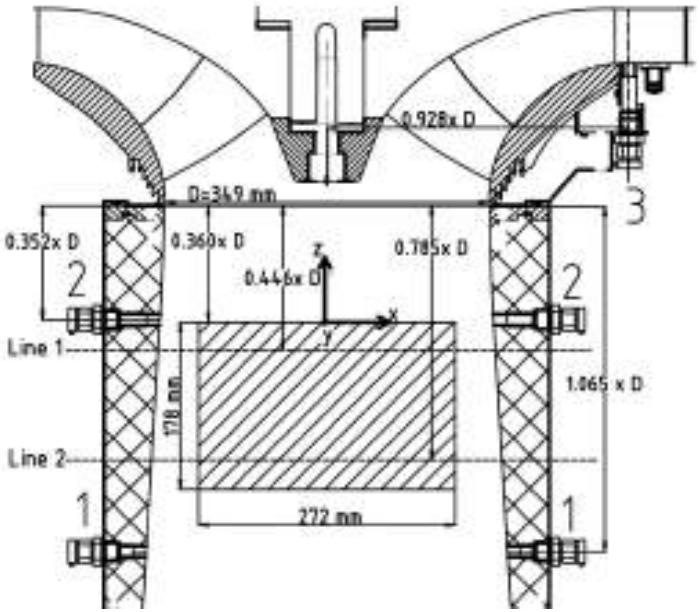


Test Case

Francis-99

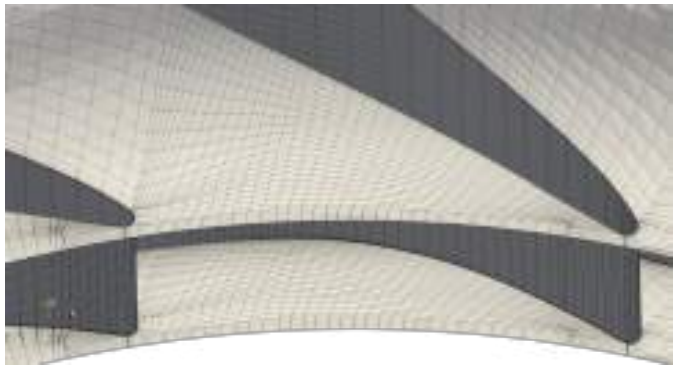
- High-head Francis turbine
- Four domains: spiral casing, guide vanes, runner and draft tube
- 15 runner blades, 15 splitters, and 28 guide vanes
- Pressure and velocity measurements in different transient operating modes

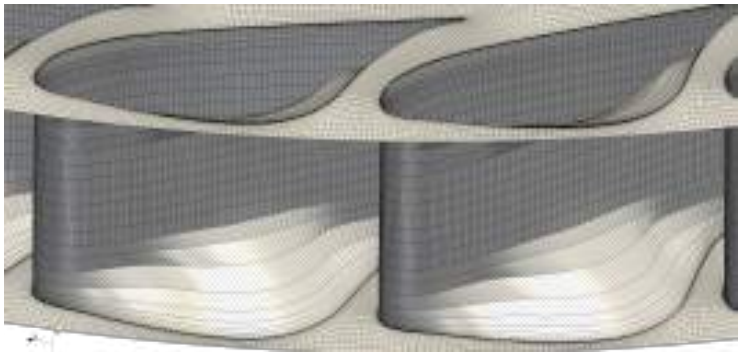




Computational Mesh

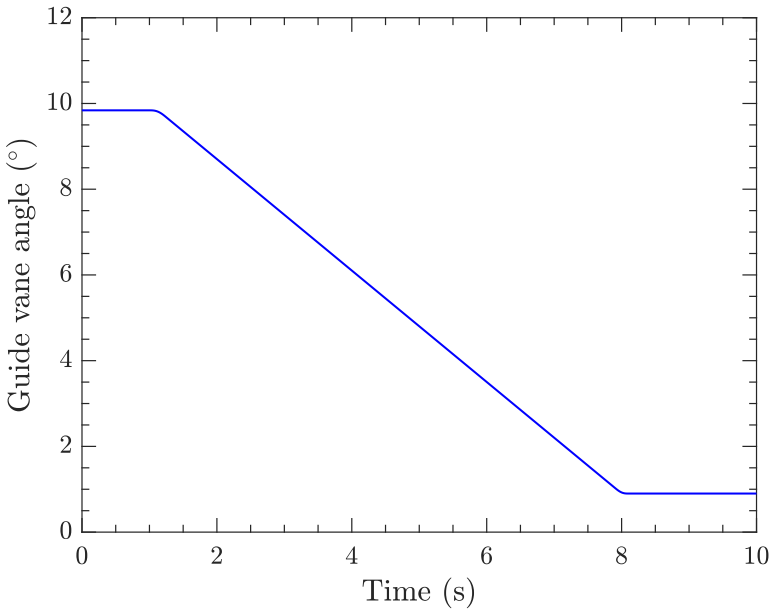
- Fully structured hex mesh
- 16 million cells in total
- Wall resolution: $y^+ < 8$

