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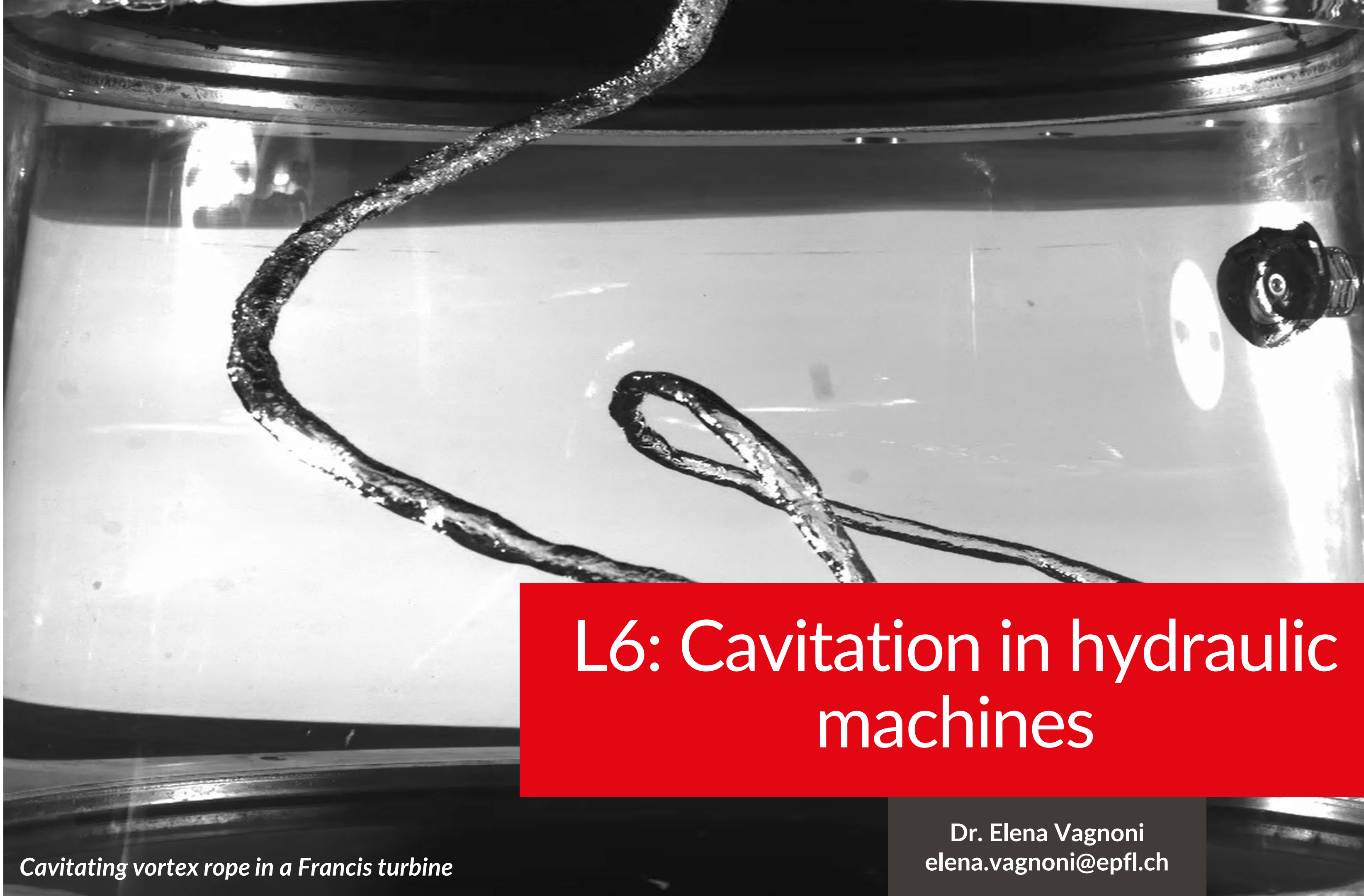

Cavitating vortex rope in a Francis turbine

L6: Cavitation in hydraulic machines

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Collapsing cavitation bubble

Topics of the lecture

Cavitation Characteristics

Setting level of hydraulic machines

Cavitation in hydraulic turbines

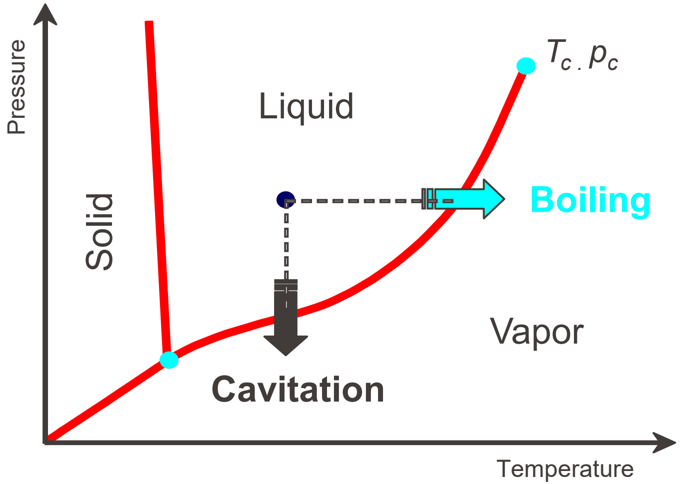
Cavitation in pumps

Cavitation Damages

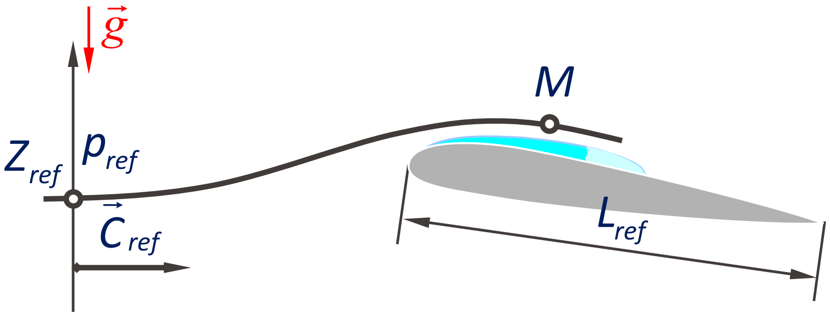
Cavitation Detection Techniques

Cavitation phenomenon

- Liquid Vaporization by **Pressure Decrease**
- Cavity Onset $p \leq p_{vapor}$



Cavitation Onset in a hydrofoil



- Local Specific Energy Balance

$$\frac{p_{ref}}{\rho} + gZ_{ref} + \frac{C_{ref}^2}{2} = \frac{p}{\rho} + gZ + \frac{C^2}{2} + gH_r$$

- Pressure Coefficient

$$Cp = \frac{p - p_{ref}}{\frac{1}{2}\rho C_{ref}^2} = 1 - \frac{C^2}{C_{ref}^2} + \frac{2gL_{ref}}{C_{ref}^2}\left(\frac{Z_{ref} - Z}{L_{ref}}\right) - \frac{2gH_r}{C_{ref}^2}$$

with $\frac{p - p_{ref}}{\rho} = \frac{C_{ref}^2 - C^2}{2} + g\left(Z_{ref} - Z\right) - gH_r$

Nomenclature:

C	(m/s)	Flow Absolute velocity
p	(Pa)	Static Pressure
Z	(m)	Elevation
g	(m/s^2)	Gravity Acceleration
H	(m)	Head
H_r	(m)	Head losses
ρ	(kg/m^3)	Water density

Cavitation onset in hydrofoil

$$Cp = 1 - \underbrace{\frac{C^2}{C_{ref}^2}}_{\text{Acceleration}} - \overbrace{e_r\left(\mathrm{Re}, \text{Turbulence}\right)}^{\text{Flow Dissipation}} + \underbrace{\frac{1}{Fr^2}\left(\frac{Z_{ref} - Z}{L_{ref}}\right)}_{\text{Level Setting}} \leq -\sigma$$

- Cavitation Onset
  - $p \leq p_v$
  - $Cp \leq -\sigma$
- Causes of Cavitation for a given level setting:
  - Flow Acceleration
  - Dissipation

- Cavitation Coefficient

$$\sigma = \frac{p_{ref} - p_v}{\frac{1}{2}\rho C_{ref}^2}$$

- Froude Number

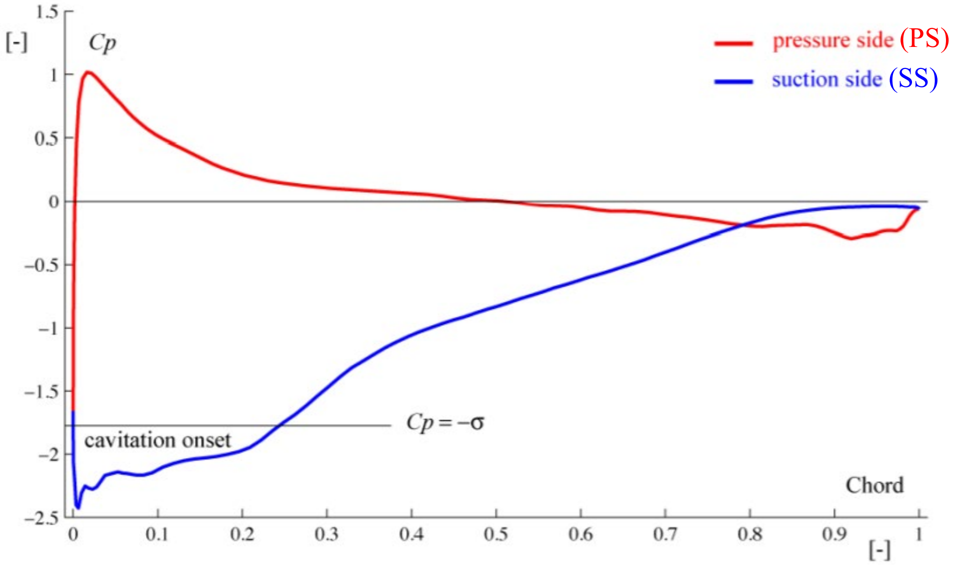
$$Fr = \frac{C_{ref}}{\sqrt{2gL_{ref}}}$$

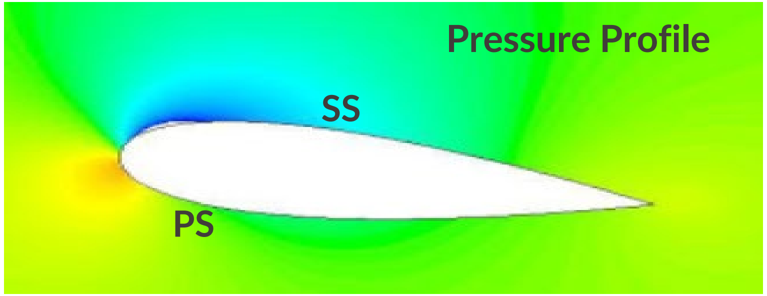
- Reynolds Number

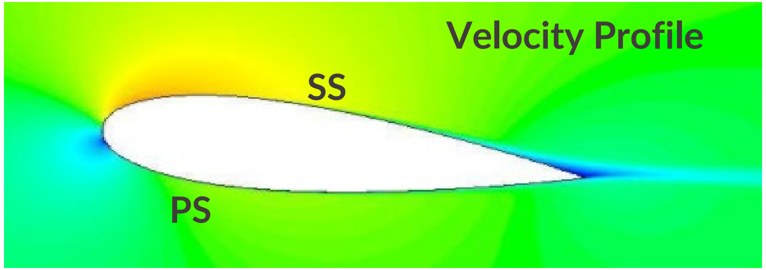
$$\mathrm{Re} = \frac{C_{ref} \cdot L_{ref}}{\nu}$$

Causes of Cavitation Onset and Development

$$Cp = 1 - \underbrace{\frac{C^2}{C_{ref}^2}}_{\text{Acceleration}} - \overbrace{e_r\left(\text{Re}, \text{Turbulence}\right)}^{\text{Flow Dissipation}} + \underbrace{\frac{1}{Fr^2}\left(\frac{Z_{ref} - Z}{L_{ref}}\right) \le -\sigma}_{\text{Level Setting}}$$



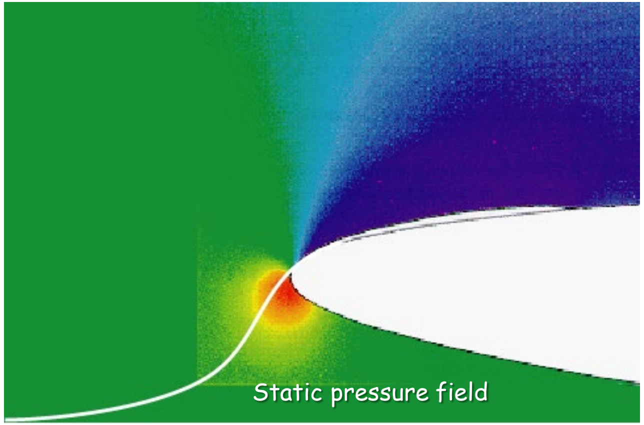


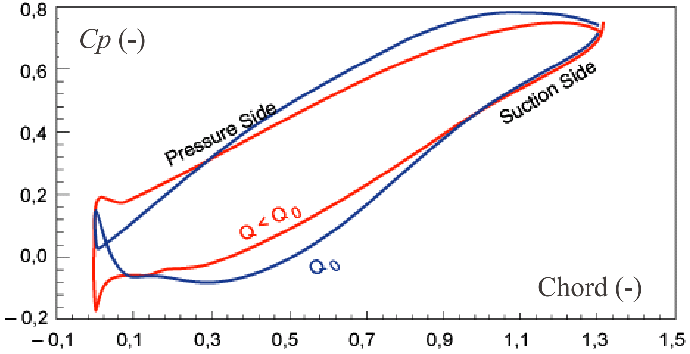


Causes of Cavitation Onset and Development

$$Cp = 1 - \underbrace{\frac{C^2}{C_{ref}^2}}_{\text{Acceleration}} - \overbrace{e_r\left(\mathrm{Re}, \text{Turbulence}\right)}^{\text{Flow Dissipation}} + \underbrace{\frac{1}{Fr^2}\left(\frac{Z_{ref} - Z}{L_{ref}}\right)}_{\text{Level Setting}} \leq -\sigma$$

