PREVENTING TURBINE INSTABILITY DURING MULTIPLE START/STOP PROCEDURES

- KNOWLEDGE AND TECHNOLOGY TRANSFER FOR HYDROPOWER -

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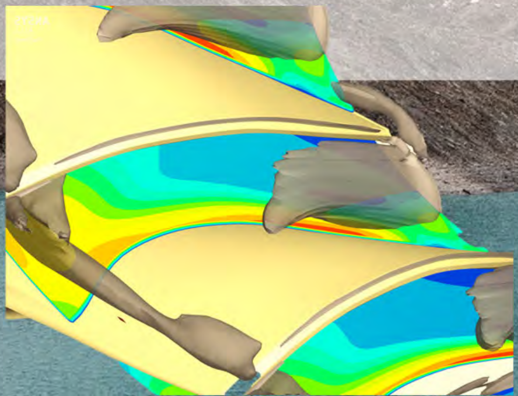

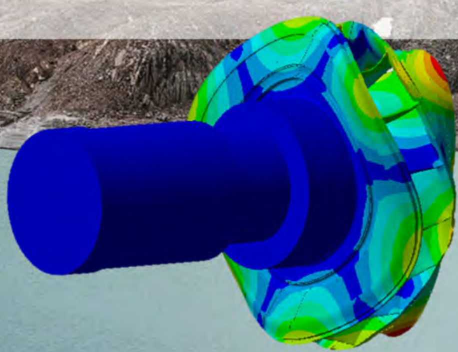

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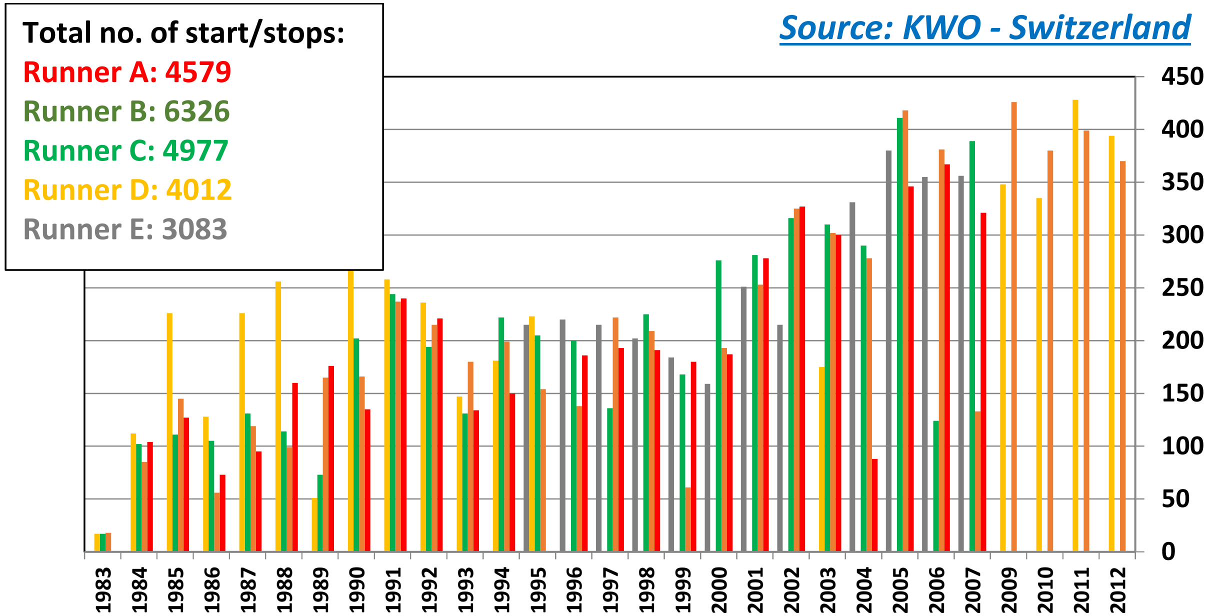
Problematic and objective

- ✓ PSPP: subject to increasing number of start/stops.



Source: KWO – Switzerland

- *Grimsel 2 PSPP*
- *4 horizontal ternary groups*

Problematic and objective

- ✓ PSPP: subject to increasing number of start/stops.
- ✓ Francis turbines: must sometimes face up to particular harsh operating conditions.

Courtesy of U Seidel et al., 2014,
IOP Conf. Ser.: Earth Environ. Sci. 22

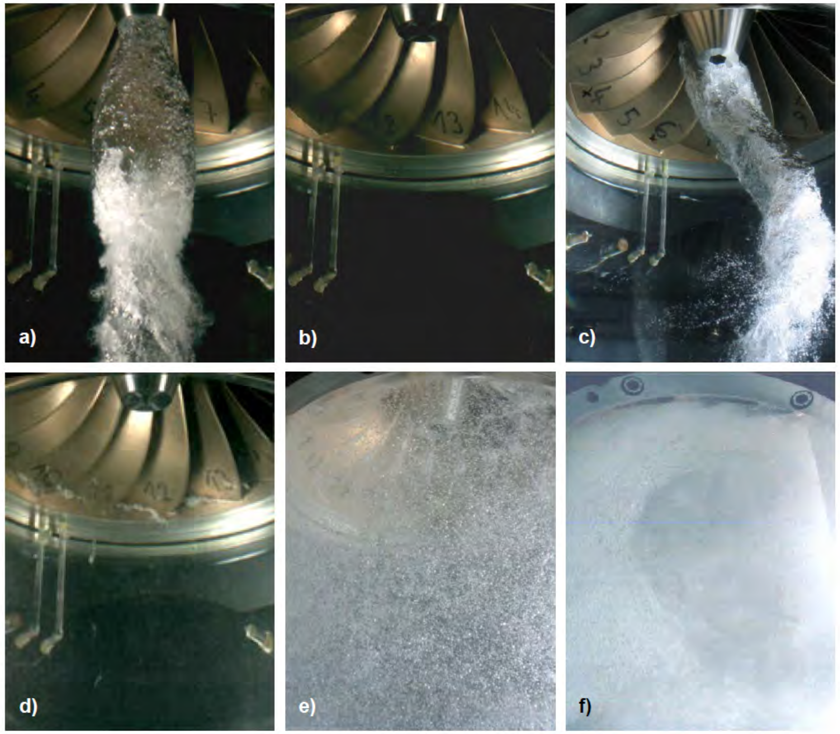
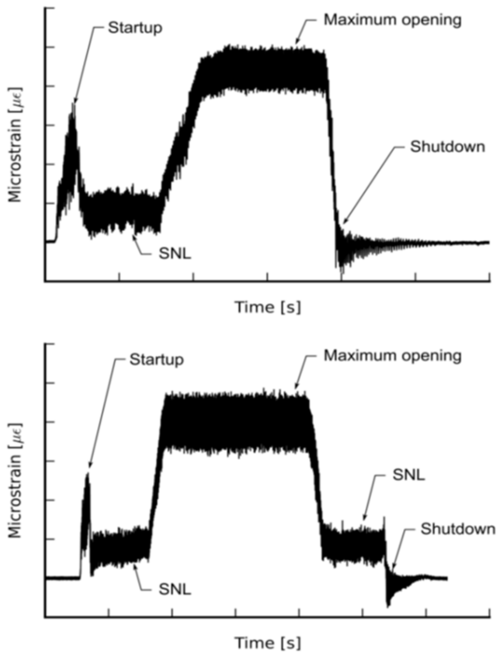


Figure 2: Typical flow patterns of a Francis turbine observed in model tests at plant sigma:
a) high load, b) around BEP, c) part load, d) low part load, e) speed no load, f) runaway

