Power Vision Engineering

Francis turbine part load resonance risk analytical assessment

C. Nicolet, **C. Landry**, S. Alligné, A. Béguin

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

SHF

AFM ASSOCIATION FRANÇAISE DE MECANIQUE

SIMSEN

Contents

- Context and key goals
- Eigenvalue computation
  - ✓Numerical equations
  - ✓Analytical equations
- Examples of application
  - ✓Hydraulic system 1
  - ✓Hydraulic system 2
  - ✓Hydraulic system 3
- Conclusions / Take away message

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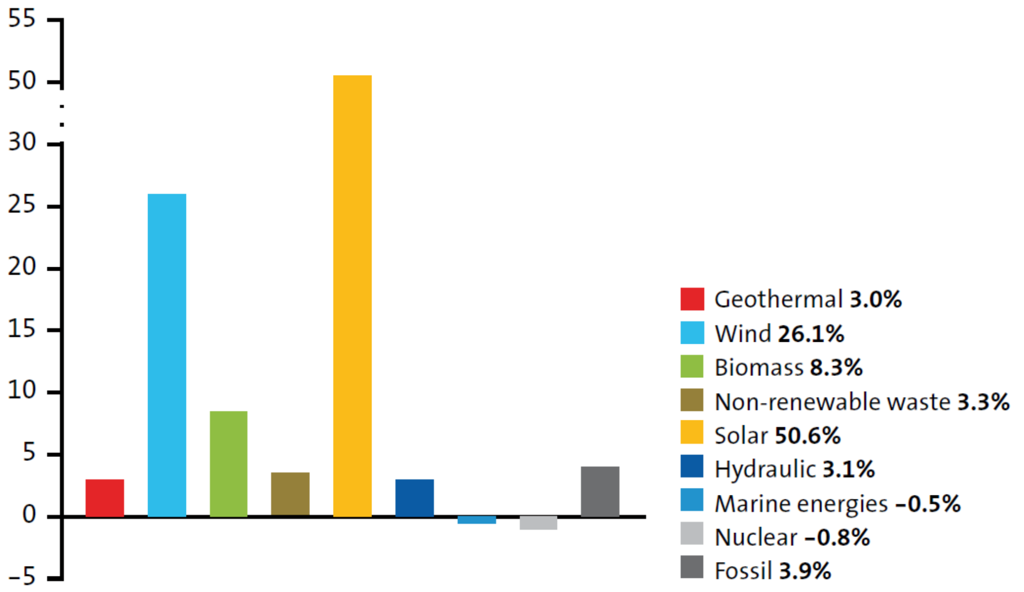
Context and Key goals

- Massive penetration of alternative renewable energies (Solar, wind power)
- Stochastic nature of the renewable energy production

- To maintain balanced production:
  - ✓ Sufficient reserve capacity
  - ✓ Primary and secondary control capabilities

→ Hydropower plants

→ Off-design operation

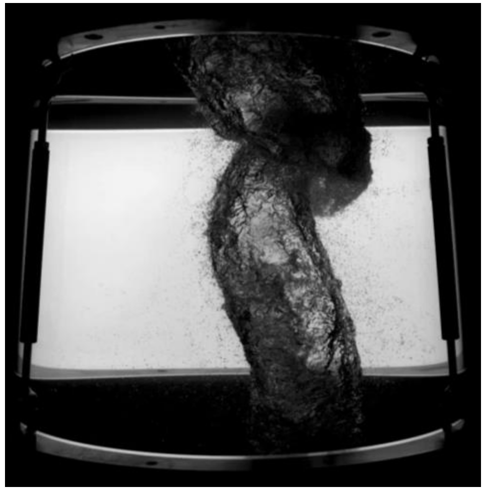


Mean annual growth rates of electricity production 2002-2012

Context and Key goals

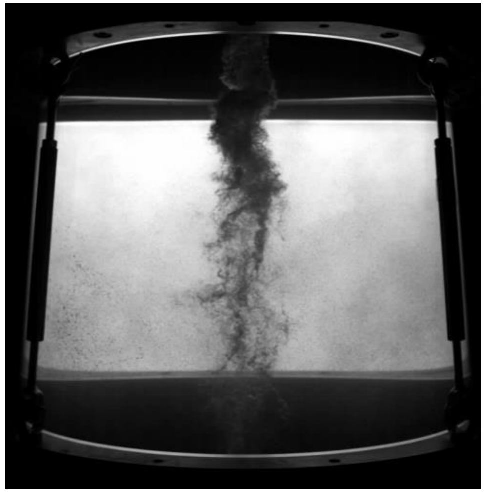
- Frequent power transients:
  - ✓ Require a wide operating range
  - ✓ May induce high levels of vibration and large pressure fluctuations

Part load condition



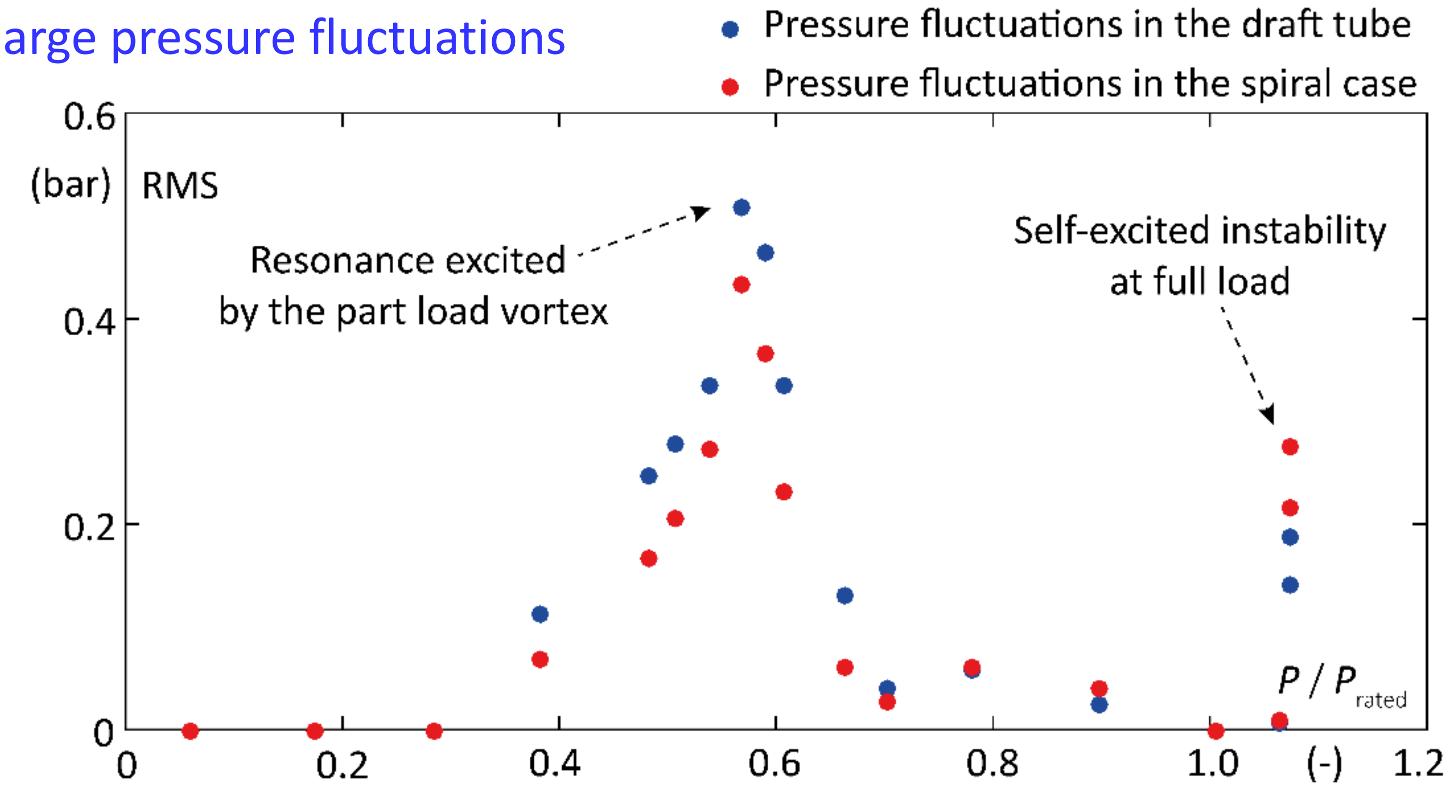
* Favrel *et al.*, 2013

Full load condition



* Müller *et al.* ,2013

[0.2 – 0.4] • Turbine rotational speed



HYPERBOLE (ERC/FP7-ENERGY-2013-1-Grant 608532)

