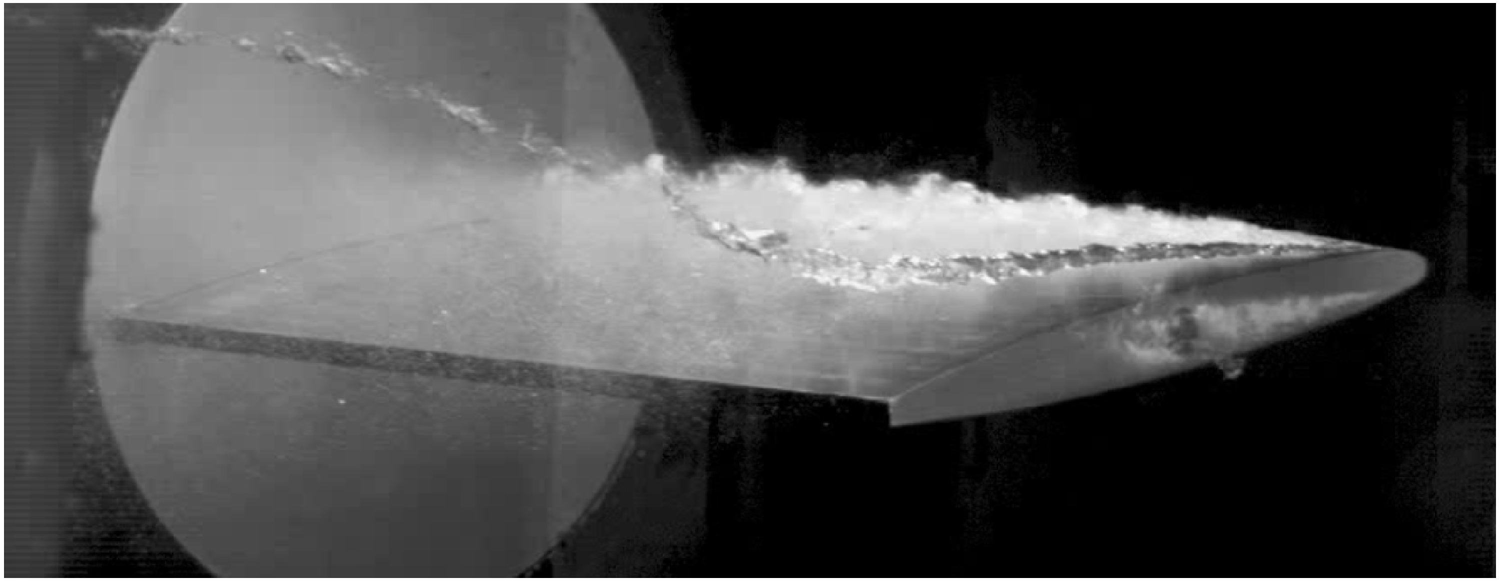
ECOLE POLYTECHNIQUE FEDERALE DE LAUSANNE
SGM - 6th & 8th Semester, Fall 2025
CAVITATION AND INTERFACE PHENOMENA

