Cavitation Surge Modelling in Francis Turbine Draft Tube

Sébastien ALLIGNÉ, Christophe NICOLET, Yoshinobu TSUJIMOTO, François AVELLAN

5th IAHR International Workshop on Cavitation and Dynamic Problems in Hydraulic Machinery

September 8 to 11, 2013, Lausanne, Switzerland

IAHR AIRH

Power Vision Engineering

大阪大学 OSAKA UNIVERSITY

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Contents

Introduction

- Cavitation vortex rope in Francis turbine draft tube may induce forced or self-oscillations in the hydraulic system

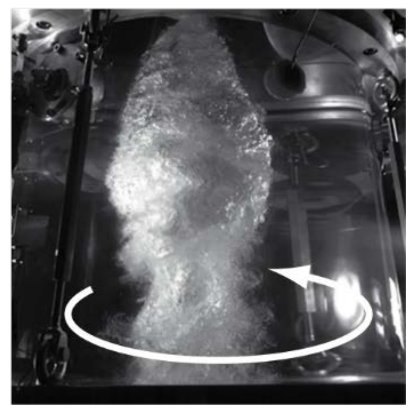
Part load

$Q < Q_{BEP}$

Full load

$Q > Q_{BEP}$

Forced oscillations

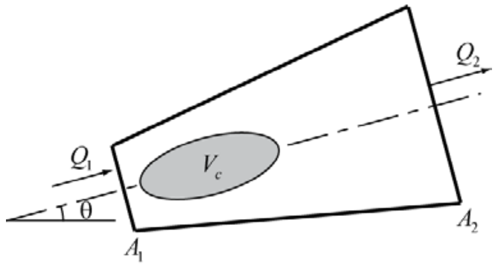


Self oscillations

- 1D model of the draft tube including cavitation volume is required for stability analysis of the system

Set of Equations

o Continuity Equation



$$V_c = f(\gamma, h)$$

$$\gamma = \frac{C_{\theta_1}}{C_{m_1}} = \cot\beta_1 - \frac{U_1 A_1}{Q_1}$$

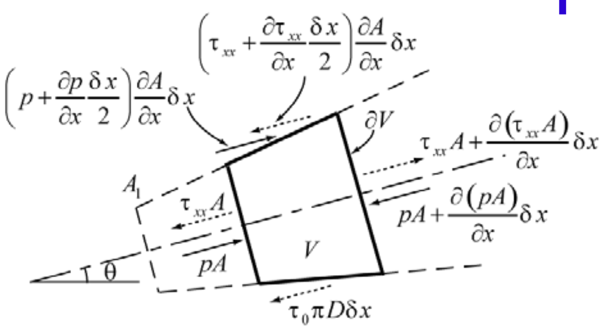
$$\rightarrow \quad Q_1 - Q_2 = \chi \frac{dQ_1}{dt} + C_c \frac{dh}{dt} \quad \leftarrow$$

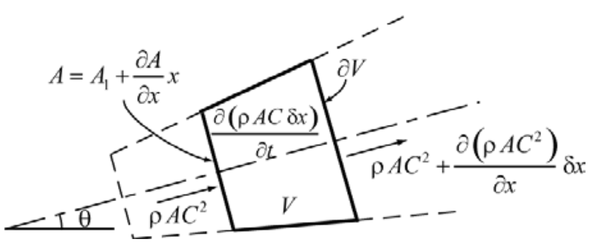
$$C_c = -\frac{\partial V_c}{\partial h}$$

$$\chi = -\frac{\partial V_c}{\partial Q_1}$$

Upstream flow rate
(Tsujimoto et al.)

o Momentum Equation





$$\frac{1}{gA}\frac{\partial Q}{\partial t} + \frac{Q}{gA^2}\frac{\partial Q}{\partial x} - \frac{Q^2}{gA^3}K_x + \frac{\partial h}{\partial x} + \frac{\tau_0 \pi D}{\rho g A} - \frac{\mu''}{\rho g A}\frac{\partial^2 Q}{\partial x^2} = 0$$

Convective terms
(New)

