FMI co-simulation 1D-3D SIMSEN-CFX

Sébastien ALLIGNE, Nathan VEUTHEY, Antoine BÉGUIN, Nicolas RUCHONNET, Christophe NICOLET
Power Vision Engineering Sàrl
Rue des Jordils 40
CH-1025 St-Sulpice
Switzerland

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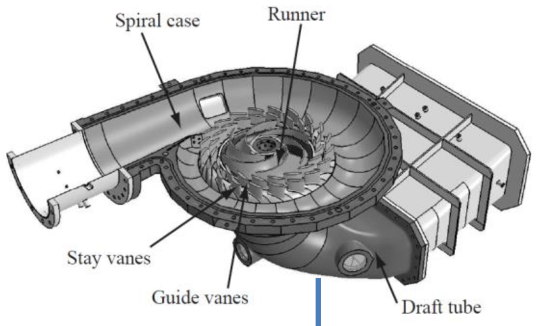
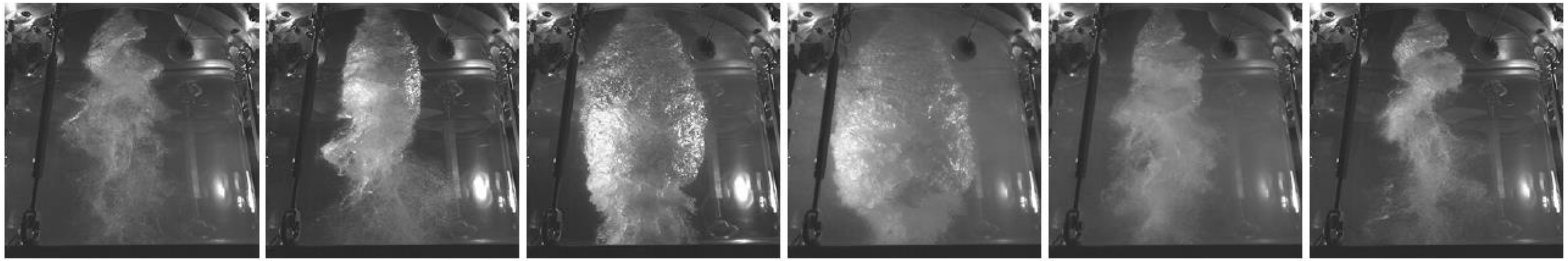
Co-Simulation 1D-3D

- Interest :
  - ✓ Hydraulic systems may experience excitation caused by complex flow patterns within various components of the system
    ➔ Characterization of the excitation source by 3D simulations
    ➔ System response with 1D compressible model
  - ✓ Co-simulation of interest if strong interaction exists between excitation source and hydraulic system response in case of resonance or instability phenomena
    ➔ excitation source modified by the hydraulic system response





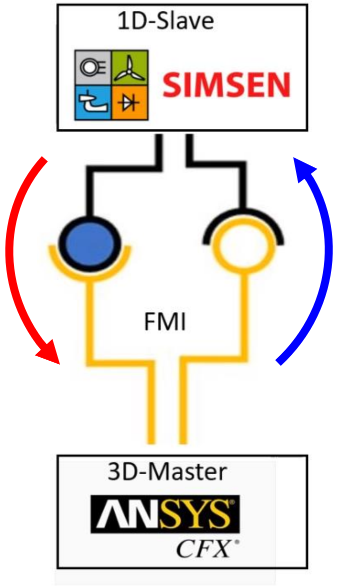
PhD EPFL 5117, Alligné, 2011

Unsteady cavitating swirling flow in Francis turbine draft tube

Numerical Tools and Setup

- SIMSEN :
  - ✓ 1D differential equations of momentum and continuity for compressible fluid in pipes
  - ✓ Transient scheme is Runge-Kutta 4th order
    ➔ Explicit scheme

- CFX :
  - ✓ Reynolds Averaged Navier Stokes Equations
  - ✓ Fluid compressibility defined by barotropic law
  - ✓ Homogeneous ZGB cavitation model with heat transfer model as isothermal
  - ✓ SST turbulence model
  - ✓ Transient scheme is second backward Euler
    ➔ Implicit scheme with maximum of 10 internal coefficient loops

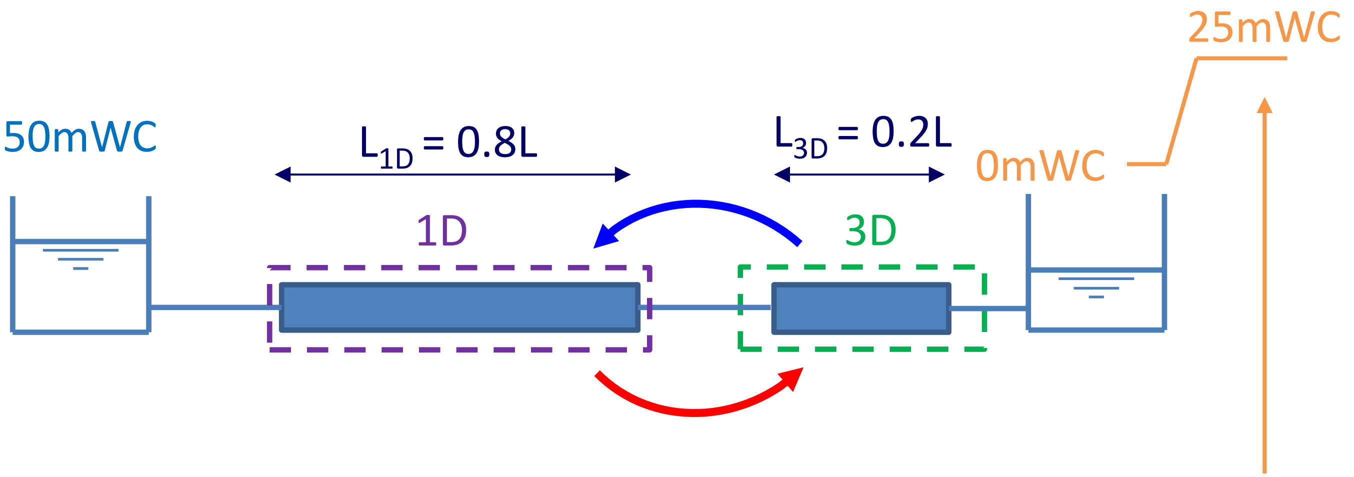


- ANSYS-CFX can run co-simulations (from 2021R2) using Functional Mock-up Interface (FMI) technology

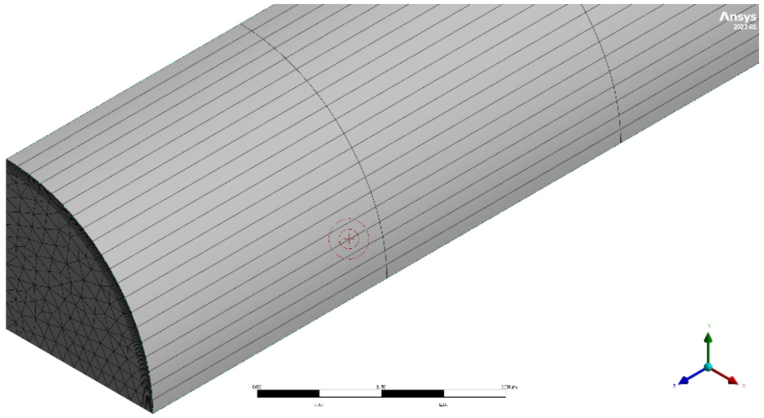
Water Hammer Case Study

- Pipe characteristics:
  - ✓ $L = 480m$, $D = 0.5m$, $\lambda = 0.089$
  - ✓ 2 parts: 1D and 3D
  - ✓ 3 wave speed combinations:
    - #1: $a_{1D} = a_{3D} = 1'444$ m/s
    - #2: $a_{1D} = a_{3D} = 150$ m/s
    - #3: $a_{1D} = 1'444$ m/s & $a_{3D} = 150$ m/s
- Co-simulation:
  - ✓ Between 1D pipe and 3D pipe & perturbation in the 3D domain
  - ✓ Time step simulation: $dt_{\#1} = 0.0015s$, $dt_{\#2} = 0.015s$ and $dt_{\#3} = 0.003$ s
  - ✓ No subcycling ➔ exchanged data at each time step
  - ✓ 1D model :
    - $L_{1D} = 0.8L = 383m$
    - Nb = 79 ➔ dx = 4.85m
    - $CFL_{\#1} = 0.446$, $CFL_{\#2} = 0.464$, $CFL_{\#3} = 0.969$
  - ✓ 3D model :
    - $L_{3D} = 0.2L = 97m$
    - dx = 0.4m
    - $CFL_{\#1} = 5.411$, $CFL_{\#2} = 5.625$, $CFL_{\#3} = 1.125$