Courtesy of
Gagnon & Thibault, 2015,
6th IAHRWG, Ljubljana, Slovenia

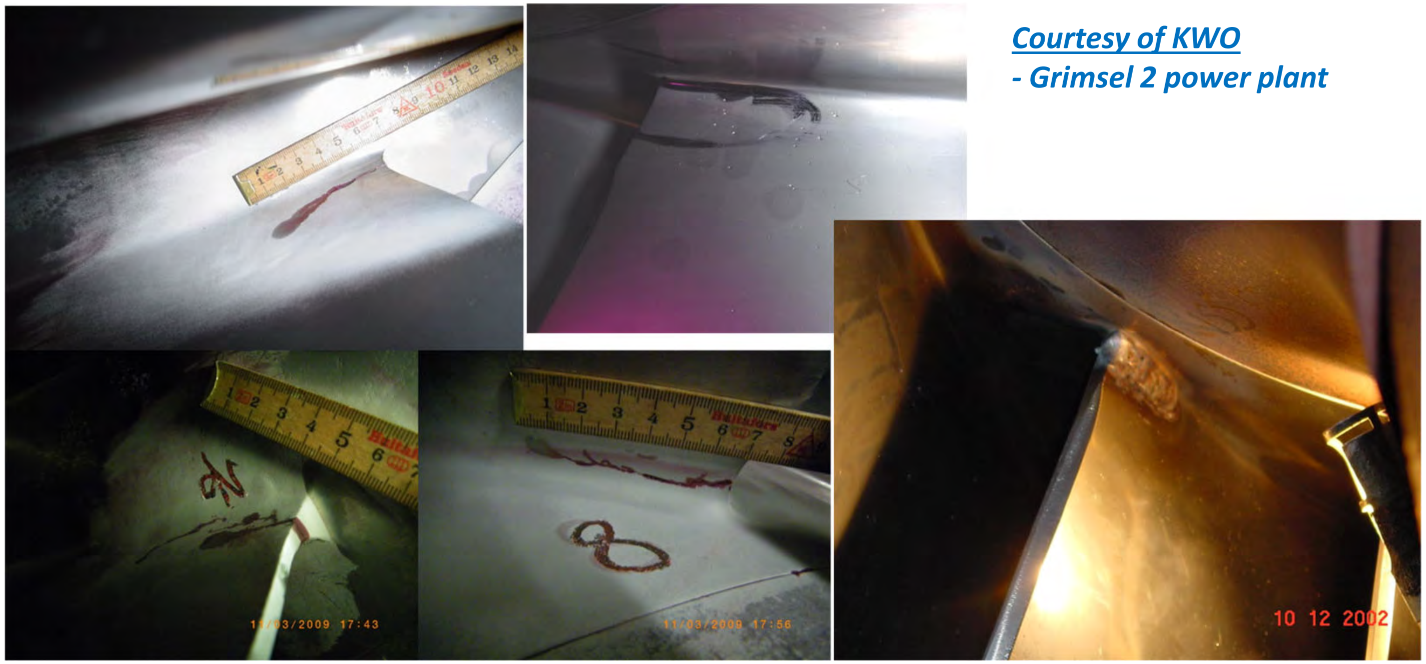


Source: KWO – Switzerland

- ***Grimsel 2 PSPP***
- ***4 horizontal ternary groups***

Problematic and objective

- ✓ PSPP: subject to increasing number of start/stops.
- ✓ Francis turbines: must sometimes face up to particular harsh operating conditions.
- ✓ Frequent operation under such conditions may conduct to premature fatigue !
- ✓ **Objective**: identification of harmful operating conditions on a 100 MW turbine prototype and proposal of a solution to extend the runners lifetime.



Courtesy of KWO
- Grimsel 2 power plant

Source: KWO – Switzerland

- Grimsel 2 PSPP
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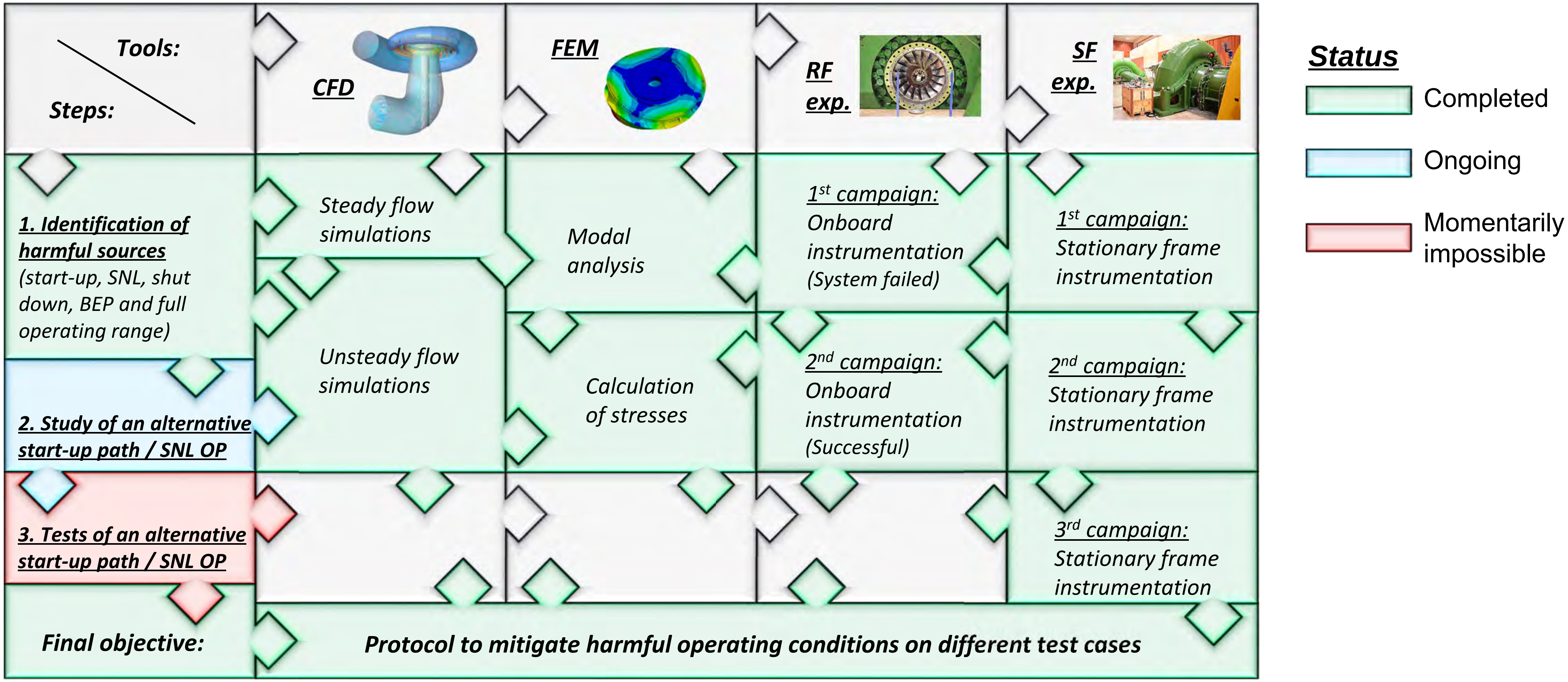
Applied strategy



*V. Hasmatuchi et al., "**A challenging puzzle to extend the runner lifetime of a 100 MW Francis turbine**", Proceedings of Hydro 2018, Gdansk, Poland.*

CFD & FEM numerical setup

CFD setup:

- Mesh: total number of nodes = 14'738'000
- Inlet: flow rate or total pressure.
- Outlet: Opening with an averaged pressure.
- Solid surfaces: no slip wall.
- Runner domain: rotational velocity N = 750 min^{-1}.
- Frozen/Stage/Transient interface.
- SAS SST k-ω turbulence model.
- Number of iterations: 2'000 / Time step = 0.4° rev/Δt
- High order scheme for the mean flow equations.
- First order scheme for the turbulent flow equations.

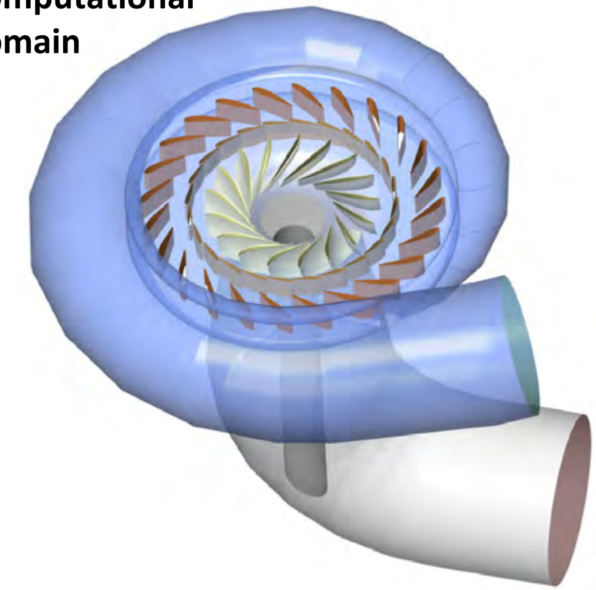
Modal analysis setup:

- Runner surrounding by a water volume.
- Mesh : 300'000 tetrahedral elements.