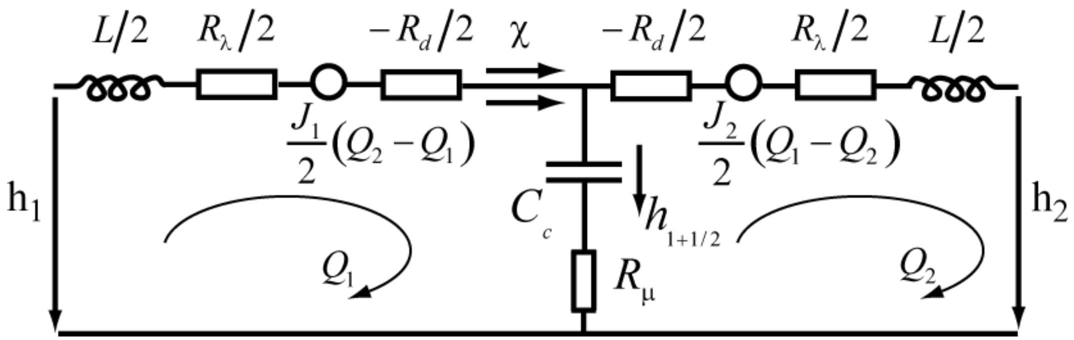
Divergent geometry
(Tsujimoto et al.)

$$K_x = \frac{\partial A}{\partial x}$$

Dilatation viscosity
(Pezzinga et al.)

Electrical Analogy

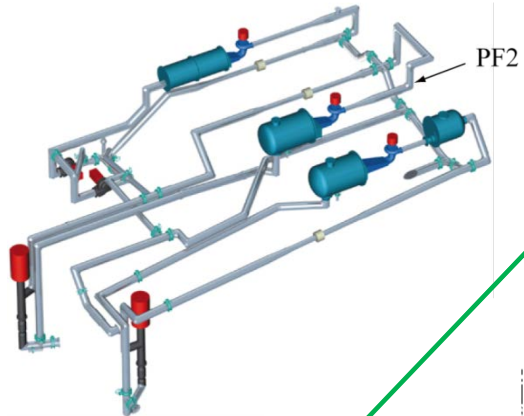
- Equivalent electrical scheme (Cone + Elbow)



- ✓ Inertia : $L=\frac{\delta x}{gA}$
- ✓ Losses : $R_\lambda=\frac{\lambda\delta x}{2gDA^2}Q$
- ✓ Convective terms : $J=\frac{Q}{gA^2}$
- ✓ Divergent geometry : $R_d=\frac{\delta x\cdot K_x}{gA^3}Q$
- ✓ Dilatation viscosity : $R_\mu=\frac{\mu''}{\rho gA\delta x}$
- ✓ Mass flow gain factor : $\chi=-\frac{\partial V_c}{\partial Q_1}$
- ✓ Cavitation compliance : $C_c=-\frac{\partial V_c}{\partial h_{1+1/2}}=\frac{gA\delta x}{a^2}$ → Wave speed

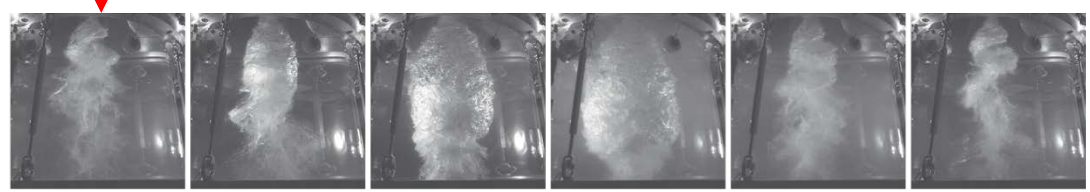
Case Study

- o 444 MW Francis turbine, British Columbia, Canada
  - ✓ Reduced scale model tested at the EPFL test rig



Operating Point	E	Q/Q_{BEP}	N_{ED}	Q_{ED}	T_{ED}	y
[-]	[J.kg^{-1}]	[-]	[-]	[-]	[-]	[°]
OP#PL	272.4	0.58	0.318	0.134	0.055	15
OP#FL	364.6	1.34	0.275	0.268	0.135	30