- Flow Acceleration:
  - Flow Deviation
  - Flow Singularity: Sharp Edges, Vorticity Lines





Nomenclature:
Q $(\mathrm{m}^3/\mathrm{s})$ Discharge

Topics of the lecture

Power House Veytaux I (Switzerland)

Cavitation Characteristics

Setting level of hydraulic machines

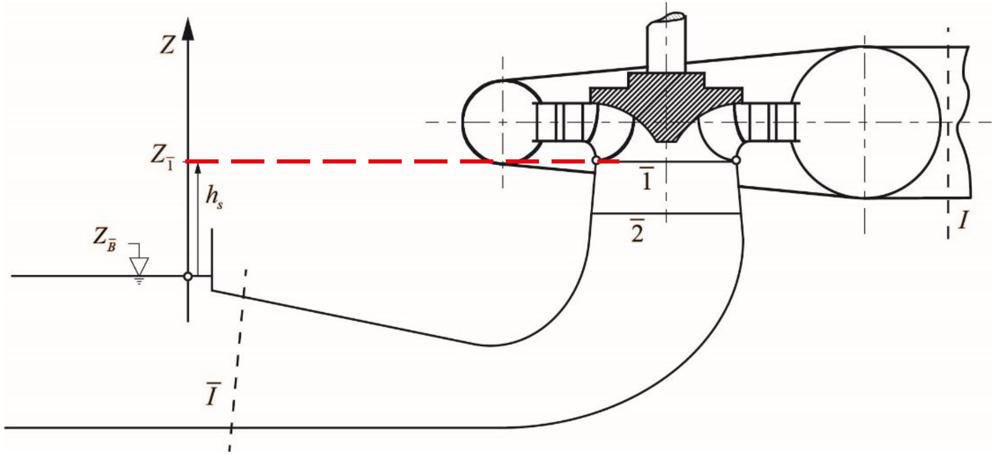
Cavitation in hydraulic turbines

Cavitation in pumps

Cavitation Damages

Cavitation Detection Techniques

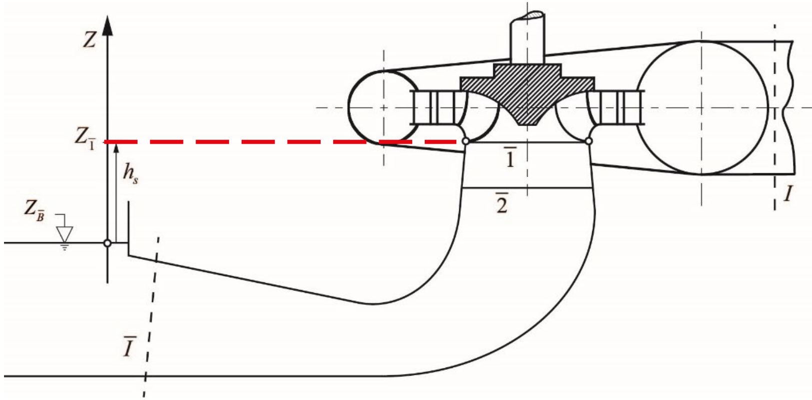
Machine Setting Level



Cut-view of a Francis turbine

- IEC 60193 Definitions
  - Specific Energy
    $$E \triangleq gH_I - gH_{\bar{I}} > 0 \quad \left(\mathrm{J \cdot kg^{-1}}\right)$$
  - Net Positive Suction Specific Energy
    $$NPSE \triangleq gH_{\bar{I}} - \frac{p_v}{\rho} - gZ_{ref} \quad \left(\mathrm{J \cdot kg^{-1}}\right)$$
  - Setting Level
    $$h_s = Z_{ref} - Z_{\bar{B}} = Z_{\bar{1}} - Z_{\bar{B}}$$

Machine Setting Level



- With Respect to the Tail Water Level $\bar{B}$
  - Specific Energy Balance $gH_{\bar{I}} = gH_{\bar{B}} + gH_{r\bar{I} \div \bar{B}}$

$$gH_{\bar{B}} = \frac{p_a}{\rho} + gZ_{\bar{B}}$$

  - For Turbines $gH_r \approx \frac{C_{\bar{I}}^2}{2}$

$$NPSE \approx \frac{p_a}{\rho} - \frac{p_v}{\rho} - gh_s + \frac{C_{\bar{I}}^2}{2} = g \times NPSH$$

  - For Pumps $gH_r \approx \frac{C_{\bar{I}}^2}{2} \approx 0$

$$NPSE \approx \frac{p_a}{\rho} - \frac{p_v}{\rho} - gh_s = g \times NPSH$$

  - Thoma number: $\sigma_{TH} = \frac{NPSE}{E}$

Nomenclature:

$NPSH$ (m) Net Positive Suction Head

Cavitation breakdown curve

Nomenclature:

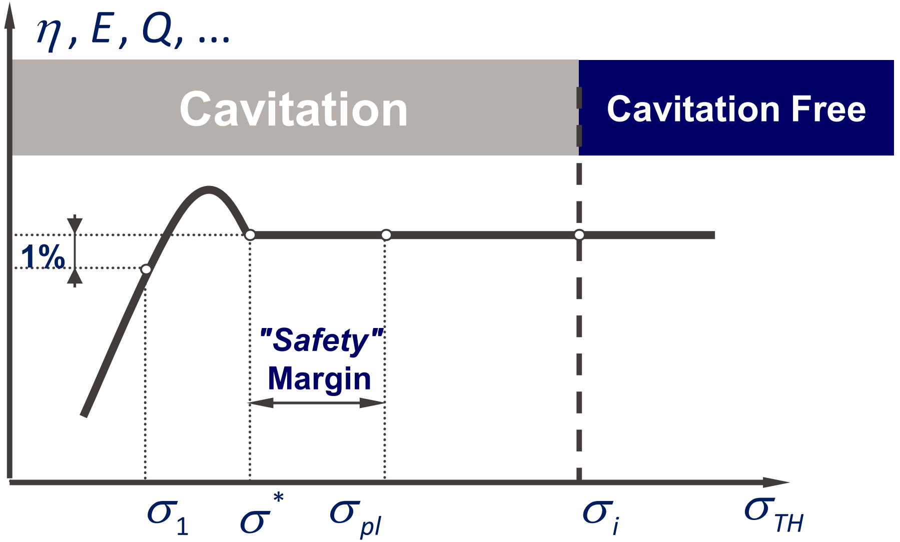
η (-) Efficiency

σ_i (-) Inception: 1st Cavity !

σ_{pl} (-) Plant Value

σ_* (-) 1st Efficiency Change

σ_1 (-) 1% Efficiency Drop



Inter-blade cavitating vortex at deep-part load condition in a Francis turbine

Topics of the lecture

Cavitation Characteristics

Setting level of hydraulic machines

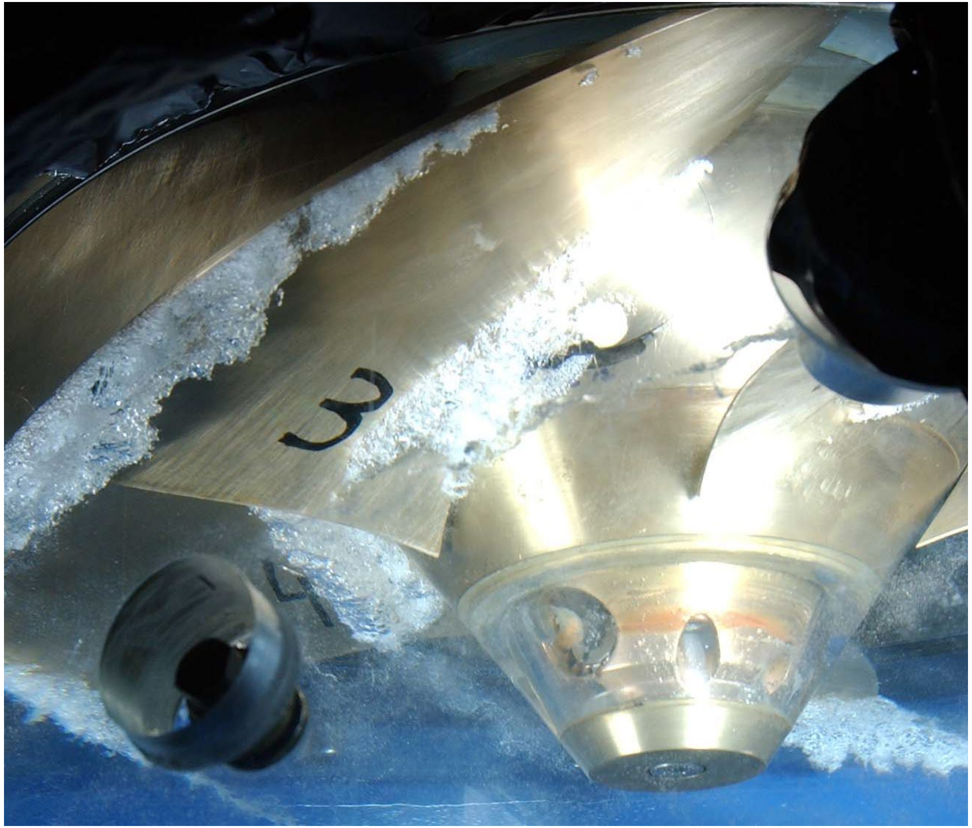
Cavitation in hydraulic turbines

Cavitation in pumps

Cavitation Damages

Cavitation Detection Techniques

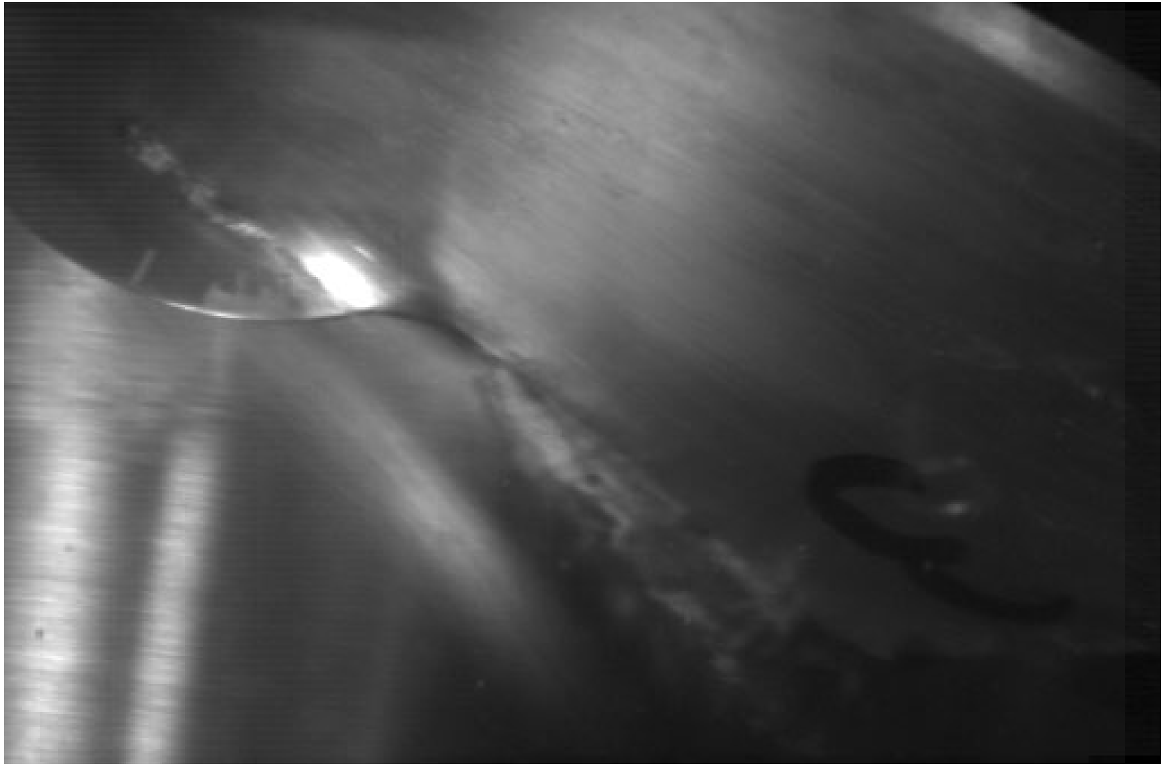
Cavitation in Axial Turbines



Kaplan Cavitation Test
Brilliant Model Acceptance Tests

Kaplan runner: double regulated hydraulic turbine (guide vanes and blades positioning can be adjusted)

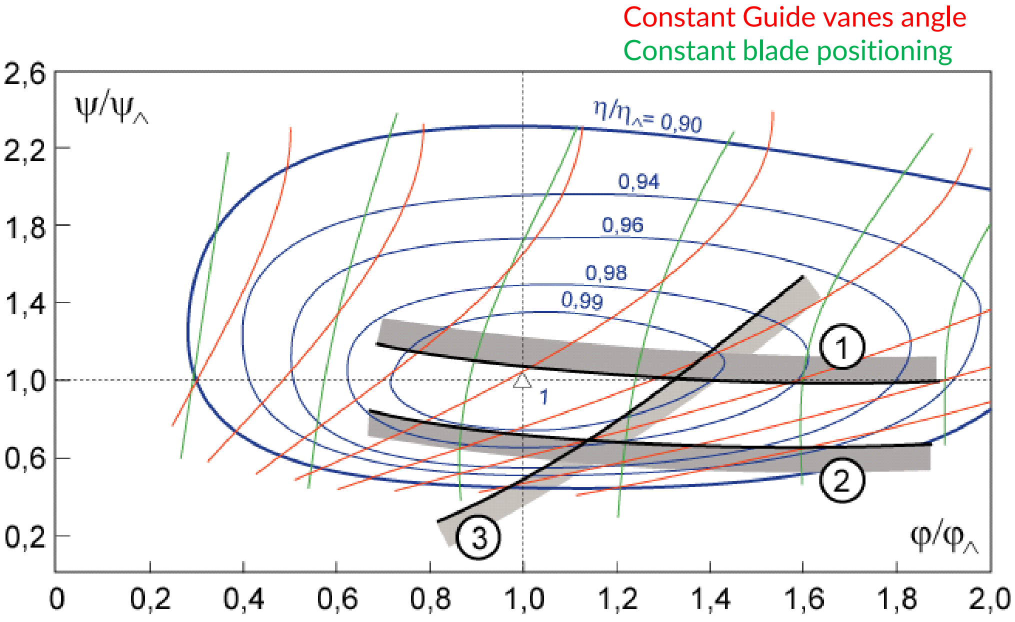
Kaplan Turbine Cavitation



Kaplan Turbine Cavitation mapping

Specific Energy Coefficient

$$\psi = \frac{2}{\pi^2}\frac{E}{n^2D^2}$$



Tip leakage Cavitation

- 1- Leading Edge Suction Side
- 2- Leading Edge Pressure Side
- 3- Hub Cavitation
- Tip leakage Cavitation