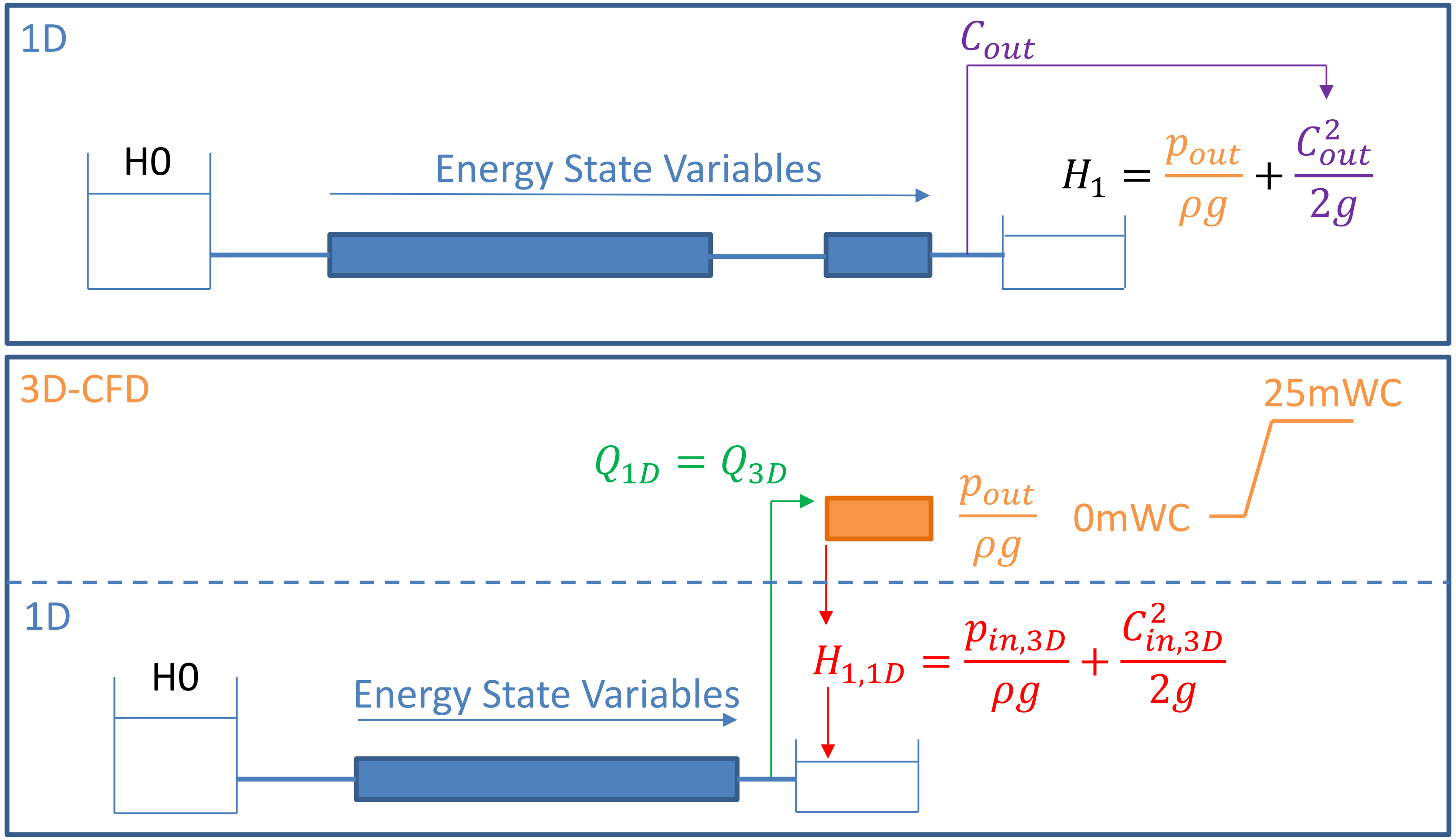
$$CFL = \frac{a \cdot \Delta t}{\Delta x}$$



Perturbation: static pressure elevation at the outlet of the 3D domain



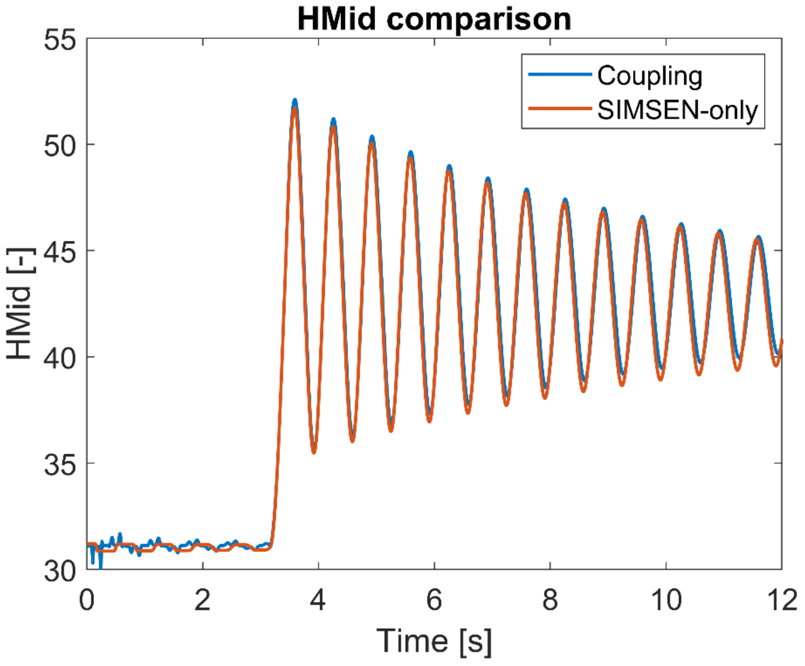
Exchanged Data



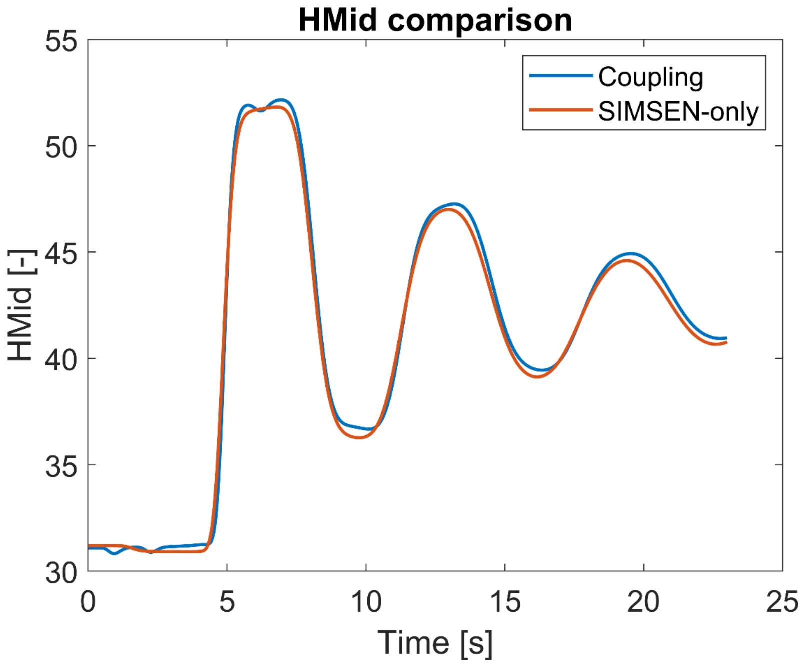
Validation of co-simulation

- Comparison with the reference 1D SIMSEN simulation
  ➔ Pressure fluctuations in the middle of the pipe, i.e. in 1D domain