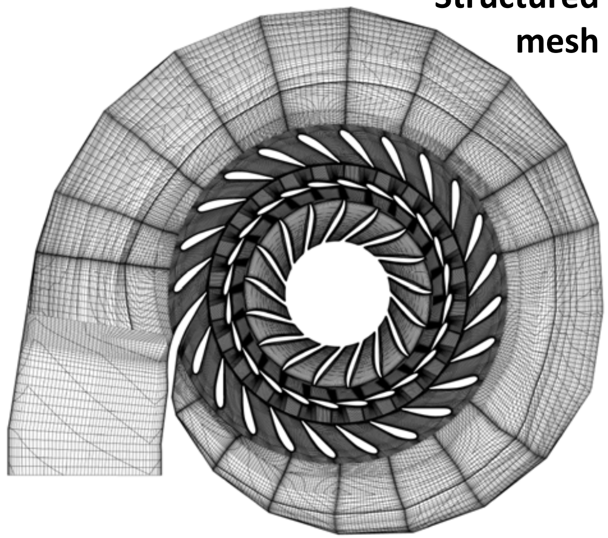
Boundary conditions :

- Fixed support condition set at the junction between the runner and the shaft and at the bottom of the water tank.
- Complex acoustic pressure at the top and around the water tank.

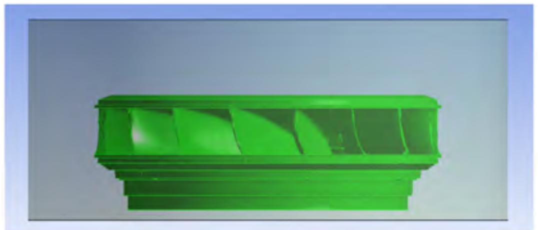
Computational domain



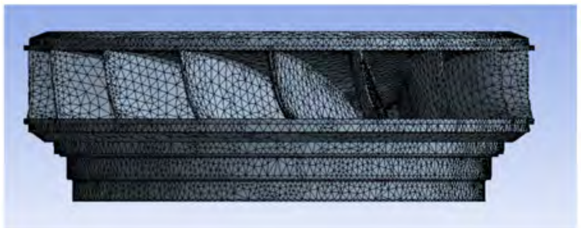
Structured mesh



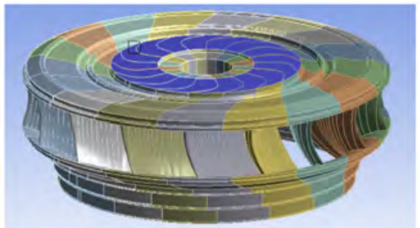
Computational domain



Mesh

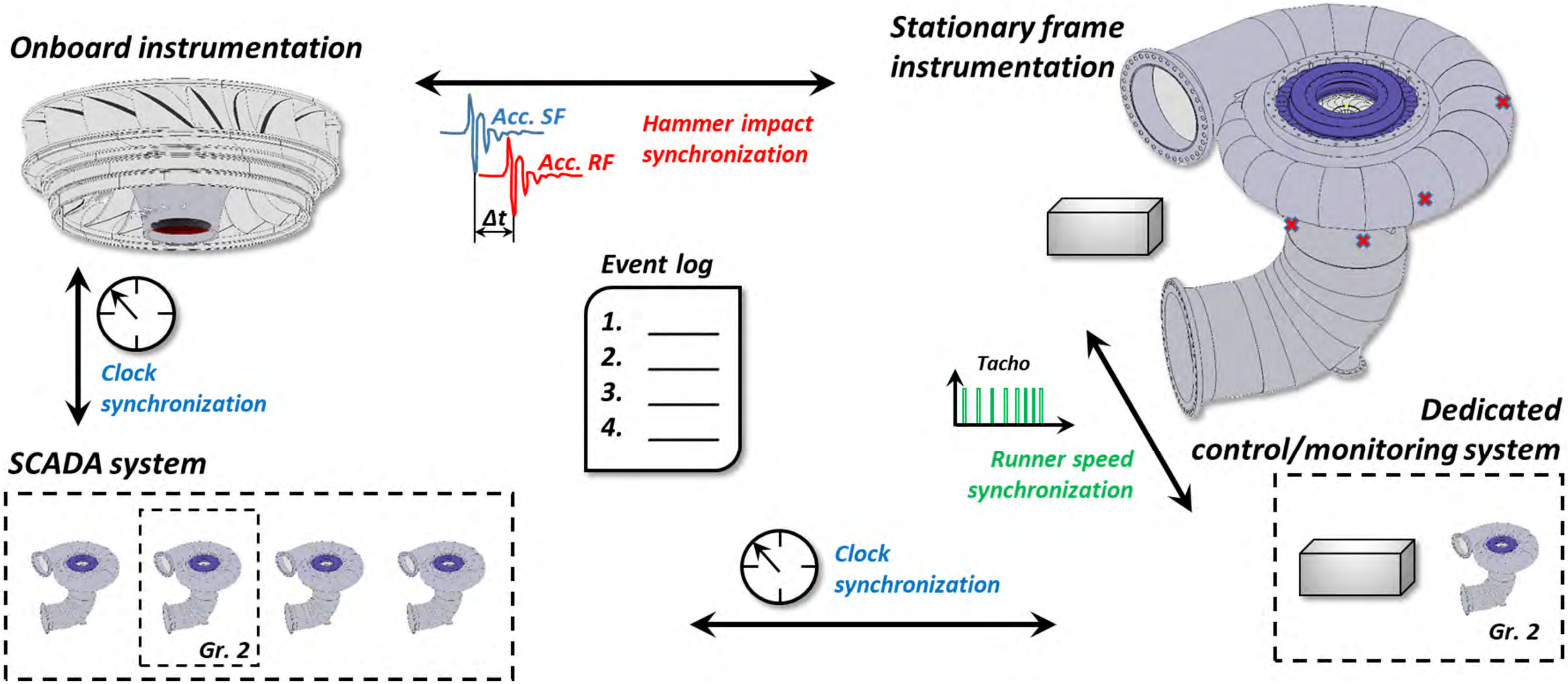


Boundary conditions



*J. Decaix et al. 2019, "**Experimental and numerical investigations of a high-head pumped-storage power plant at speed no-load**", IOP Conf. Series: Earth and Environmental Science 240(8).*

In-situ experimental measurements – global architecture



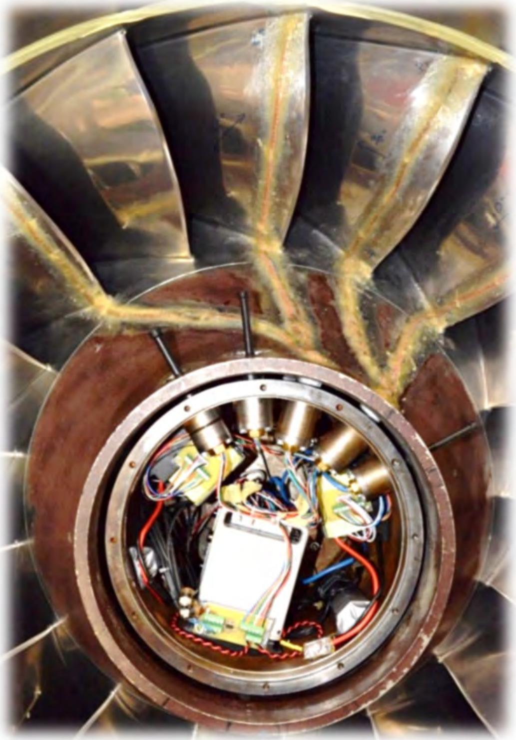
In-situ experimental measurements – rotating frame setup

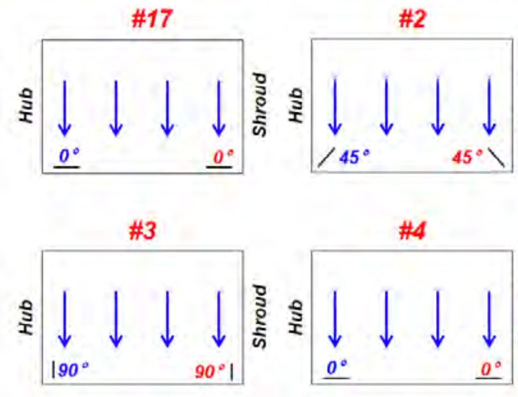
Components:

