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

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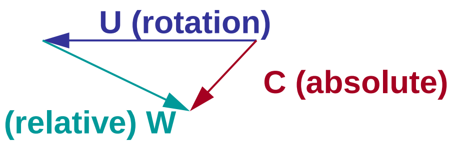
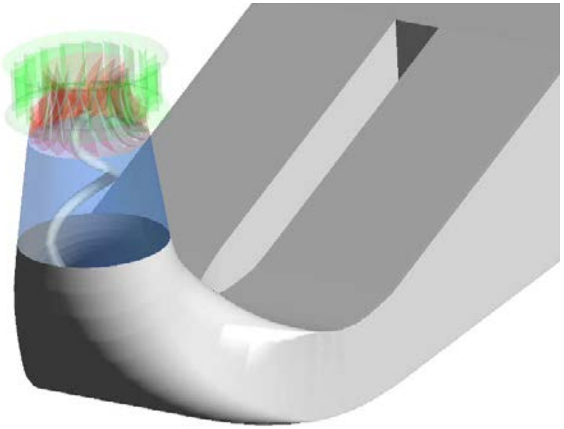
Types of draft tube vortex ropes

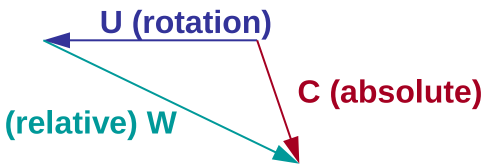
Low Discharge : Co-rotating swirl



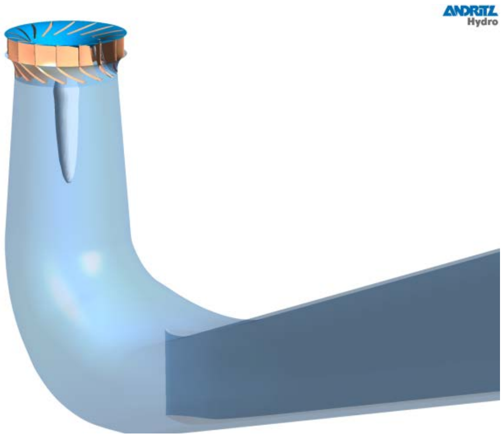
Cork-screw like unstable vortex

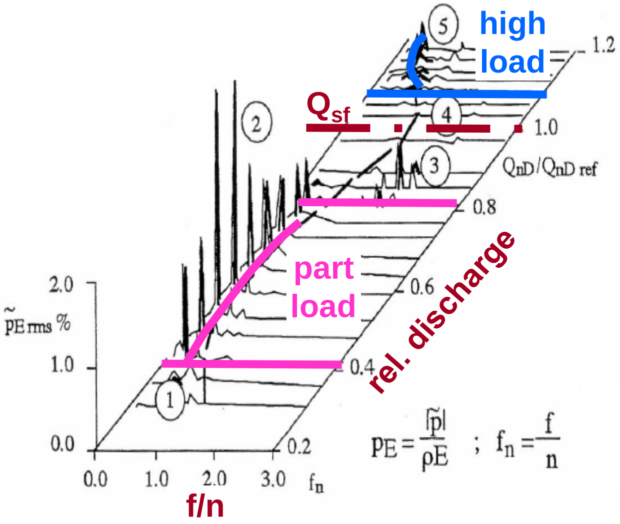


High Discharge : Counter-Rotating Swirl



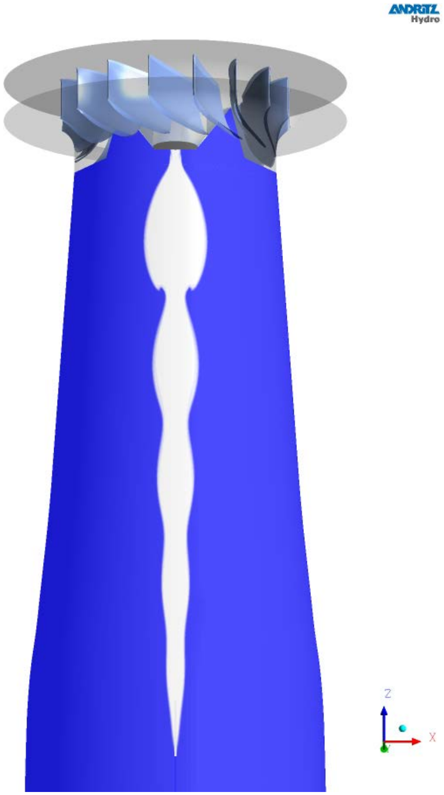
Axisymmetric, stable vortex shape



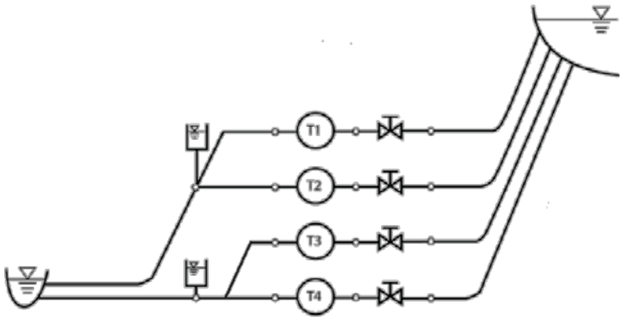


Courtesy of EPFL

Full load draft tube surge - fundamentals



$C = -\partial V/\partial H_{DT}$	**Cavitation compliance**
$\chi = -\partial V/\partial Q$	**Mass flow gain factor**