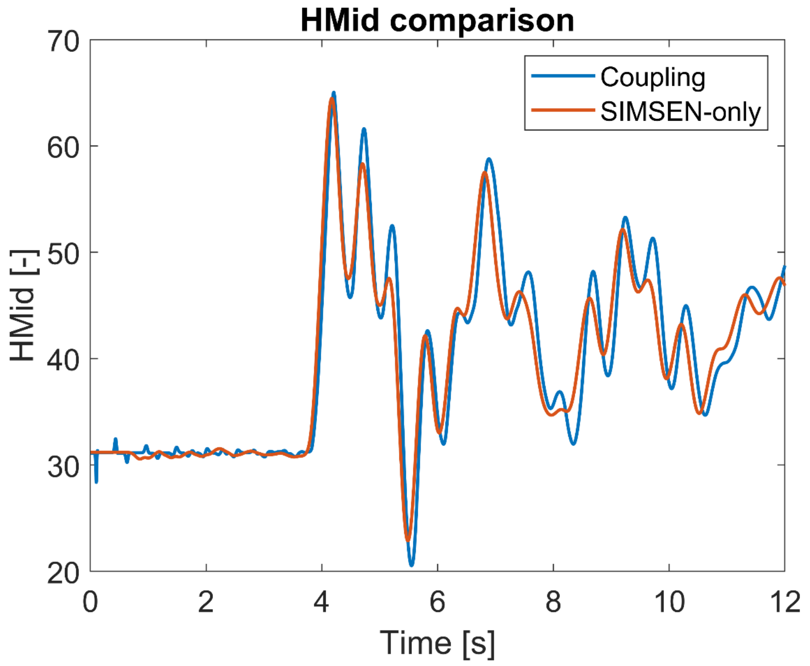
#1 : $a_{1D} = a_{3D} = 1'444$ m/s



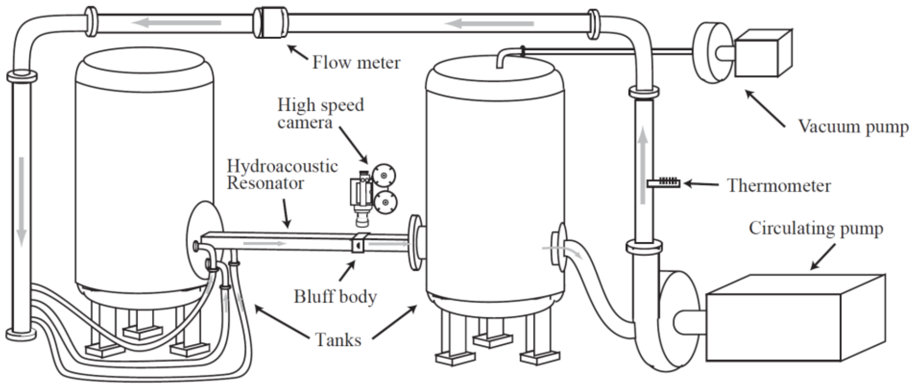
#2 : $a_{1D} = a_{3D} = 150$ m/s

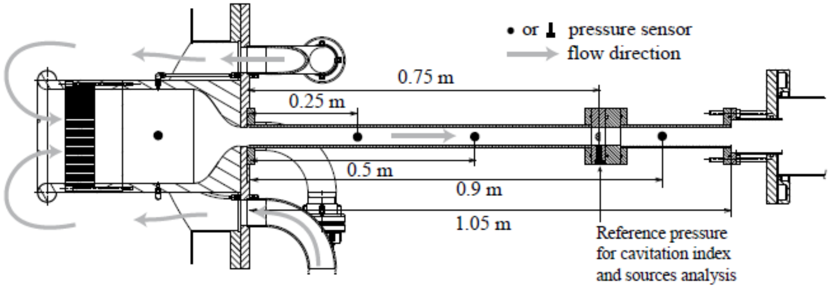


#3 : $a_{1D} = 1'444$ m/s & $a_{3D} = 150$ m/s



Vortex Shedding Resonance Case Study





Parameter	Symbol	Unit	Value
Pipe length	L	m	1.05
Pipe width	W	mm	40
Hydraulic diameter	D_h	mm	40
Wall thickness	e	mm	2
Position of bluff body	x_{bb}/L	-	0.75
Diameter of bluff body	D	mm	20
Cavitation free natural frequency	f_n	Hz	96.5
Measured cavitation incipience	σ_i	-	9
Reynolds number at pipe inlet	Re	-	60'000
Wave speed	a	m/s	202.65

- Resonance in square pipe due to von Karman vortex shedding
  - ✓ Cavitating condition or not with setup of vacuum pump
  - ✓ In non-cavitating condition resonance occurs with 1st pipe's eigenmode
  - ✓ In cavitating condition, resonance occurs with 2nd pipe's eigenmode

- Test case setup by Ruchonnet N. at EPFL (PhD N°4778 - 2010) to validate coupled simulation without FMI protocol

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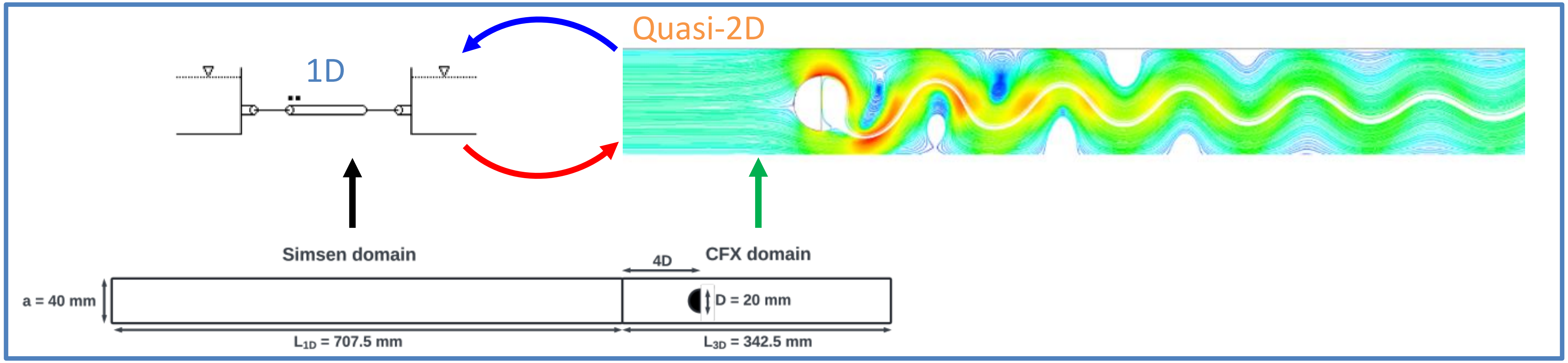
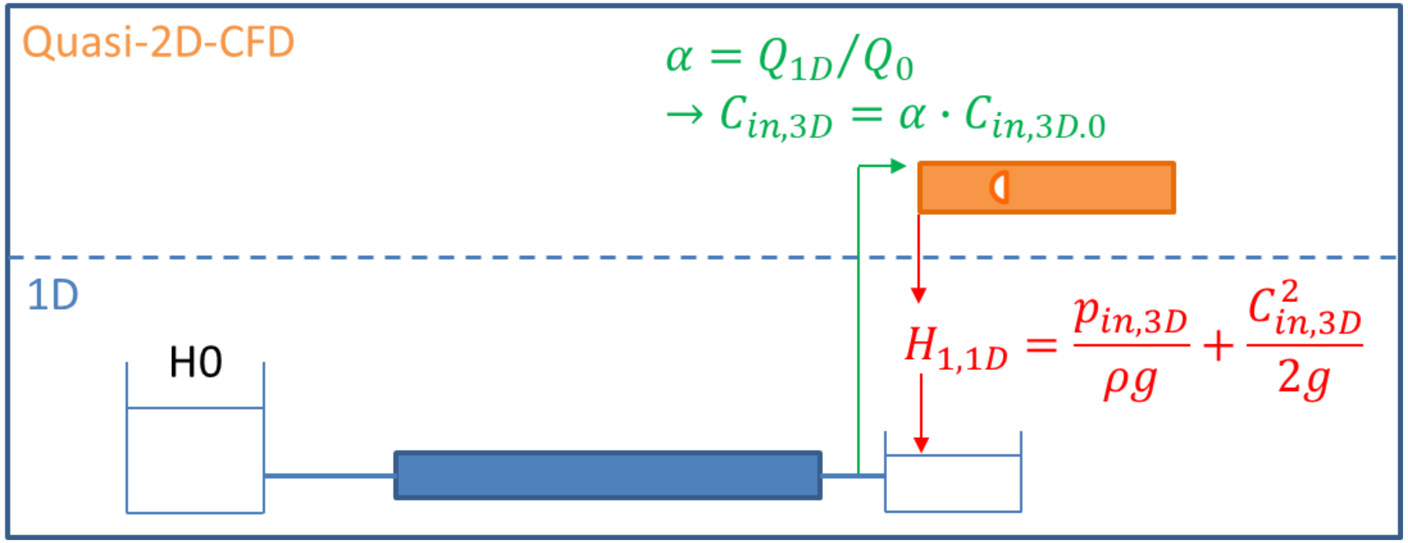
Domains and Exchanged Data