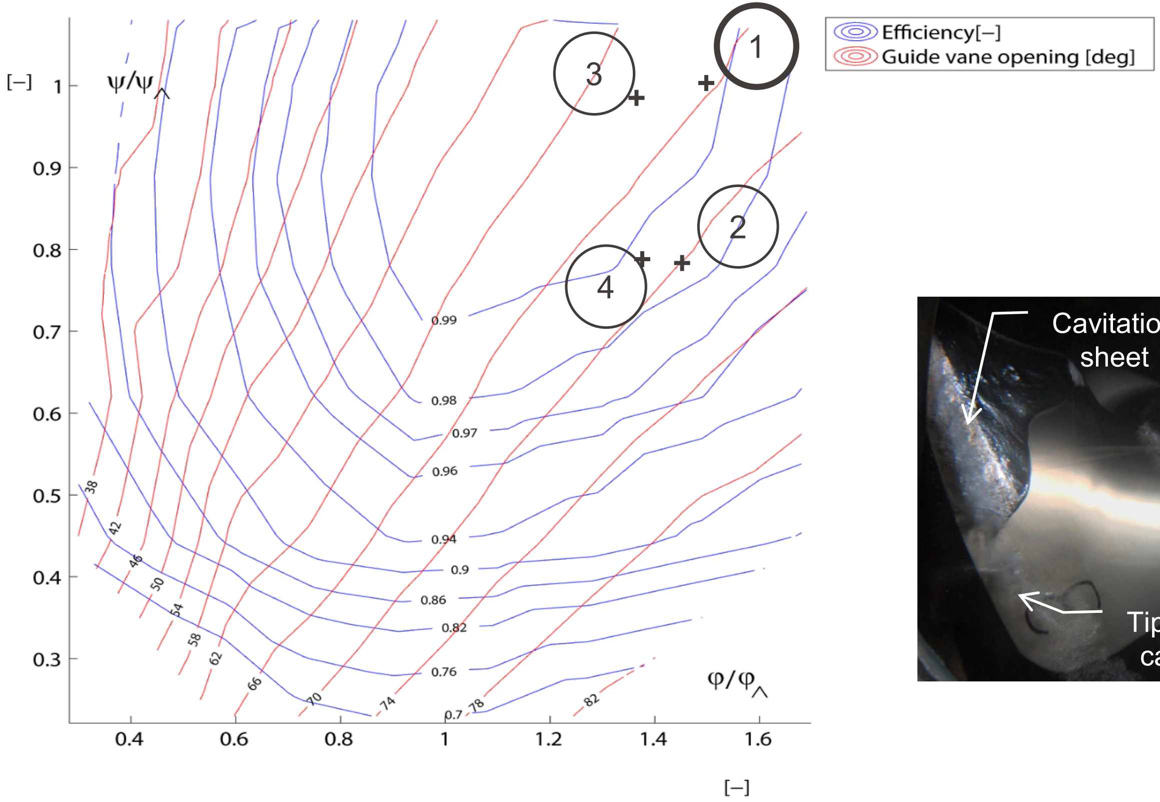
Nomenclature:

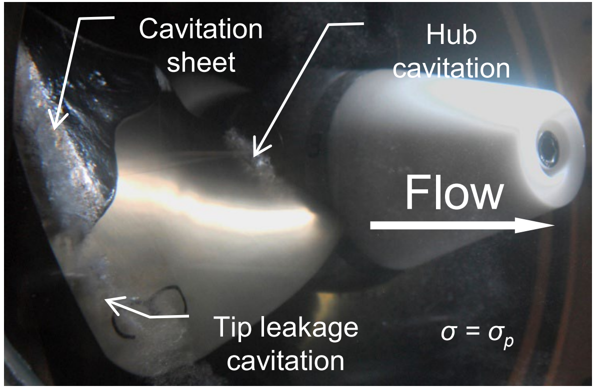
η_Δ (-) Efficiency at Best Efficiency Point (BEP)

Discharge Coefficient

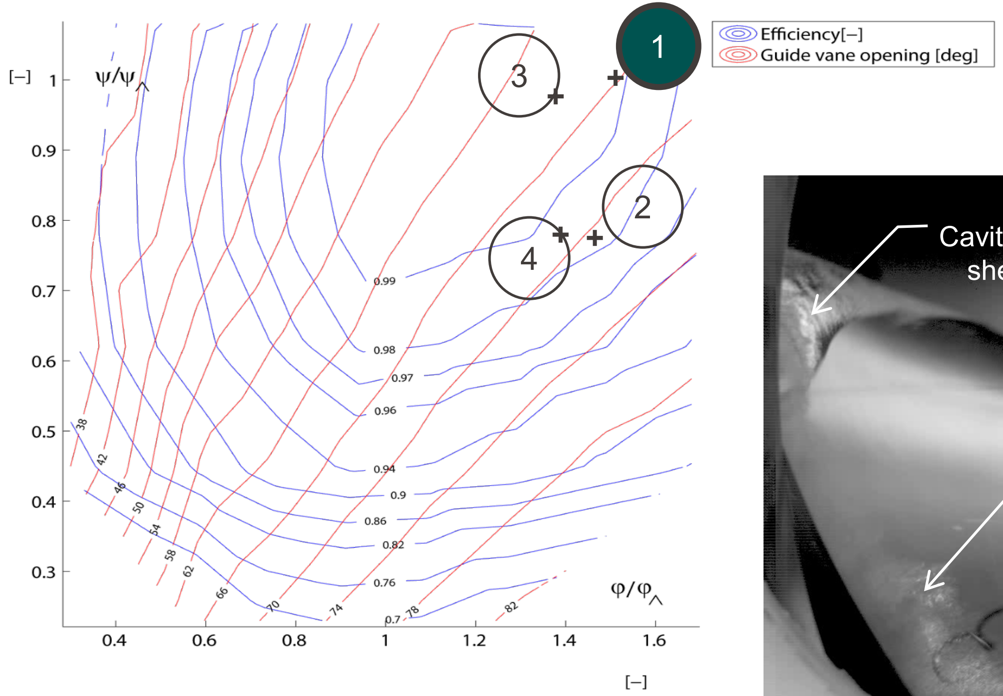
$$\varphi = \frac{4}{\pi^2}\frac{Q}{nD^3}$$