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SIMSEN software

- SIMSEN software
  - ✓ Hydraulic circuit
  - ✓ Electrical installations
  - ✓ Rotating inertias
  - ✓ Control system

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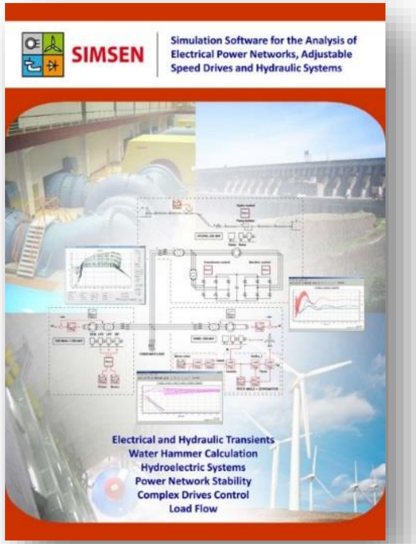
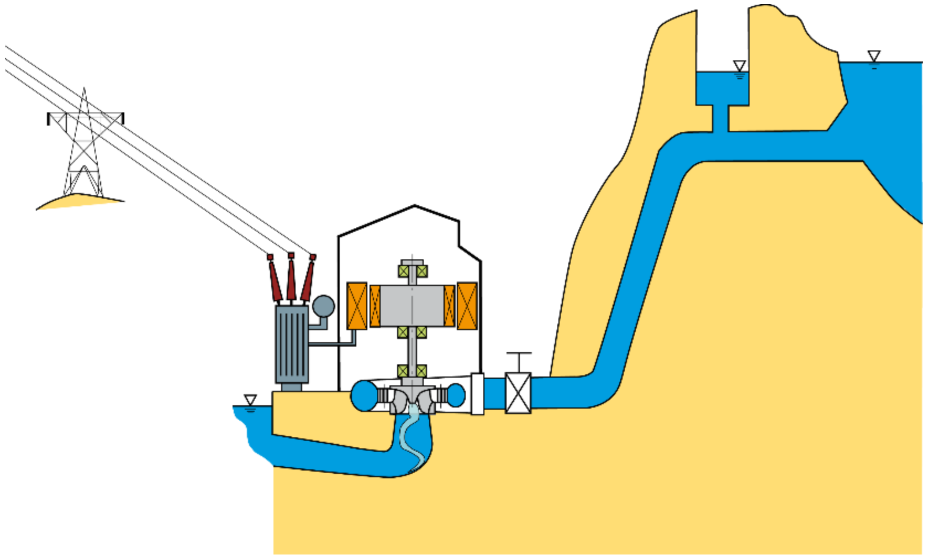
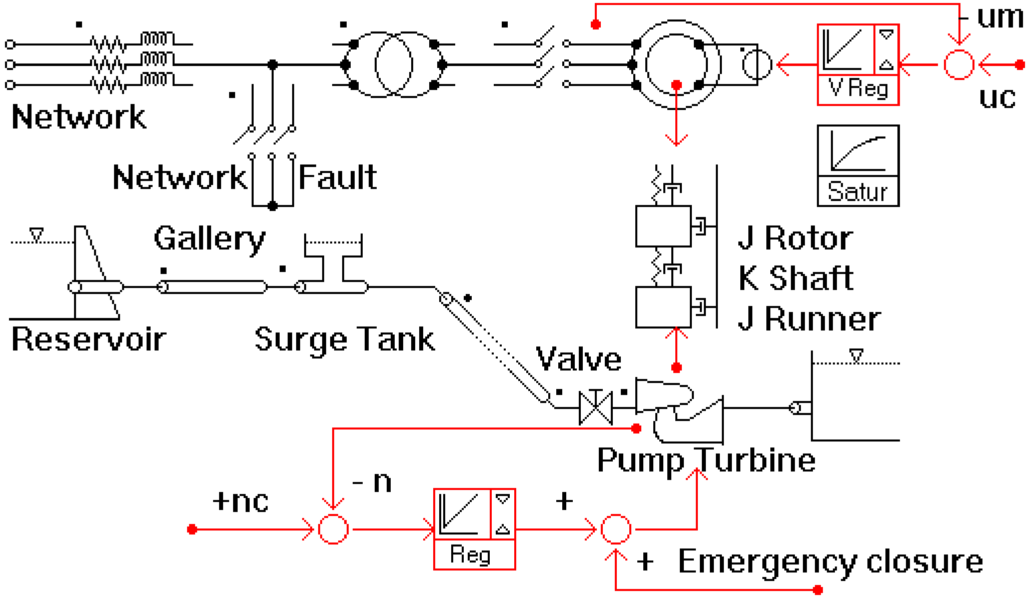
EPFL





Modeling from water to wire



Electrical Analogy

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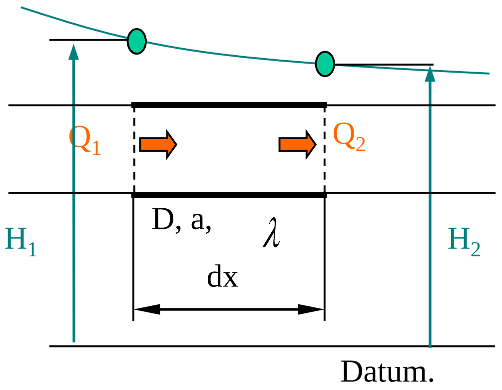
- Mass and momentum equations:



$$\frac{\partial H}{\partial t} + \frac{a^2}{gA}\frac{\partial Q}{\partial x} = 0$$

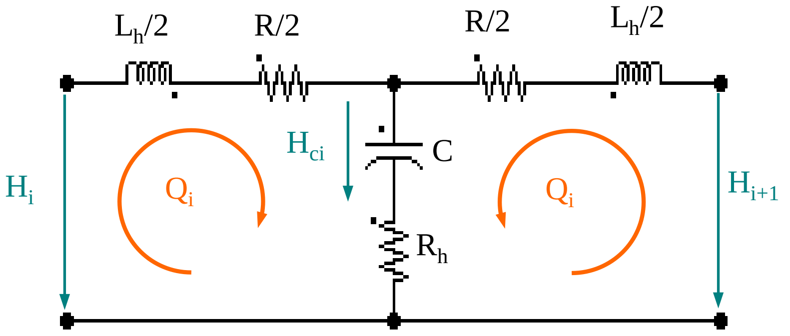
Storage

$$\frac{\partial H}{\partial x} + \frac{1}{gA}\frac{\partial Q}{\partial t} + \frac{\lambda |Q|}{2gDA^2} Q = 0$$

Losses

Inertia

- Electrical analogy:
  - ✓ (Bergeron, 1950; Paynter, 1953)