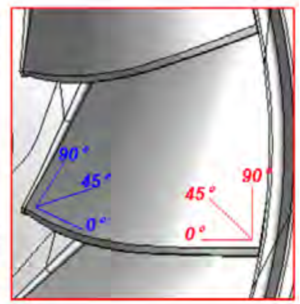
- **1x** Gantner Q.brixx acquisition system
- **2x** 21 Ah, 22.2 VDC LiPo batteries
- **1x** power supply protection electronics
- **8x** quarter bridge strain gauges
- **2x** single-axis IEPE accelerometers
- **2x** inductive tachometers

Challenges:

- Operating conditions: up to 17 bars
- Centrifugal forces: 750 rpm
- Horizontal axis shaft
- Impossible runner frontal access
- Autonomous power supply, continuous acquisition of signals and data storage







In-situ experimental measurements – stationary frame setup

Components:

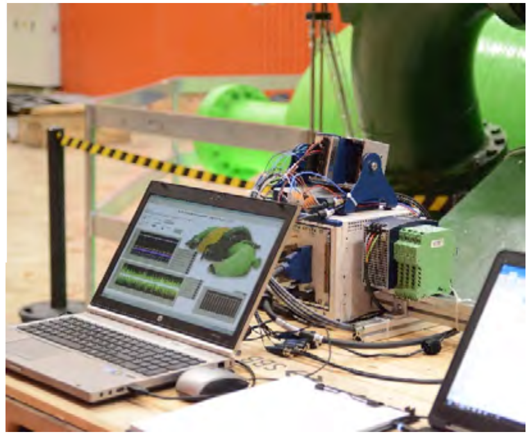
1x National Instruments PXIe-1073

- **1x** tri-axial + 1x mono-axial accelerometers (turbine)
- **2x** mono-axial accelerometers (pump)
- **1x** microphone
- **1x** optical tachometer

1x National Instruments cDAQ-9174

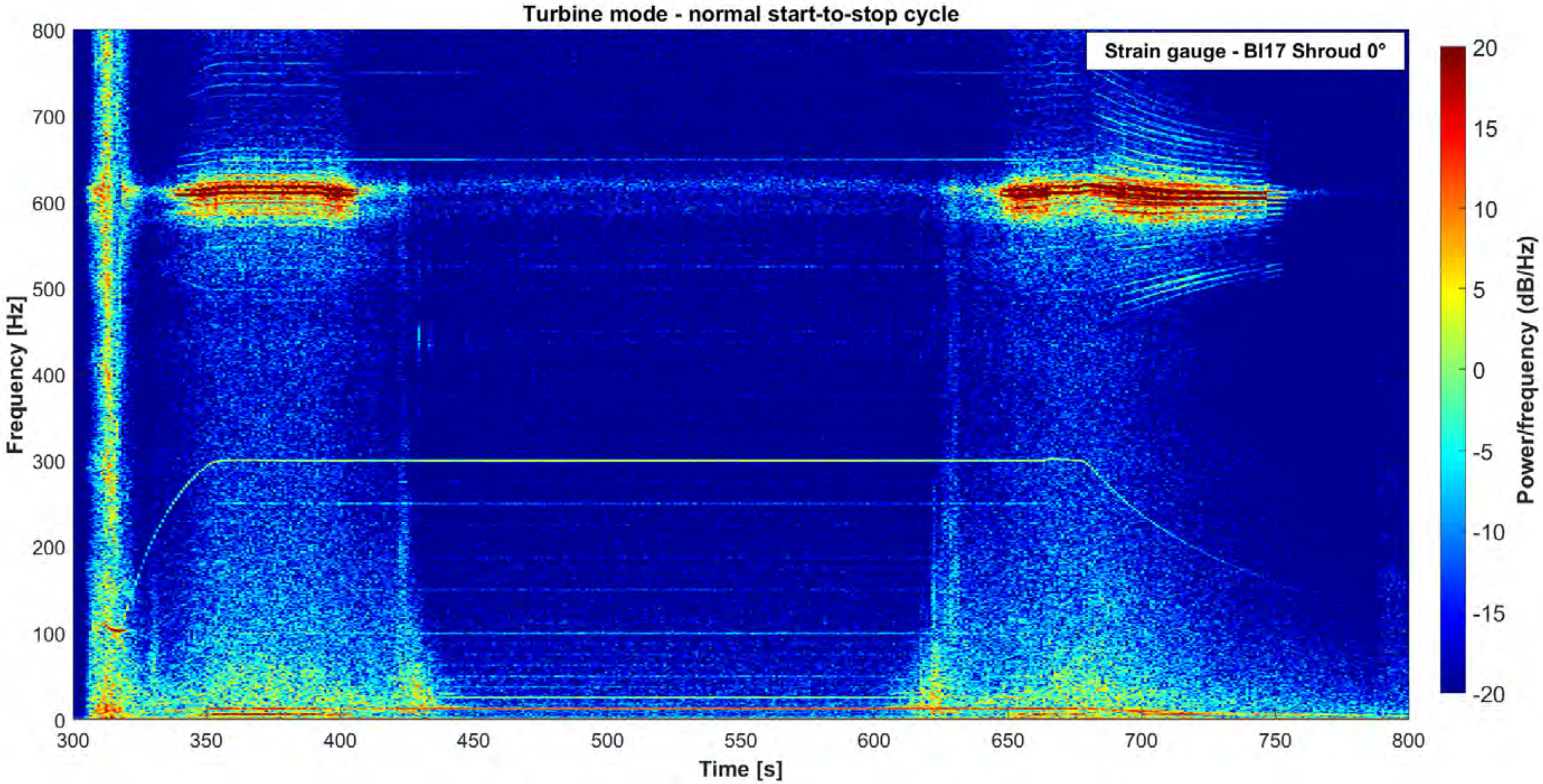
- **1x** relative pressure sensor (inlet of spiral casing)
- **1x** absolute pressure sensor (outlet of draft tube)
- **1x** absolute pressure sensor (atmospheric pressure)
- **1x** temperature sensor (water temperature)
- **1x** mono-axial inclinometer
- **1x** ultrasonic flowmeter (turbine upstream pipe)
- **2x** bearing eddy-current proxymeters

**Autonomous multichannel synchronous continuous acquisition (10 kHz)*



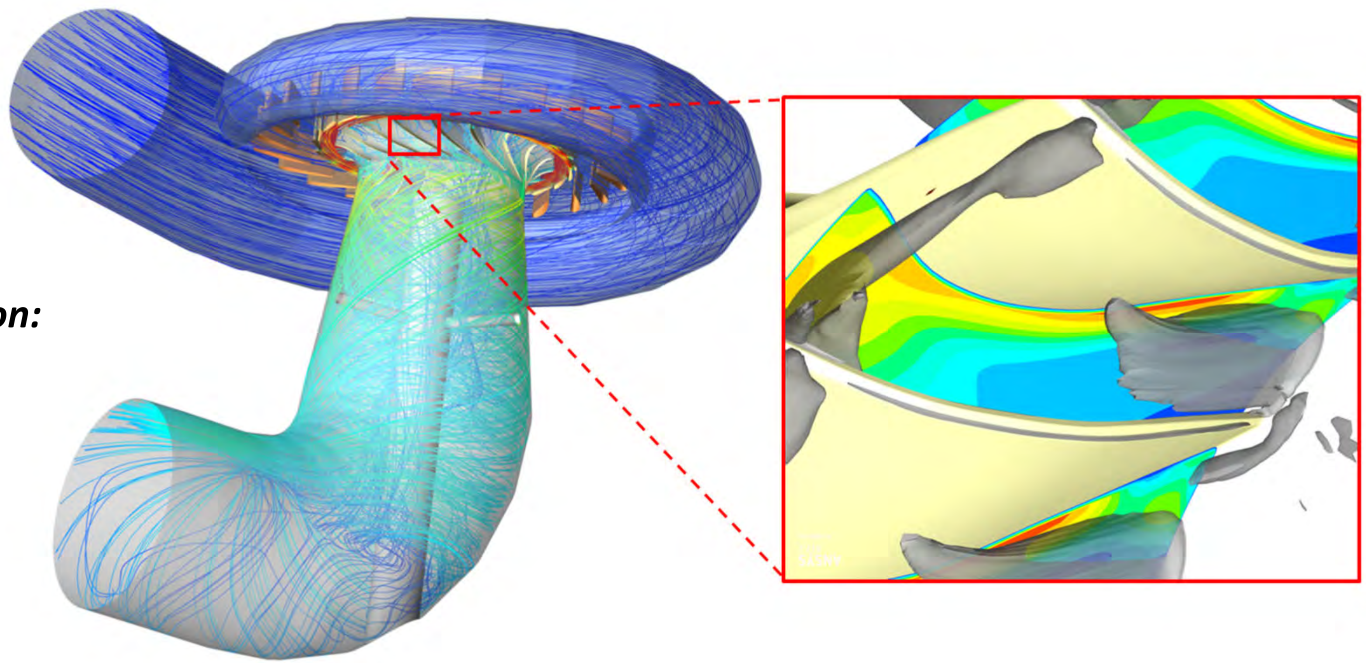
Experimental evidence of harsh excitation

- ✓ History of strain and vibration signals recorded during a full start-to-stop cycle.
- ✓ Abnormal level of structural loading evidenced at SNL condition during the start-up and shut-down procedures.