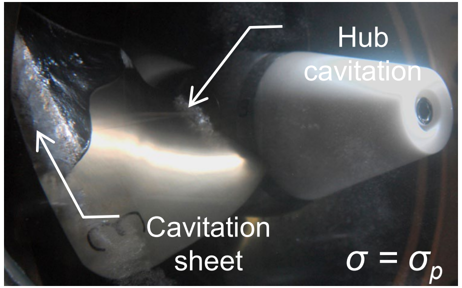
Bulb Turbine Cavitation Mapping

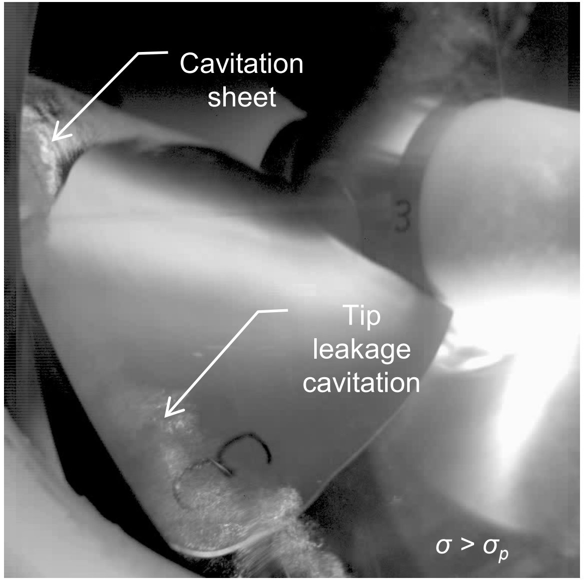




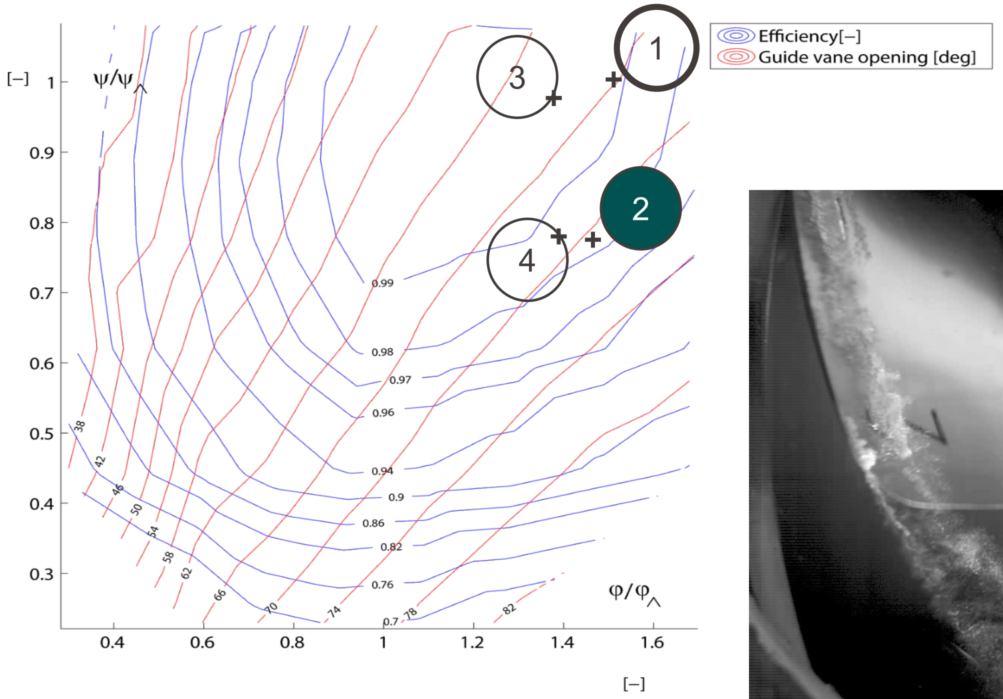
Bulb Turbine Cavitation Mapping

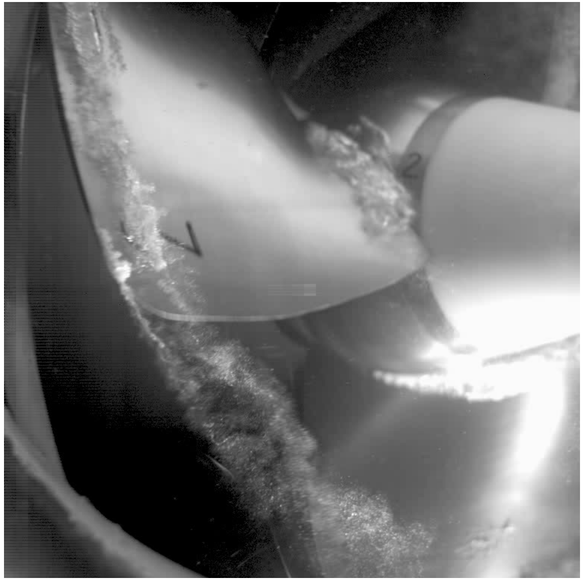


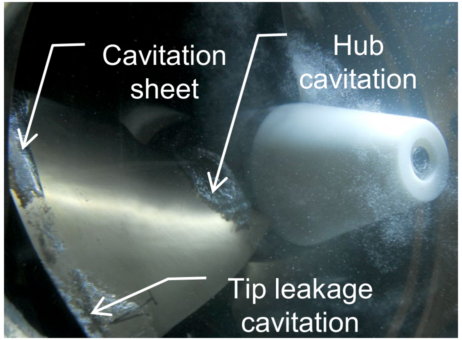




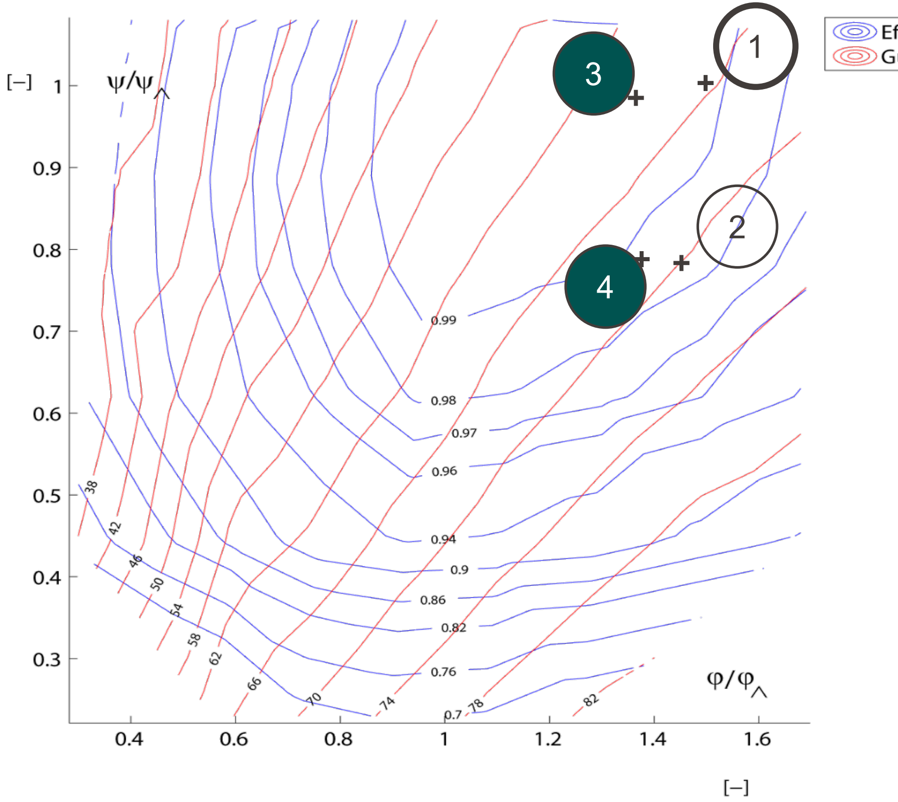
Bulb Turbine Cavitation Mapping

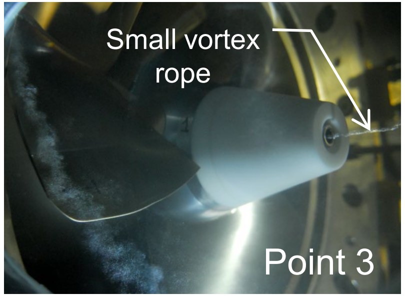


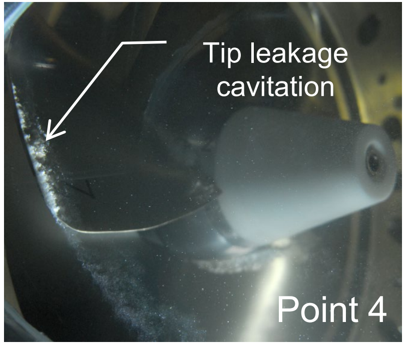




Bulb Turbine Cavitation Mapping





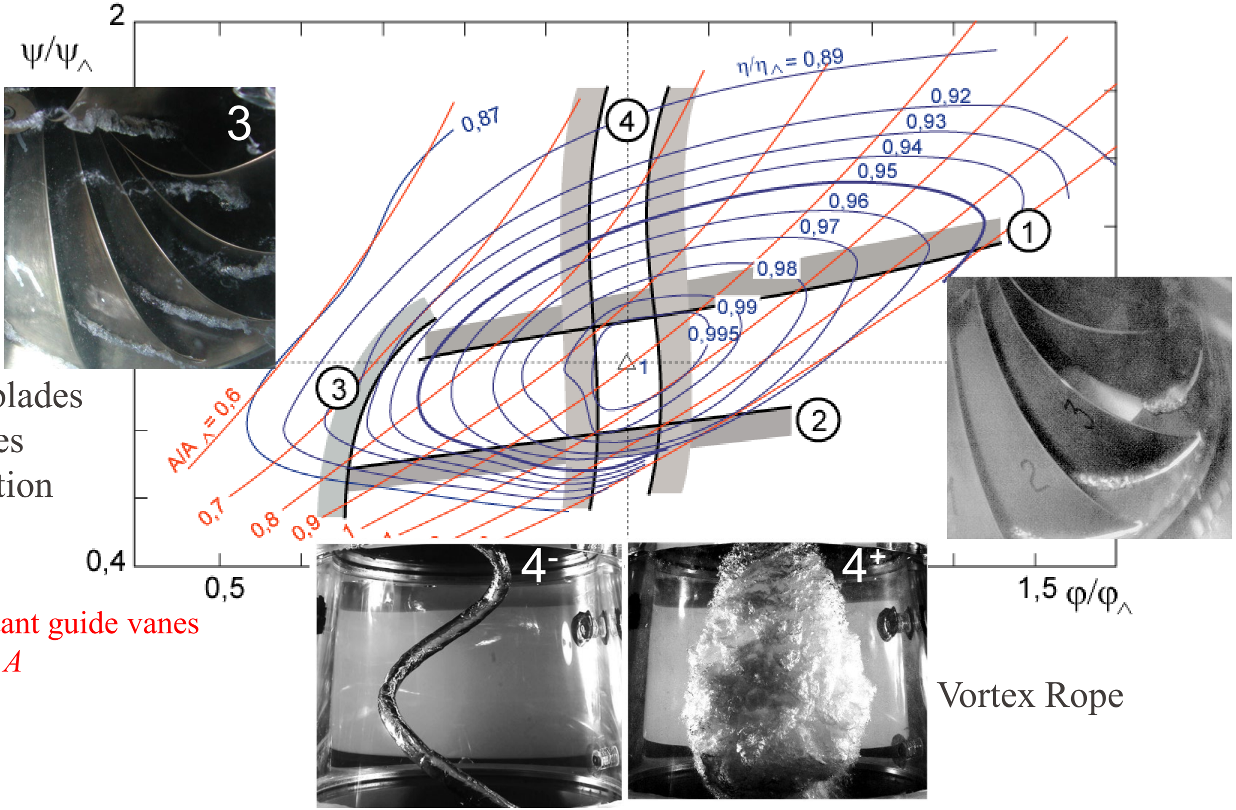


Cavitation in Francis Turbines

Cavitating vortex rope

Francis runner

Francis Turbine Cavitation Mapping



Inter-blades vortices cavitation

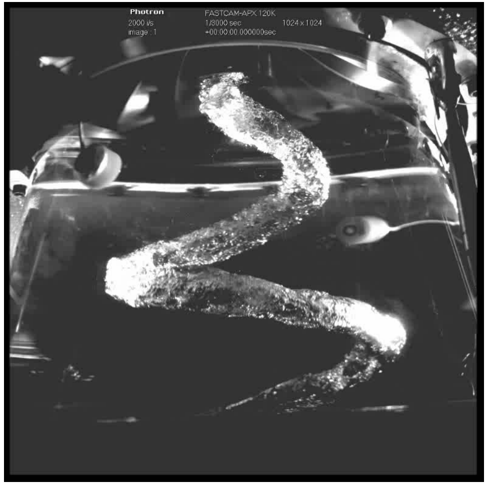
Leading edge sheet cavitation

Vortex Rope

Constant guide vanes angle *A*

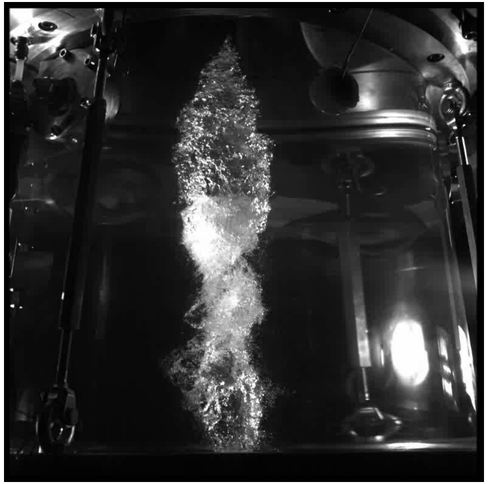
Francis Turbine Cavitation Vortex Rope

Part Load Condition



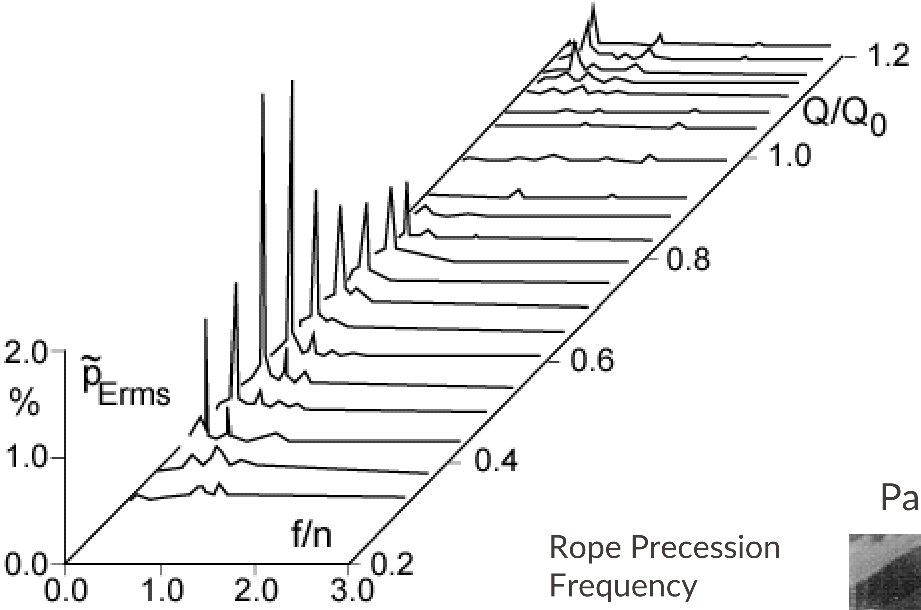
$Q < Q_0$

Full Load Condition



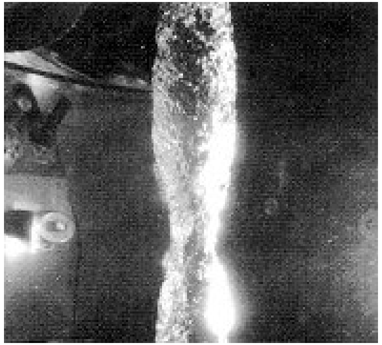
$Q > Q_0$

Francis Turbine Cavitation Vortex Rope



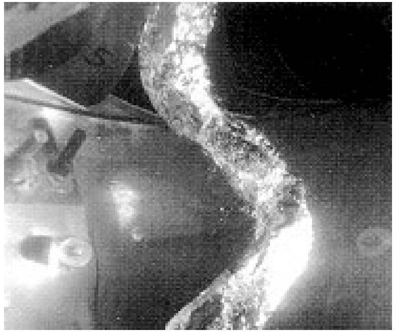
Rope Precession Frequency
f/n = 0.25 – 0.4