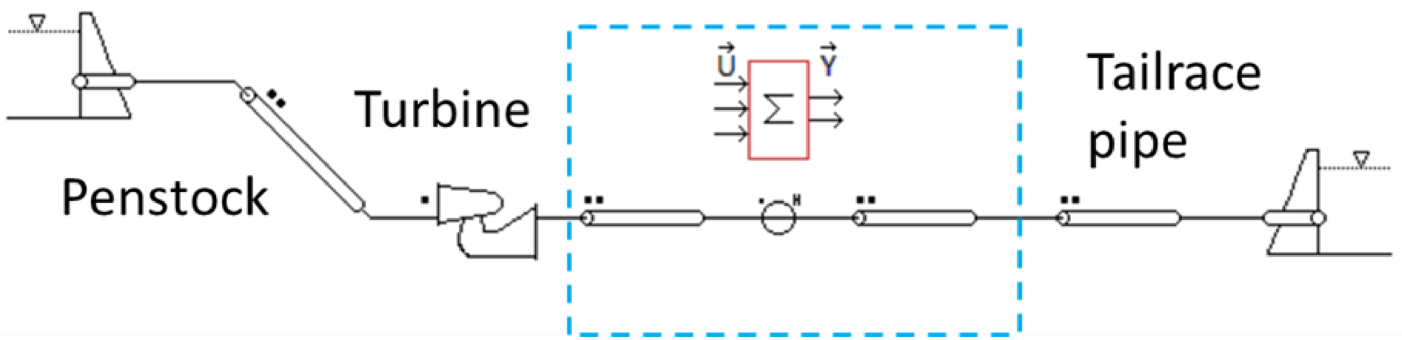
$$\frac{\partial U}{\partial t} + \frac{1}{C_e}\frac{\partial I}{\partial x} = 0$$

$$\frac{\partial U}{\partial x} + L_e\frac{\partial I}{\partial t} + R_e I = 0$$

- Assumptions:
  - ✓ Uniform flow
  - ✓ 1-D approach
  - ✓ Convective terms neglected
  - ✓ Vertical displacements neglected

Eigenvalue computation

- Set of differential equations



$$\left[A\right]\cdot\frac{d\vec{X}}{dt}+\left[B\left(\vec{X}\right)\right]\cdot\vec{X}=C\left(\vec{x}\right)$$

- Small perturbation

$$\vec{X}=\vec{X}_0+\delta\vec{X}\quad\left\{\frac{d\left(\vec{X}_0+\delta\vec{X}\right)}{dt}=\vec{f}\left(\vec{X}_0+\delta\vec{X}\right)\right.$$

- Eigenfrequency

$$\det\left(\left[I\right]\cdot s+\left[A_l\right]^{-1}\left[B_l\right]\right)=0$$

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Natural frequencies

- Hydraulic system modelled by an equivalent pipe

Total length

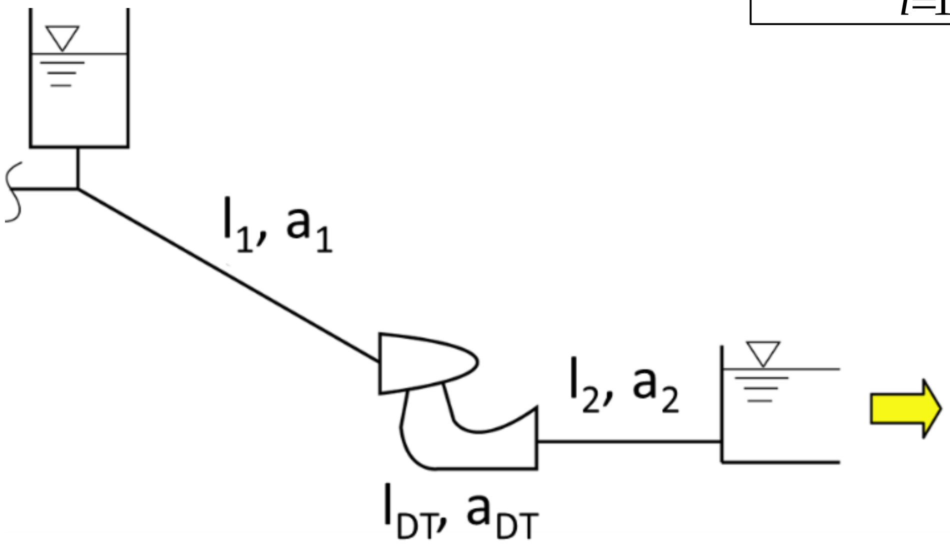
$$l_{tot} = \sum_{i=1}^{n} l_i$$

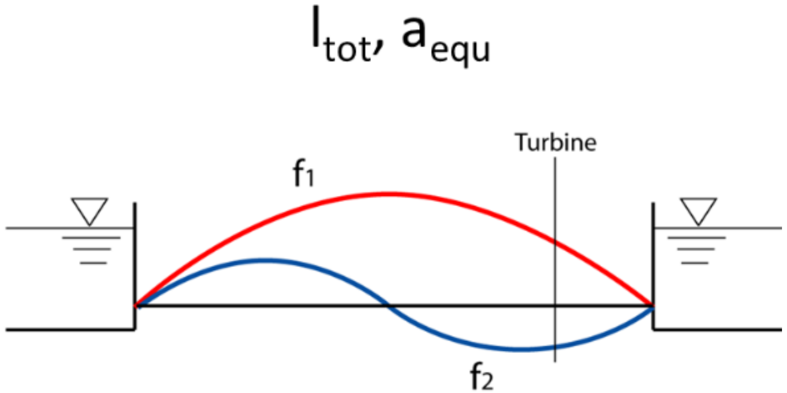
Equivalent wave speed

$$a_{equ} = \frac{l_{tot}}{\sum_{i=1}^{n} \frac{l_i}{a_i}}$$

Natural frequency (Order k)

$$f_k = \frac{a_{equ}}{\lambda_k} = \frac{a_{equ}}{2 \cdot l_{tot}} \cdot k$$





Standing wave

First natural frequency of the cavitating draft tube

- Simplified hydroacoustic model of the frictionless cavitating draft tube

Cavitation compliance

$$C_{DT}=\frac{l_{DT}\cdot g\cdot \bar{A}_{DT}}{a_{DT}^{2}}$$

$$k\approx\frac{1}{C_{DT}}$$

Draft tube inductance

$$L_{DT}=\frac{l_{DT}}{g\cdot \bar{A}_{DT}}$$

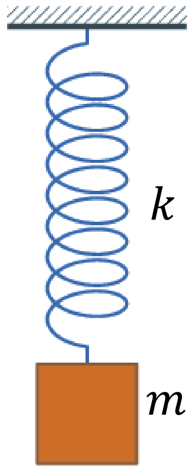
$$m\approx L_{DT}$$

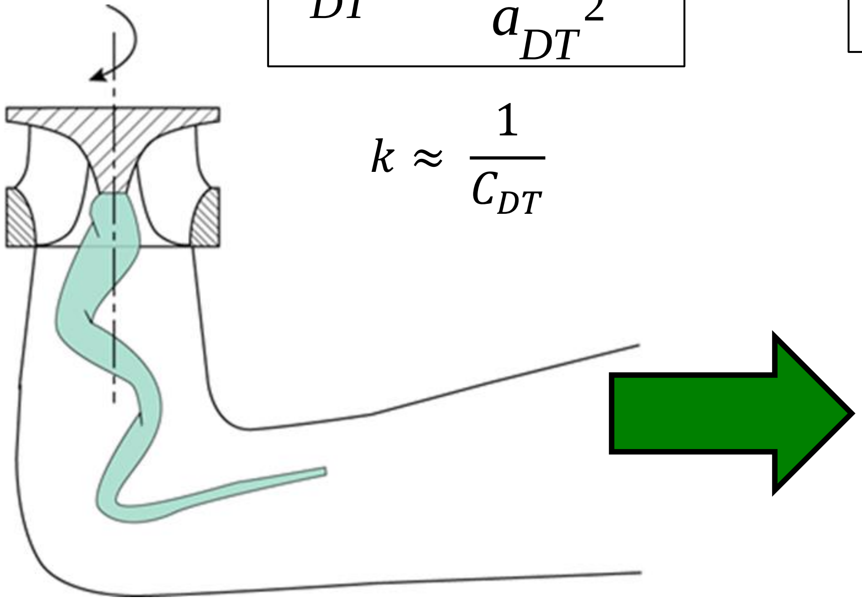
First natural frequency * Jacob, *1993*

$$f_o=\frac{1}{2\cdot\pi}\frac{1}{\sqrt{L_{DT}\cdot C_{DT}}}=\frac{1}{2\cdot\pi}\frac{a_{DT}}{l_{DT}}$$