Numerical domains



Exchanged data



Co-simulations Operating Conditions

- 4 co-simulations performed:
  - ✓ Non-cavitating and out of resonance condition
  - ✓ Non-cavitating and resonance condition
  - ✓ Cavitating and out of resonance condition
  - ✓ Cavitating and resonance condition
- Targeted resonance with :
  - ✓ 1st eigenmode in non-cavitating condition
  - ✓ 2nd eigenmode in cavitating condition which frequency is decreased due to cavitation

Variable	Unit	Out of resonance (1)	In resonance (2)
C	m/s	3	2.54
f_s/f_n	-	1.18	0.99
St	-	0.38	0.38
σ_{corr}/σ_i	-	1.96	1.40

Variable	Experimentally expected Found numerically as Unit	Out of resonance Near resonance (3)	In resonance Out of resonance (4)
C	m/s	3	3.27
f_s/f_n	-	1.34	1.59
St	-	0.43	0.47
σ_{corr}/σ_i	-	0.84	0.78

$$St = \frac{f \cdot D}{C} \qquad \sigma = \frac{p - p_v}{\frac{1}{2}\rho C^2}$$

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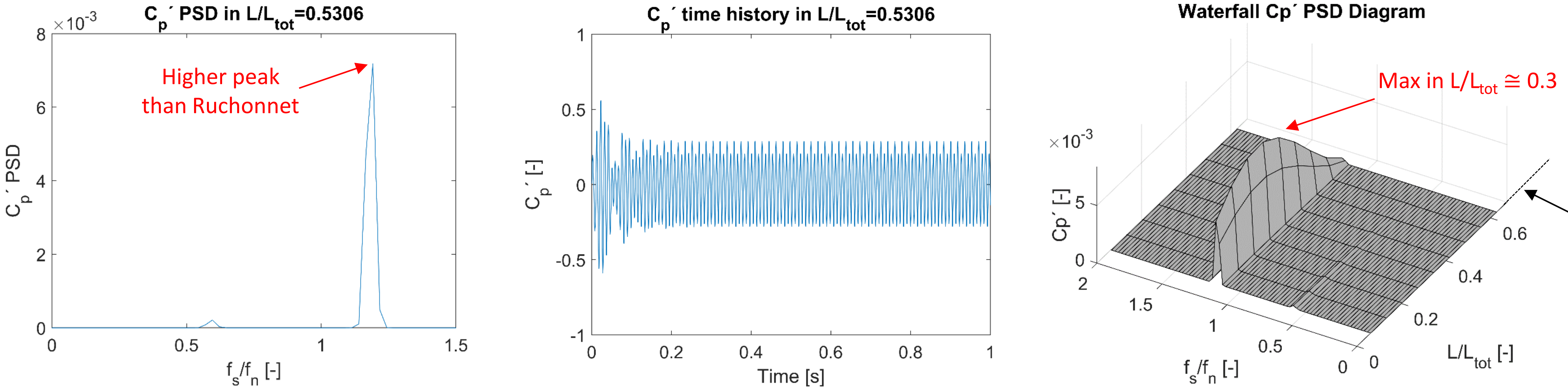
Non-cavitating and out of resonance conditions

1

Pressure coefficient fluctuations c_p' at $L=L_{TOT} = 0.5$

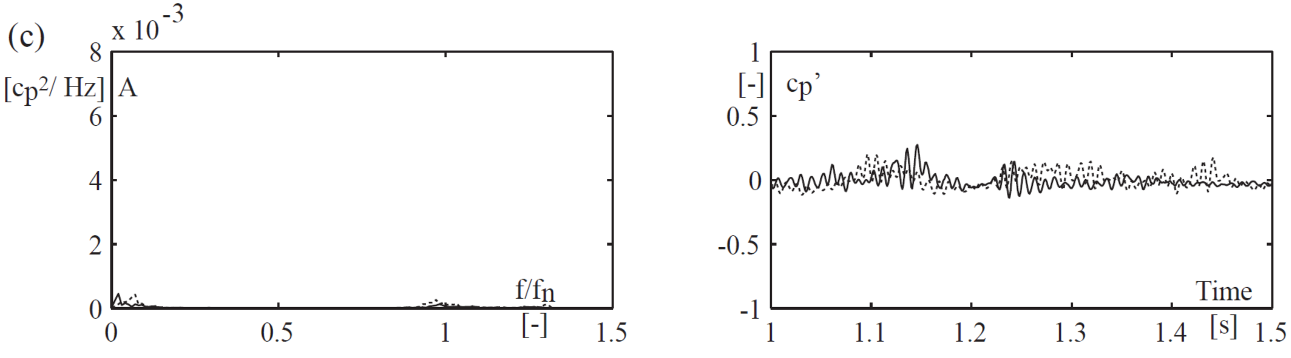
Power spectrum density (PSD), time history and waterfall diagram