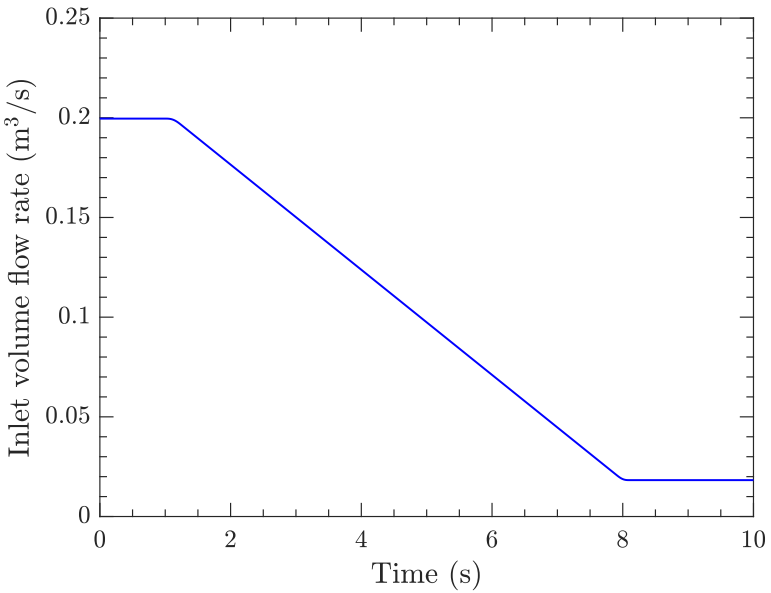




Flow condition

- Turbine shutdown procedure
- Runner rotation speed: constant at 333 rpm
- Guide vanes closing speed: 1.3 °/s
- Flow rate changing linearly with guide vanes angle





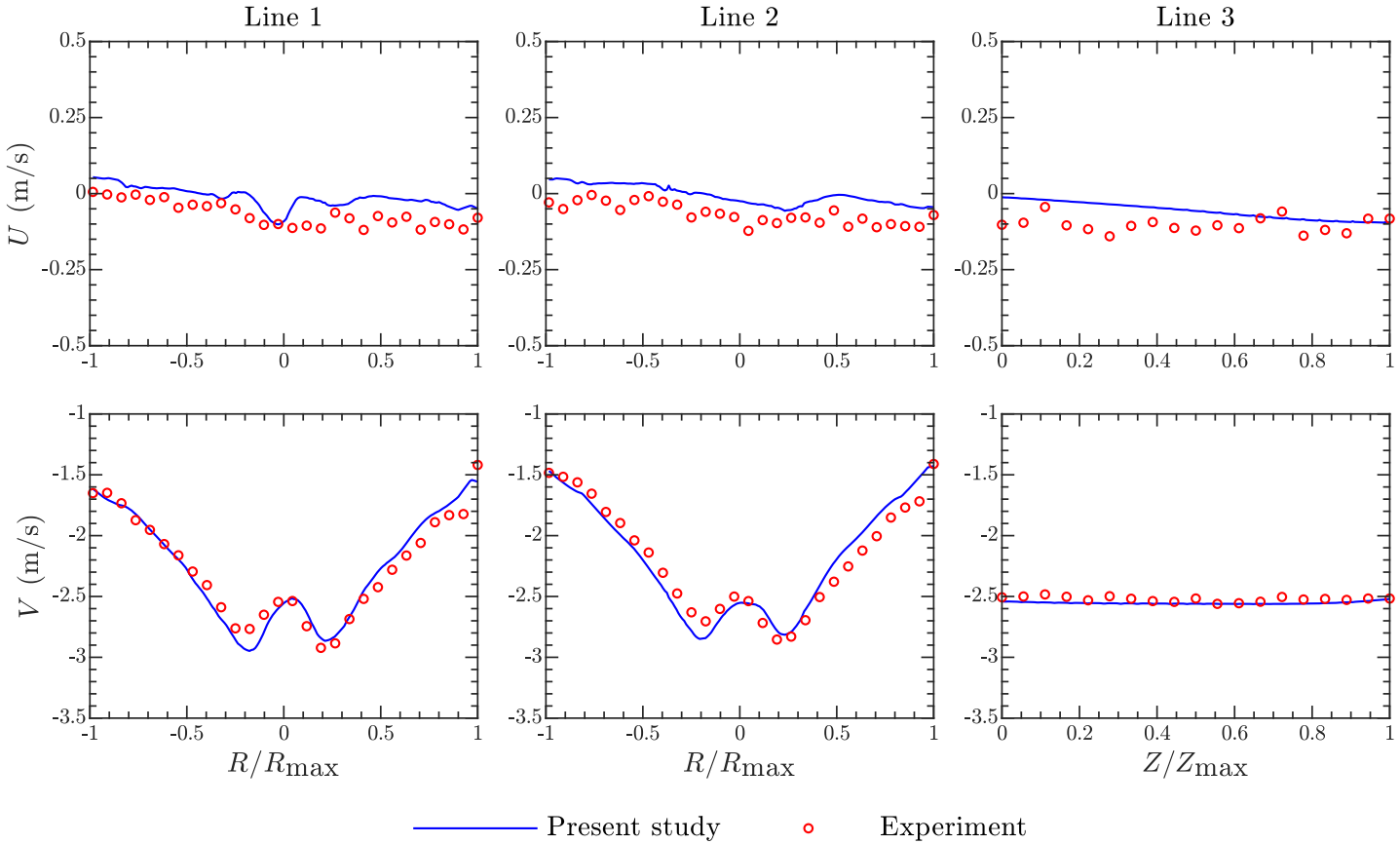
Computational Details

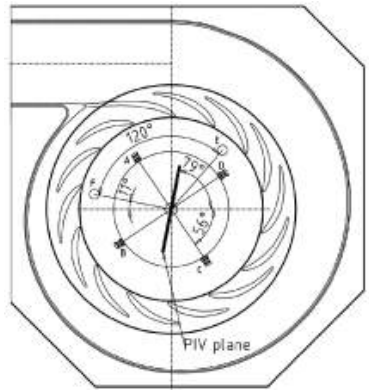
Highlights

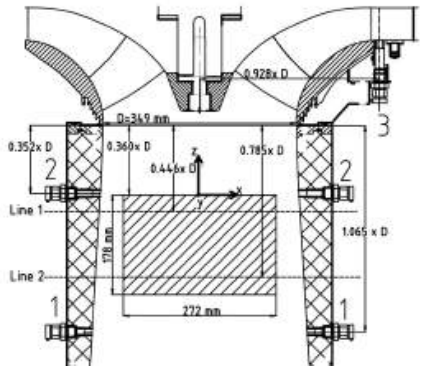
- OpenFOAM-v1912
- Solver: `pimpleFoam`:
  - ✓ `nOuterCorrectors`: 10
  - ✓ `nCorrectors`: 2
  - ✓ `nNonOrthogonalCorrectors`: 1
- $dt = 1.25 \times 10^{-4}$ s, 0.25 $^\circ$ runner rotation per time-step, $CFL_{\max} < 20$
- Turbulence modeling: scale resolving simulation (**SAS**, DES)
- `cyclicAMI` for interfaces between spiral casing, guide vane, runner, and draft tube domains
- Laplacian solver with `inverseDistance` diffusivity
- `ddtSchemes`: `backward`
- `div(phi,U)`: `LUST`
- Each simulation takes around 15 days using 300 cores on SNIC supercomputers