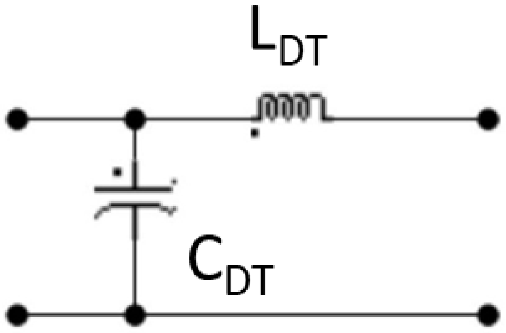
$$f_0=\frac{1}{2\pi}\sqrt{\frac{k}{m}}\approx\frac{1}{2\pi}\sqrt{\frac{1}{C_{DT}L_{DT}}}$$

Similar to a spring–mass system





Draft tube



l_{DT}	=	DT length [m]
A_{DT}	=	DT cross section area [m^2]
a_{DT}	=	DT wave speed [m/s]

First natural frequency of the cavitating draft tube

- Simplified hydroacoustic model of the frictionless cavitating draft tube

Cavitation compliance

$$C_{DT} = \frac{l_{DT} \cdot g \cdot \bar{A}_{DT}}{a_{DT}^{2}}$$

Tailrace pipe inductance

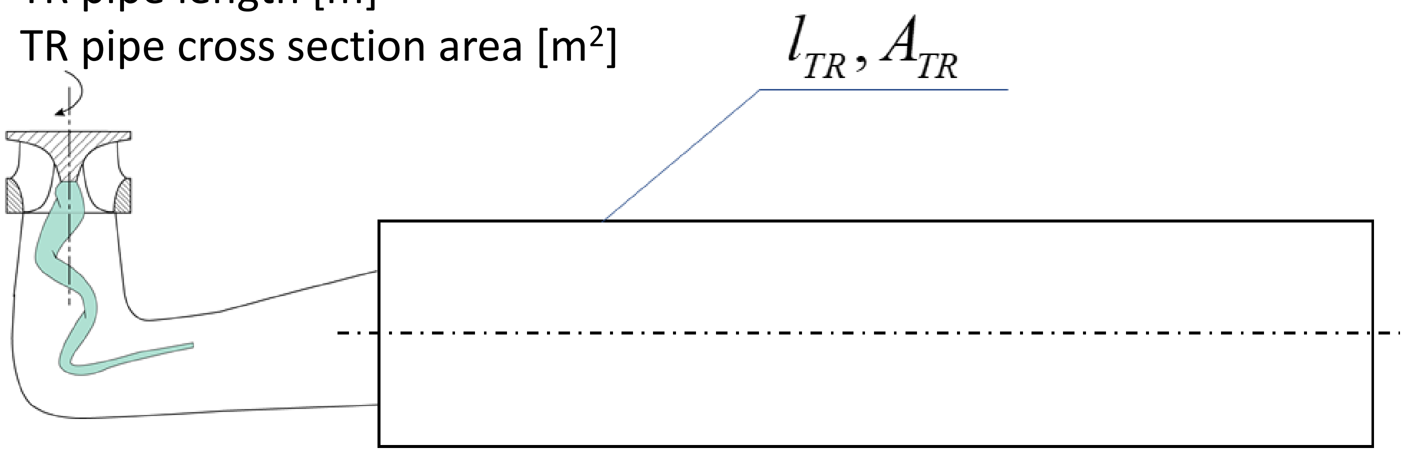
$$L_{TR} = \frac{l_{TR}}{g \cdot A_{TR}}$$

First natural frequency * Dörfler, *2013*

$$f_o = \frac{1}{2 \cdot \pi} \frac{1}{\sqrt{L_{TR} \cdot C_{DT}}} = \frac{1}{2 \cdot \pi} \frac{a_{DT}}{\sqrt{l_{DT} \cdot l_{TR} \frac{A_{DT}}{A_{TR}}}}$$

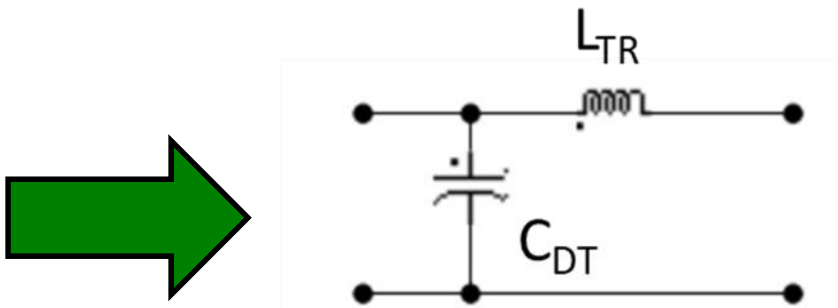
l_{TR} = TR pipe length [m]

A_{TR} = TR pipe cross section area [m²]



Draft tube

Tailrace pipe



Analytical equations

- Summary

	Equivalent pipe	Draft tube without TR	Draft tube with TR
1st order	$f_1 = \frac{a_{equ}}{\lambda_k} = \frac{a_{equ}}{2 \cdot l_{tot}}$	$f_o = \frac{1}{2 \cdot \pi} \frac{a_{DT}}{l_{DT}}$	$f_o = \frac{1}{2 \cdot \pi} \frac{a_{DT}}{\sqrt{l_{DT} \cdot l_{TR} \frac{A_{DT}}{A_{TR}}}}$
2nd-6th order	$f_k = \frac{a_{equ}}{\lambda_k} = \frac{a_{equ}}{2 \cdot l_{tot}} \cdot k$	$f_k = \frac{a_{equ}}{\lambda_k} = \frac{a_{equ}}{2 \cdot l_{tot}} \cdot k$	$f_k = \frac{a_{equ}}{\lambda_k} = \frac{a_{equ}}{2 \cdot l_{tot}} \cdot k$

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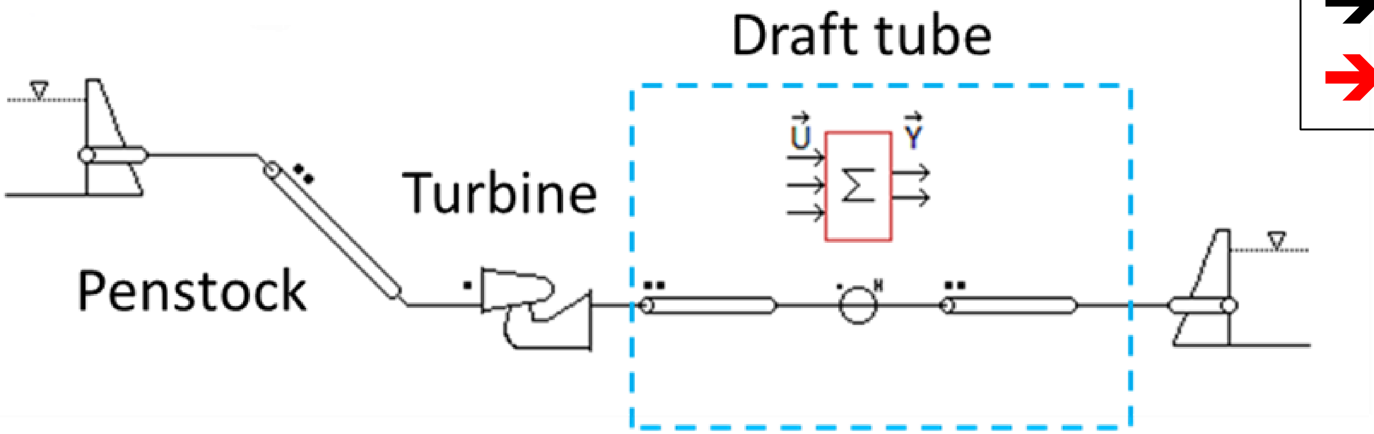
Example of applications