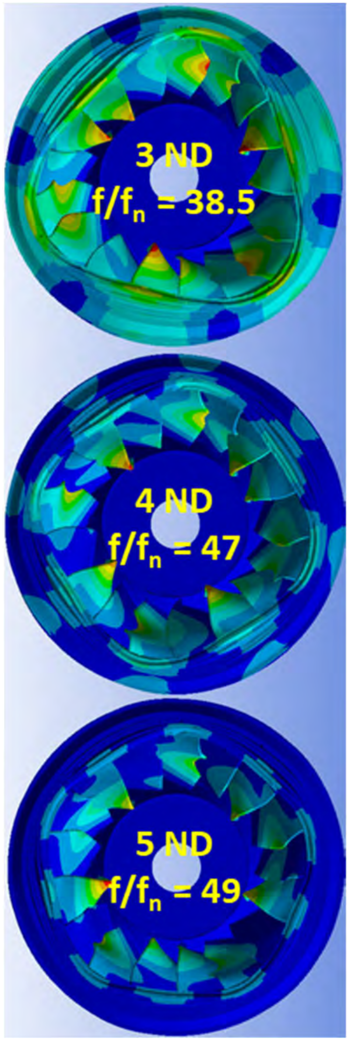


Numerical flow configuration

- ✓ The pressure contour on the runner wall as well as the Q-criterion show the presence of a large vortex at the trailing edge of the runner blades.
- ✓ Appling the theory of Tanaka for 24 guide vanes and 17 runner blades, RSI seems to be excluded. The number of nodal diameters does not match.
- ✓ The mode $f/f_n \approx 49$ is close to the frequency observed on the measurements.

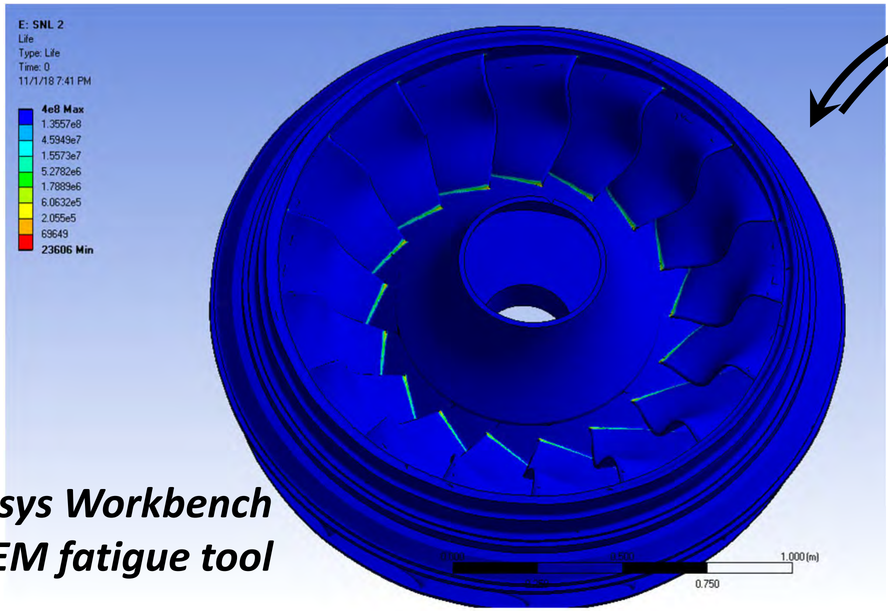


Flow field at SNL operating condition:

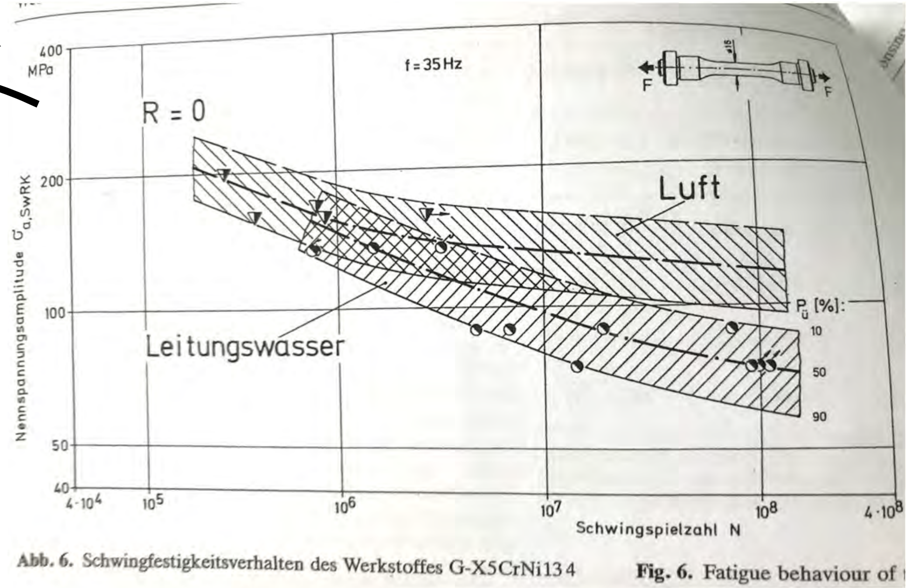


FEM fatigue investigation

- ✓ Performed using periodic sinusoidal strain fluctuations from measurements:
  - Amplitude of 50 MPa (equivalent to 250 µm/m) imposed on the runner blades at the junction with the hub
  - Equivalent stress fluctuations σ_d of 55 MPa (considering the Soderberg's criterion for an elastic limit of R_e = 550 Mpa)
- ✓ Reported in the Wholer curve of the runner's steel, cracks could be expected after 10^8 cycles
- ✓ **The lower limit of the number of cycles could be reached after approximately 1'500 starts**