Results

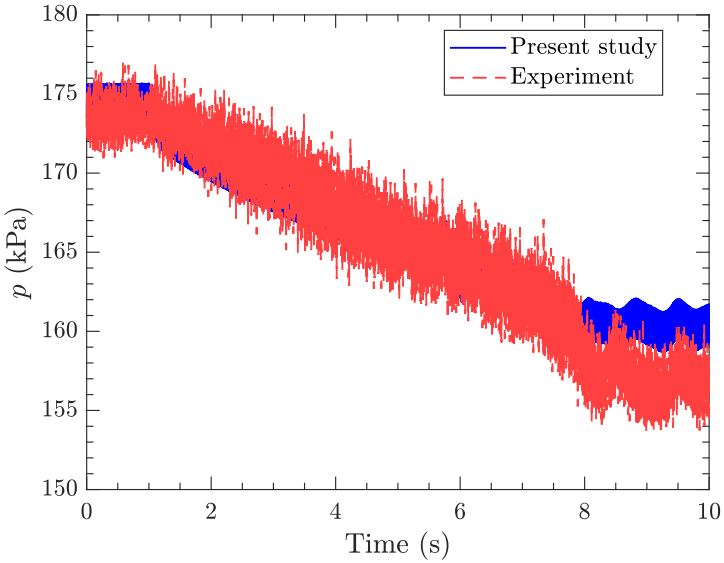
Steady at Best Efficiency Point

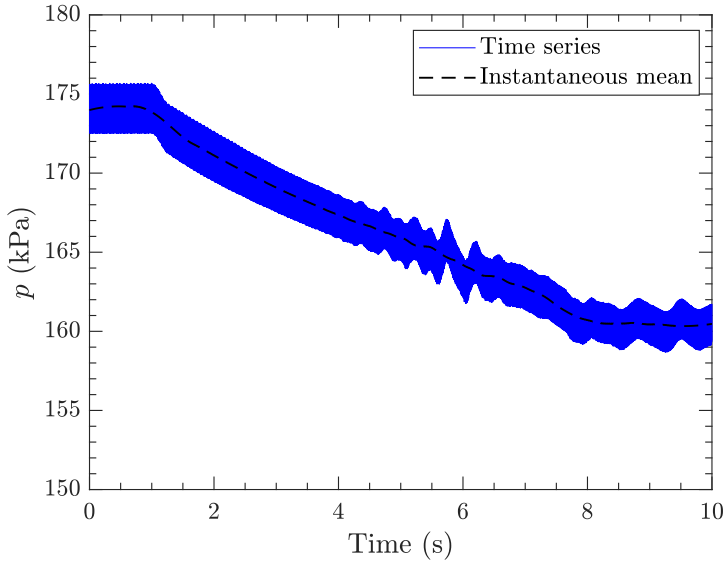


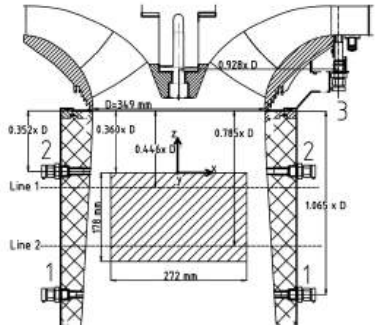


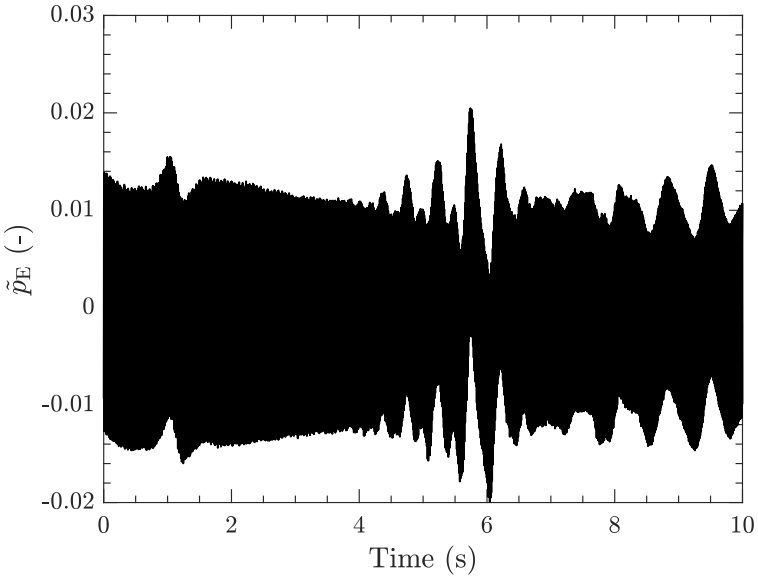


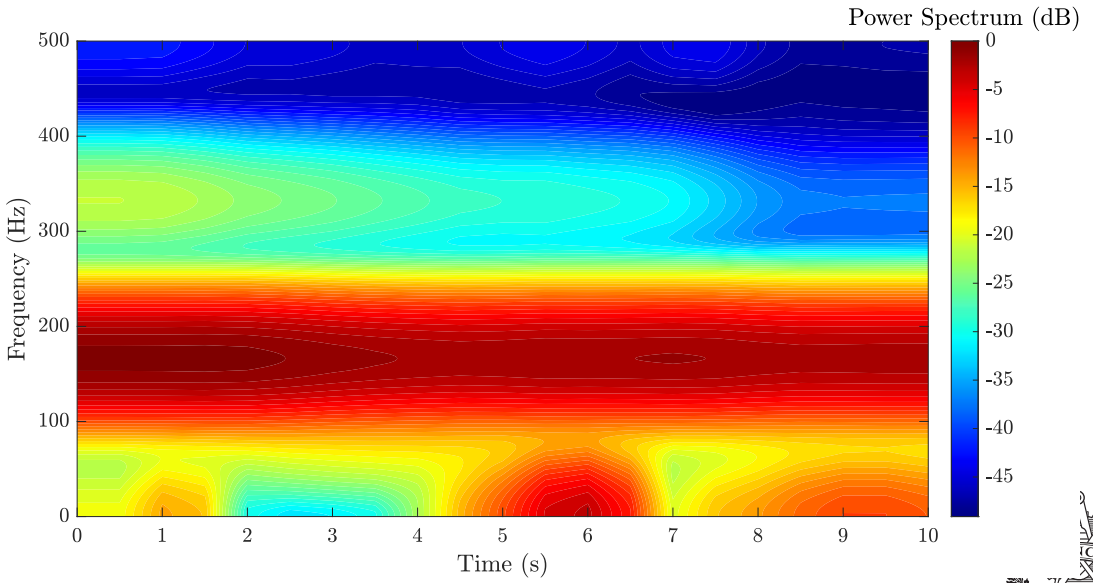
Pressure Probes