Chapter 5: Vortex Cavitation
5.4 : Tip Leakage Vortex Cavitation



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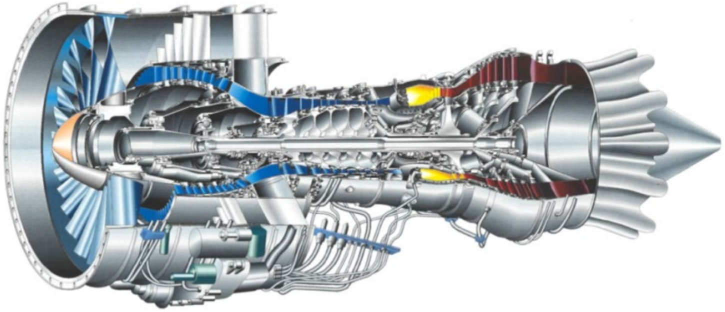
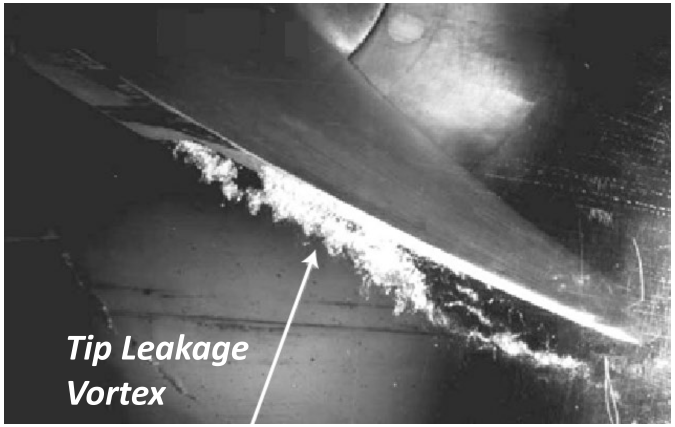
On The Tip Leakage Vortex (TLV)

- ***TLV may develop at the tip of the blades of any ducted rotating impeller***
  - ***The flow leaks and rolls up from pressure to suction sides through the gap***