Co-simulation

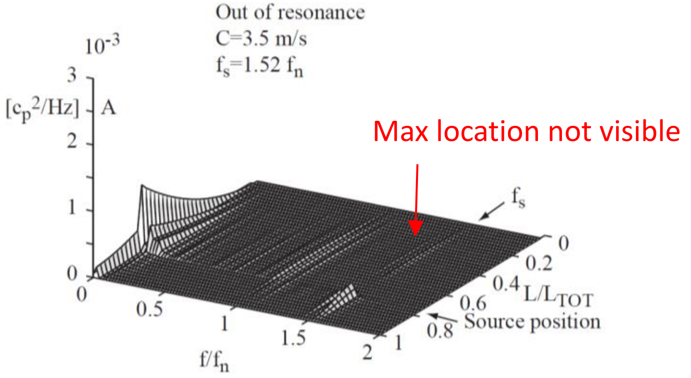


Coupled simulation
$f_s/f_n = 1.18$
C = 3 m/s
$\sigma_{corr} / \sigma_i = 1.95$

PhD co-simulation



Out of resonance
fs/fn=1.27
C=3 m/s
One way
Two way



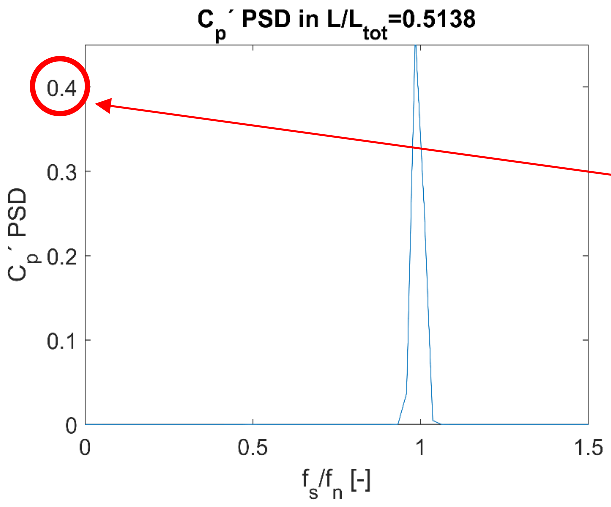
Non-cavitating and resonance conditions

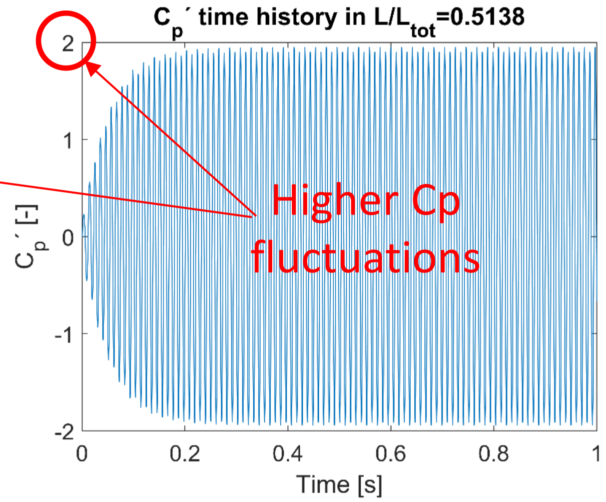
1

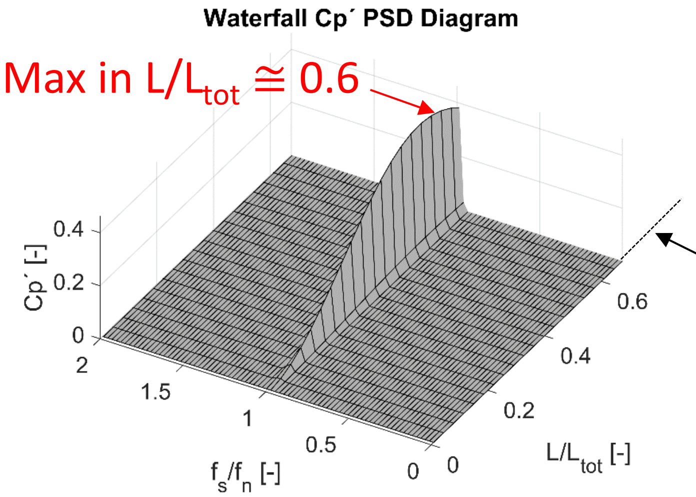
Pressure coefficient fluctuations c_p' at $L = L_{TOT} = 0.5$

Power spectrum density (PSD), time history and waterfall diagram

Co-simulation



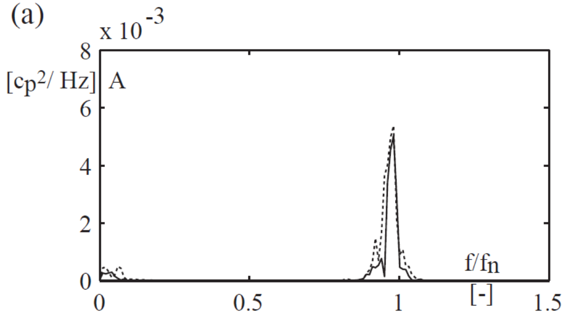


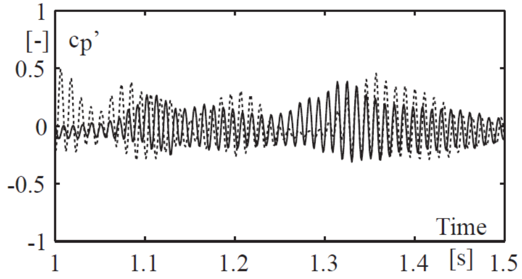


Coupled simulation
$f_s/f_n = 0.99$
$C = 2.5368$ m/s
$\sigma_{corr} / \sigma_i = 1.95$

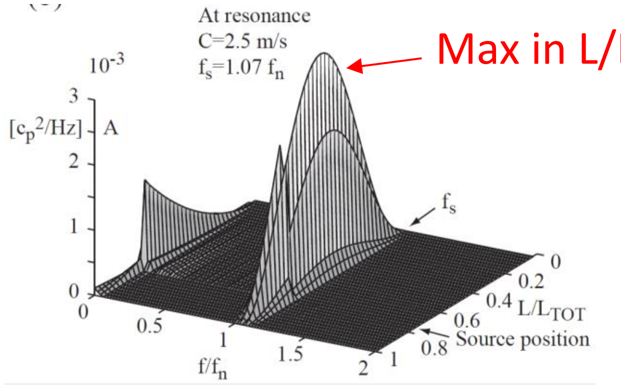
Bluff body position

PhD co-simulation





At resonance
f_s/f_n=0.96
$\overline{C}$=2.25 m/s
One way
Two way



Max in $L/L_{tot} \cong 0.55$

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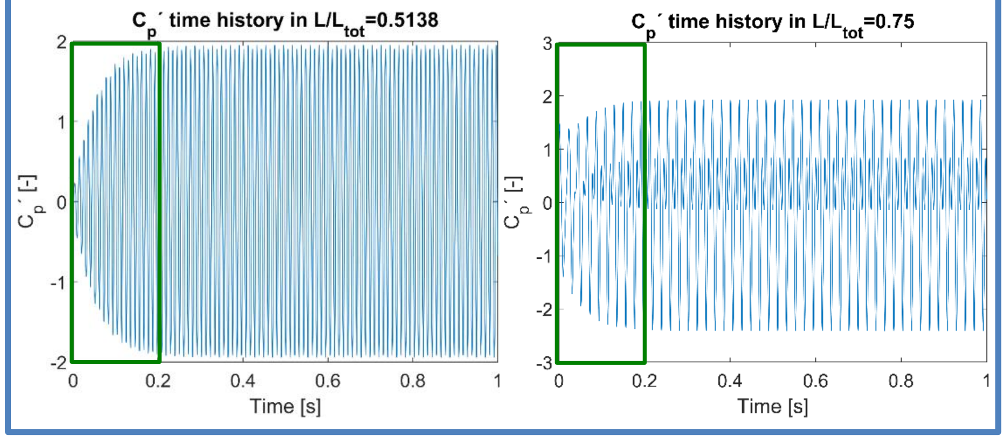
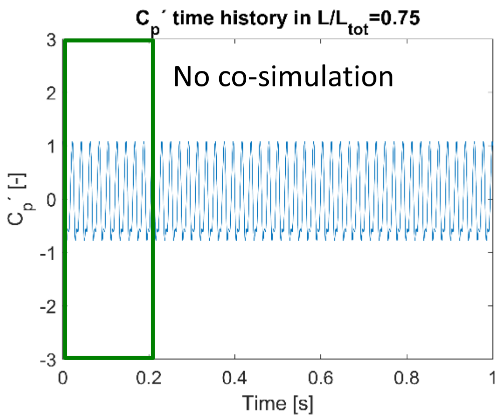
Non-cavitating and resonance conditions