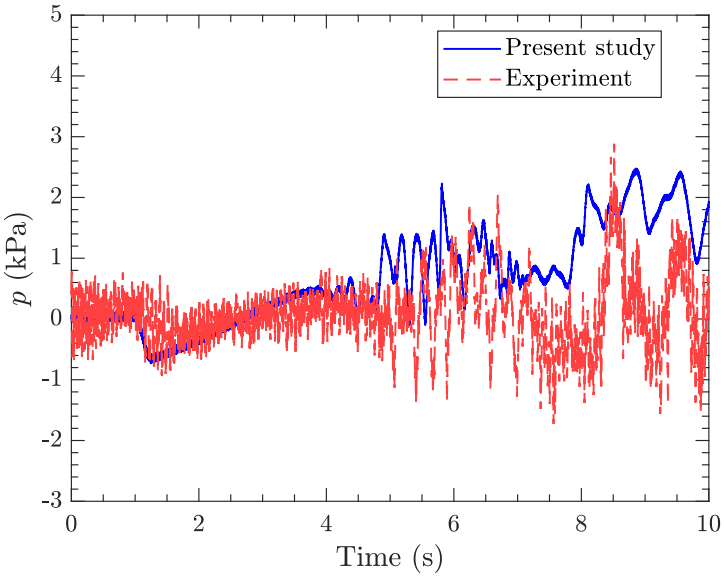


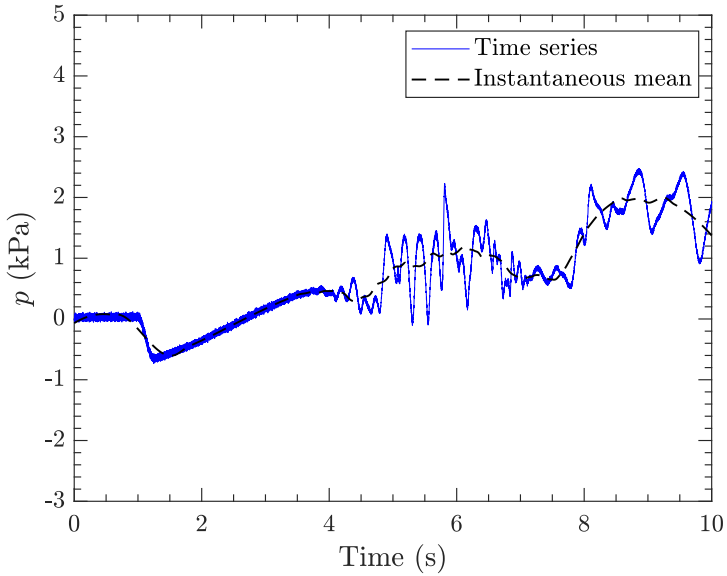


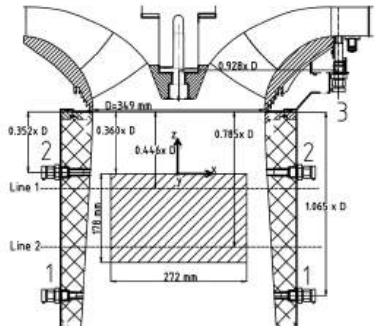


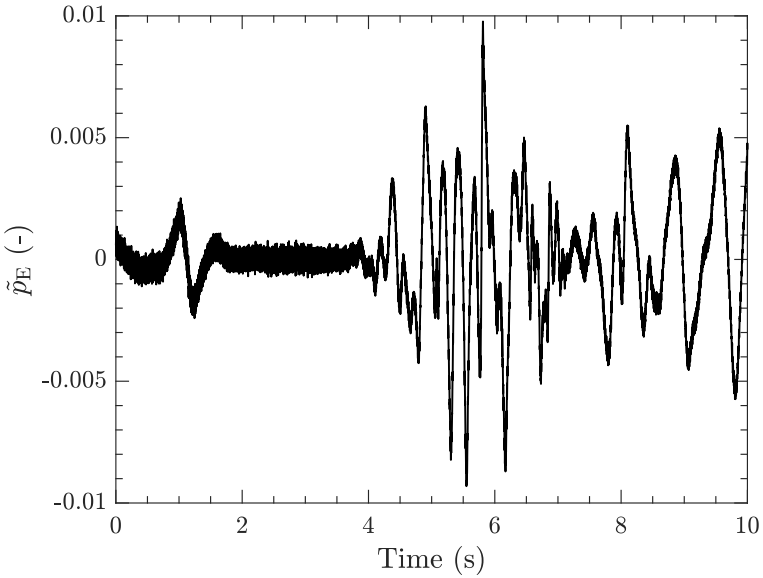


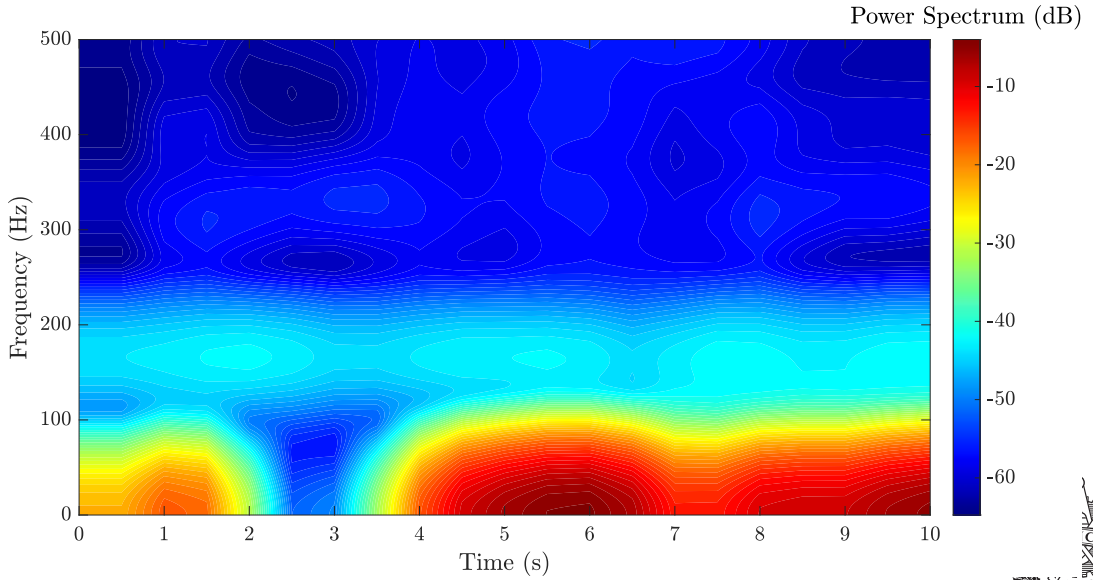
Pressure Probes



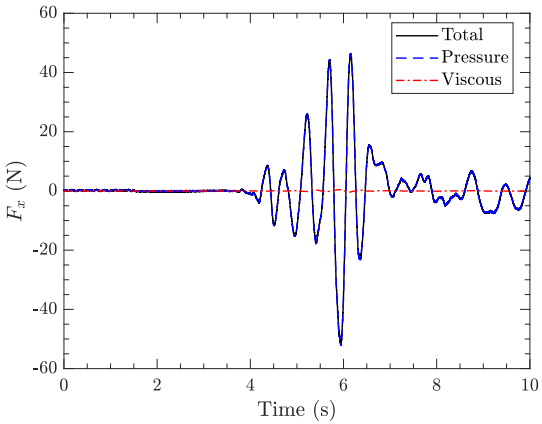


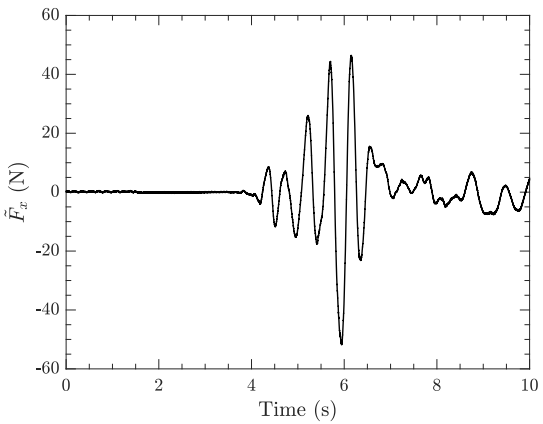