- **Hydraulic system 1**

N_n = 750 rpm = 12.5 Hz
→ $f_{excitation}$ = [0.2 – 0.4]·f_n
→ $f_{excitation}$ = [2.5 – 5 Hz]



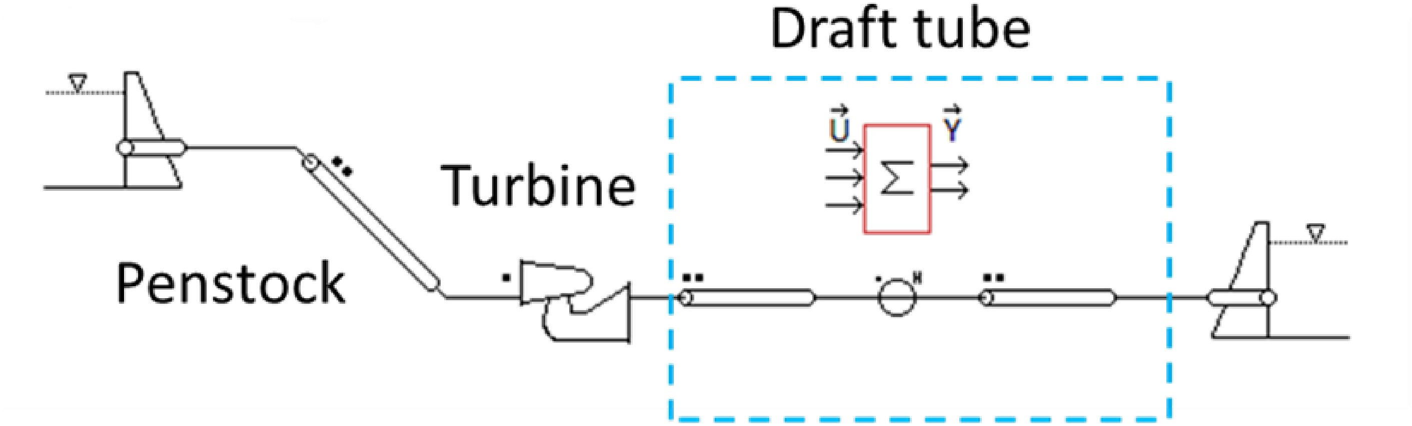
Penstock			
L	=	300	m
D	=	1.2	m
a	=	1’250	m/s
λ	=	0.012	-

Turbine			
Pn	=	5	MW
Qn	=	5.0	m^3/s
Hn	=	100	mWC
Nn	=	750	rpm
Dref	=	0.846	m
Nq	=	53	-

Draft tube			
L	=	10	m
D	=	1.2	m
a	**=**	**[50-100]**	**m/s**
λ	=	0.012	-

Example of applications

- **Hydraulic system 1**

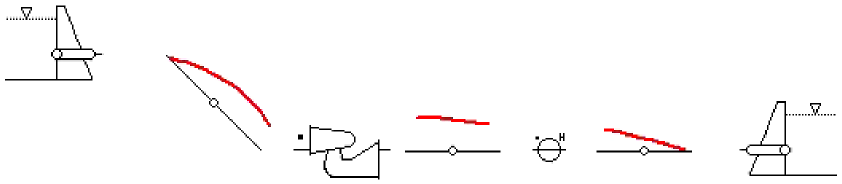


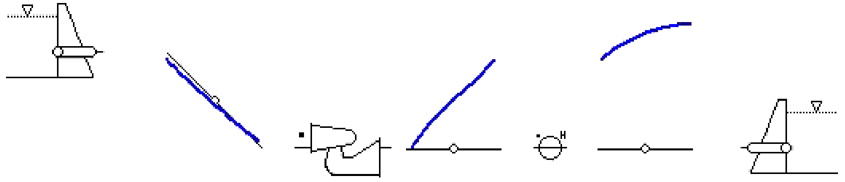
Elastic mode shape

- ✓ Non-Linear amplitude variation of pressure in the TR as function of the length
- ✓ Non-constant amplitude variation of discharge in the TR as function of the length

$$f_1 = \frac{a_{equ}}{\lambda_1} = \frac{a_{equ}}{2 \cdot l_{tot}} \cdot 1$$

$$f_o = \frac{1}{2 \cdot \pi} \frac{a_{DT}}{l_{DT}}$$



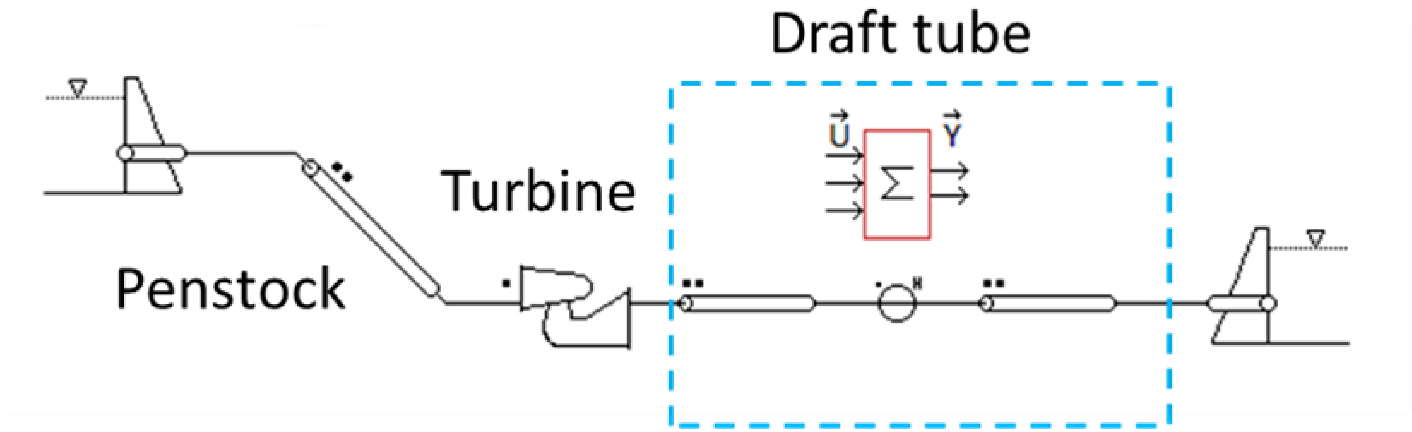


1st Pressure mode   Elastic mode shape   1st Discharge mode

Example of applications

$f_{excitation}$ = [2.5 – 5 Hz]

- **Hydraulic system 1**



a = 50 m/s

System 1	Analytical calculation a DT (min) [m/s]	Eigen value calculation a DT (min) [m/s]	Relative error [%]
f0 [Hz]	0.8	1.24	-35.48
f1 [Hz]	1.14	1.24	-8.06
f2 [Hz]	2.27	2.09	8.61
f3 [Hz]	3.41	3.67	-7.08
f4 [Hz]	4.55	4.18	8.85
f5 [Hz]	5.68	5.99	-5.18
f6 [Hz]	6.82	6.15	10.89

$$f_1 = \frac{a_{equ}}{\lambda_1} = \frac{a_{equ}}{2 \cdot l_{tot}} \cdot 1$$

$$f_o = \frac{1}{2 \cdot \pi} \cdot \frac{a_{DT}}{l_{DT}}$$

- 1st order: Better agreement with f_1
- 2nd-6th order: Rather good agreement for natural frequencies Maximum error of 14%.
- Risk of resonance with the draft tube in red.