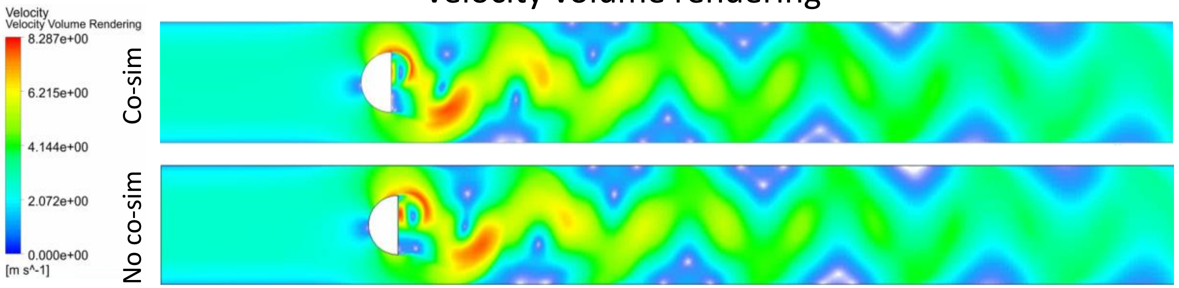
2

Co-simulation

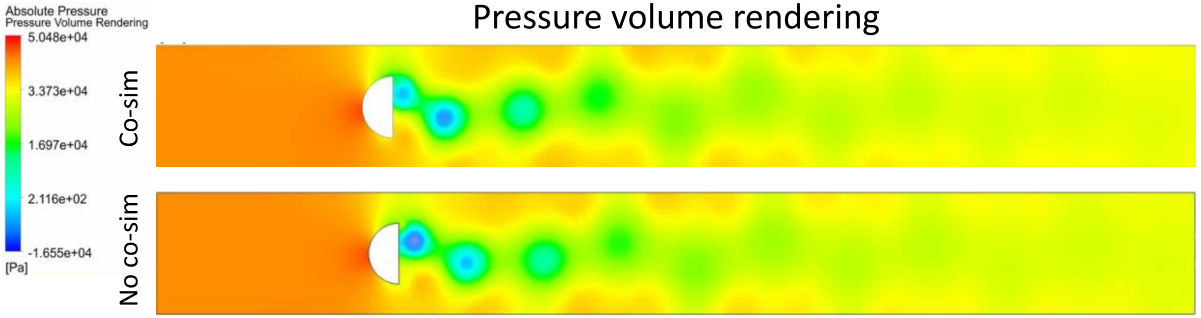




Velocity volume rendering



Pressure volume rendering



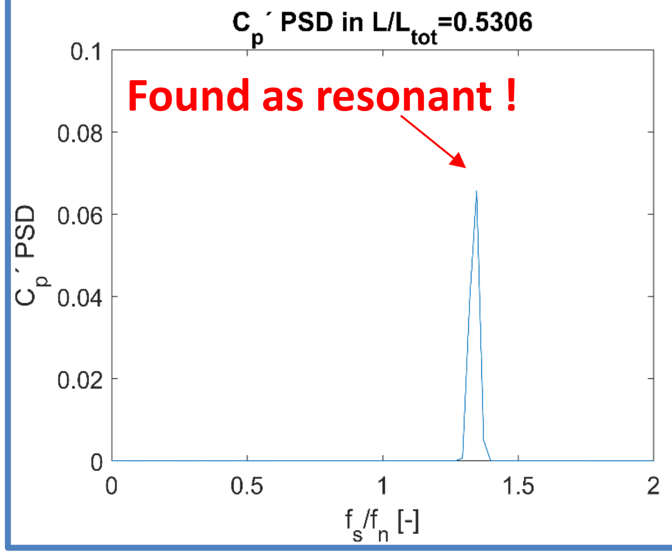
- Comparison between co-simulation and CFD simulation without coupling :
  - ✓ No difference in velocity profile
  - ✓ Pressure pulsation due to resonance with 1D system with the co-simulation

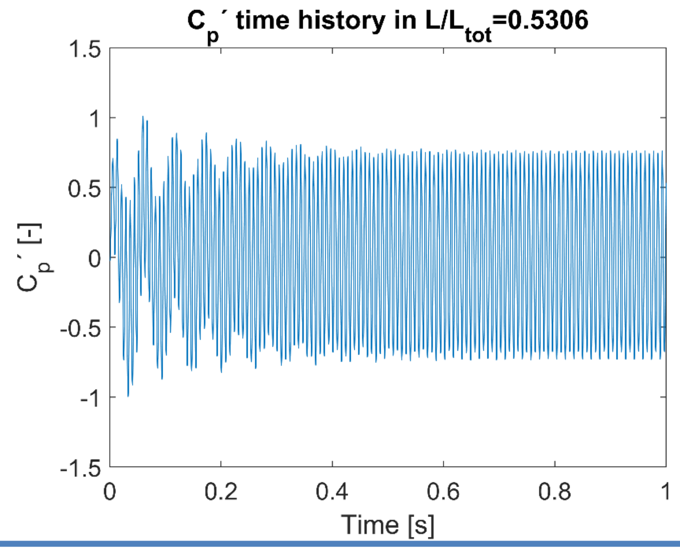
Cavitating condition ③ ④

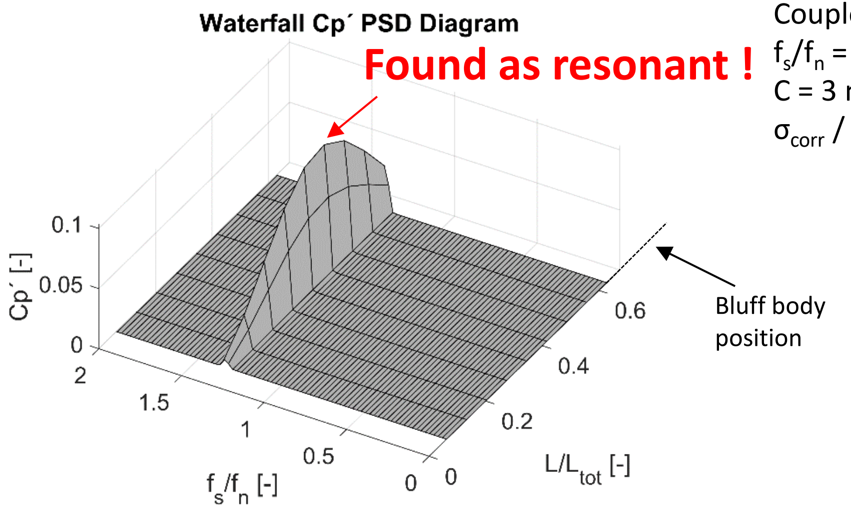
Pressure coefficient fluctuations c_p' at $L=L_{TOT} = 0.5$