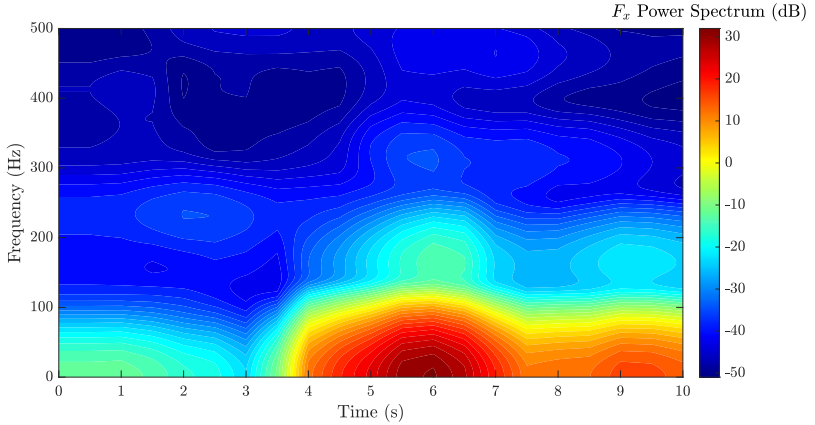


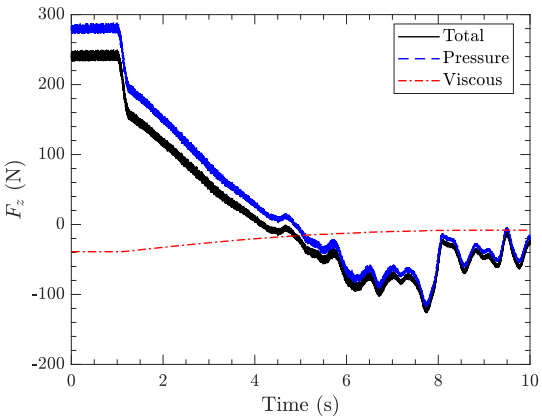


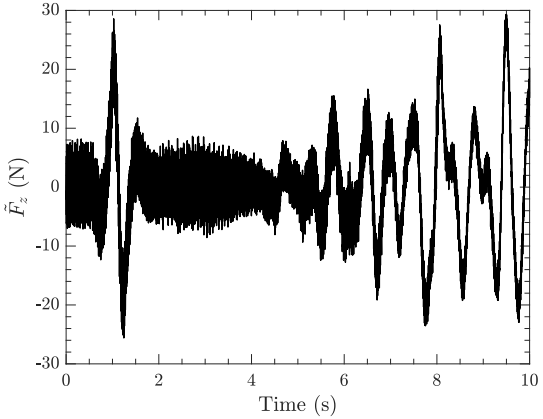
Forces

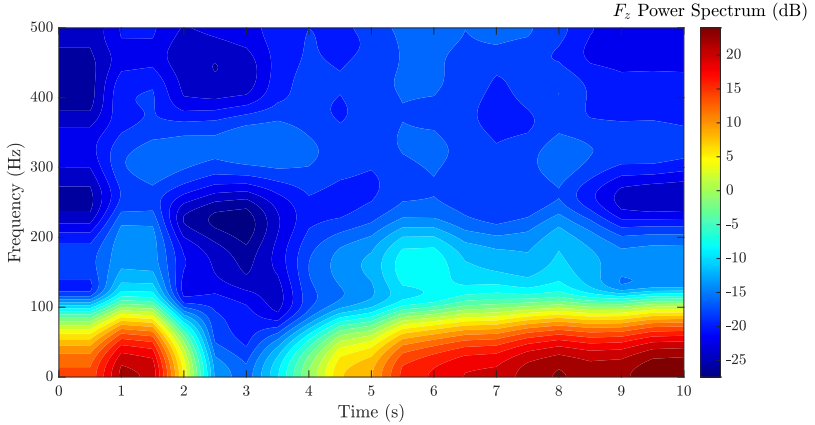

Total
Pressure
Viscous
F_x (N)
Time (s)


$\tilde{F}_x$ (N)
Time (s)

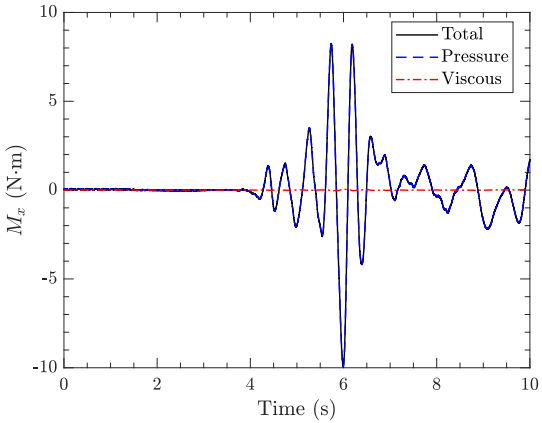

