Numerical investigations of the dynamics of the full load vortex rope in a Francis turbine

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Types of draft tube vortex ropes

Low Discharge: Co-rotating swirl
- Cork-screw like unstable vortex

High Discharge: Counter-Rotating Swirl
- Axisymmetric, stable vortex shape

Courtesy of EPFL
Full load draft tube surge - fundamentals

- Vortex volume depends on:
  - More discharge -> more swirl -> bigger volume
  - Lower tail water level -> lower pressure in draft tube -> bigger volume

- Self excitation mechanism via positive damping from mass flow gain factor?

\[ C = - \frac{\partial V}{\partial H_{DT}} \]
\[ \chi = - \frac{\partial V}{\partial Q} \]

Cavitation compliance
Mass flow gain factor

1D-model of power plant for system stability analysis
Focus on CFD Methods to determine vortex rope dynamics

**Previous Work**
- Steady state methods to determine basic model parameters
- 2D unsteady isolated draft tube model – assuming DT inlet profiles
  - Free oscillation – Numerical parameter studies
  - Response on external excitation – Parameter identification and stability studies

**Axisymmetric transient coupled draft tube and runner segment simulation**
- Further auto-excitation mechanism for small vortex rope
- Regular cycles with total collapse of vortex rope

**Conclusions on numerical modelling influence factors in draft tube full load surge**
- Nonlinear effects well modelled by CFD including runner

**Outlook and discussion**
Francis full-load surge mechanism – the object

Discharge coefficient $Q_{nd}$, midpoints at $n_{ED} = 0.274$

medium-head Francis turbine

CFD done in 350 mm model scale

point used for example
Basic parameters of full load vortex rope from steady state CFD
Mass flow gain and cavitation compliance under steady conditions

<table>
<thead>
<tr>
<th>Operating Point</th>
<th>OP1 -5% Q</th>
<th>OP1</th>
<th>OP1 +5% Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavity Volume Vc/D³ %</td>
<td>1-phase</td>
<td>2-phase</td>
<td>1-phase</td>
</tr>
<tr>
<td></td>
<td>2.6</td>
<td>1.7</td>
<td>6.4</td>
</tr>
<tr>
<td></td>
<td>6.5</td>
<td>13.8</td>
<td></td>
</tr>
</tbody>
</table>

Influence of discharge Q ⇒ mass flow gain \( \chi \)

Some improvement obtained by mesh refinement on runner trailing edge
Smaller vortex rope size coincides better with observations

Influence of DT pressure ⇒ compliance \( C_C \)
1DOF Free oscillator numerical experiments

\[
\begin{align*}
\dot{x} &= 0 \\
F &= k (x - x_0) \\
F &= m_1 \ddot{x} \\
Q_1 &= \text{const} \\
H_1 &= f(t) \\
Q_2 &= \frac{dV}{dt} \\
H - H_0 &= I \frac{dQ_2}{dt} + \ldots \\
\end{align*}
\]

- Typical decaying free oscillation, slightly nonlinear with high amplitudes

Frequency, damping ratio
CC: Cavitation compliance
I: Inertia of DT flow
R: Friction coefficient

5th IAHR International Workshop on Cavitation and Dynamic Problems in Hydraulic Machinery, September 2013, Lausanne
Unsteady simulations with excitation by Q1 and p2
Parameter identification from response of system
Response on chirp excitation: Fluctuation around average size

Good identification of lumped parameters

excitation
Q1(t), H2(t)

system response
V(t), Q2(t)
Obtaining model parameters from system response

- **Extended 1D-model:**
  - Vortex Volume depends on both $Q_1$ and $Q_2$
  - Vortex Volume depends on local head $H_c$, linked to inlet and outlet by simple "pipes":
    
    (I) \[ H_1 - H_c = R_1 Q_1 + I_1 \frac{dQ_1}{dt} \]
    
    (II) \[ V_c = -CC \cdot H_c - \chi \cdot (\kappa \cdot Q_1(t - t_d) + (1 - \kappa) \cdot Q_2) \]
    
    (III) \[ H_c - H_2 = R_2 Q_2 + I_2 \frac{dQ_2}{dt} \]

  - $CC$: Cavitation compliance
  - $\chi$: Mass flow gain factor
  - $\kappa$: Portion of mass flow factor acting on inlet discharge $Q_1$, $(1 - \kappa)$ on $Q_2$
  - $t_d$: Time delay between $Q_1 \rightarrow V_c$

- **Set of parameters for lumped parameter model**
  - To be used in system simulations and stability analysis
Formerly identified numerical shortcomings solved
Coupled volume fraction solution solves conservation inconsistency

Limitation to small timesteps (512 per estimated period) can be released
Free oscillation frequency slightly changed from $dt > 1 / 64 \, fn$
Coarser mesh gives only slightly higher frequency (3%)
Inlet swirl uncertainty has a much bigger influence