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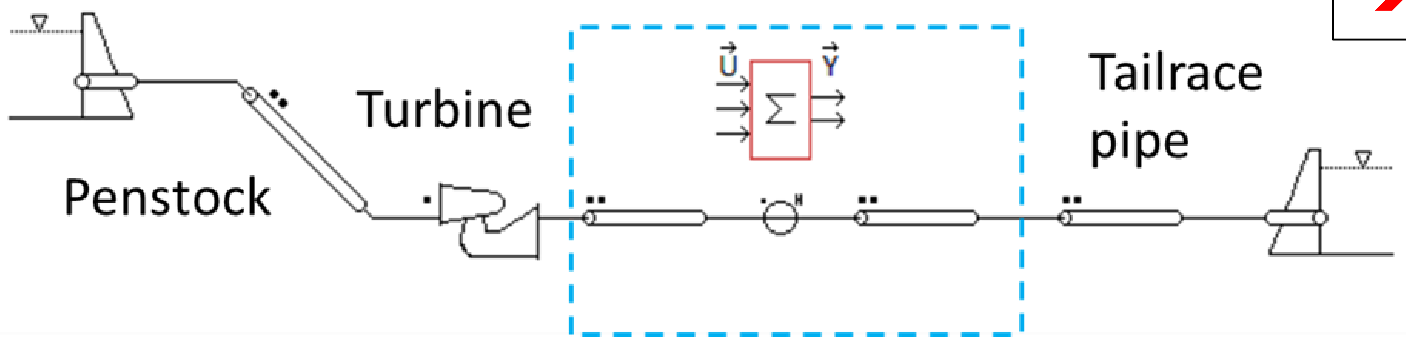
Example of applications

- **Hydraulic system 2**

$N_n = 750\ rpm = 12.5\ Hz$

➔ $f_{excitation} = [0.2 – 0.4] \cdot f_n$

➔ $f_{excitation} = [2.5 – 5\ Hz]$



Penstock

L	=	300	m
D	=	1.2	m
a	=	1’250	m/s
λ	=	0.012	-

Turbine

Pn	=	5	MW
Qn	=	5.0	m^3/s
Hn	=	100	mWC
Nn	=	750	rpm
Dref	=	0.846	m
Nq	=	53	-

Draft tube

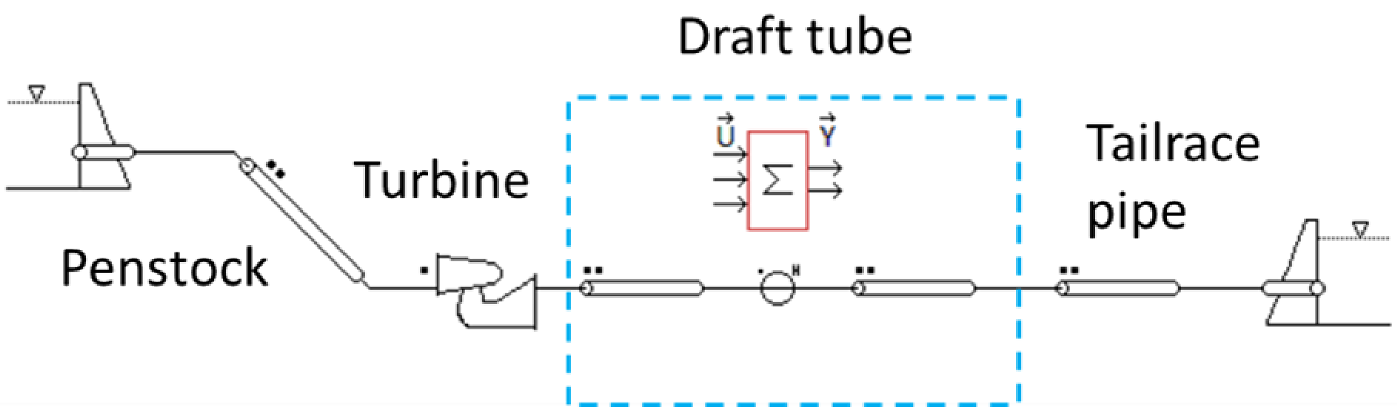
L	=	10	m
D	=	1.2	m
a	**=**	**[50-100]**	**m/s**
λ	=	0.012	-

Tailrace pipe

L	=	100	m
D	**=**	**1.2**	**m**
a	=	1’250	m/s
λ	=	0.012	-

Example of applications

- **Hydraulic system 2**

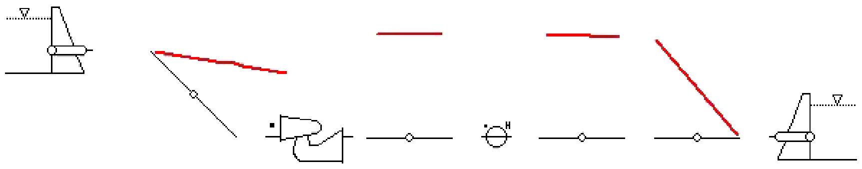


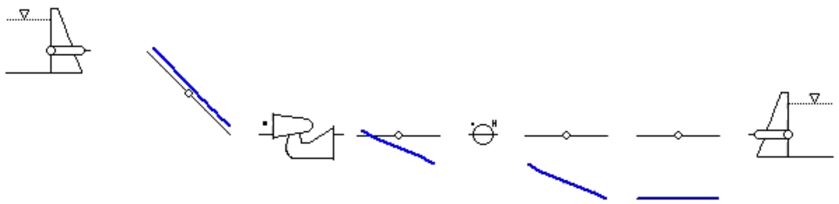
Rigid column mode shape

- ✓ Linear amplitude variation of pressure in the TR
- ✓ Constant amplitude variation of discharge in the TR
- → Similar to surge tank mass oscillation between TR pipe and DT compliance

$$f_1 = \frac{a_{equ}}{\lambda_1} = \frac{a_{equ}}{2 \cdot l_{tot}} \cdot 1$$

$$f_o = \frac{1}{2 \cdot \pi} \frac{a_{DT}}{\sqrt{l_{DT} \cdot l_{TR} \frac{A_{DT}}{A_{TR}}}}$$





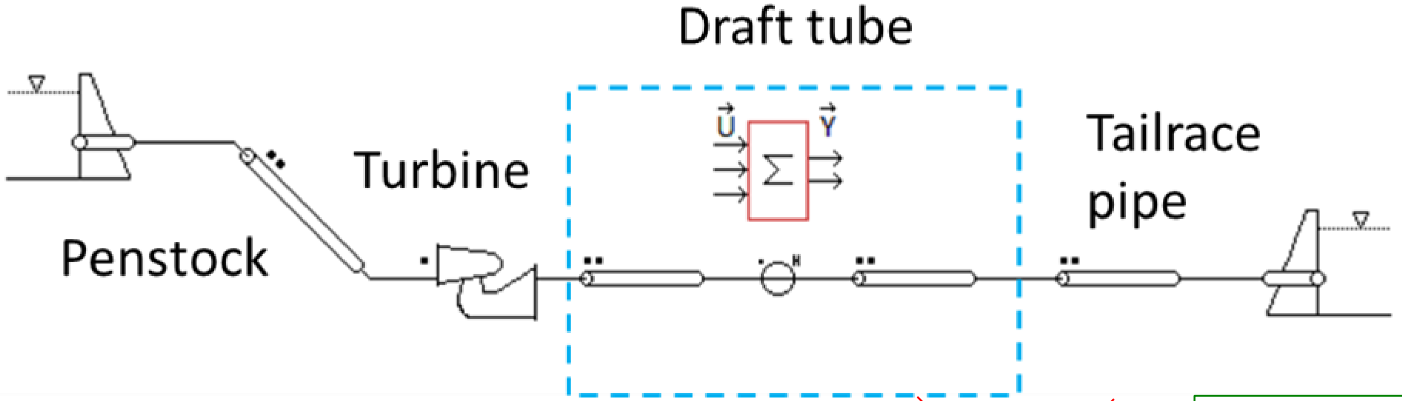
1st Pressure mode   Rigid column mode shape   1st Discharge mode