1D-model of power plant for system stability analysis

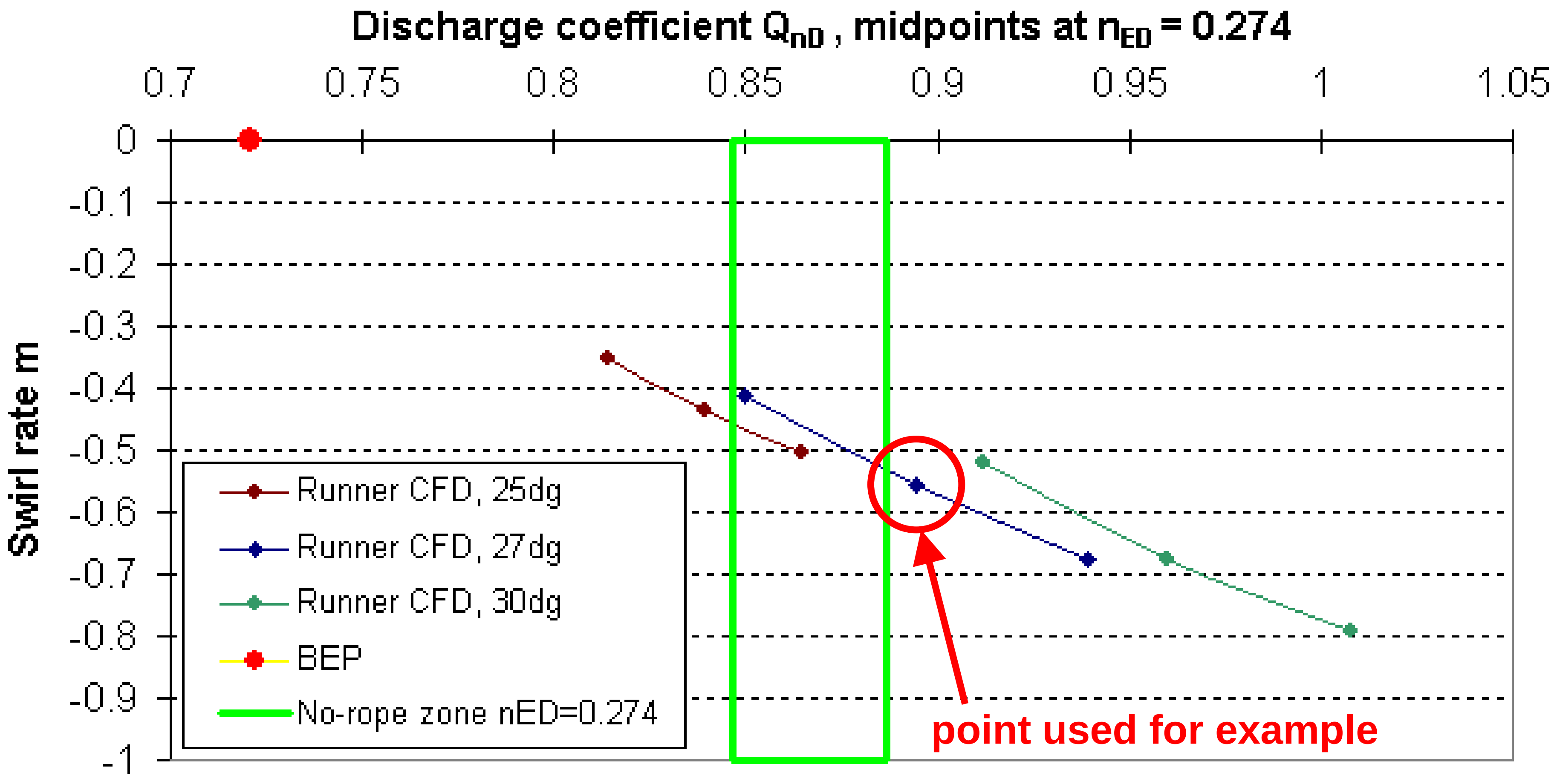
- **Vortex volume depends on:**
  - ***More discharge*** **-> more swirl ->** ***bigger volume***
  - ***Lower tail water level*** **-> lower pressure in draft tube ->** ***bigger volume***
- **Self excitation mechanism via positive damping from mass flow gain factor ?**

Outline

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

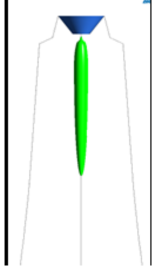
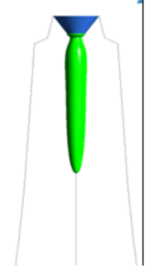
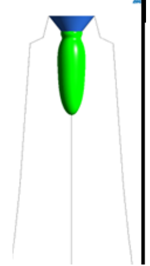
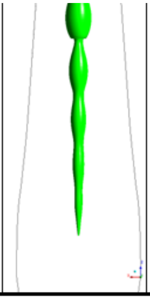
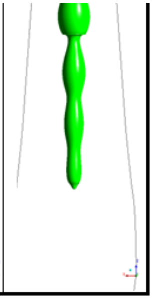


medium-head Francis turbine

CFD done in 350 mm model scale

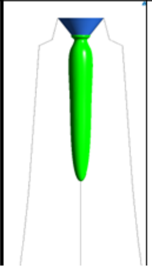
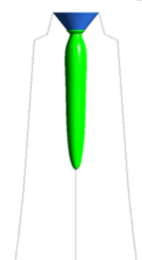
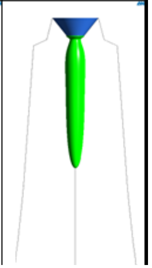
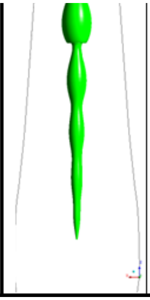
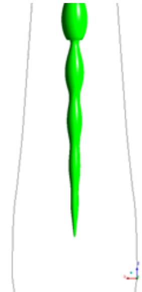
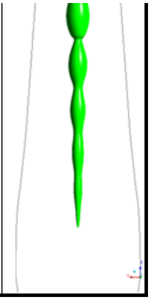
Basic parameters of full load vortex rope from steady state CFD