F_x Power Spectrum (dB)
Frequency (Hz)
Time (s)

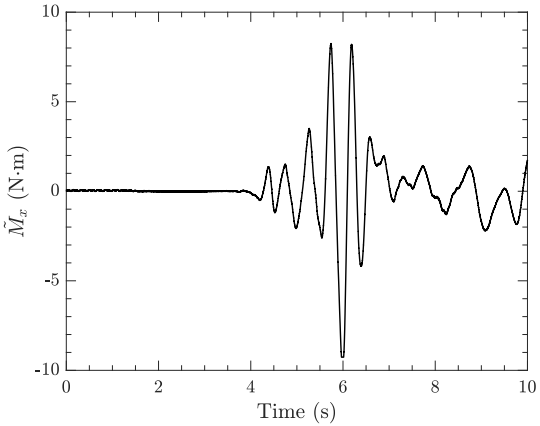

Total
Pressure
Viscous
F_z (N)
Time (s)

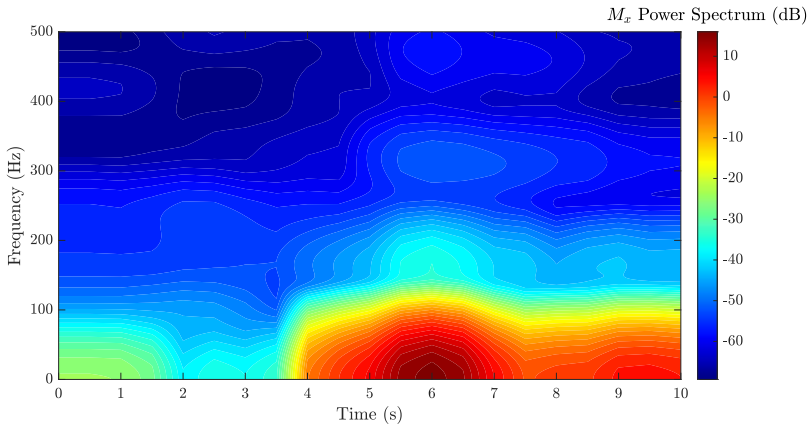

$\tilde{F}_z$ (N)
Time (s)

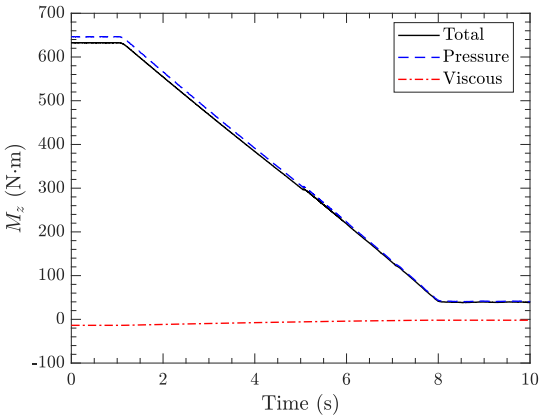

F_z Power Spectrum (dB)
Frequency (Hz)
Time (s)