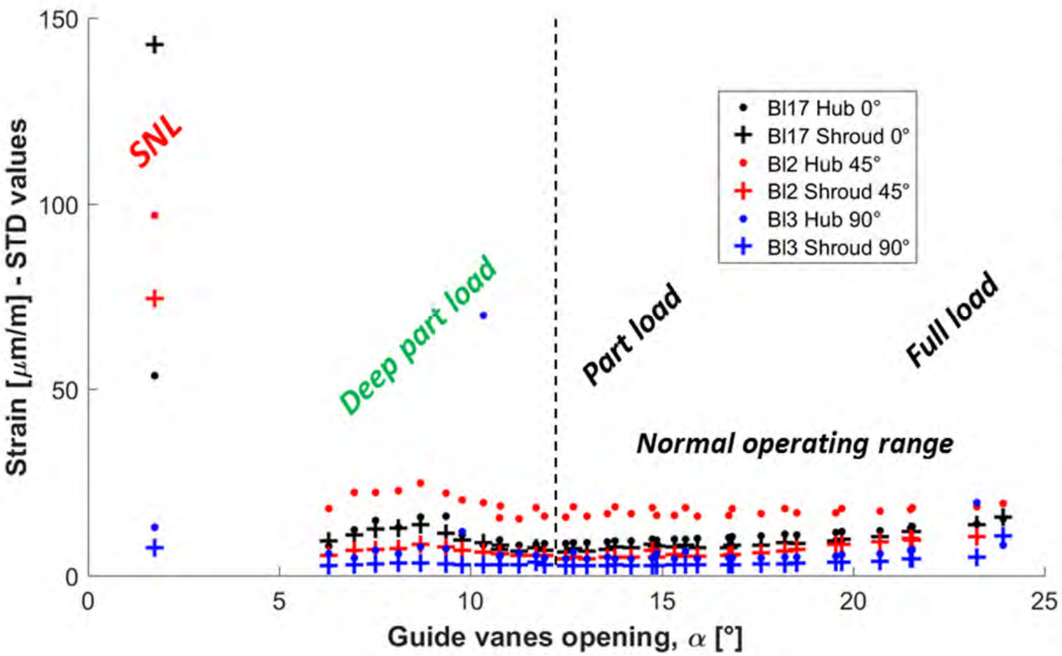
Ansys Workbench FEM fatigue tool

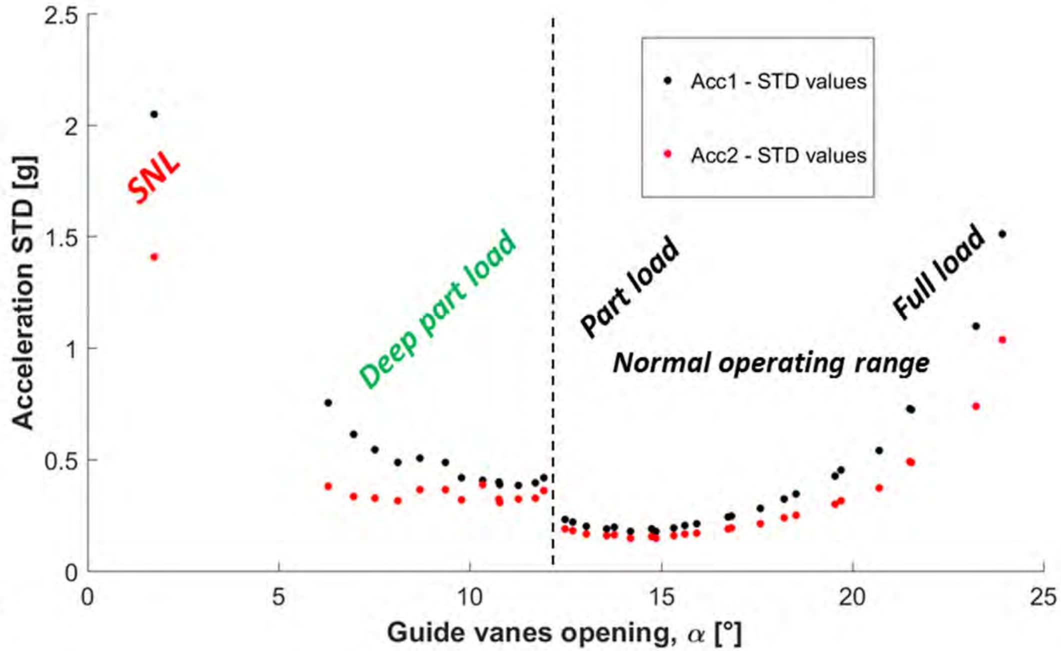


Courtesy of Sonsino C. M. & Dieterich K.,
Materials and Corrosion, 41(6), June 1990, pp. 330-342

Instability diagrams

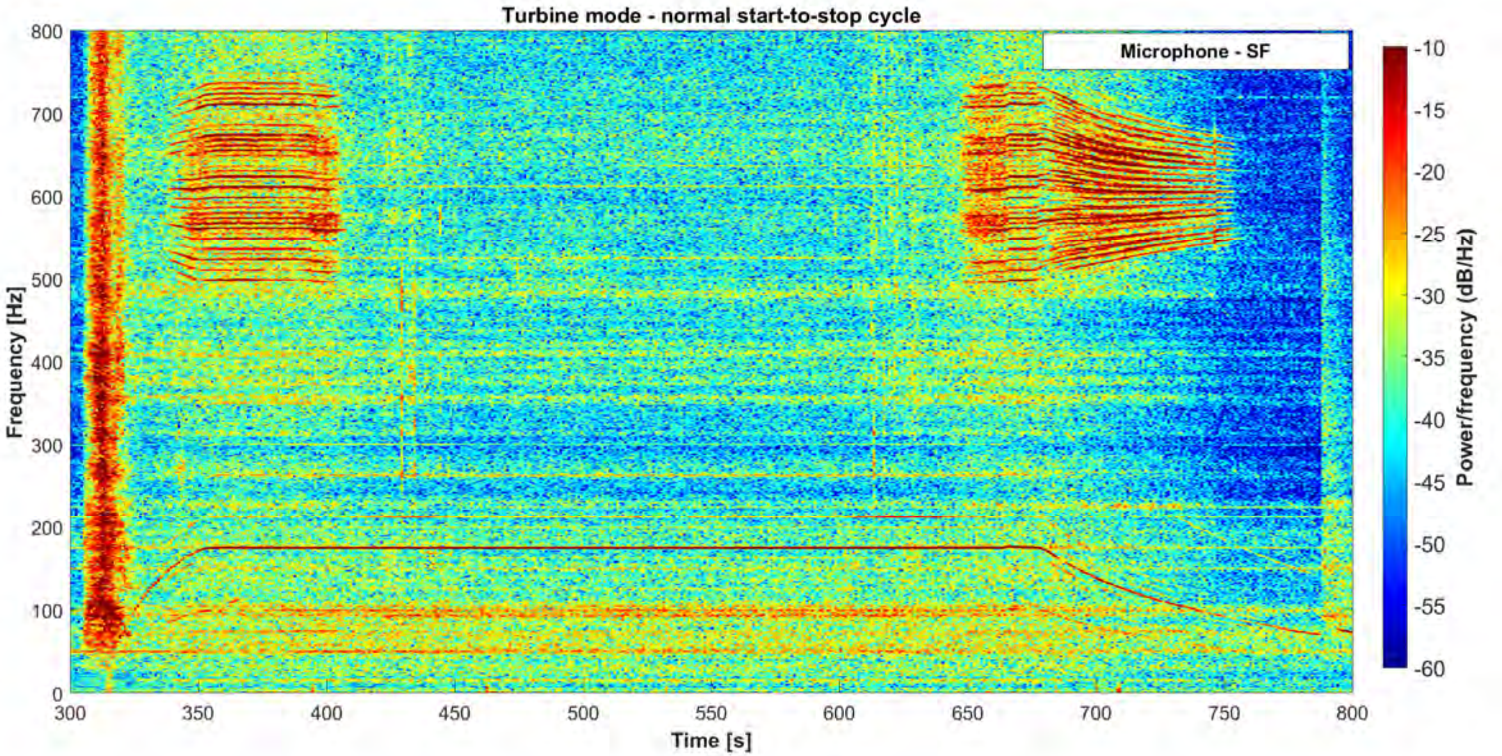
- ✓ Hydro-structural diagnosis diagram of the prototype established for the whole operating range.
- ✓ **The amplitude of blades loading fluctuations and of the vibrations is up to 6 times larger at SNL than on the full operating range.**

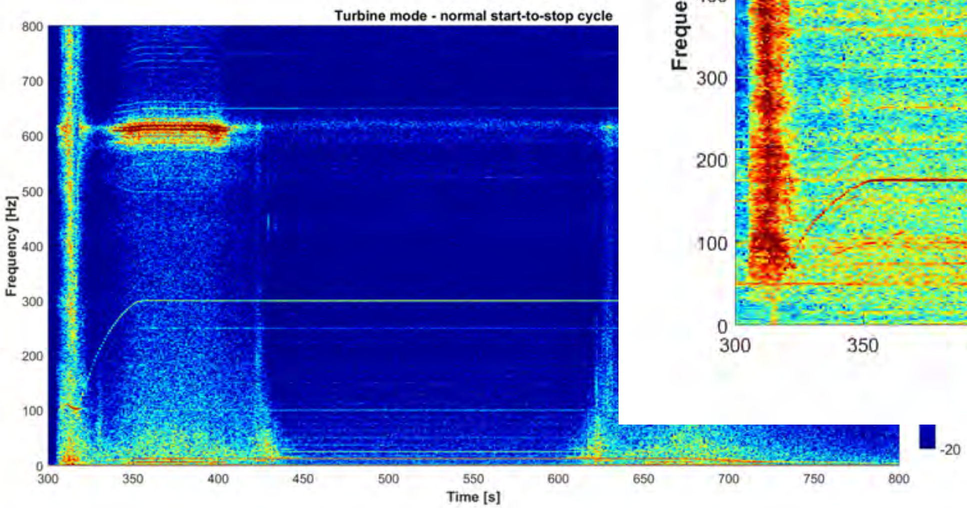




Non-intrusive detection capability

✓ **Strong strain fluctuations of the runner blades successfully detected by the non-intrusive instrumentation.**