Mass flow gain and cavitation compliance under steady conditions

Operating Point		OP1 -5% Q	OP1	OP1 +5% Q
Cavity Volume V_C/D^3 %	1-phase	**2.6**	**6.4**	**6.5**
	2-phase	**1.7**	**6.9**	**13.8**
Picture Vortex	1-phase			
	2-phase			

influence of discharge Q

⇒ mass flow gain χ

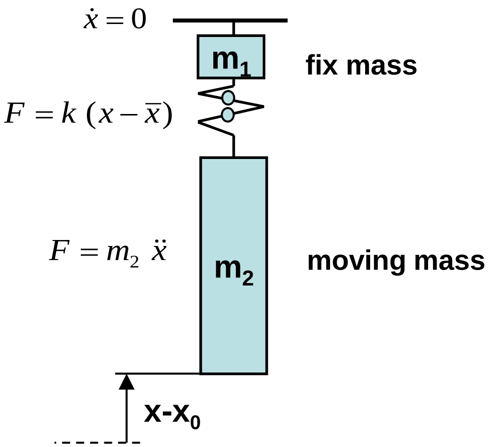
Operating Point		OP1 $\sigma\downarrow$	OP1	OP1 $\sigma\uparrow$
Cavity Volume V_C/D^3 %	1-phase	**8.1**	**6.4**	**5.3**
	2-phase	**8.4**	**6.9**	**5.7**
Picture Vortex	1-phase			
	2-phase			