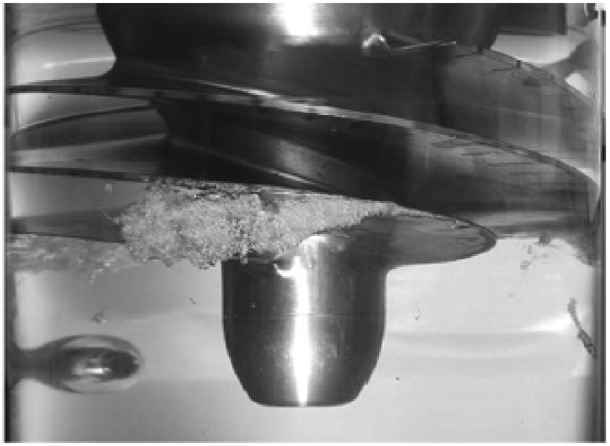
- *Turbo jet*



- *Axial turbines*

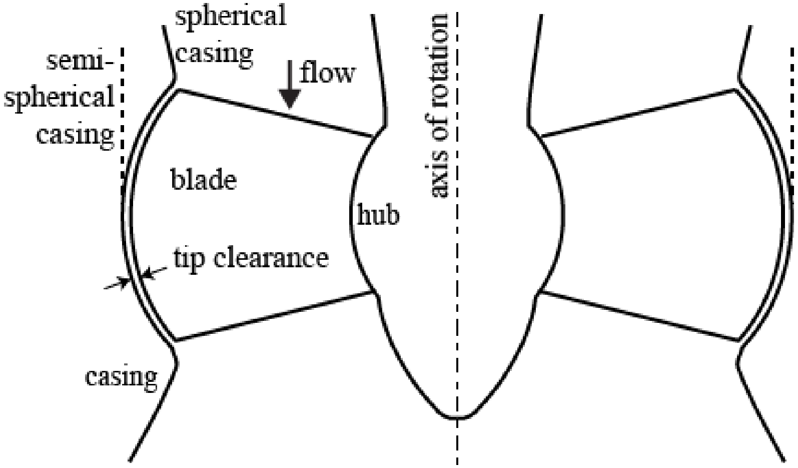


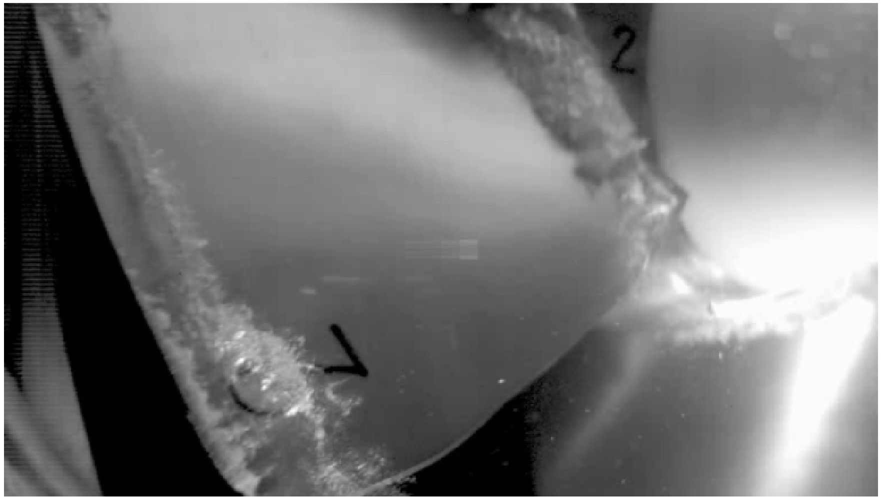
- *Space rocket inducers*



Tip leakage vortex in hydraulic turbines

- ***Tip leakage vortex (TLV) cavitation → severe erosion in axial turbines***
    - ***Cavitation highly dependent on gas content, Reynolds Nb and gap width***
- ***TLV cavitation prediction?***
    - ***Actual Numerical simulations are not reliable***
    - ***Model tests:***
        - ***Scale up rules are insufficient and may lead to wrong predictions.***
        - ***Similarity of (i) gas content, (ii) Reynolds number and (iii) gap width impossible to achieve***



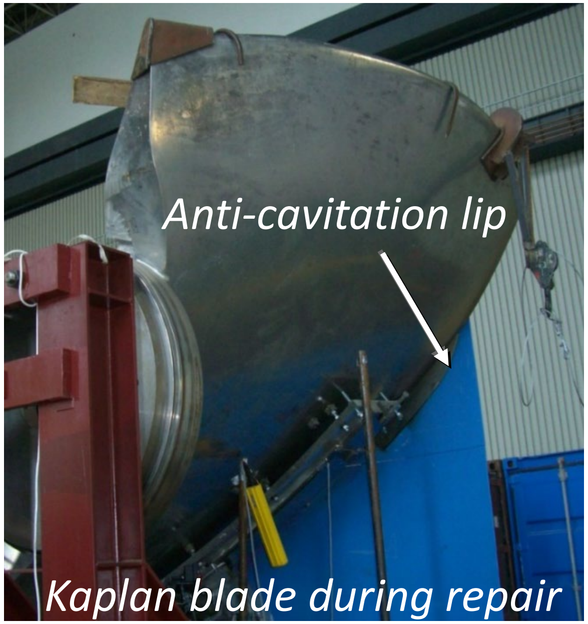


Tip leakage vortex in hydraulic turbines

- *The case of “IRON GATES” Power Plant*
  - *On the Danube river, on the Romanian-Serbian border*
  - *6 x Kaplan units: 200 MW/unit, 35 m water head, 9.5 m runner diameter*
  - *2nd world largest Kaplan turbines*
  - *Severe cavitation erosion on the prototype*
    - *No cavitation observed during model tests !*

Tip leakage vortex in hydraulic turbines

- ***The case of "IRON GATES" Power Plant***



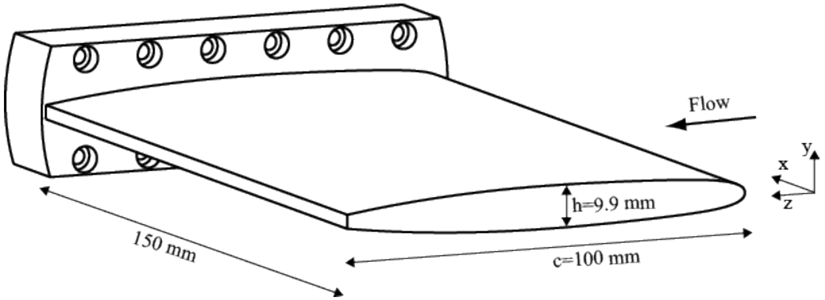
- ***Severe erosion of the blades tip & the discharge ring (TLV cavitation)***
  - ***Periodic repairs (increased operational cost)***
  - ***Remedy:***
    - ***Coating of exposed zones with more resistant material (e.g. Stellite)***
    - ***Removable anti-cavitation lip***
  - ***Search for more viable solution still underway***