Power Vision Engineering

Example of applications

$f_{excitation} = [2.5 – 5 \text{ Hz}]$

- **Hydraulic system 2**



$$f_1 = \frac{a_{equ}}{\lambda_1} = \frac{a_{equ}}{2 \cdot l_{tot}} \cdot 1$$

$$f_o = \frac{1}{2 \cdot \pi} \frac{a_{DT}}{\sqrt{l_{DT} \cdot l_{TR} \frac{A_{DT}}{A_{TR}}}}$$

a = 50 m/s

System 2	Analytical calculation a DT (min) [m/s]	Eigen value calculation a DT (min) [m/s]	Relative error [%]
f0 [Hz]	0.25	0.27	-7.41
f1 [Hz]	0.96	0.27	255.56
f2 [Hz]	1.92	2.04	-5.88
f3 [Hz]	2.88	2.53	13.83
f4 [Hz]	3.85	4.12	-6.55
f5 [Hz]	4.81	4.87	-1.23
f6 [Hz]	5.77	5.16	11.82

a = 100 m/s

System 2	Analytical calculation a DT (max) [m/s]	Eigen value calculation a DT (max) [m/s]	Relative error [%]
f0 [Hz]	0.5	0.55	-9.09
f1 [Hz]	1.19	0.55	116.36
f2 [Hz]	2.38	2.1	13.33
f3 [Hz]	3.57	4.05	-11.85
f4 [Hz]	4.76	4.88	-2.46
f5 [Hz]	5.95	6.18	-3.72
f6 [Hz]	7.14	6.36	12.26

- 1st order: Good agreement with f_0
- 2nd-6th order: Rather good agreement for natural frequencies Maximum error of 14%.
- Risk of resonance with the draft tube in red.

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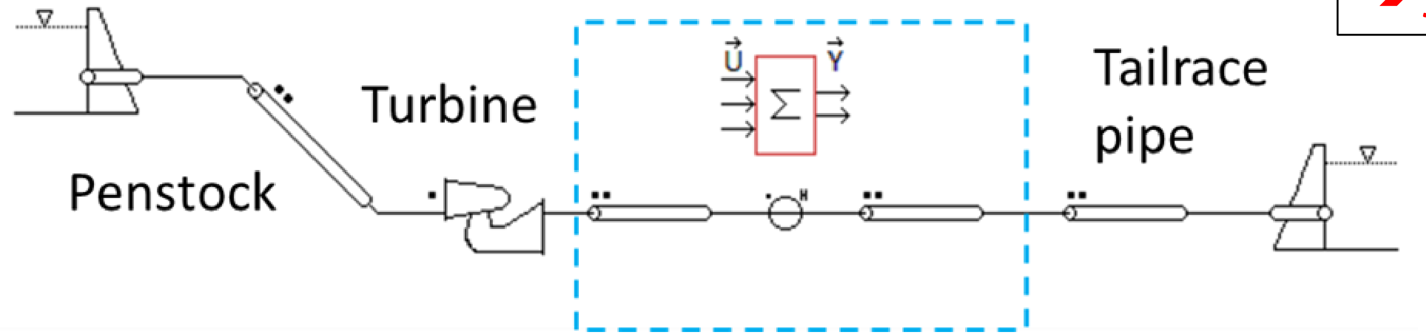
Example of applications

- **Hydraulic system 3**

N_n = 750 rpm = 12.5 Hz
➔ $f_{excitation}$ = [0.2 – 0.4]·f_n
➔ $f_{excitation}$ = [2.5 – 5 Hz]



$f_{excitation}$ = [2.5 – 5 Hz]

Penstock			
L	=	300	m
D	=	1.2	m
a	=	1’250	m/s
λ	=	0.012	-

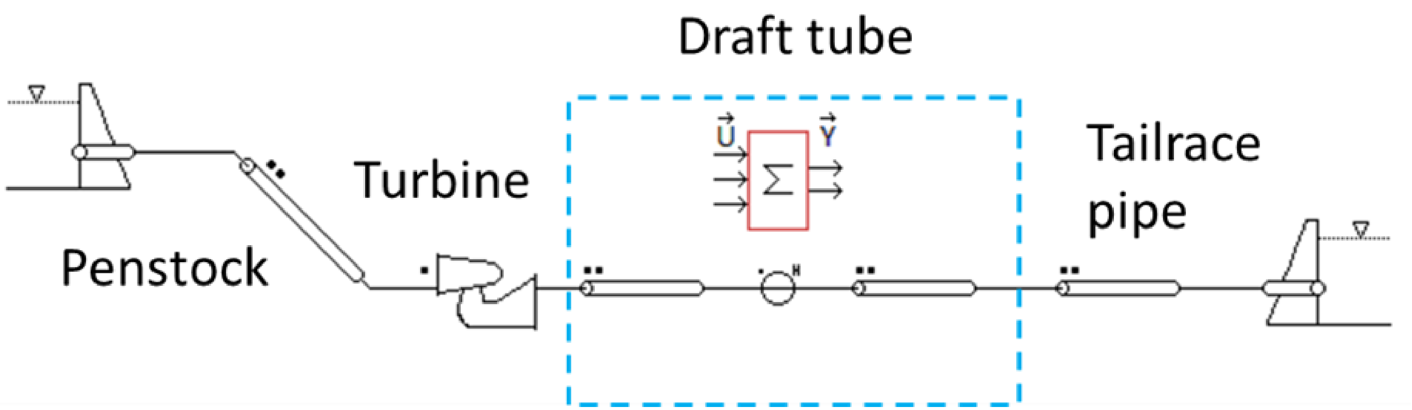
Turbine			
Pn	=	5	MW
Qn	=	5.0	m^3/s
Hn	=	100	mWC
Nn	=	750	rpm
Dref	=	0.846	m
Nq	=	53	-

Draft tube			
L	=	10	m
D	=	1.2	m
a	**=**	**[50-100]**	**m/s**
λ	=	0.012	-

Tailrace pipe			
L	=	100	m
D	**=**	**2**	**m**
a	=	1’250	m/s
λ	=	0.012	-

Example of applications

- **Hydraulic system 3**

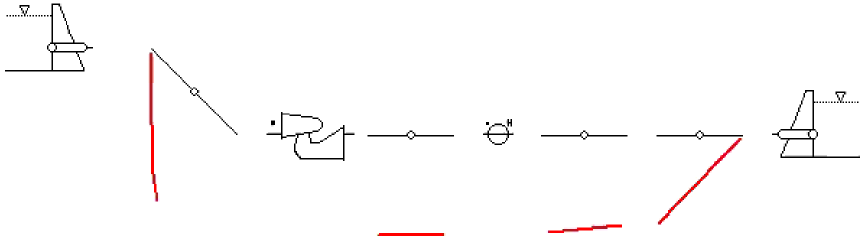


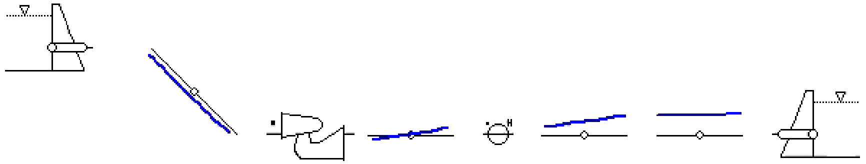
Rigid column mode shape

- ✓ Linear amplitude variation of pressure in the TR
- ✓ Constant amplitude variation of discharge in the TR
- → Similar to surge tank mass oscillation between TR pipe and DT compliance

~~$$f_1 = \frac{a_{equ}}{\lambda_1} = \frac{a_{equ}}{2 \cdot l_{tot}} \cdot 1$$~~

$$f_o = \frac{1}{2 \cdot \pi} \frac{a_{DT}}{\sqrt{l_{DT} \cdot l_{TR} \frac{A_{DT}}{A_{TR}}}}$$