influence of DT pressure

⇒ compliance C_C

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

1DOF Free oscillator numerical experiments



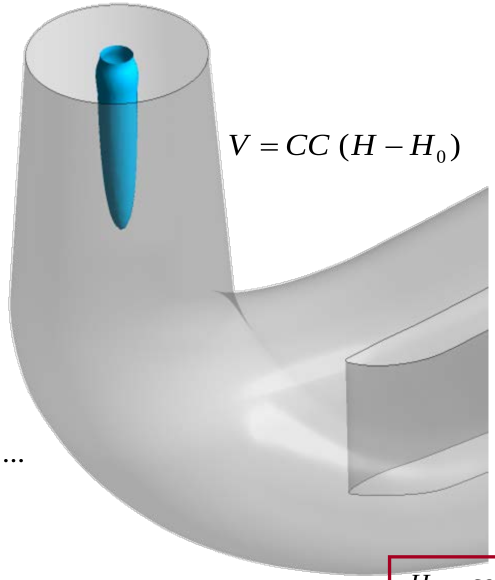
$$\dot{x} = 0$$

fix mass

$$F = k\,(x - \bar{x})$$

$$F = m_2\,\ddot{x}$$

moving mass



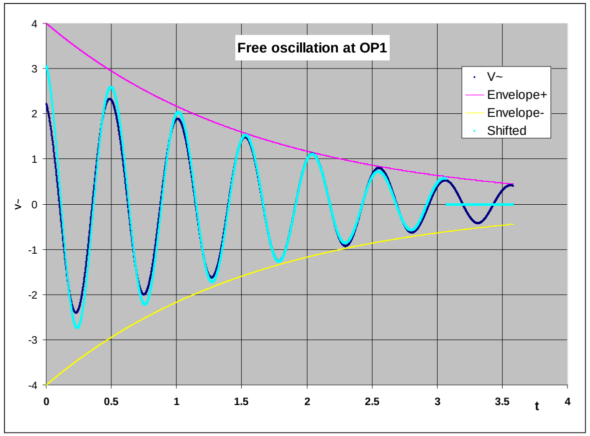
$$Q_1 = const$$
$$H_1 = f\,(t)$$

$$V = CC\,(H - H_0)$$

$$Q_2 = \frac{dV}{dt}$$

$$H - H_0 = I\,\frac{dQ_2}{dt} + \ldots$$

$$H_2 = const$$
$$Q_2 = f\,(t)$$



Free oscillation at OP1

- **Typical decaying free oscillation, slightly nonlinear with high amplitudes**

Frequency, damping ratio

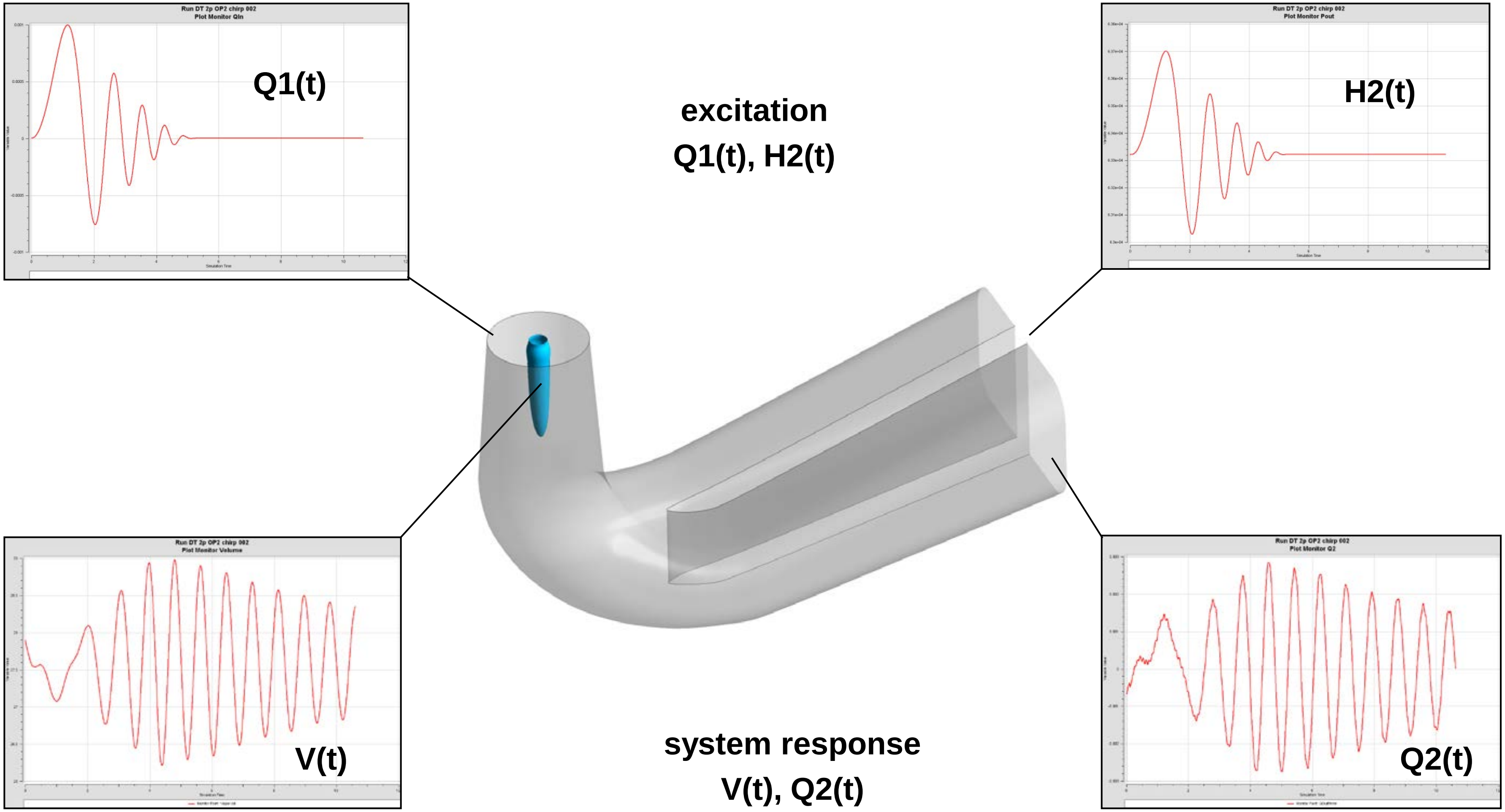
CC: Cavitation compliance

I: Inertia of DT flow

R: Friction coefficient

Unsteady simulations with excitation by Q1 and p2

Parameter identification from response of system



excitation
Q1(t), H2(t)

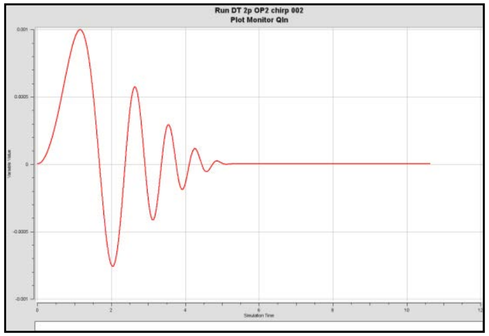
system response
V(t), Q2(t)

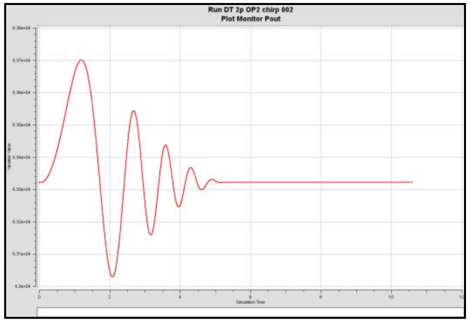
Response on chirp excitation: Fluctuation around average size

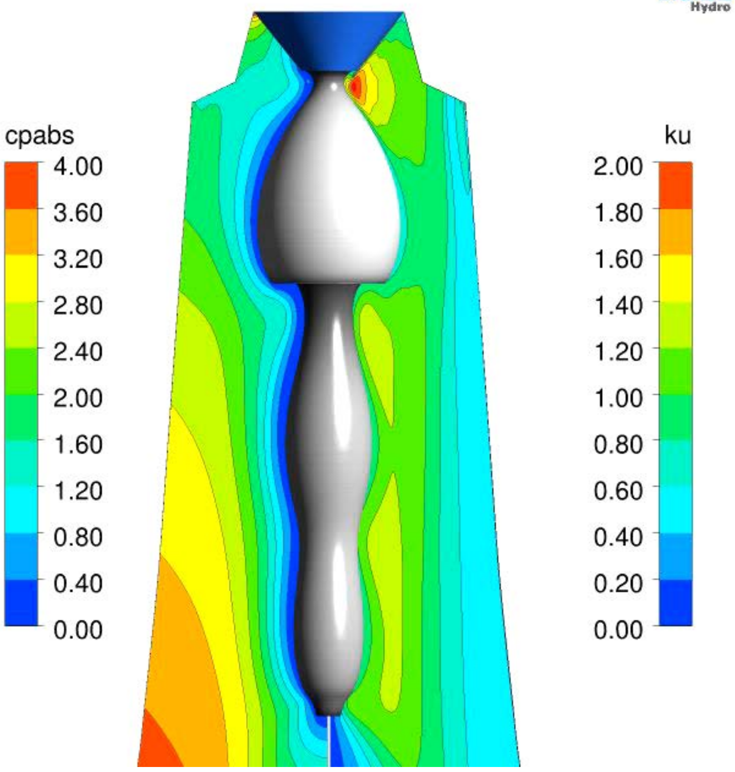
Good identification of lumped parameters

excitation

Q1(t), H2(t)

