PREVENTING TURBINE INSTABILITY DURING MULTIPLE START/STOP PROCEDURES

- Knowledge and Technology Transfer for Hydropower -

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Problematic and objective

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

Total no. of start/stops:
- Runner A: 4579
- Runner B: 6326
- Runner C: 4977
- Runner D: 4012
- Runner E: 3083

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 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_  
_- 4 horizontal ternary groups_
Applied strategy

1. Identification of harmful sources (start-up, SNL, shut down, BEP and full operating range)
   - CFD: Steady flow simulations

2. Study of an alternative start-up path / SNL OP
   - FEM: Modal analysis
   - RF exp.: Calculation of stresses

3. Tests of an alternative start-up path / SNL OP

Final objective: Protocol to mitigate harmful operating conditions on different test cases

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


**Motivation**

**Methods**

**Main Results**

**Contribution to FlexSTOR Toolbox**

**Main Outcome**

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**CFD & FEM numerical setup**

**CFD setup:**

*MOTIVATION | METHODS | MAIN RESULTS | CONTRIBUTION TO FLEXSTOR TOOLBOX | MAIN OUTCOME*

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-\(\omega\) turbulence model.

**Number of iterations:** 2,000

**Time step:** \( \Delta t = 0.4 \) \(^\circ\) rev/\(\Delta t\)

High order scheme for the mean flow equations.
First order scheme for the turbulent flow equations.

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*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.
- Applying 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 $\sigma_d$ 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

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!

![Graph showing Pump mode - normal start-up procedure with Q[m^3/s], α[°], N[Hz], 0.29P_{elec}[MW] vs Time [s]]

![Graph showing Strain gauge - BI17 Hub 0° with Strain [µm/m] vs Time [s]]

![Graph showing Pump mode - normal start-up procedure with Frequency [Hz] vs Time [s]]
Protocol of experimental diagnosis for hydropower units showing premature fatigue signs

*MOTIVATION*

- List & analysis of possible excitation sources
  - Part and full-load vortex rope
  - Cavitation
  - Karman or other exciting phenomenon
  - Hydrodynamic rotation-stator interaction
  - Hydraulic-elastic coupling
  - External excitation sources (electrical generator, alternators, etc.)

- List & analysis of possible harsh conditions
  - Start-up procedure
  - Steady-state procedure
  - Deep part-load operating conditions
  - Low setting level operation condition
  - High head variation condition
  - Sudden load rejection event

- Definition of an investigation strategy
  - List of numerical tools and experimental tools
  - List of partial flow phenomena
  - Selection of reference operating condition

- Numerical simulations
  - Preliminary steady-state simulations: Introduce flow simulations of the potential to identify harsh operating points
  - Post-processing of numerical simulations
  - Numerical simulations: Confirm simulations, check for discrepancies between in-situ and numerical findings

- In-situ experimental measurements
  - Definition of a global instrumentation architecture
  - On-board measurement setup (improved): Non-invasive instrumentation setup dedicated and operated (SCADA, event control systems)
  - Use of the synchronization procedure

- Definition of a testing protocol including:
  - List of reference operating points
  - List of operating conditions on the full starts
  - Basic and dynamic measurements on the full possible operating ranges
  - Test of the system and influence of the test menu

- Proposal of alternative solutions
  - Alternative start-up operating conditions
  - Alternative start-up operating procedures

- Main results
  - Validation of alternative solution(s)
  - Evidence of measurement results of the amplitude of the magnitude of harsh condition
  - Evaluation of the low-amplitude transient

- Contributing to FlexSTOR Toolbox
  - Tests and analysis of alternative solutions
    - Complementary test protocols (on design modifications)
    - Complementary numerical simulations
    - Additional experimental measurements using model
    - Representative pre-treatment

- Evidence of change in the magnitude of harsh condition

- Technical discussion
  - Effective implementation of new solutions
  - Modification of operating procedures relative to the standard protocols
  - Attitude survey of the machine with a more frequent inspection time at the beginning

- Case study
  - FlexSTOR WP6 partners:

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

Sion, August 2019

Supported by:
Main achievements of WP6

- **Development of a novel adapted investigation methodology**
  - Identification of objectives
  - List of excitation modes
  - List of partial excitation
  - List of harsh conditions
  - List of available data

- **Challenging onboard measurements**
  - Setup of a reusable robust autonomous system
  - Sensors: strain gauges, accelerometers, tachometers
  - Synchronous acquisition

- **Advanced numerical CFD & FEM investigation**
  - Setup of a reusable robust autonomous system
  - Sensors: strain gauges, accelerometers, tachometers
  - Synchronous acquisition

- **Setup of non-intrusive excitation**
  - Clear evidence of non-intrusive measurements
  - Proven capability
  - List of possible sensors

- **Identification of fatigue signs**
  - Protocol of diagnosis
  - Useful to repeat the investigation on a different test case

- **Flexible STOR Toolbox**
  - Main outcome
  - Contribution to flexible STOR toolbox
List of publications

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