Full Load Condition



Axisymmetric vortex

Part Load Condition



Topics of the lecture

Cavitation Chacteristics

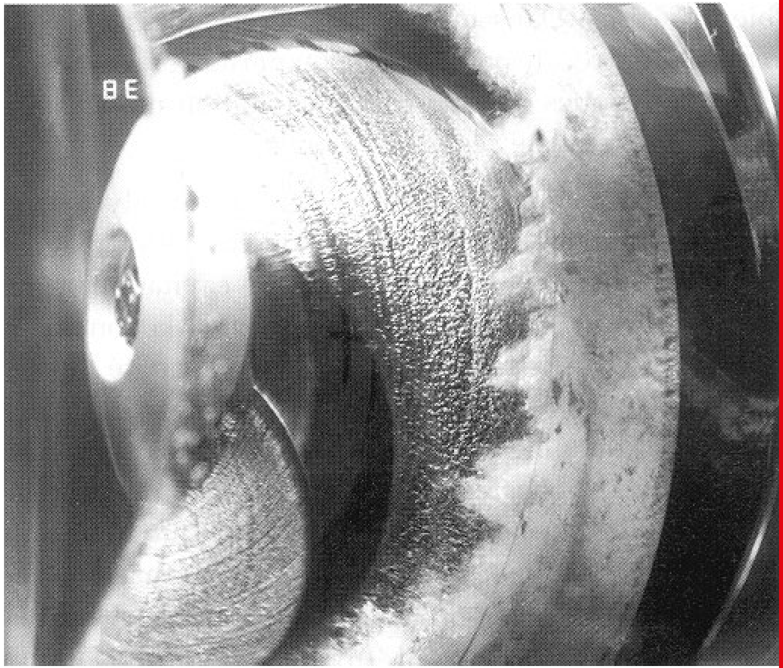
Setting level of hydraulic machines

Cavitation in hydraulic turbines

Cavitation in pumps

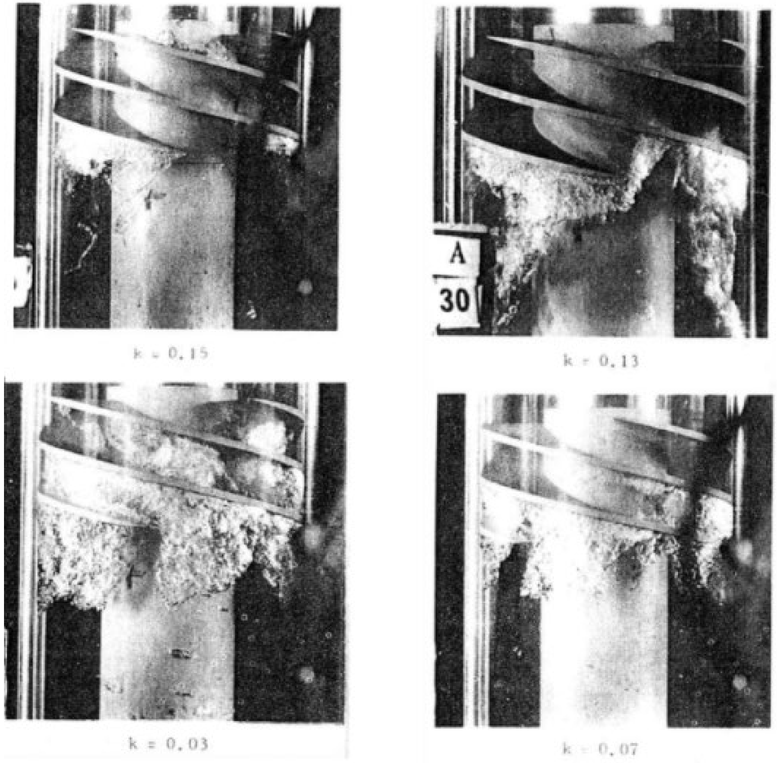
Cavitation Damages

Cavitation Detection Techniques

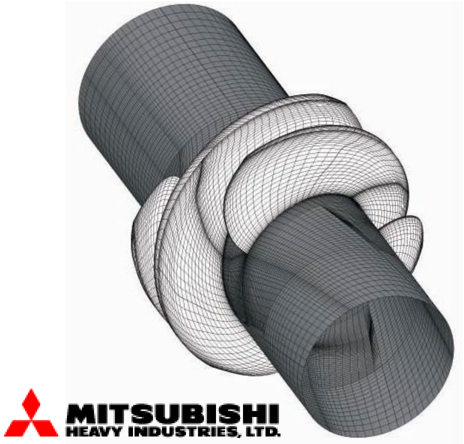


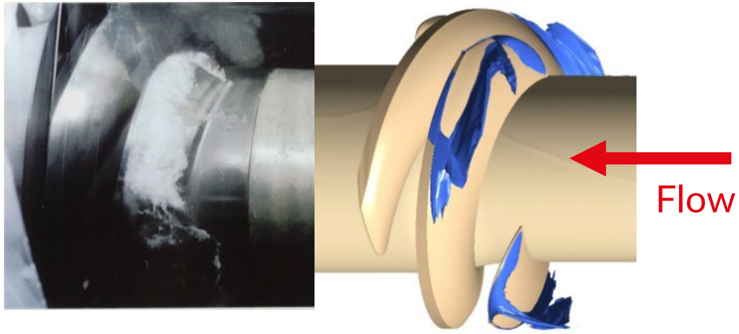
LH_2 Inducer Cavitation Development

Cavitation in Axial pumps



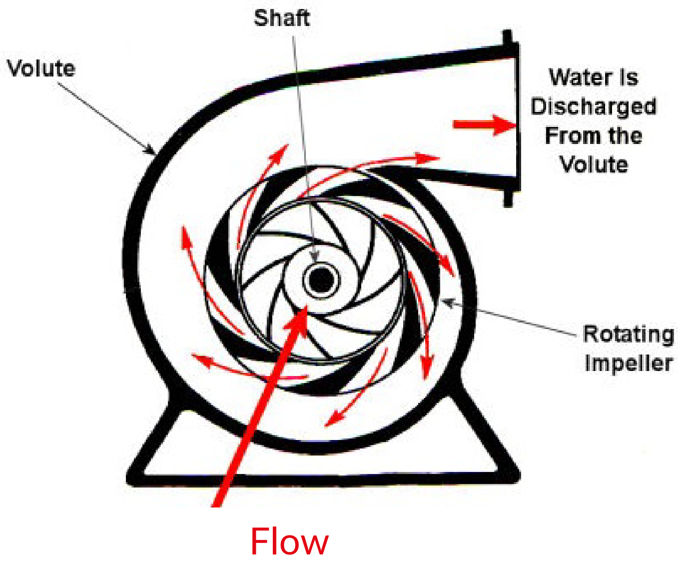
Cavitating structures in a rocket inducer, Acosta (1958).



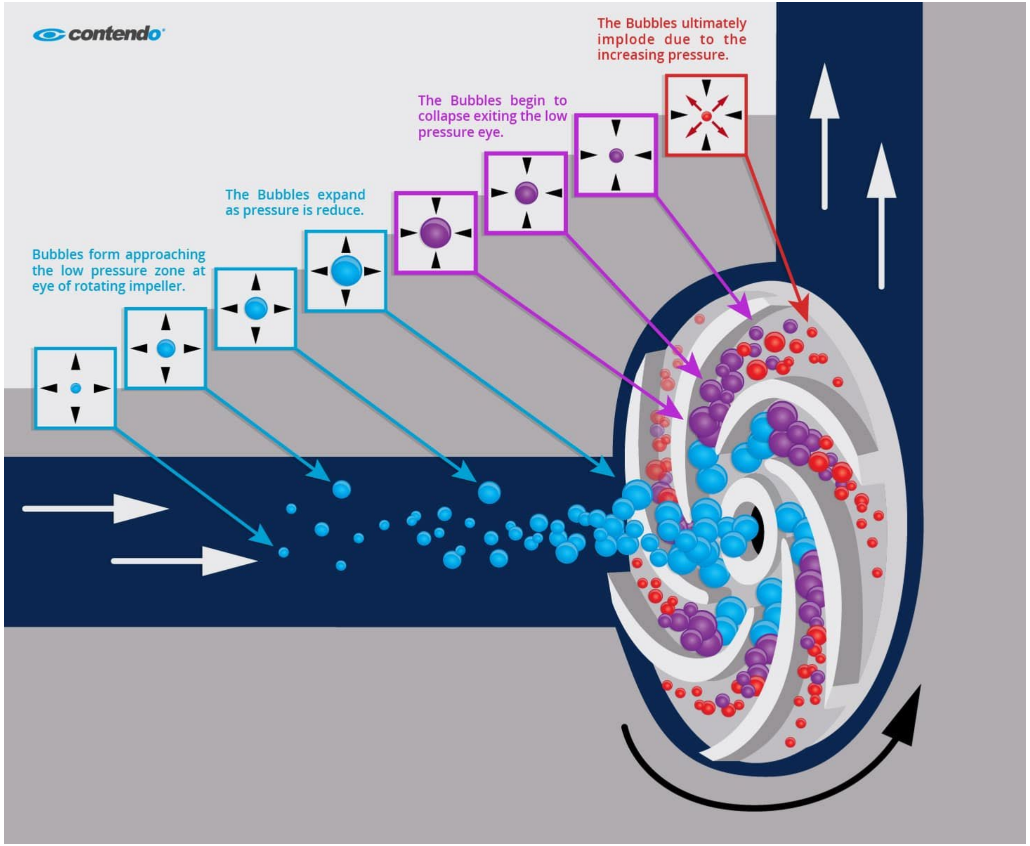


Industrial inducer, BOUZIAD (1994)

Cavitation in Centrifugal pumps



Centrifugal pump, Philip J. O'Keefe (2018)



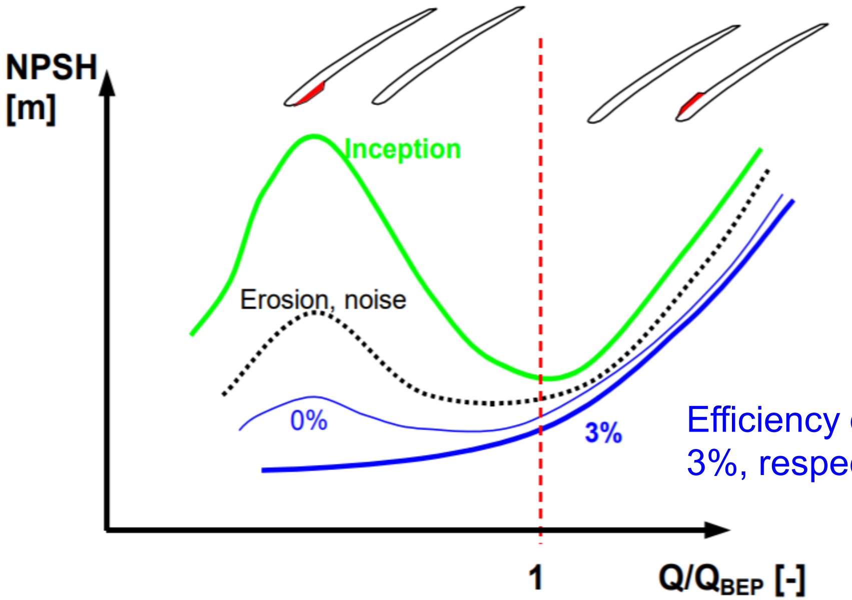
Cavitation in Pumps: *"Bucket"* Curves

Main Cavitation types:

- Suction Cavitation
- Discharge Cavitation

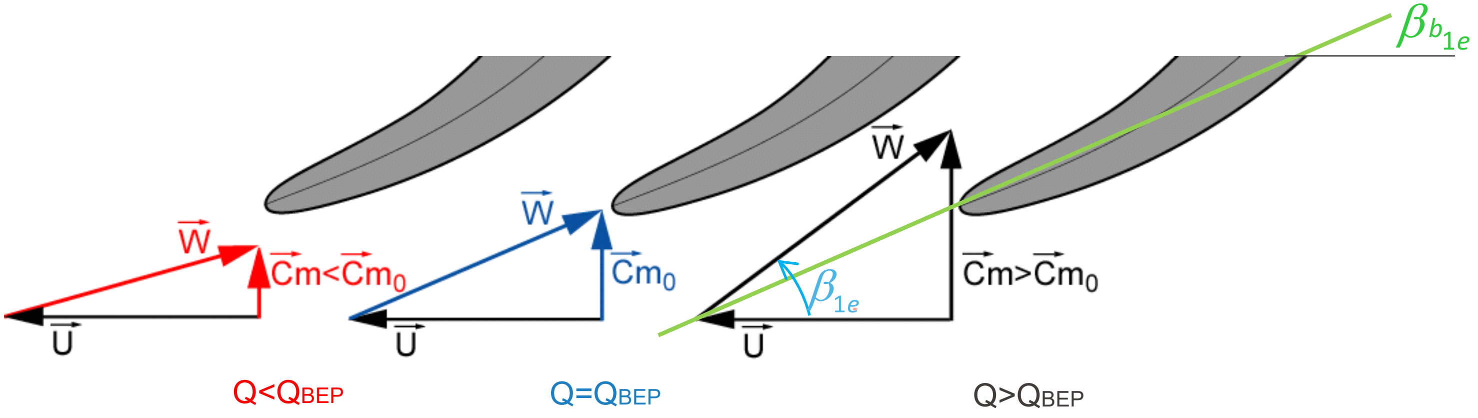
Main Cavitation structures in pumps:

- Sheet Cavitation at the leading edge (suction side or pressure side)
- Travelling bubbles
- Vortical structure



Efficiency decrease of 0% and 3%, respectively

Relative flow angle incidence



Negative incidence

i = 0

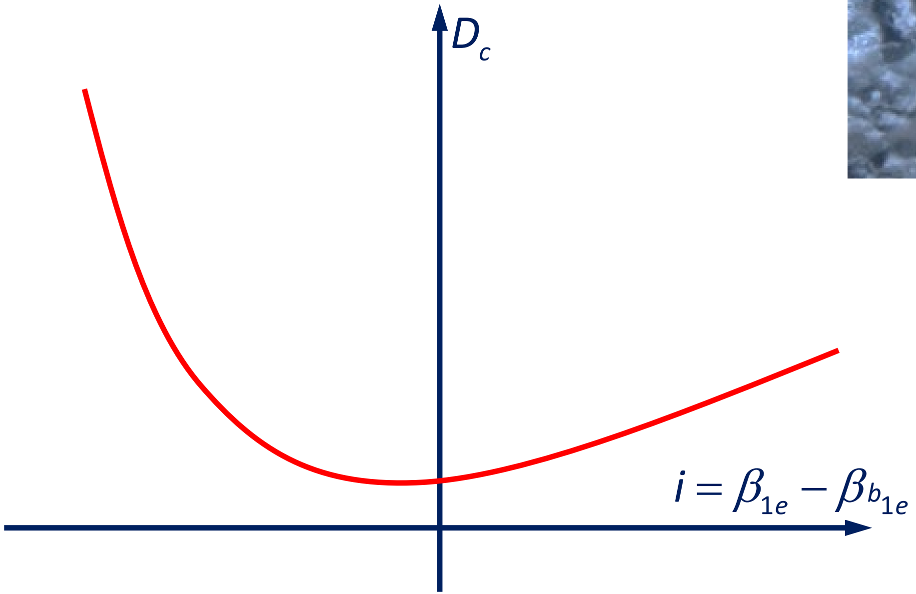
Positive incidence

Nomenclature:

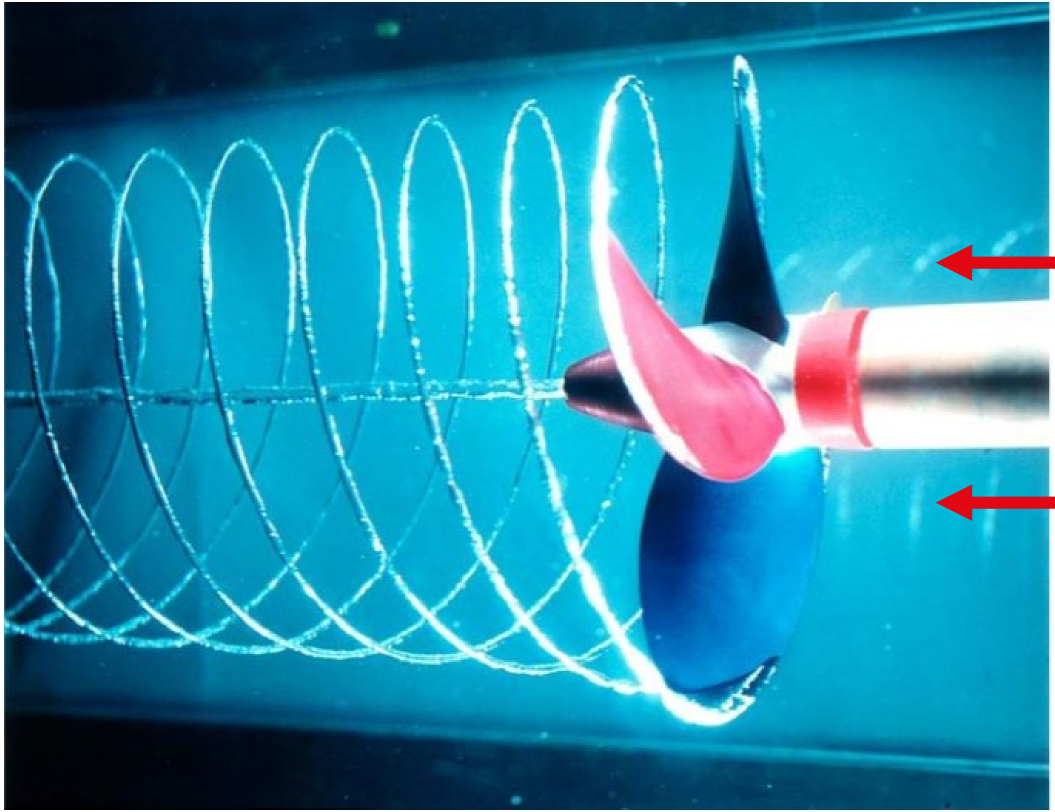
$\beta_{b,1e}$ (°) Blade Pitch Angle
β_{1e} (°) Relative Flow Angle
W (m/s) Relative Flow Velocity
U (m/s) Tangential Flow Velocity
Cm (m/s) Meridional component of the flow absolute velocity