Power spectrum density (PSD), time history and waterfall diagram

③ Co-simulation expected as non-resonant

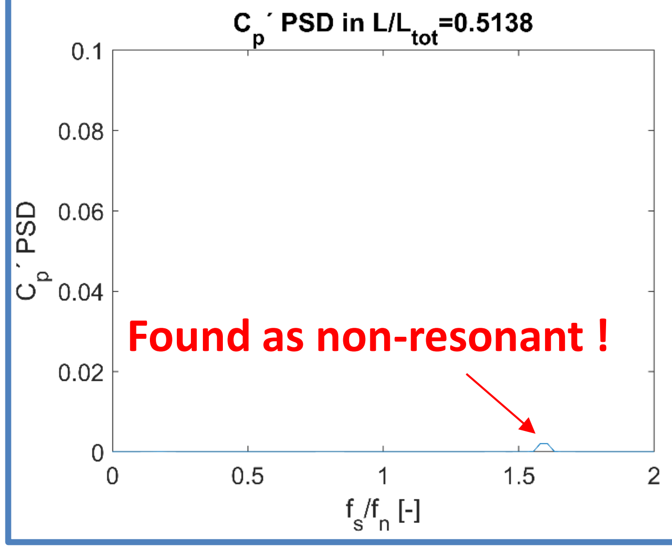


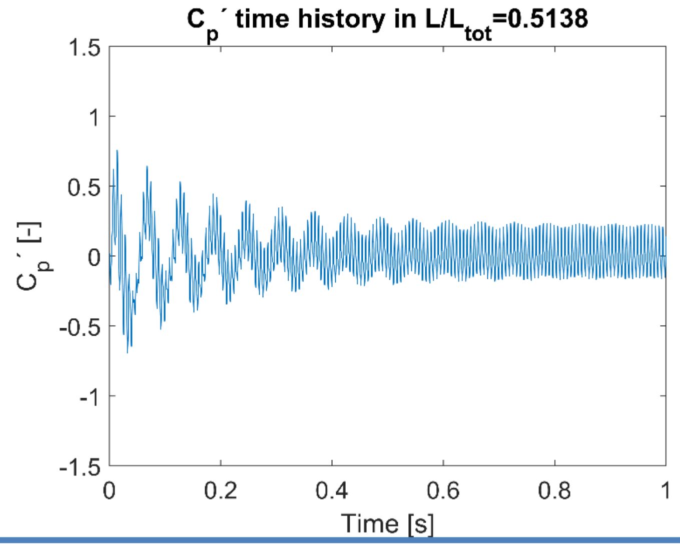


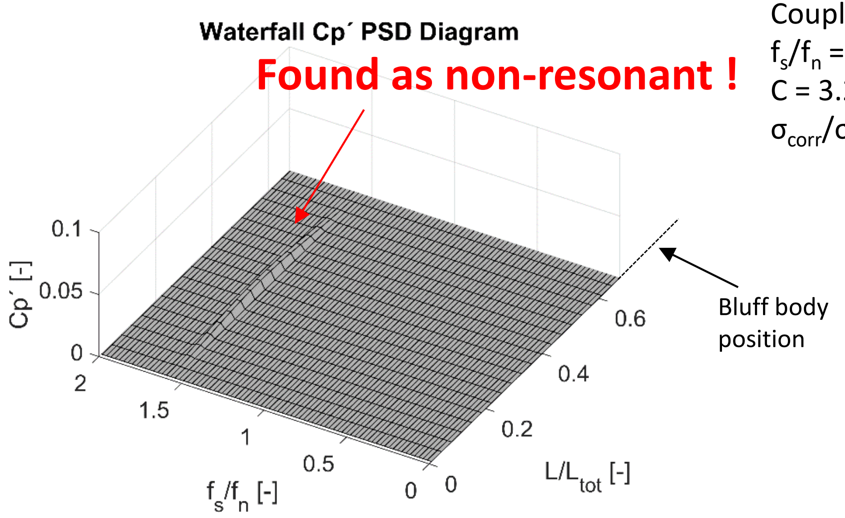


Coupled simulation
$f_s/f_n = 1.34$
C = 3 m/s
$\sigma_{corr} / \sigma_i = 0.8$

④ Co-simulation expected as resonant





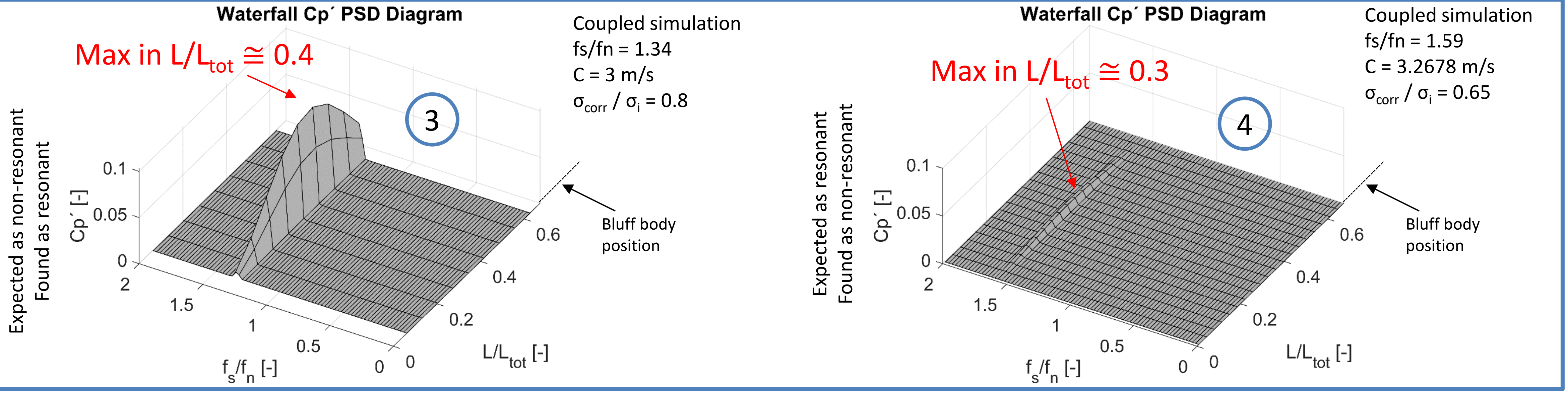


Coupled simulation
$f_s/f_n = 1.59$
C = 3.2678 m/s
$\sigma_{corr}/\sigma_i = 0.65$

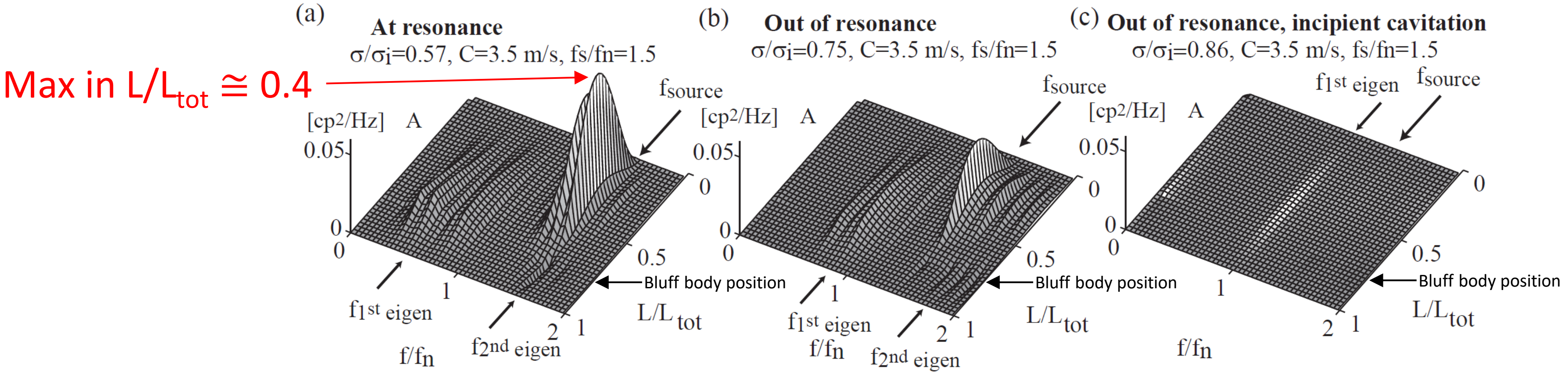
Cavitating condition ③ ④

Waterfall diagram of Power spectrum density (PSD)