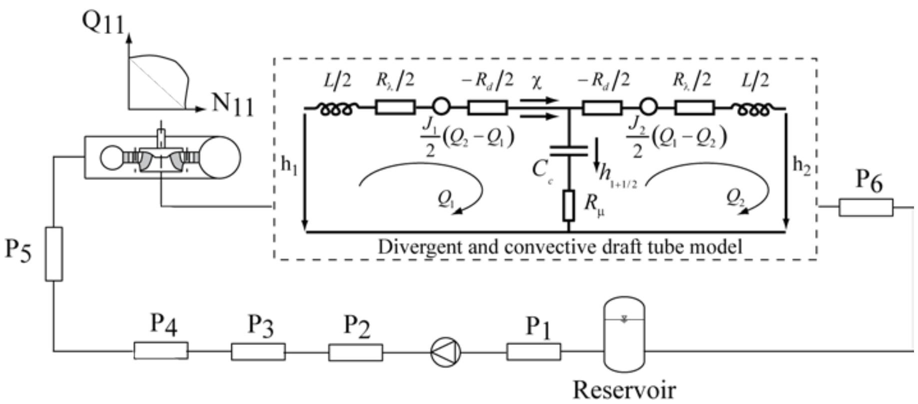
Part load : no cavitation surge phenomenon
(Favrel A.)



Full load: cavitation surge phenomenon
Self-oscillations of the cavitation vortex rope at frequency
$f = 2.5$ Hz

Stability Analysis

- SIMSEN model of the hydraulic system



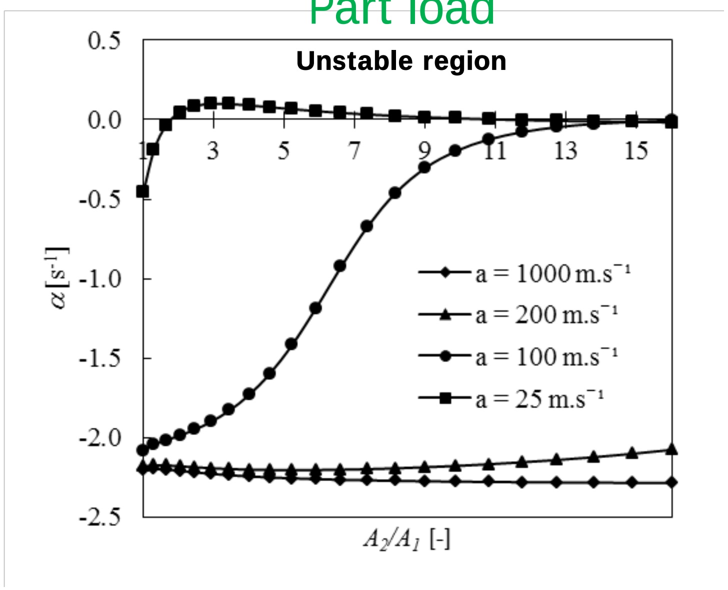
$$\mathbf{A}\frac{d\boldsymbol{X}}{dt}+\left[\mathbf{B}(\boldsymbol{X})\right]\boldsymbol{X}=\boldsymbol{V}(\boldsymbol{X})$$

- Small perturbation stability analysis
  - ✓ Analysis of the damping α of the first eigenmode
  - ✓ Positive damping corresponds to unstable eigenmode leading to self-oscillations of the hydraulic system.

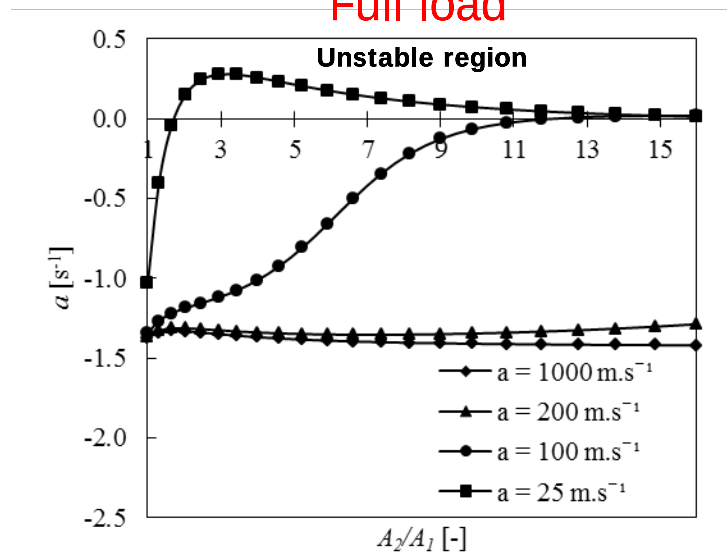
Influence of Divergent Geometry

- Damping of the 1st eigenmode as function of the divergent ratio ($\chi = 0\ \mathrm{s}$, $\mu'' = 0\ \mathrm{Pa.s}$)