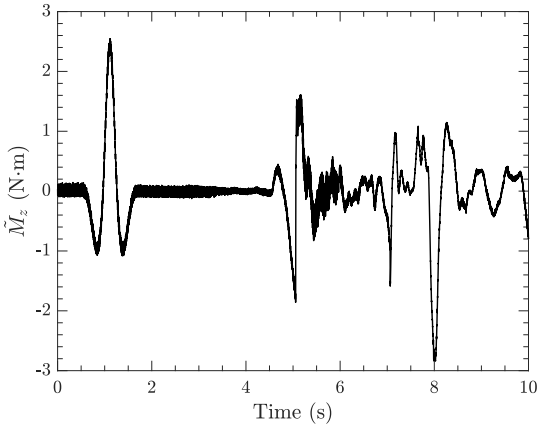
Moments

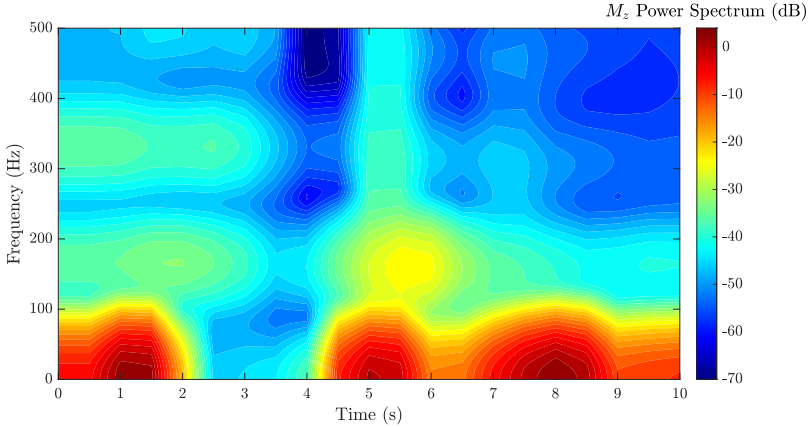

Total
Pressure
Viscous
M_x (N·m)
Time (s)


$\tilde{M}_x$ (N·m)
Time (s)


M_x Power Spectrum (dB)
Frequency (Hz)
Time (s)


Total
Pressure
Viscous
M_z (N·m)
Time (s)


$\tilde{M}_z$ (N·m)
Time (s)

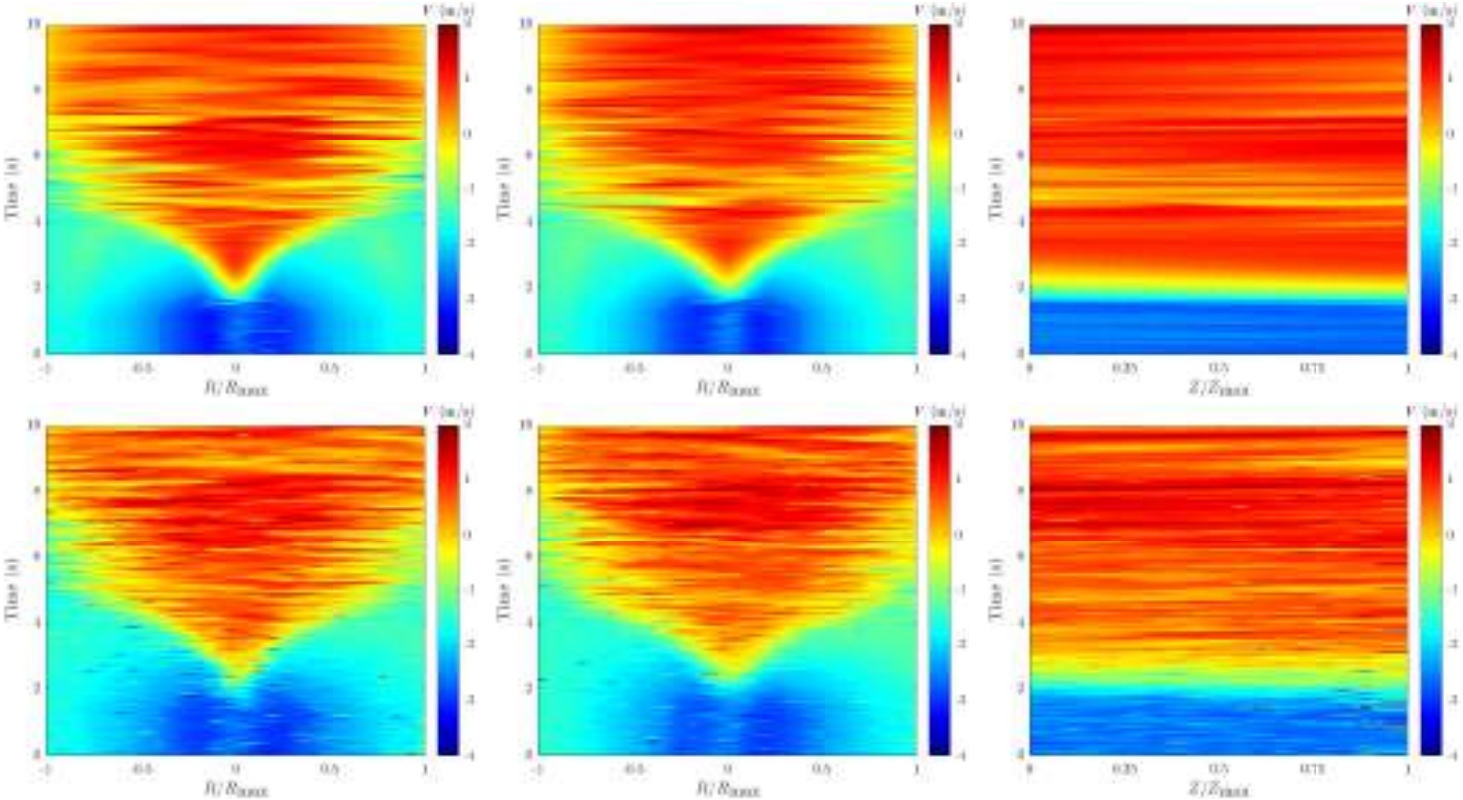

M_z Power Spectrum (dB)
Frequency (Hz)
Time (s)