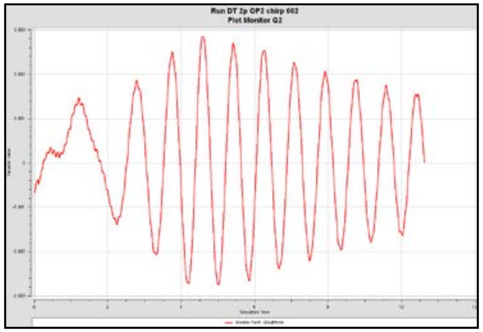


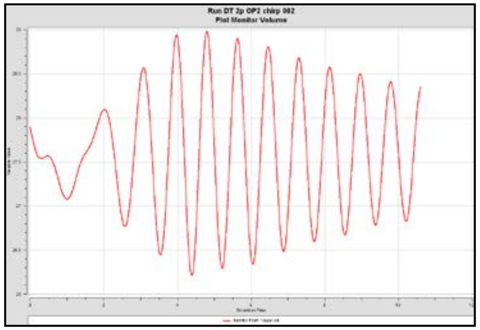




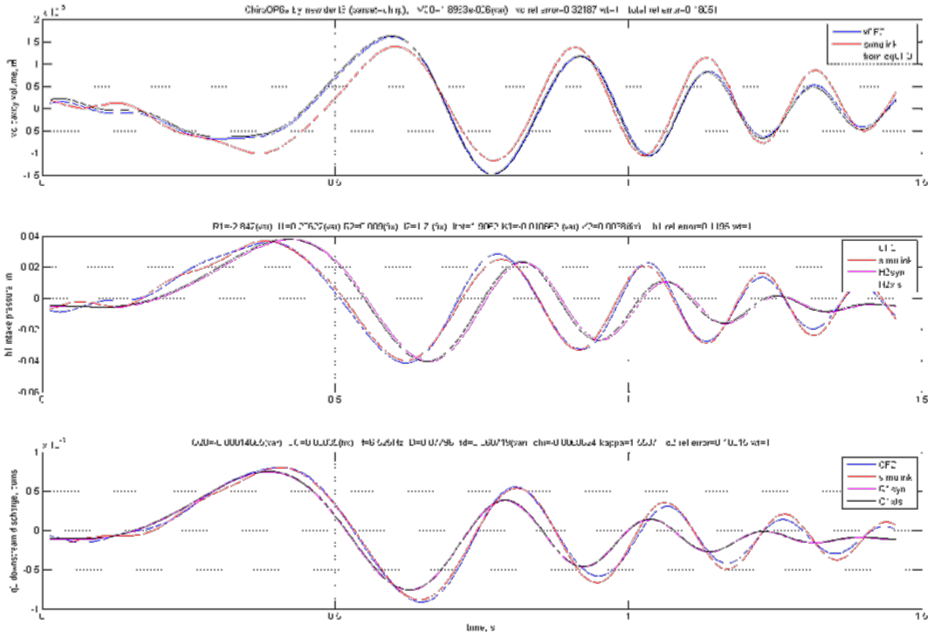
system response

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 Hc, linked to inlet and outlet by simple "pipes":**

(I) $H_1 - Hc = R1^* Q_1 + I_1^* dQ_1/dt$

(II) $V_c = - CC \cdot H_c - \chi \cdot (\kappa \cdot Q_1(t-t_d) + (1-\kappa) \cdot Q_2)$

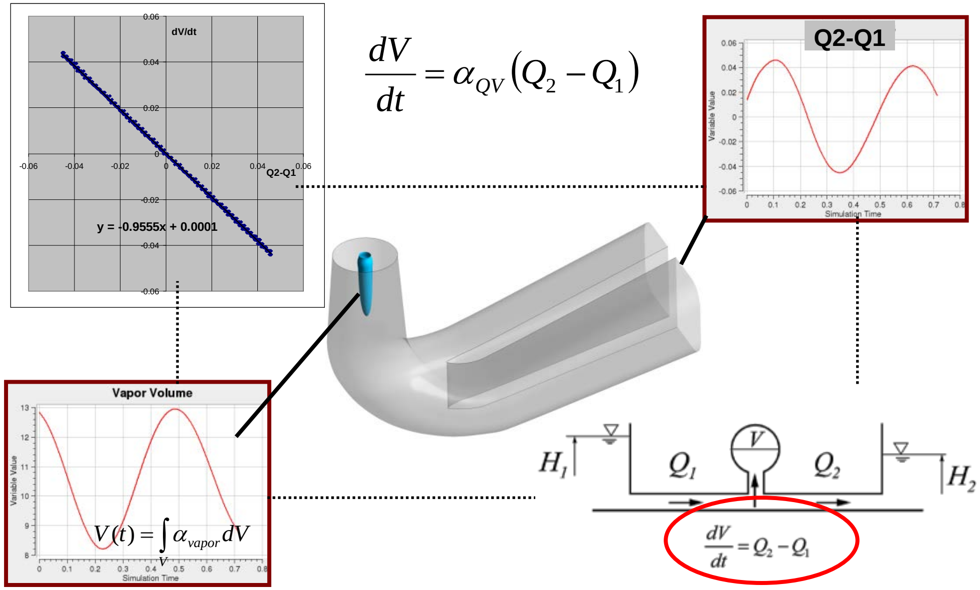
(III) $H_c - H_2 = R_2^* Q_2 + I_2^* dQ_2/dt$