Part load



Full load



✓ High wave speed : influence of divergent is negligible

✓ Low wave speed : damping is modified by the divergent ratio

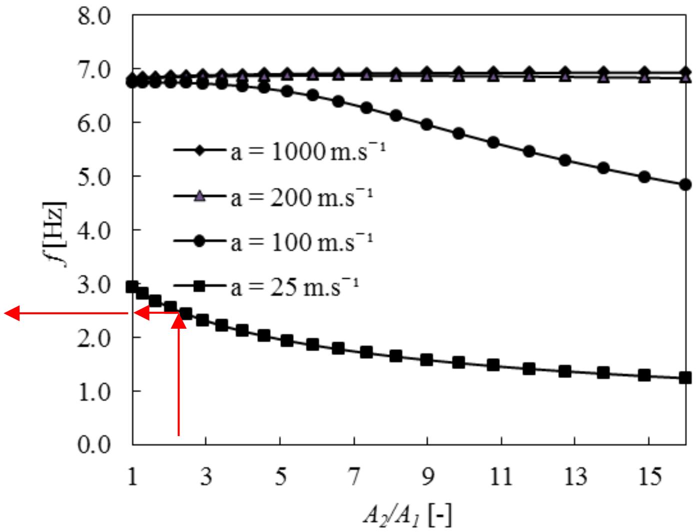
→ Potential self oscillations due to the divergent ratio
(similar results to Tsujimoto et al.)

Influence of Divergent Geometry

- Frequency of the 1st eigenmode as function of the divergent ratio ($\chi = 0$ s , $\mu'' = 0$ Pa.s)

Part load & Full load

$f = 2.5$ Hz



- ✓ Eigenfrequency modified by the divergent ratio for low wave speed values
- ✓ For the case study divergent ratio, $a = 25$ m.s^{-1} predicts first eigenfrequency at $f = 2.5$ Hz

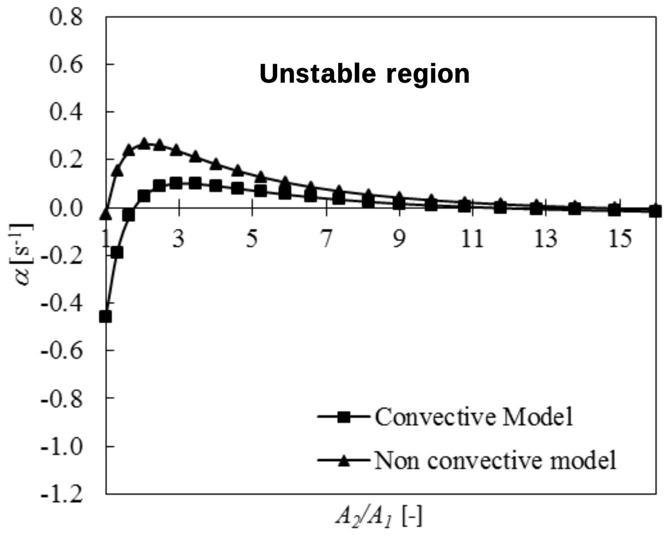
Power Vision Engineering

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

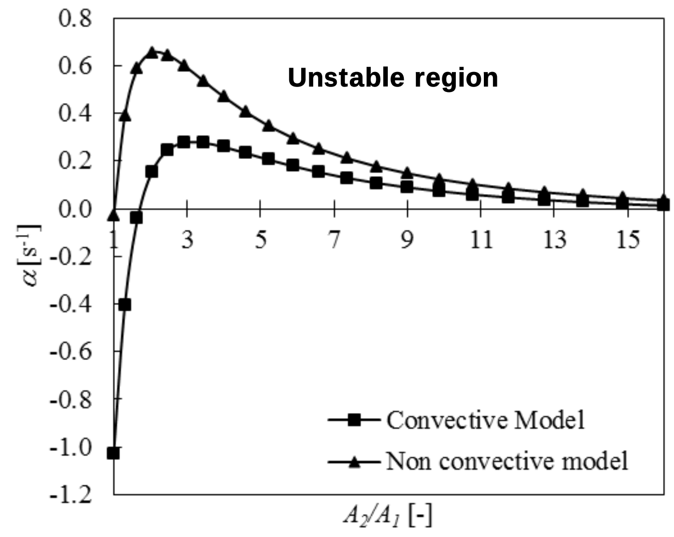
Influence of Convective Terms

- Damping modification by the convective terms ratio ($a = 25 \text{ m.s}^{-1}, \chi = 0 \text{ s}, \mu'' = 0 \text{ Pa.s}$)