Co-simulation

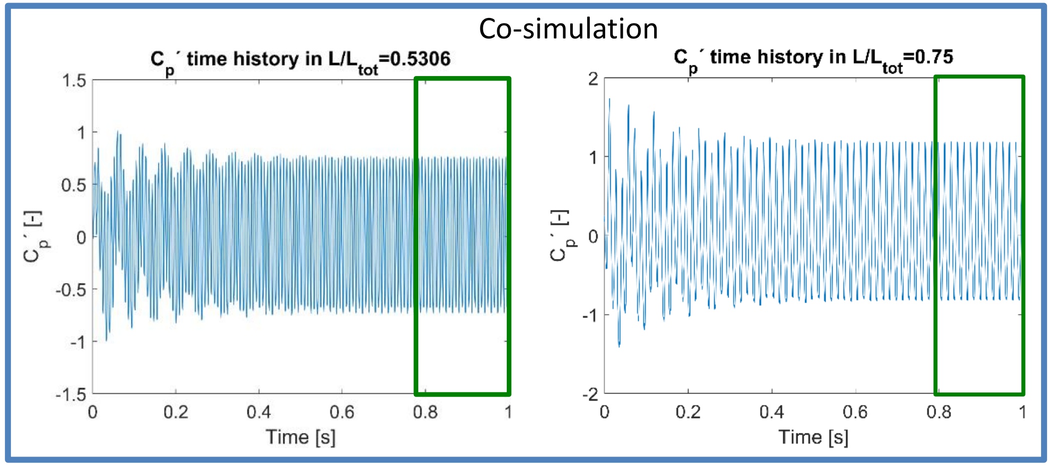


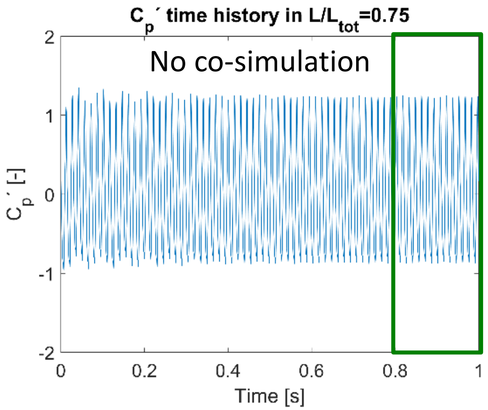
PhD simulation
No-coupled simulation



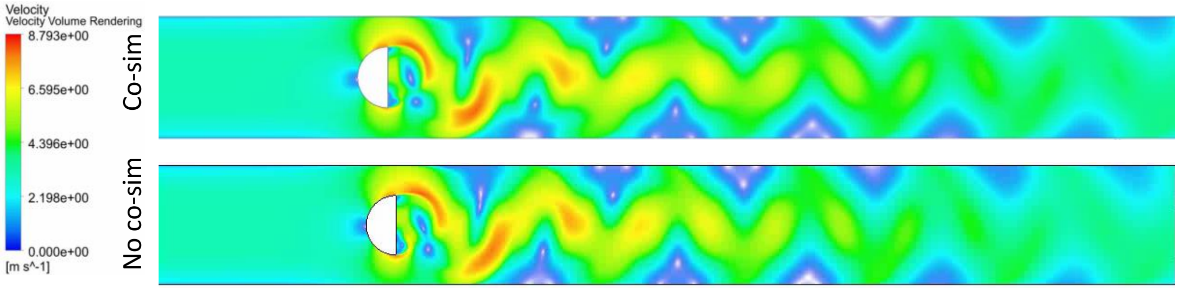
Cavitating condition

Pressure coefficient fluctuations c_p' at $L = L_{TOT} = 0.5$
Power spectrum density (PSD), time history and waterfall diagram

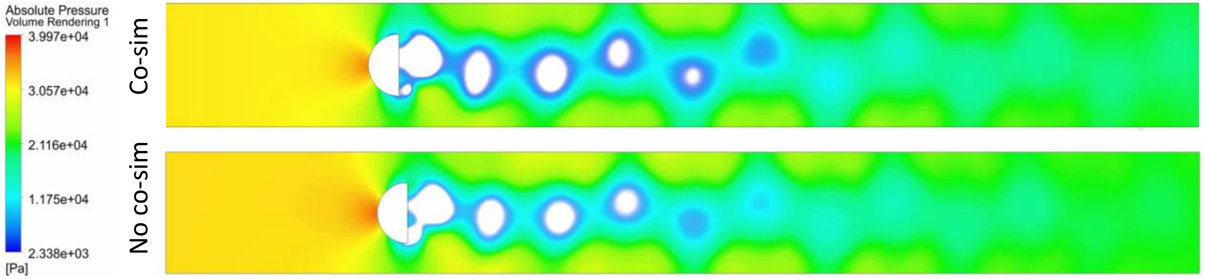




Velocity volume rendering



Pressure volume rendering



- Comparison between co-simulation and CFD simulation without coupling :
  - ✓ No difference in velocity profile
  - ✓ Pressure pulsation due to resonance with 1D system with the co-simulation is not visible like in non-cavitating condition since maximum amplitude of the eigenmode is located in the 1D domain (L/Ltot ≅ 0.4)

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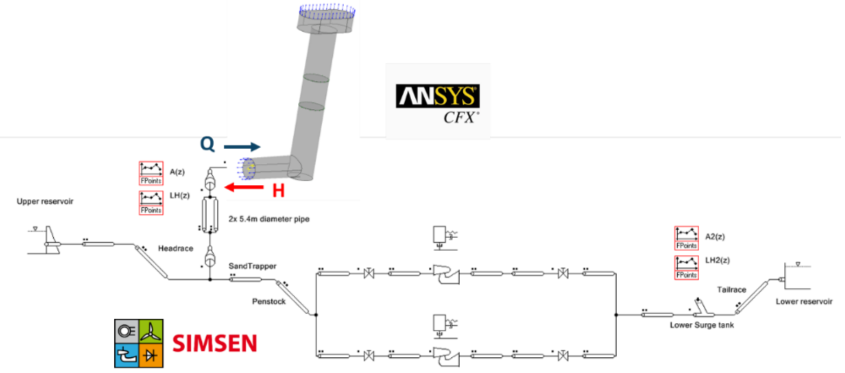
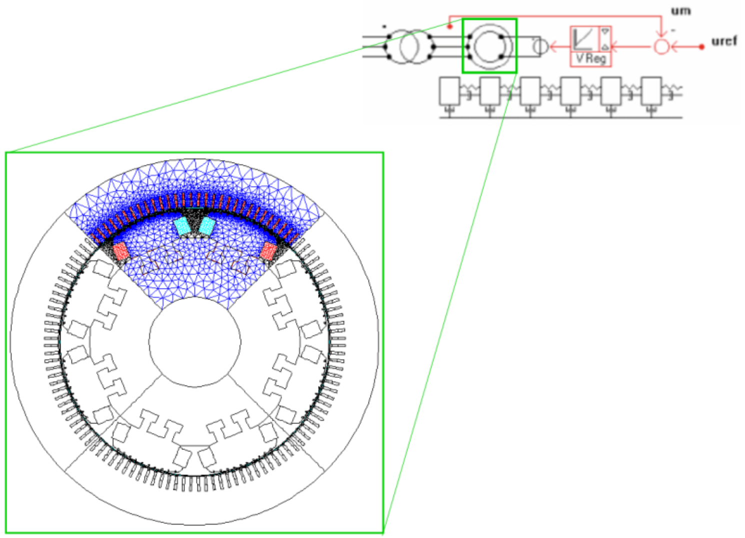
Conclusions

- FMI co-simulation between SIMSEN and CFX is now operational. Two case studies have been investigated to validate robustness of the FMI protocol :
  - ✓ Pressure wave propagation through the numerical domains
  - ✓ Resonance in cavitating condition with strong interaction between 1D model and 3D model including the excitation source
- Co-simulation could be of interest for any CFD simulations having unsteady and realistic boundary conditions driven by the 1D hydraulic system like surge tank device
- Co-simulation with SIMSEN could be extended to other physics like electromagnetics with Finite Element Analysis in electrical machines





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Power Vision Engineering Sàrl
Rue des Jordils 40
CH-1025 St-Sulpice
Switzerland
www.powervision-eng.ch
info@powervision-eng.ch

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