Flow Incidence: $i = \beta_{1e} - \beta_{b_{1e}}$

Relative flow angle incidence
Effect on cavitation onset

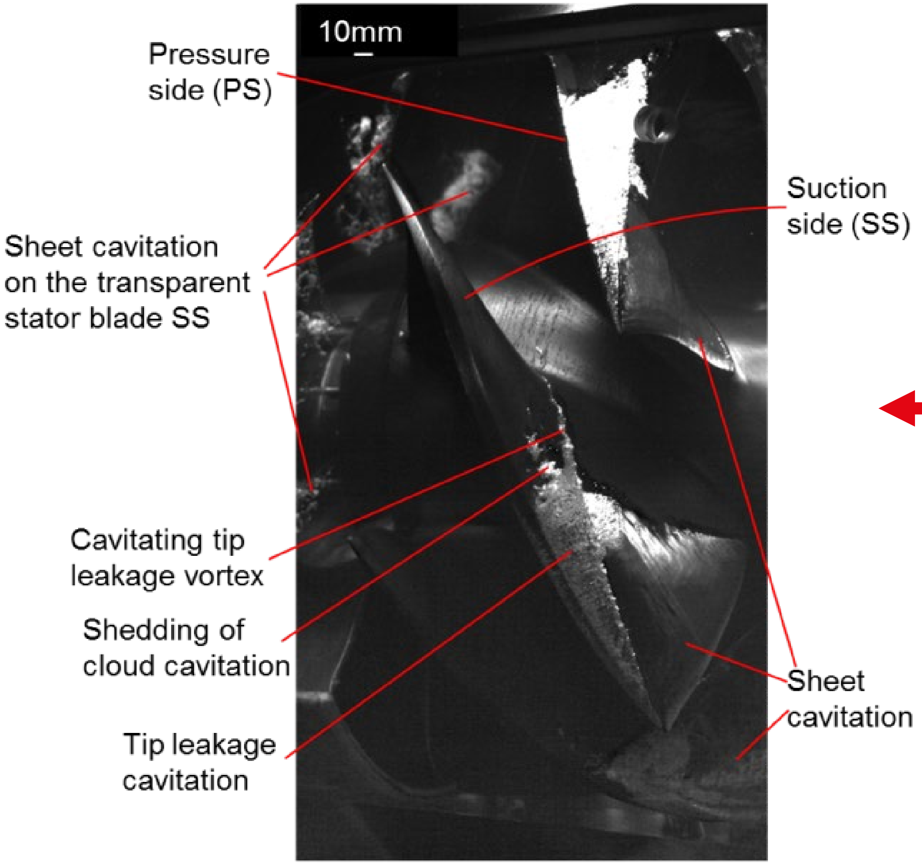


Cavitation in marine propellers



Flow Direction

Cavitation in marine propellers

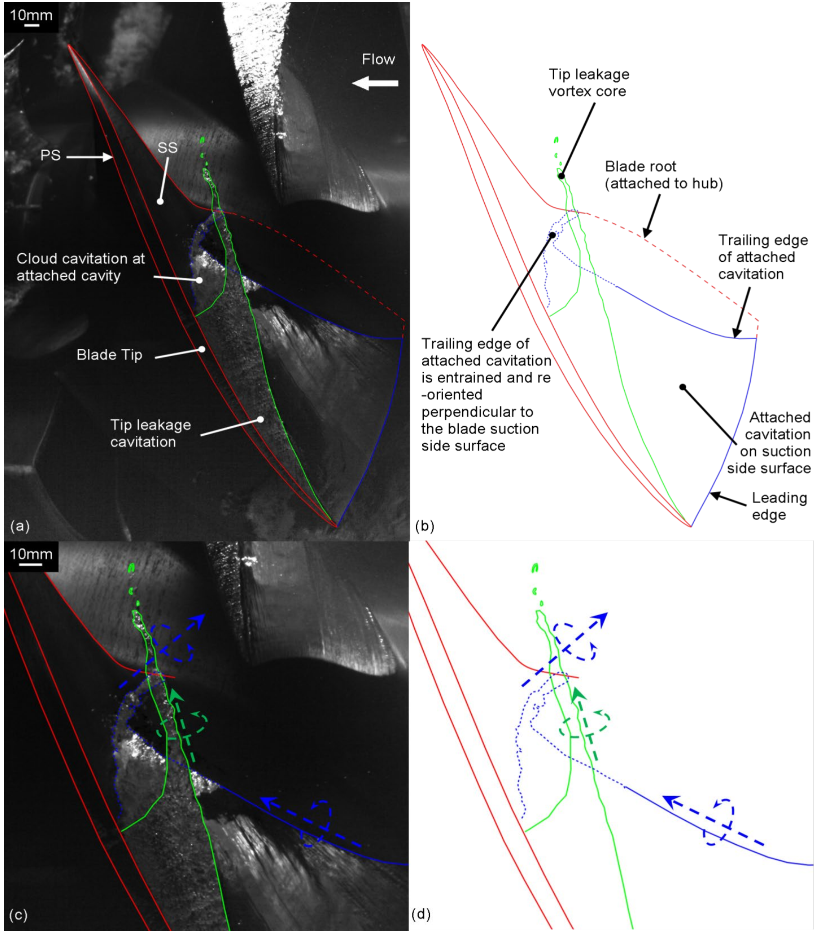


Flow Direction

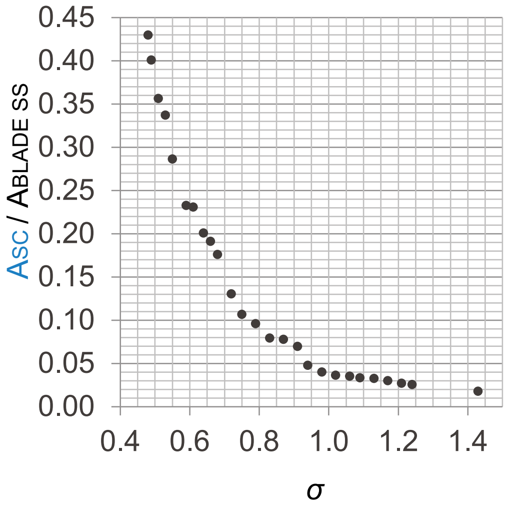
Cavitating structures in a marine propeller, Tan et al (2015).

Cavitation in marine propellers

Tip leakage cavitation outlined in green. Sheet cavitation outlined in blue



Sheet cavitation Area



Cavitating structures in a marine propeller, Tan et al (2015).

Eroded Francis turbine blades

Topics of the lecture

Cavitation Chacteristics

Setting level of hydraulic machines

Cavitation in hydraulic turbines

Cavitation in pumps

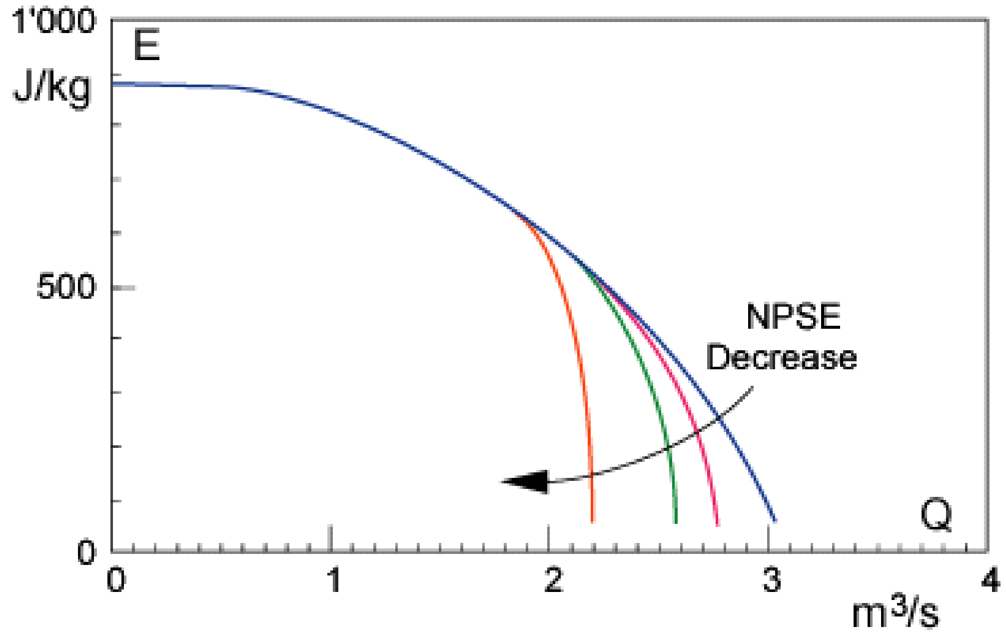
Cavitation Damages

Cavitation Detection Techniques

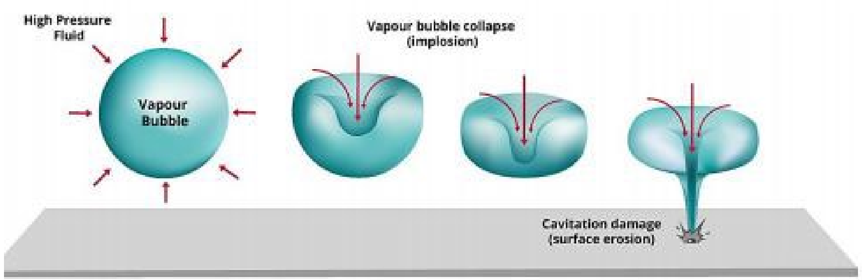
Cavitation Damages

- Erosion
- Fatigue
- Noise and Vibrations
- Operation Instability
- Performance Alteration
  - Efficiency
  - Head/Discharge
  - Runaway Speed

Performance Degradation

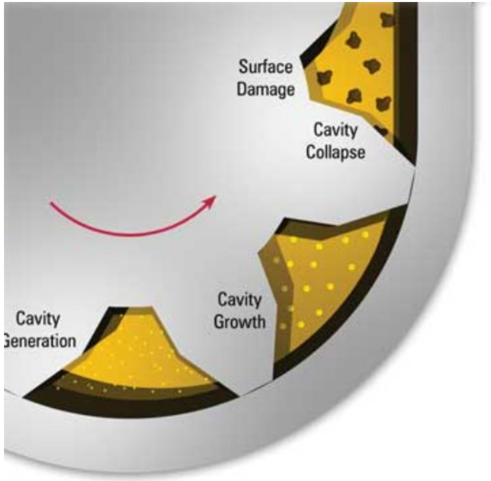


Cavitation Damages



Cavitation wear process:

- **Incubation period -** microcracks nucleate around grain boundaries and inclusions due to both elastic and plastic deformation of the surface.
- **Accumulation period** - crack growth proceeds in relation to the degree of splitting, shearing and tearing action on the material.
- **Steady-state period** - the rate of crack nucleation and propagation becomes constant for the remainder of the exposure time.

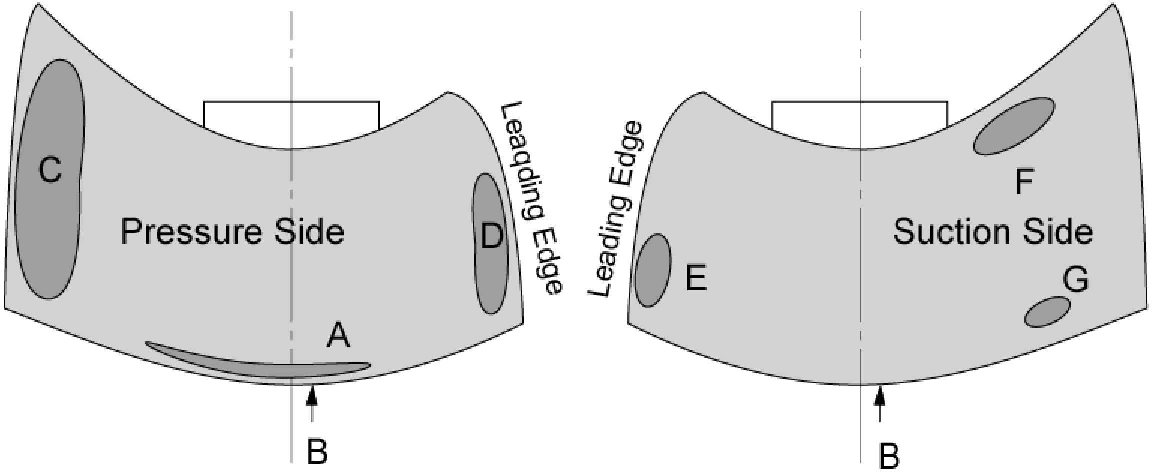


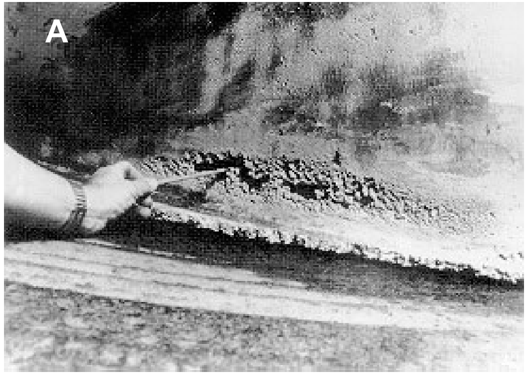
Cavitation in axial turbines: Main Issues

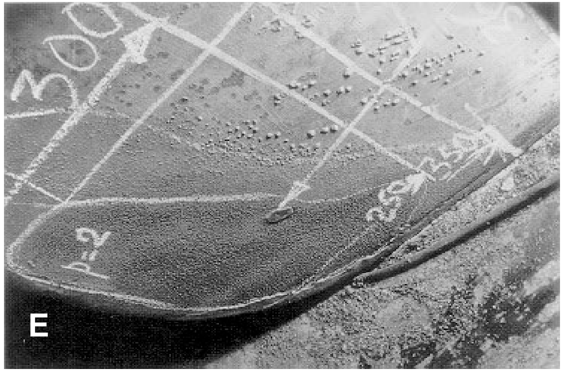
- Erosion Risk
  - Leading Edge Cavitation
  - Tip Vortex
  - Discharge ring cavitation erosion
- Efficiency Alteration
  - Hub Cavitation