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

- **Set of parameters for lumped parameter model**
  - **To be used in system simulations and stablity analysis**

Formerly identified numerical shortcomings solved

Coupled volume fraction solution solves conservation inconsistency



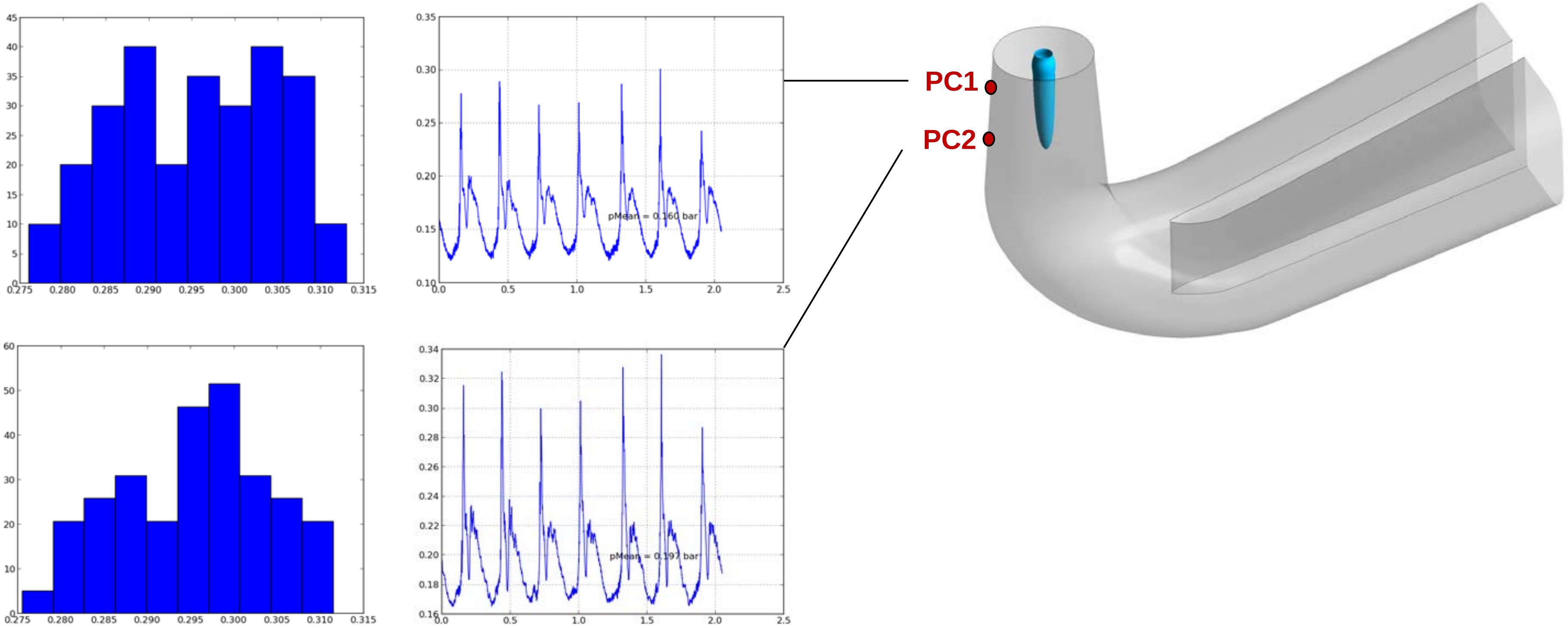
$$\frac{dV}{dt}=\alpha_{QV}\left(Q_2-Q_1\right)$$

- **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**

Numerics	ts per period	Mesh refinement	Frequency	Ratio α_{QV} dV/dT : Q_{diff}
1 ms, CFX12.1, segregated multiphase	**1024**	Fine (1mm)	1.20 Hz	0.987
1 ms, CFX14.5, segregated multiphase	**1024**	Fine (1mm)	1.20 Hz	0.995
1 ms, CFX14.5, coupled multiphase	1024	Coarse (3mm)	1.24 Hz	1.00
4 ms, CFX14.5, coupled multiphase	256	Coarse (3mm)	1.24 Hz,	0.99
8 ms, CFX14.5, coupled multiphase	**128**	**Coarse (3mm)**	**1.235 Hz**	**0.985**
16 ms, CFX14.5, coupled multiphase	**64**	Coarse (3mm)	1.22 Hz	0.97
32 ms, CFX14.5, coupled multiphase	**32**	Coarse (3mm)	1.16 Hz	0.96