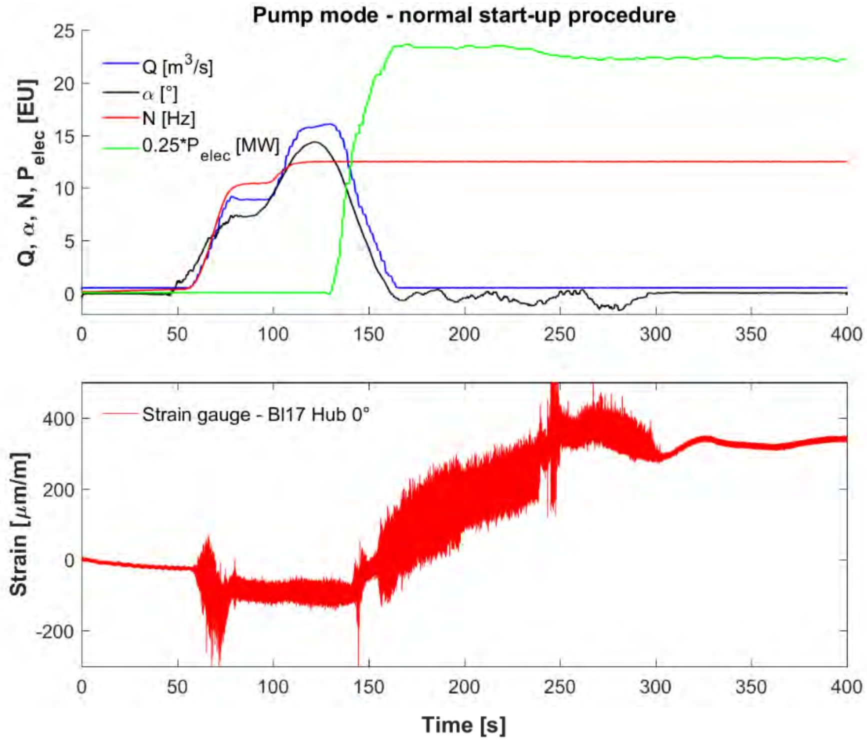
Possible technical solutions

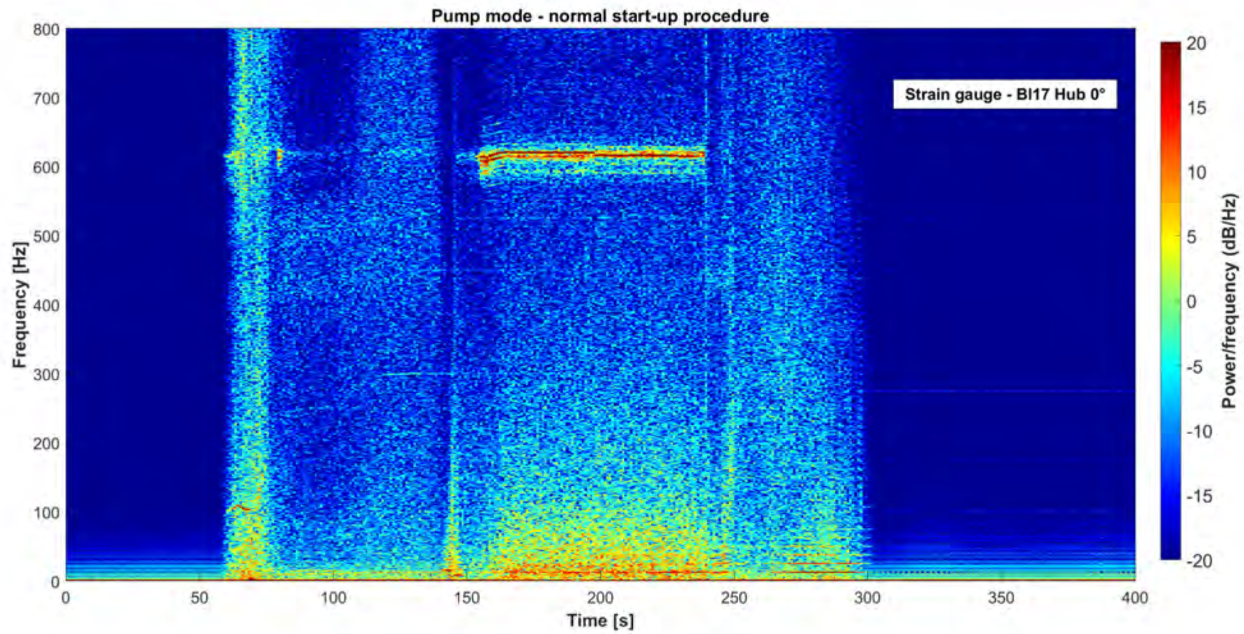
- ✓ Three alternative slower start-up procedures have been tested

  - No beneficial effect noticed since the synchronization process remains unchanged.

- ✓ Synchronization procedure during in pump mode start-up **–>** **looks safe for the turbine**

  - However, the same high structural loading is noticed during the turbine drain phase !





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Protocol of experimental diagnosis for hydropower units showing premature fatigue signs

***Note:** - The present diagram summarizes a suite of operations supposed to conduct to the identification of harsh hydro-structural operating conditions that could cause premature fatigue on hydropower units designed to work in completely different conditions than exploited today

- This statement is the results of complex investigations performed on a 100 MW Francis turbine prototype in the framework of FlexStor project

1st step

Review of the history of hydropower unit
- Incident reports
- Inspection & maintenance prescriptions
- Cumulated working hours & start-to-stop cycles
- Histogram of operating conditions
- Cross checking of data
- ...

List & analysis of possible excitation sources
- Part- and full-load vortex rope
- Cavitation
- Karman or other exciting phenomenon
- Hydrodynamic rotor-stator interaction
- Hydrodynamic rotating-stall
- External excitation sources (electrical generator, actuators, etc.)
- ...

List & analysis of possible harsh conditions
- Start-up procedure
- Shut-down procedure
- Deep part-load operating conditions
- Low setting level season operating condition
- High head season operating condition
- Sudden load rejection events
- ...

Definition of an investigation strategy
- List of numerical tools and experimental tools
- List of partial and final objectives
- Selection of a reference operating condition
- ...

2nd step

Numerical and experimental analysis
- Identification of the Eigen modes (modal analysis)
- Identification of the maximum strain regions (feed-back for the instrumentation)
- Harmonic simulations
- Structural steady / unsteady simulations
- ...

Numerical simulations
- Preliminary steady flow simulations
- Unsteady flow simulations of the potential (or identified) harsh operating points
- Feed-back of pressure/force fields to the FEM simulations and/or advanced FSI simulations
- ...

In-situ experimental measurements
- Definition of a global instrumentation architecture
- Onboard instrumentation setup (optional)
- Non-intrusive instrumentation setup: dedicated and/or derived (SCADA, exiting control systems)
- Setup of the synchronisation procedure
- Definition of a testing protocol including:
  - List of reference operating point(s)
  - List of operating conditions on the full start-to-stop cycle
  - Static and/or dynamic measurements on the full possible operating range (to be eventually repeated under several head conditions)
  - Test of the setting level influence (to be eventually repeated under several seasons)
- Measurements following the testing protocol
- Feed-back to the numerical and FEM investigations
- ...

3rd step

Detailed evaluation of results
- Validation between numerical and experimental results
- Targeted complementary analysis of numerical and experimental data
- Identification of harsh operating point(s) and behaviour (characteristic frequency, intensity, etc.)
- Identification of the possible hydrodynamic excitation source(s)
- Evaluation of the probability of excitation of each Eigen mode
- ...

Proposal of alternative solutions
- Alternative still operating conditions
- Alternative start/stop/operating procedure(s)
- Slight/consequent mechanical design change(s)
- ...

Feasibility study on the implementation
- Evaluation of testing feasibility for the new alternative solution(s)
- Evaluation of costs to implement the new alternative solutions
- Evaluation of periodical maintenance costs without any change
- Evaluation of lifetime gain under new alternative still operating conditions
- Risk analysis of eventual undesired secondary effects during testing and under permanent implementation
- ...

4th step

Tests and analysis of alternative solution(s)
- Complementary modal analysis (for design modifications)
- Complementary numerical simulations
- Additional experimental measurements using mainly non-intrusive instrumentation
- ...