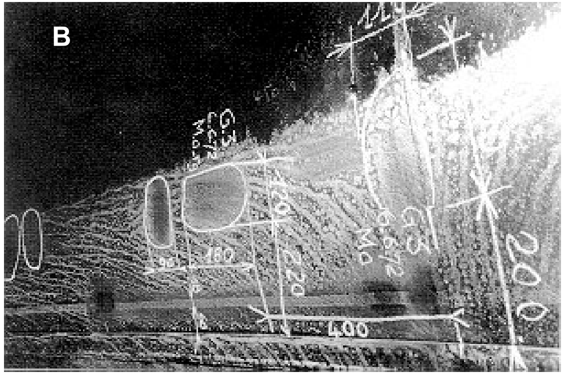
Example: Discharge ring cavitation erosion

Axial turbine Blades Erosion





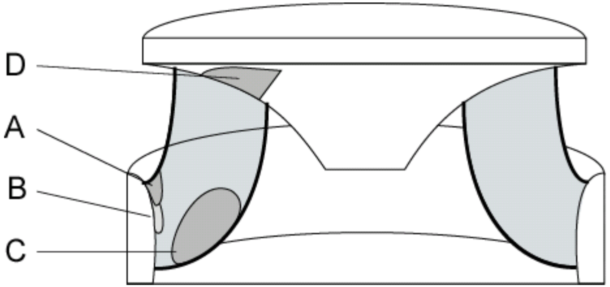


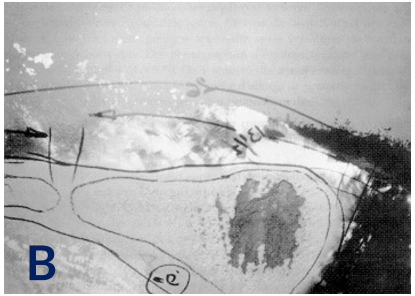


Cavitation in Francis turbines: Main Issues

- Efficiency Alteration
  - Traveling Bubble Cavitation
  - Vortex Rope
- Erosion Risk
  - Leadinge Edge Cavitation
- Operation Instability
  - Vortex Rope
  - Inter-Blade Vortices
- Fatigue

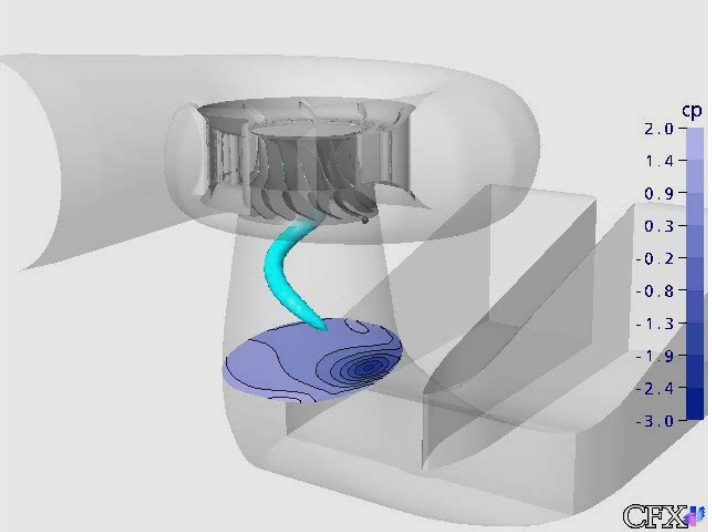
Francis turbine Blades Erosion

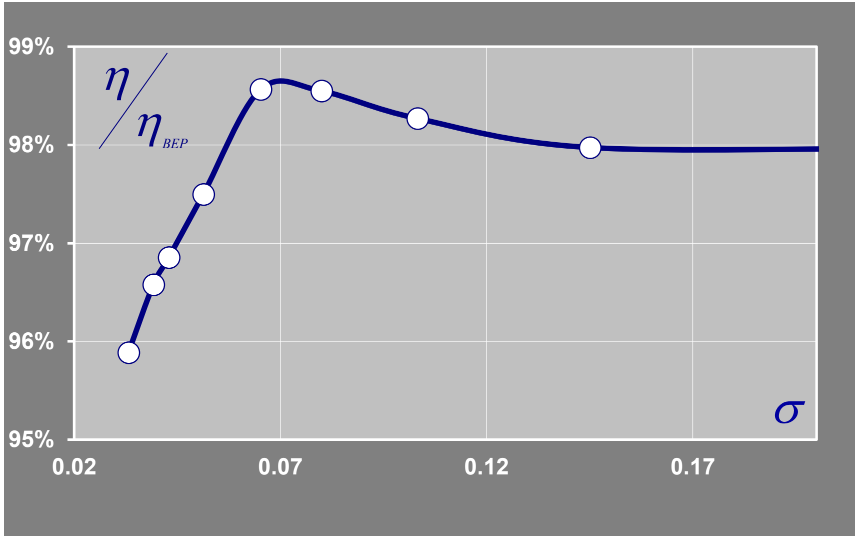




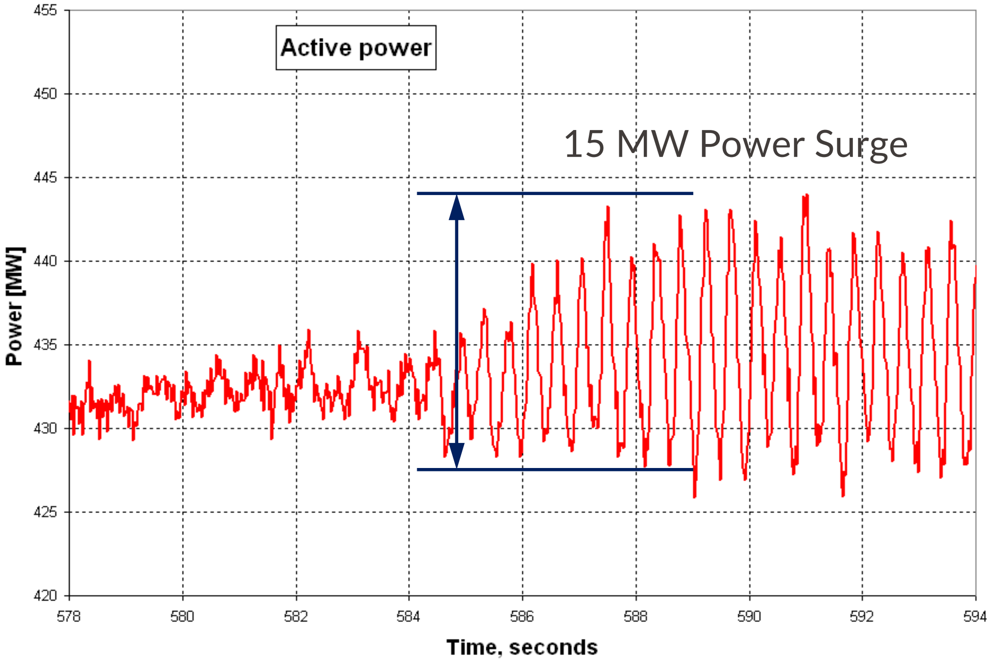
ESCALER X., EGUSQUIZA E., MEBARKI T., AVELLAN F., FARHAT M.; "Field Assessment of Cavitation Detection Methods in Hydropower Plants", Proc. of the 21st IAHR Symposium on Hydraulic Machinery and Systems, Lausanne, Suisse, September 9-12, 2002, pp. 483-490.

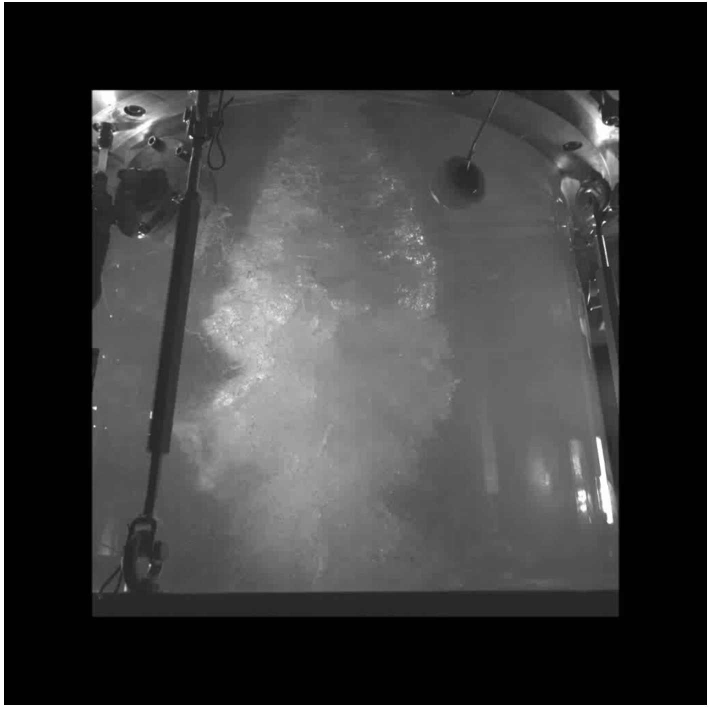
Francis Turbine Cavitation Vortex Rope





Francis turbine Surge



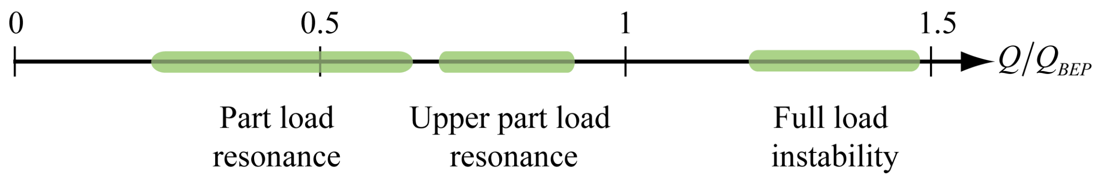


J. KOUTNIK, Ch. NICOLET , G.A. SCHOHL, F. AVELLAN, "Overload Surge Event in a Pumped-Storage Power Plant", Proceedings of the 23rd IAHR Symposium on Hydraulic Machinery and Systems, Yokohama, Japan, Oct. 2006

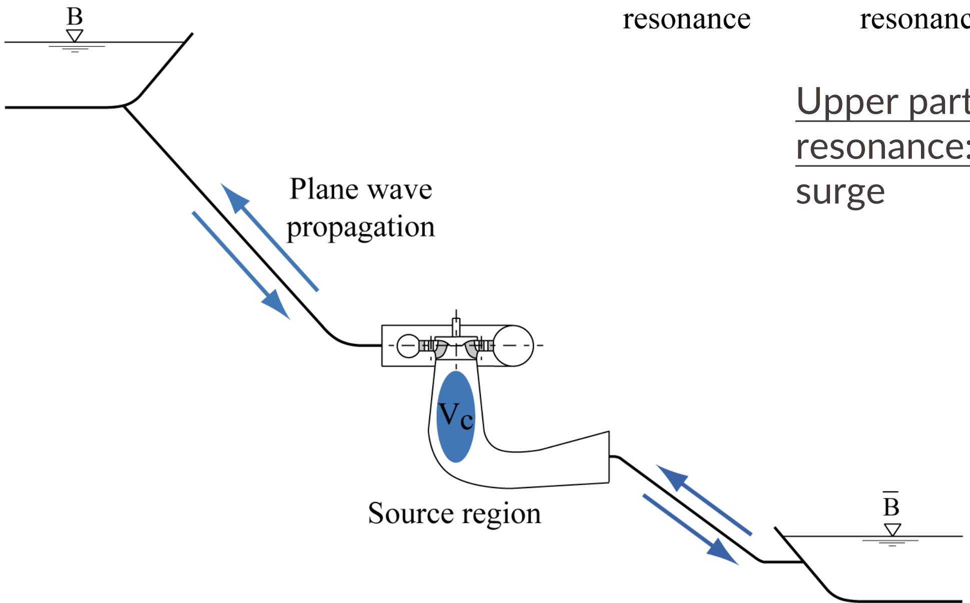
Francis turbine Surge

<u>Part load resonance:</u> Pressure surge induced by the helical vortex rope precession frequency.

<u>Full load instability:</u> Axial pulsations of the cavitation.