Part load



Full load

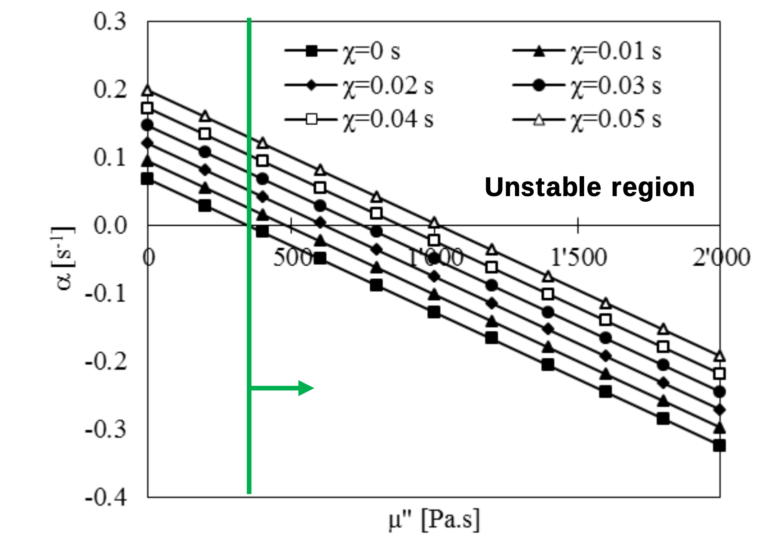


✓ Convective terms have a stabilizing influence

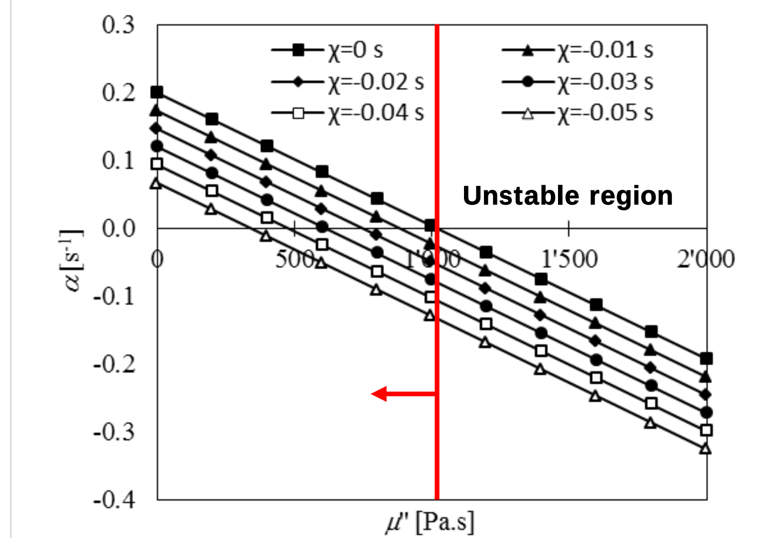
Influence of MFGF & Dilatation Viscosity

- Damping of the 1st eigenmode as function of the dilatation viscosity and the MFGF ($a = 25\ \mathrm{m.s^{-1}}$)

Part load



Full load



- ✓ Damping: decreases linearly to stabilize the system
- ✓ MFGF: destabilizing effect in part load
- ✓ MFGF: stabilizing effect in full load
- ✓ Higher than 400 Pa.s for part load conditions
- ✓ Lower than 1000 Pa.s for full load conditions

→ Similar results to Tsujimoto et al. (MFGF effects in part load and full load)

Conclusions

- Divergent ratio is the destabilizing parameter of the draft tube model;
- Convective terms have a stabilizing influence;
- Mass flow gain factor stabilizes or destabilizes cavitation volume fluctuations respectively for full load and part load conditions;
- To avoid prediction of self-oscillations at part load conditions, dilatation viscosity must be considered .

Thank you for your attention!

Power Vision Engineering
1, ch. Des Champs-Courbes
CH-1024 Ecublens
Switzerland
http://www.powervision-eng.ch
info@powervision-eng.ch