Validation of alternative solution(s)
- Evidence of mitigation/reduction of the amplitude of the undesired harsh condition
- Evaluation of the new residual lifetime
- ...

Effective implementation of new solutions
- Modification of operating procedure(s) in respect to the standard protocols
- Attentive survey of the machine with a more frequent inspection time at the beginning
- ...

Road-plan for a no-go decision
- Attentive survey of the machine with more frequent inspections
- Installation of additional monitoring sensors
- Evaluation of the cumulated cycles number on the Wöhler curve of the weaken components
- Evaluation/monitoring of cracks grown (Paris law)
- Plan of periodical repairing/replacement of damaged components
- ...

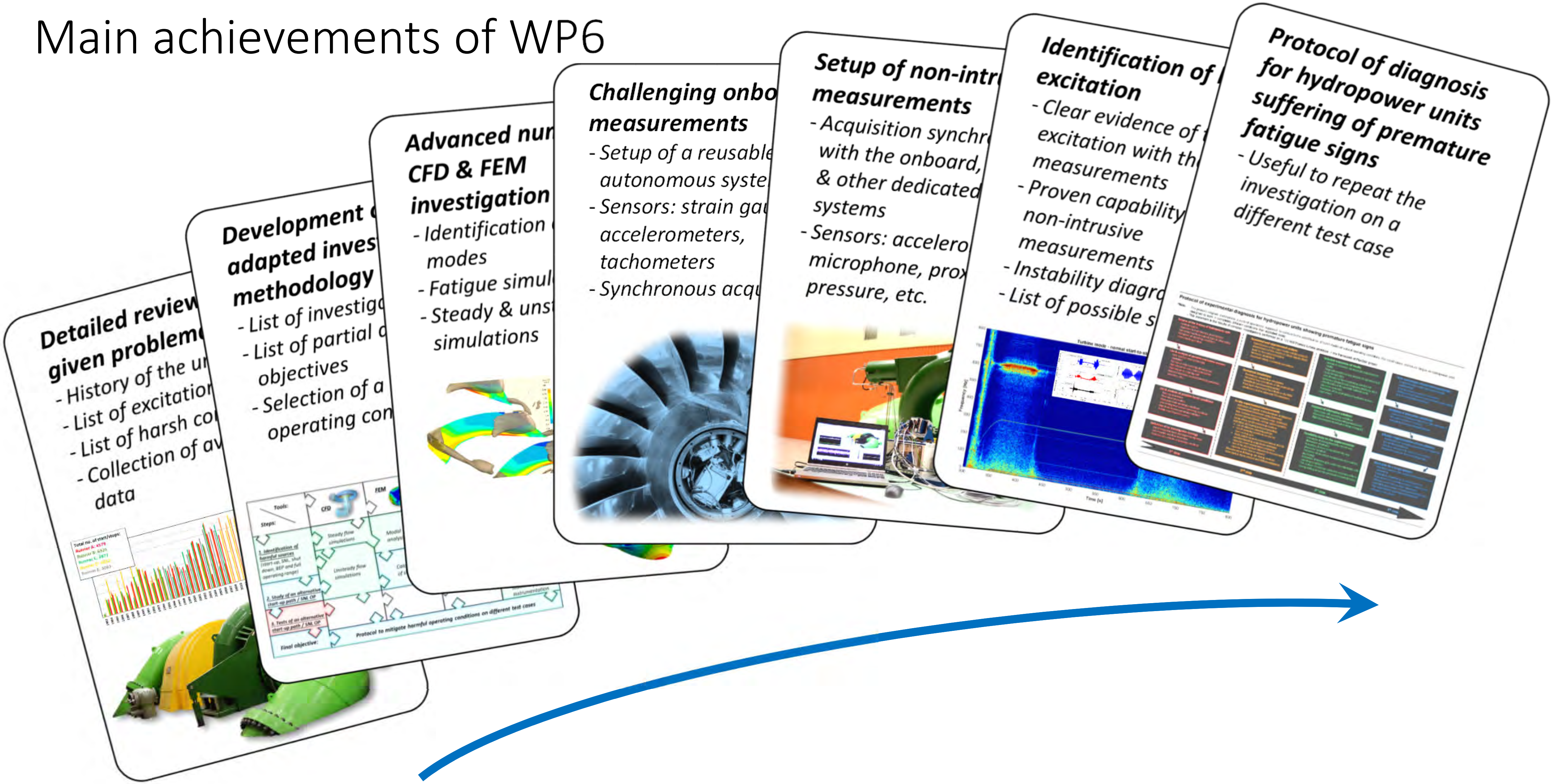
<u>FlexSTOR WP6 partners:</u> Hes·SO VALAIS WALLIS School of Engineering; KWO GRIMSELSTROM; EPFL ECOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Supported by: Schweizerische Eidgenossenschaft, Confédération suisse, Confederazione Svizzera, Confederaziun svizra, Swiss Confederation, Innosuisse – Swiss Innovation Agency

V. Hasmatuchi, J. Decaix, M. Titzschkau & C. Munch-Alligné

Sion, August 2019

Main achievements of WP6



List of publications

- ✓ V. Hasmatuchi, M. Titzschkau, J. Decaix, F. Avellan & C. Münch-Alligné, 2017, "**Challenging onboard measurements in a 100 MW high-head Francis turbine prototype**", Poster & Presentation at the SCCER-SoE Annual Conference 2017, Birmensdorf, Switzerland.
- ✓ J. Decaix, V. Hasmatuchi, M. Titzschkau, F. Avellan & C. Münch-Alligné, 2017, "**CFD investigation of a Francis turbine to help the experimental measurements and the definition of start-up procedures**", Poster at the SCCER-SoE Annual Conference 2017, Birmensdorf, Switzerland.
- ✓ V. Hasmatuchi, J. Decaix, M. Titzschkau & C. Münch-Alligné, 2018, "**A challenging puzzle to extend the runner lifetime of a 100 MW Francis turbine**", Proceedings of Hydro 2018, Gdansk, Poland.
- ✓ J. Decaix, V. Hasmatuchi, M. Titzschkau & C. Münch-Alligné, 2018, "**CFD investigation of a high head Francis turbine at speed no-load using advanced U-RANS models**", Applied Sciences, 8(12).
- ✓ J. Decaix, V. Hasmatuchi, M. Titzschkau, L. Rapillard, P. Manso, F. Avellan & C. Münch-Alligné, 2018, "**CFD and FEM investigations of a Francis turbine at speed no-load**", Poster at the SCCER-SoE Annual Conference 2018, Horw, Switzerland.
- ✓ V. Hasmatuchi, J. Decaix, M. Titzschkau, L. Rapillard, P. Manso, F. Avellan & C. Münch-Alligné, 2018, "**Detection of harsh operating conditions on a Francis prototype based on in-situ onboard and non-intrusive measurements**", Poster at the SCCER-SoE Annual Conference 2018, Horw, Switzerland.
- ✓ M. Titzschkau, V. Hasmatuchi, J. Decaix & C. Münch-Alligné, 2018, "**On-board measurements at a 100MW high-head Francis turbine**", Proceedings of Vienna Hydro 2018, Vienna, Austria.
- ✓ J. Decaix, V. Hasmatuchi, M. Titzschkau, L. Rapillard, P. Manso, F. Avellan & C. Münch-Alligné, 2019, "**Experimental and numerical investigations of a high-head pumped-storage power plant at speed no-load**", IOP Conf. Series: Earth and Environmental Science 240(8).
- ✓ M. Titzschkau, V. Hasmatuchi, J. Decaix & C. Münch-Alligné, 2019, "**On-board measurements at a 100MW high-head Francis turbine**", To appear in WasserWirtschaft 2019.
- ✓ J. Decaix, V. Hasmatuchi, M. Titzschkau, L. Rapillard. & C. Münch-Alligné, 2019, "**Hydro-structural stability investigation of a 100 MW Francis turbine based on experimental tests and numerical simulations**", To appear in IOP Conf. Series: Earth and Environmental Science.
- ✓ V. Hasmatuchi, J. Decaix, M. Titzschkau, O. Pacot & C. Münch-Alligné, 2019, "**Detection of harsh operating conditions on a Francis prototype based on in-situ non-intrusive measurements**", Prepared for Hydro 2019, Porto, Portugal.
- ✓ …

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KWO:	*M. Titzschkau*

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