<u>Upper part load resonance:</u> Pressure surge

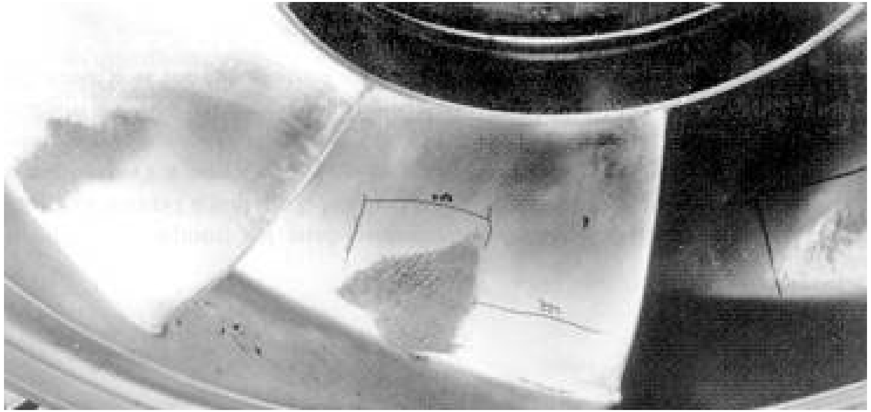


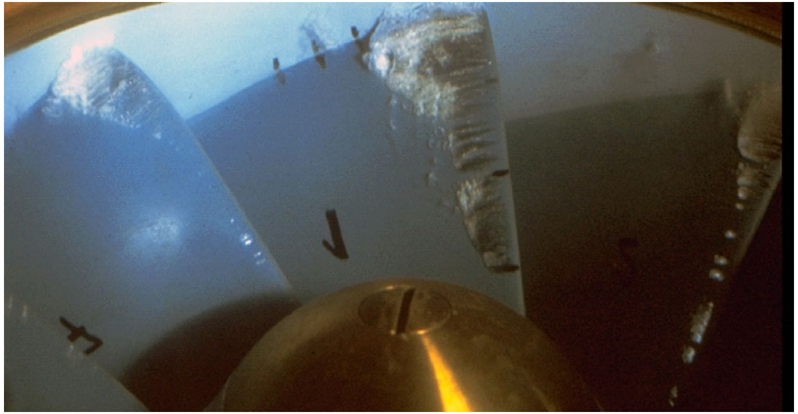
Cavitation in pumps and propellers: Main Issues

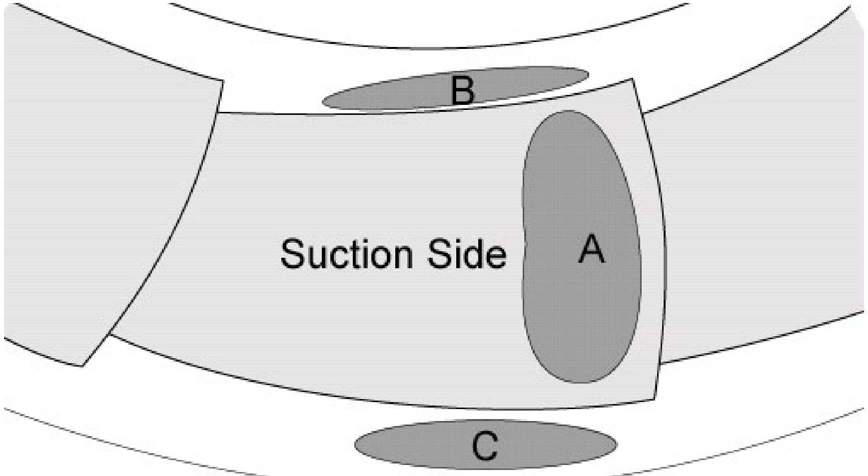
- Erosion Risk:
  - Impeller
  - Pump (suction) inlet
  - Mechanical seals
  - Bearings
- Shaft alignment
- Efficiency Alteration
- Suction Capability

Example: Propeller with cavitation pitting erosion

Typical Pump Cavitation Erosion





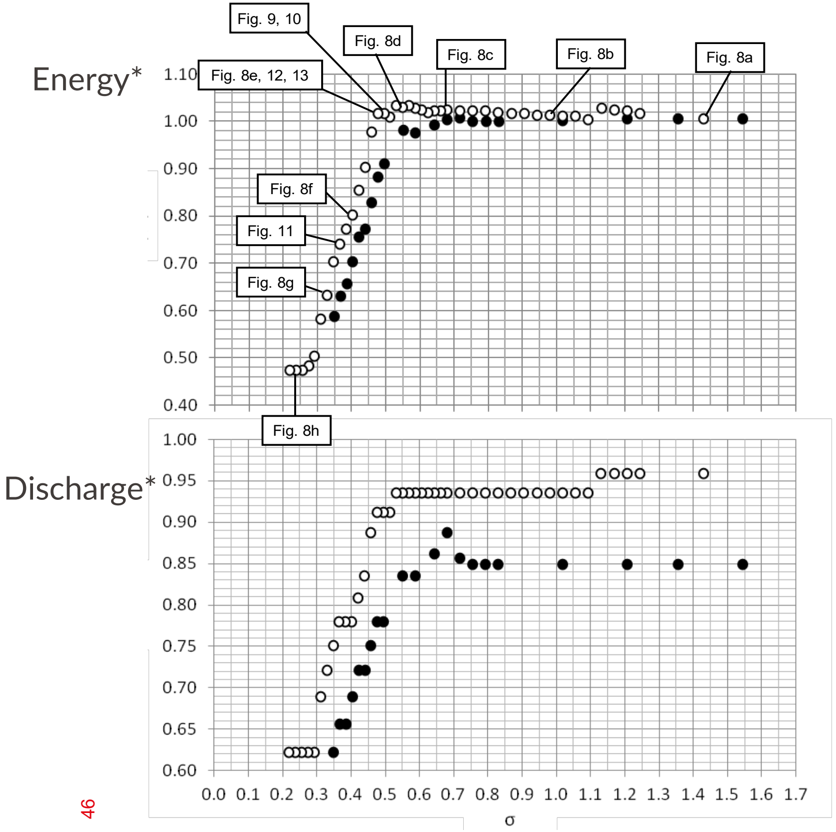


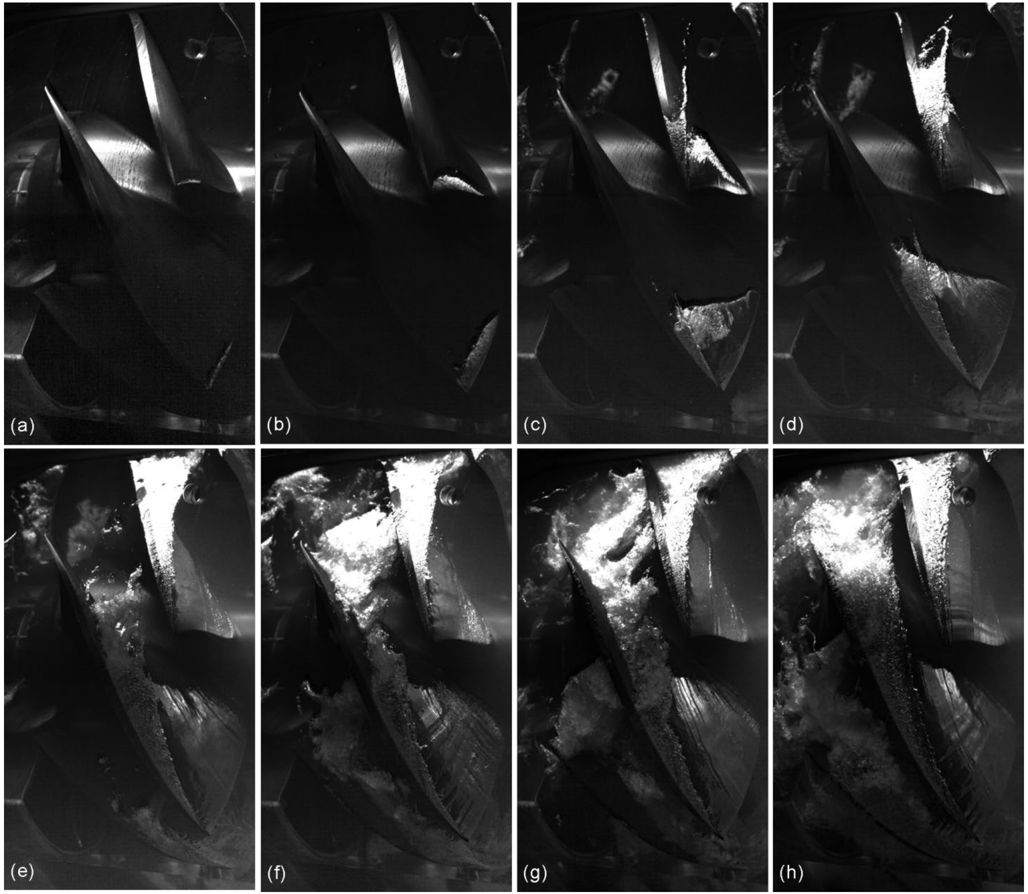
Centrifugal Pump Cavitation Erosion

Erosion due to suction cavitation: too low pressure or setting level

Erosion due to discharge cavitation

Performance Degradation in Marine Propellers





* In respect to the nominal set-point

Topics of the lecture

Cavitation Chacteristics

Setting level of hydraulic machines

Cavitation in hydraulic turbines

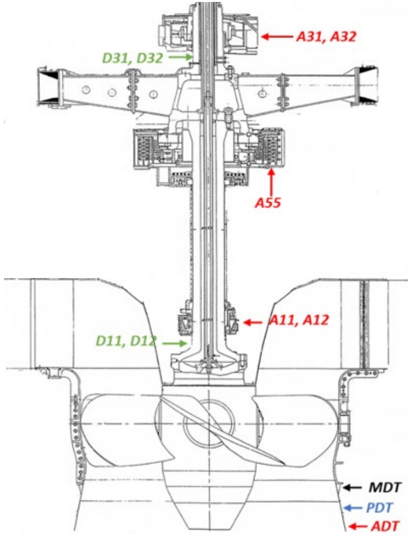
Cavitation in pumps

Cavitation Damages

Cavitation Detection Techniques

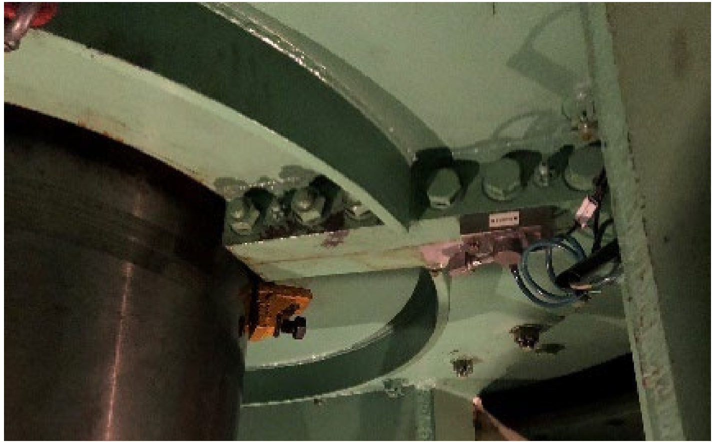
Cavitation Detection Techniques

- Efficiency deviation from the expected value
- E-Monitoring:
  - Noise: Hydrophones or Microphones are often adopted (dB threshold)
  - Vibrations: Accelerometers are placed on the shaft-line of the hydraulic machine



Vogelgrun Run of River Hydropower plant (France)

ACCELEROMETERS



Cavitation Detection Techniques

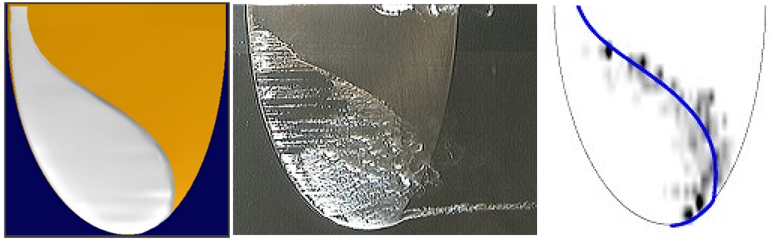
Observations during maintenance:

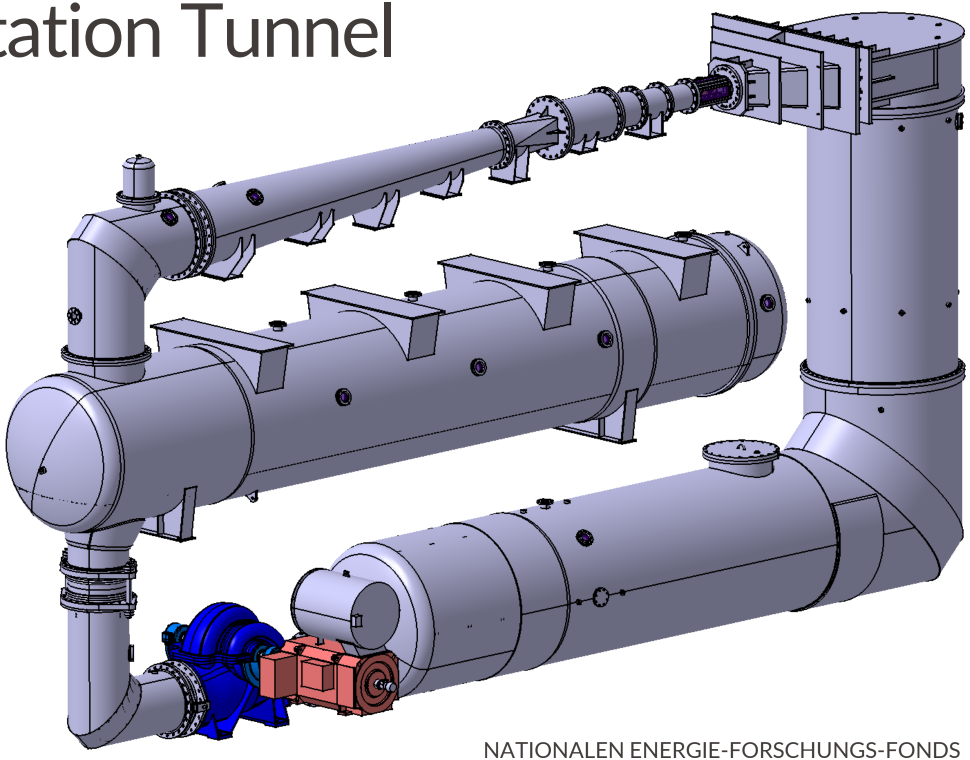
- **Periodic maintenance intervals** (typically every 4000h of operation) allows observing the status of the machine components and eventual damages due to cavitation erosion

- **Predictive maintenance:** with Industry 4.0, new forecasting methods are currently under development to predict when cavitation damages may occur depending on the duration and severity of the operation in off-design condition and the material of the machine components

Cavitation Research Facility: EPFL High Speed Cavitation Tunnel

- Max Flow Velocity: 50 m/s
- Max Pressure : 20 bar
- Optical Instrumentation
  - PIV, LDV
  - Laser Vibrometer
  - High-Speed Cameras
- Acceleration and p-sensors
- 5 Components Load Cell





NATIONALEN ENERGIE-FORSCHUNGS-FONDS

KTI CTI

Roland HIRSCHI, "Prédiction par modélisation numérique tridimensionnelle des effets de la cavitation à poche dans les turbomachines hydrauliques. EPFL Thesis n° 1777 (1998)

THANK YOU!

QUESTIONS?

École
polytechnique
fédérale
de Lausanne