1st Pressure mode

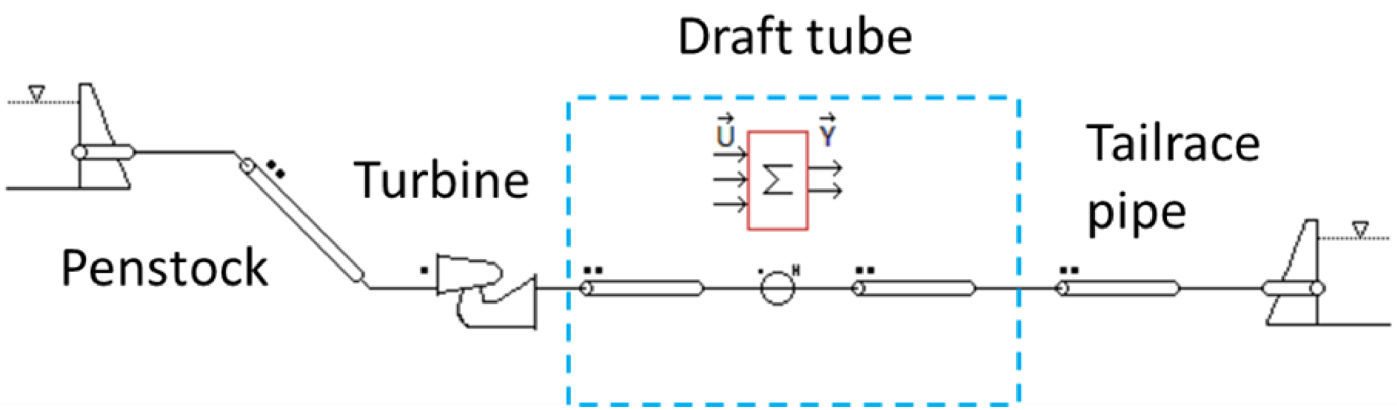
Rigid column mode shape

1st Discharge mode

Example of applications

$f_{excitation}$ = [2.5 – 5 Hz]

- **Hydraulic system 3**



a = 50 m/s

System 3	Analytical calculation a DT (min) [m/s]	Eigen value calculation a DT (min) [m/s]	Relative error [%]
f0 [Hz]	0.42	0.42	0.00
f1 [Hz]	0.96	0.42	128.57
f2 [Hz]	1.92	2.04	-5.88
f3 [Hz]	2.88	2.55	12.94
f4 [Hz]	3.85	4.12	-6.55
f5 [Hz]	4.81	4.84	-0.62
f6 [Hz]	5.77	6.16	-6.33

a = 100 m/s

System 3	Analytical calculation a DT (max) [m/s]	Eigen value calculation a DT (max) [m/s]	Relative error [%]
f0 [Hz]	0.84	0.81	3.70
f1 [Hz]	1.19	0.81	46.91
f2 [Hz]	2.38	2.1	13.33
f3 [Hz]	3.57	4.03	-11.41
f4 [Hz]	4.76	4.72	0.85
f5 [Hz]	5.95	6.14	-3.09
f6 [Hz]	7.14	6.55	9.01

- 1st order: Good agreement with f_0
- 2nd-6th order: Rather good agreement for natural frequencies Maximum error of 14%.
- Risk of resonance with the draft tube in red.

Contents

- Context and key goals
- Eigenvalue computation
  - ✓Numerical equations
  - ✓Analytical equations
- Examples of application
  - ✓Hydraulic system 1
  - ✓Hydraulic system 2
  - ✓Hydraulic system 3
- Conclusions / Take away message

Conclusions

- Analytical approach to determine the possible risk of resonance with the draft tube vortex rope excitation (2.5-5Hz)

- **1st order:** Better agreement with f_1 for the hydraulic system without a tailrace pipe (hydraulic system 1) → Elastic mode shape
- **1st order:** Good agreement with f_0 for the hydraulic system with a tailrace pipe (hydraulic system 2 & 3) → rigid column mode shape

- **2nd-6th order:** Rather good agreement for natural frequencies (Maximum error of 14%).

- Limitations of the methodology
  - ✓ Parallel branches:
    - Modelling by a single branch with equivalent parameters to obtain a first order of magnitude.
    - Real system will feature much more complex and numerous eigenvalues (hydraulic system asymmetry, diameters, bifurcations)

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Take away Message

- This analytical method is included as ANNEXE E.2 of the new IEC Technical Specification 62882 ED1 (to be issued in 2020)

Without a tailrace pipe

1st order

$$f_k = \frac{a_{equ}}{\lambda_k} = \frac{a_{equ}}{2 \cdot l_{tot}} \cdot k$$

2nd–6th order

$$f_k = \frac{a_{equ}}{\lambda_k} = \frac{a_{equ}}{2 \cdot l_{tot}} \cdot k$$

With a tailrace pipe

1st order

$$f_o = \frac{1}{2 \cdot \pi} \frac{a_{DT}}{\sqrt{l_{DT} \cdot l_{TR} \frac{A_{DT}}{A_{TR}}}}$$

2nd–6th order

$$f_k = \frac{a_{equ}}{\lambda_k} = \frac{a_{equ}}{2 \cdot l_{tot}} \cdot k$$

Hydraulic machines – IEC Technical specification for Francis turbine pressure fluctuation


IEC

4/375/DTS

DRAFT TECHNICAL SPECIFICATION (DTS)

PROJECT NUMBER: IEC TS 62882 ED1	
DATE OF CIRCULATION: 2019-08-30	CLOSING DATE FOR VOTING: 2019-11-22
SUPERSEDES DOCUMENTS: 4/352/CD,4/369A/CC	

IEC TC 4 : HYDRAULIC TURBINES	
SECRETARIAT: Canada	SECRETARY: Mr Robert Arseneault
OF INTEREST TO THE FOLLOWING COMMITTEES: TC 2,TC 114	
FUNCTIONS CONCERNED: ☐ EMC ☐ ENVIRONMENT ☐ QUALITY ASSURANCE ☐ SAFETY	

This document is still under study and subject to change. It should not be used for reference purposes.

Recipients of this document are invited to submit, with their comments, notification of any relevant patent rights of which they are aware and to provide supporting documentation.

TITLE:

Hydraulic machines – Technical specification for francis turbine pressure fluctuation transposition

proposed stability date: 2022

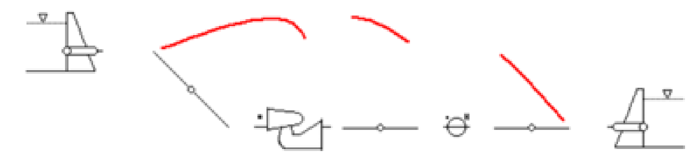
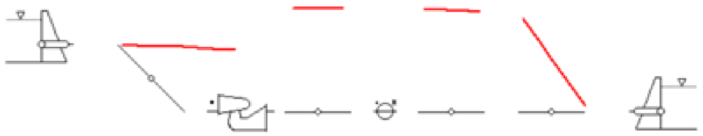
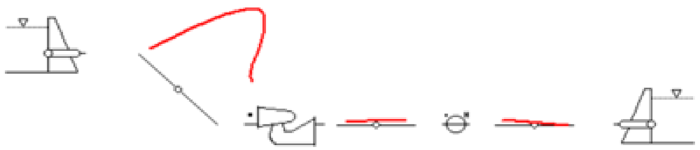
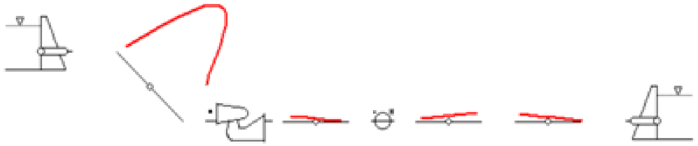
NOTE FROM TC/SC OFFICERS:

Thank you for your attention!

Power Vision Engineering

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

Example of applications

	Hydraulic system 1	Hydraulic system 2
f1		
f2		
f3