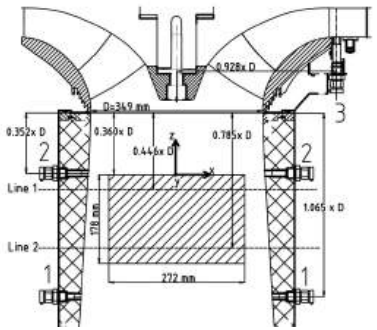
Velocity field

Line 1 Line 2 Line 3

Present Study

Experiments





Q-Criterion

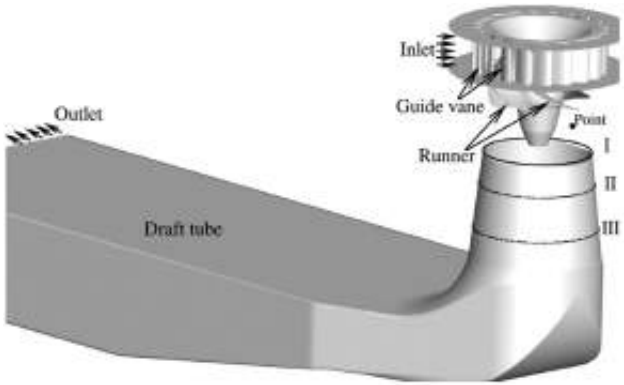
Conclusions

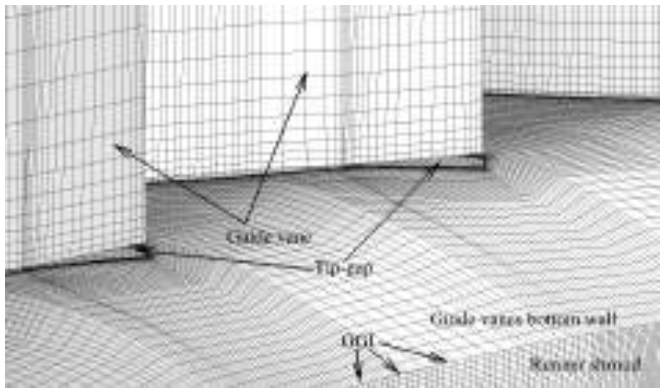
Concluding Remarks

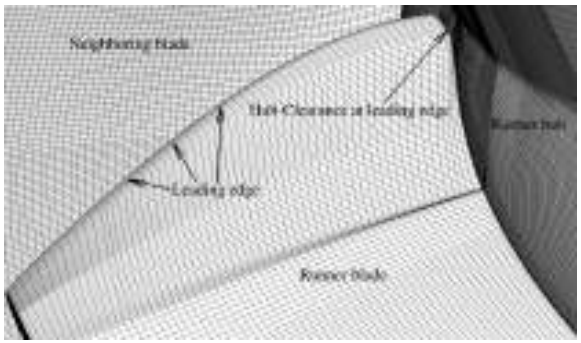
- Different `dynamicFvMesh` libraries, mesh motion solver, and boundary conditions were developed.
- Numerical predictions of the Francis-99 during transient mode correlate well with experiment.
- OpenFOAM provides a trustworthy CFD tool for prediction of transient operation of hydraulic turbines.
- Frequency analysis of numerical results reveals vibration load on the turbine during transient

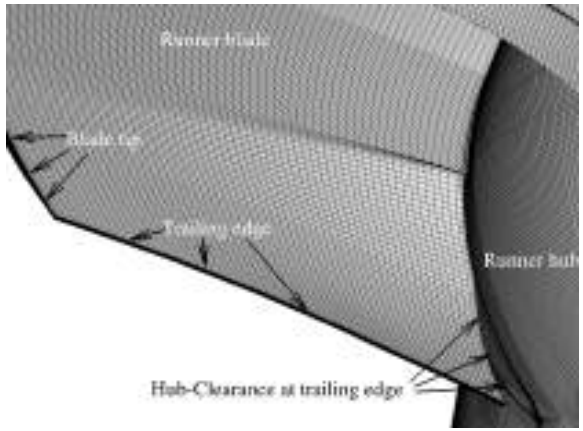
Future works

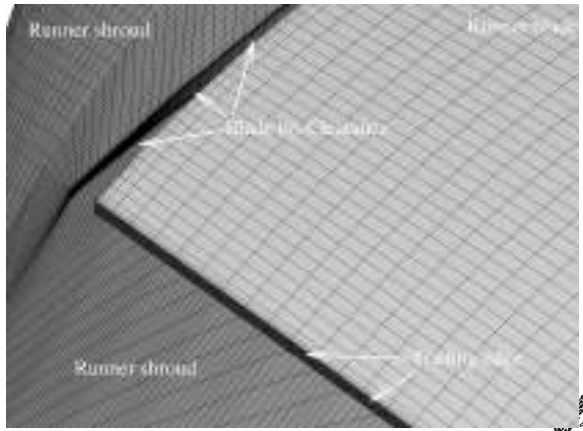
- 1:3.1 scale model of a Porjus U9 prototype
- More challenging case












Thank
You
Merci
Gracias
TerimaKasih
Spacibo
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Arigatô
KamSahHamnida
Xièxie
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Grazie
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Takk
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ThintKo
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Köszönöm
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WaadMahadsantahay
Malondo
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Koszonom
TapadhLeat
WaadMahadsanlahay
Nurakaze
Grazzi


WHY?
WHAT?
WHERE?
WHEN?
HOW?
WHO?