New Measurements :Pressure at the draft tube cone

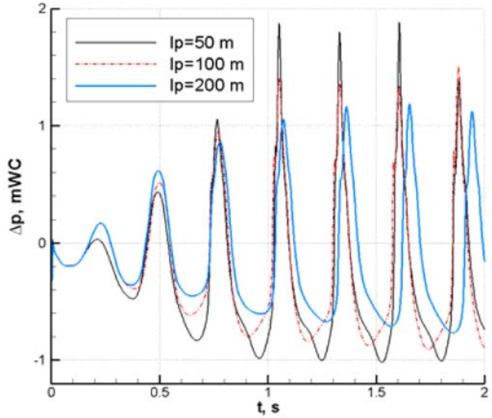
Operating condition: OP1



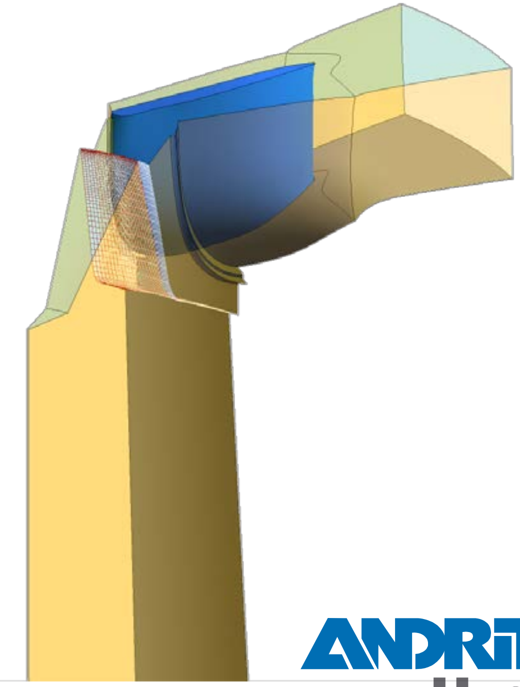
- Highly nonlinear behavior
  - Pressure peak indicates total collapse of DT vortex – as reported from observation
  - Cyclic phenomenon, average frequency 3.33 Hz, period 0.3 s
  - Individual peak-to peak cycles last from 0.275 to 0.312 s (~12.5%)

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



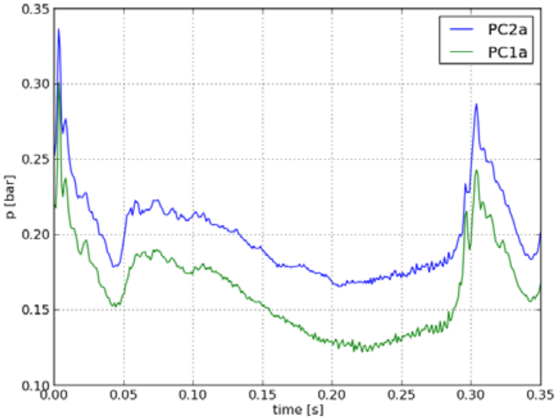
- Application to the present study case
  - No penstock model to begin with: Q_{Runner} = const
  - Runner channel with cylindrical velocity components
  - Angular segment: 1 Runner channel passage (22.5°) + DT
  - Transient rotor stator interface –
    - Best conservation properties and pressure feedback

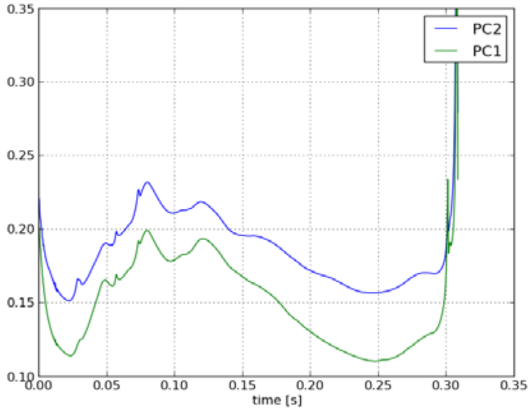


Pressure fluctuations obtained in coupled CFD

Existence of instability mechanism regardless of Q1 fluctuation

Boundary Condition	Inlet	Cylindrical velocity components, flow angle from GV-RN simulation, Q1=const
	Interface RN-DT	Transient Rotor-Stator
	Outlet	Parabolic pressure profile according to swirl - Stable
	Wall	Smooth walls, No slip
CFD Setup	Domain	RN: 1 channel, standard mesh (220.000 elements) DT: axisymmetric segment (22.5°) – inner pinch cut out (2mm), (480.000 elements)
	Turbulence Model	k-omega SST
	Multiphase Model	Homogeneous Model
	Mass Transfer Model	Rayleigh Plesset Cavitation model (CFX standard), Coupled multiphase solver
	Time Scale Control	Physical Timescale, 1.125° of runner revolution
	Advection Scheme	High Resolution
	Convergence Criteria	Res.Max <= 1E-4, 10 coefficient loops limites, mostly achieves 3e-4 ResMax
	Simulation duration	One cycle of instability, Numerical issues after infinite pressure peak



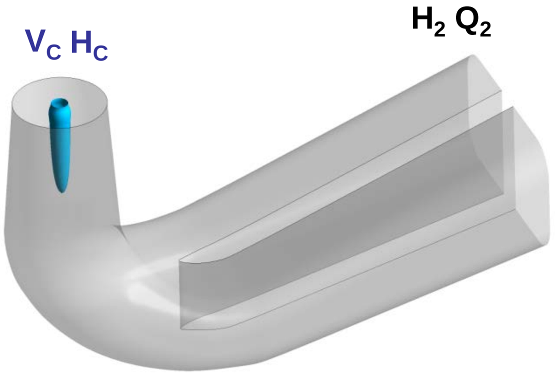


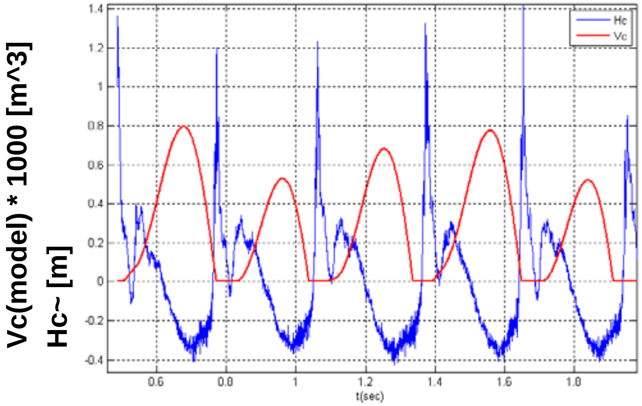
- **Good agreement !**
  - **Cycle well reproduced by simple setup with Q1=const**
- **Possible shift by including system**