<table>
<thead>
<tr>
<th>Numerics</th>
<th>ts per period</th>
<th>Mesh refinement</th>
<th>Frequency</th>
<th>Ratio $\frac{\alpha_{QV}}{dV/dT : Q_{diff}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ms, CFX12.1, segregated multiphase</td>
<td>1024</td>
<td>Fine (1mm)</td>
<td>1.20 Hz</td>
<td>0.987</td>
</tr>
<tr>
<td>1 ms, CFX14.5, segregated multiphase</td>
<td>1024</td>
<td>Fine (1mm)</td>
<td>1.20 Hz</td>
<td>0.995</td>
</tr>
<tr>
<td>1 ms, CFX14.5, coupled multiphase</td>
<td>1024</td>
<td>Coarse (3mm)</td>
<td>1.24 Hz</td>
<td>1.00</td>
</tr>
<tr>
<td>4 ms, CFX14.5, coupled multiphase</td>
<td>256</td>
<td>Coarse (3mm)</td>
<td>1.24 Hz</td>
<td>0.99</td>
</tr>
<tr>
<td>8 ms, CFX14.5, coupled multiphase</td>
<td>128</td>
<td>Coarse (3mm)</td>
<td>1.235 Hz</td>
<td>0.985</td>
</tr>
<tr>
<td>16 ms, CFX14.5, coupled multiphase</td>
<td>64</td>
<td>Coarse (3mm)</td>
<td>1.22 Hz</td>
<td>0.97</td>
</tr>
<tr>
<td>32 ms, CFX14.5, coupled multiphase</td>
<td>32</td>
<td>Coarse (3mm)</td>
<td>1.16 Hz</td>
<td>0.96</td>
</tr>
</tbody>
</table>
New Measurements: Pressure at the draft tube cone

Operating condition: OP1

- Highly nonlinear behavior
  - Pressure peak indicates total collapse of DT vortex – as reported from observation
  - Cyclic phenomenon, average frequency 3.33 Hz, period 0.3 s
  - Individual peak-to-peak cycles last from 0.275 to 0.312 s (~12.5%)
Numerical investigation coupling runner and draft tube

- Coupled simulation by Chirkov et al, 2012
  - 1D acoustic model of penstock
  - 3D model of 1 WG + RN passage + Draft Tube
  - Periodic but nonlinear behaviour obtained
  - No experimental comparison

- Application to the present study case
  - No penstock model to begin with: $Q_{\text{Runner}} = \text{const}$
  - Runner channel with cylindrical velocity components
  - Angular segment: 1 Runner channel passage ($22.5^\circ$) + DT
  - Transient rotor stator interface –
    - Best conservation properties and pressure feedback
## Pressure fluctuations obtained in coupled CFD

Existence of instability mechanism regardless of Q1 fluctuation

### Boundary Condition

<table>
<thead>
<tr>
<th>Inlet</th>
<th>Cylindrical velocity components, flow angle from GV-RN simulation, Q1=const</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interface RN-DT</td>
<td>Transient Rotor-Stator</td>
</tr>
<tr>
<td>Outlet</td>
<td>Parabolic pressure profile according to swirl - Stable</td>
</tr>
<tr>
<td>Wall</td>
<td>Smooth walls, No slip</td>
</tr>
</tbody>
</table>

### CFD Setup

<table>
<thead>
<tr>
<th>Domain</th>
<th>RN: 1 channel, standard mesh (220,000 elements)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DT: axisymmetric segment (22.5°) – inner pinch cut out (2mm), (480,000 elements)</td>
</tr>
<tr>
<td>Turbulence Model</td>
<td>k-omega SST</td>
</tr>
<tr>
<td>Multiphase Model</td>
<td>Homogeneous Model</td>
</tr>
<tr>
<td>Mass Transfer Model</td>
<td>Rayleigh Plesset Cavitation model (CFX standard), Coupled multiphase solver</td>
</tr>
<tr>
<td>Time Scale Control</td>
<td>Physical Timescale, 1.125° of runner revolution</td>
</tr>
<tr>
<td>Advection Scheme</td>
<td>High Resolution</td>
</tr>
<tr>
<td>Convergence Criteria</td>
<td>Res.Max &lt;= 1E-4, 10 coefficient loops limits, mostly achieves 3e-4 ResMax</td>
</tr>
<tr>
<td>Simulation duration</td>
<td>One cycle of instability, Numerical issues after infinite pressure peak</td>
</tr>
</tbody>
</table>

### Simulation Results

- **Good agreement !**
  - Cycle well reproduced by simple setup with Q1=const
- **Possible shift by including system**
Further comparisons of measurements and simulation

Approximative Integration of vapor volume from pressure $H_c$

- Estimate $V_C$ based on pressure fluctuations measured close to rope ($H_c$)
  - Assumption: $Q_1$ fluctuations much smaller than $Q_2$ fluctuations
  - $dV_C/dt = Q_2 - Q_1 = (1+a) \, Q'_2$ with $|a| \ll 1$
  - $dQ_2/dt = (H_c - H_2 - R_2 * Q_2) / I_2$
  - Observation: «Slender, unstable rope, grows & disappears in regular cycles»

No perfect fit obtained yet, more thorough parameter fitting to follow

- Include upstream part into model
- Simplistic model consistent with Volume from CFD simulation
What is the mechanism behind it?
Influence of DT pressure fluctuations into the runner flow?

- Correlation of pressure and runner outlet swirl
  - Possible influence of cavitation on runner flow?
  - Trailing edge separation with cavitation?

- To be further investigated
Conclusions

- Parameter identification from small fluctuations around average value
  - Using decoupled approach, Velocity inlet profiles interpolated
  - Presented in 2010, some numerical improvements meanwhile
  - Good prediction of frequencies of pulsations

- CFD simulations coupling runner and draft tube reproduce cyclic collapse of rope
  - Influence of upstream impedance and compressibility to be included in future studies

- Further experimental and numerical investigations: HYPERBOLE
  - EU-Funded project focusing on integration of new renewables into the networks
  - Role of hydraulic energy to provide even more balancing power

- Thank you for listening! Time for questions!