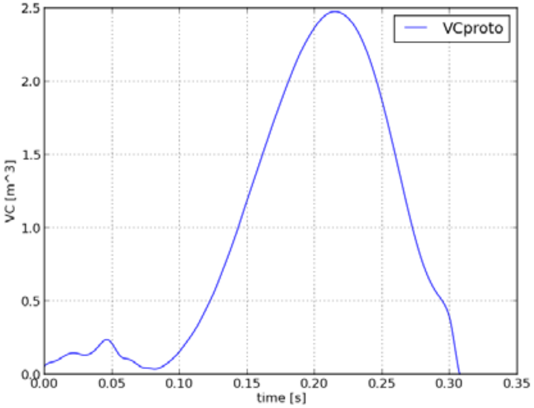
Further comparisons of measurements and simulation

Approximative Integration of vapor volume from pressure Hc

- Estimate V_C based on pressure fluctuations measured close to rope (H_C)
  - Assumption: Q_1 fluctuations much smaller than Q_2 fluctuations
  - $dV_C/dt = Q2 – Q1 = (1+a)\ Q'_2$ with $|a| << 1$
  - $dQ_2/dt = (H_c – H_2 - R_2 * Q_2) / l_2$
  - Observation: «Slender, unstable rope, grows & disappears in regular cycles»



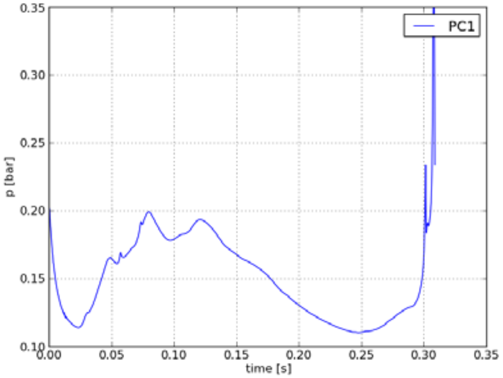




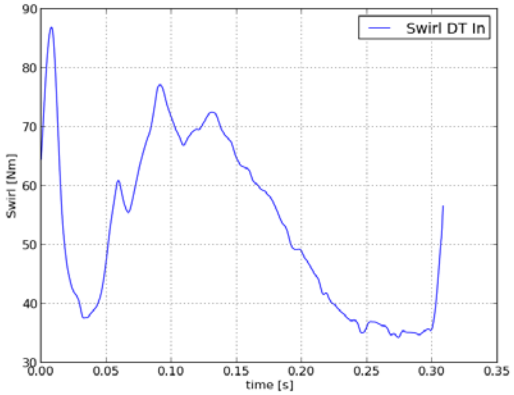
- No perfect fit obtained yet, more thorough parameter fitting to follow
  - Include upstream part into model
  - Simplistic model consistent with Volume from CFD simulation

What is the mechanism behind it ?

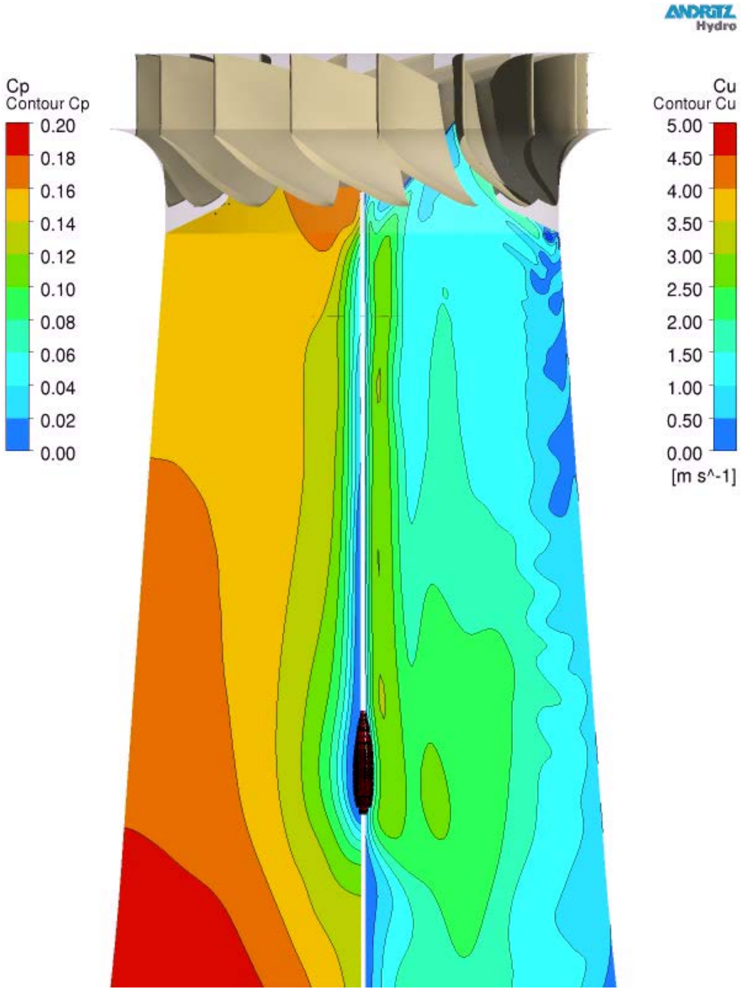
Influence of DT pressure fluctuations into the runner flow ?



Pressure at cone level



Swirl at DT Inlet



- **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 focussing 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 !**