Tip Leakage Vortex Cavitation

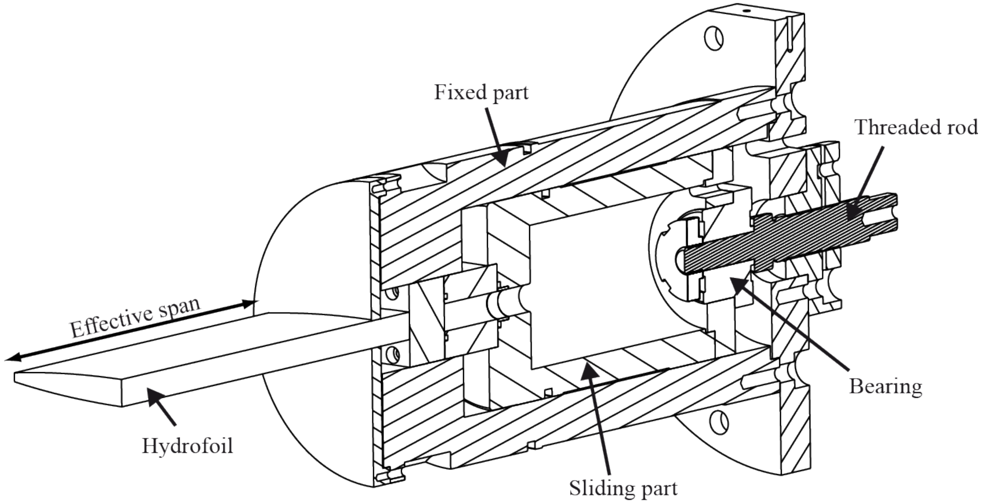
- **Current procedure for reduced scale model testing of axial turbines**
  - **IEC 60193 standard**
    - **Geometrical similarity of the impeller**
    - **Full-scale clearance must not exceed the one of reduced scale model**
  - **Geometrical similarity is hard to satisfy in practice**
    - **The gap is measured in dewatered and still conditions**
      - **no direct measurement during turbine operation**
    - **Gap width variations due to pressure and thermal stresses**

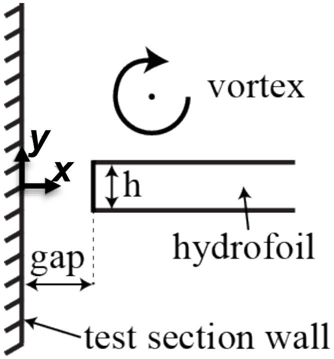
- **Open Questions**
  - **Effect of gap width on the TLV ?**
  - **Control of the TLV in hydraulic turbines ?**

Effect of gap width on TLV: A Simplified Case Study



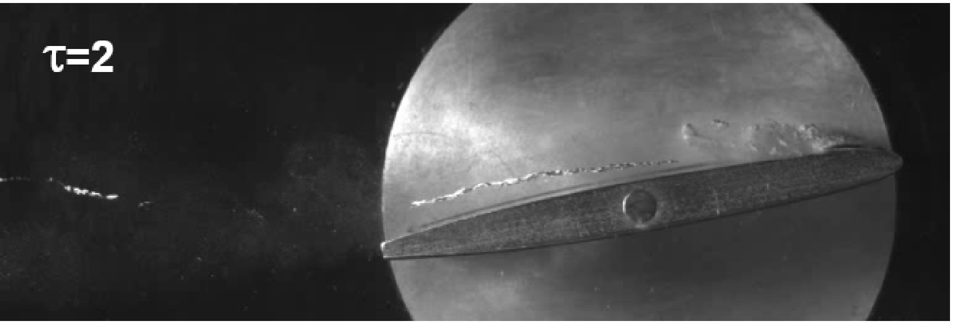
- **High speed cavitation tunnel**
- **NACA0009 hydrofoil**
  - ***Smooth and roughened leading edge (natural and tripped transition of boundary layer to turbulence)***
- **Sliding support of the hydrofoil**
- **Velocity measurements**
- **High-speed flow visualizations**

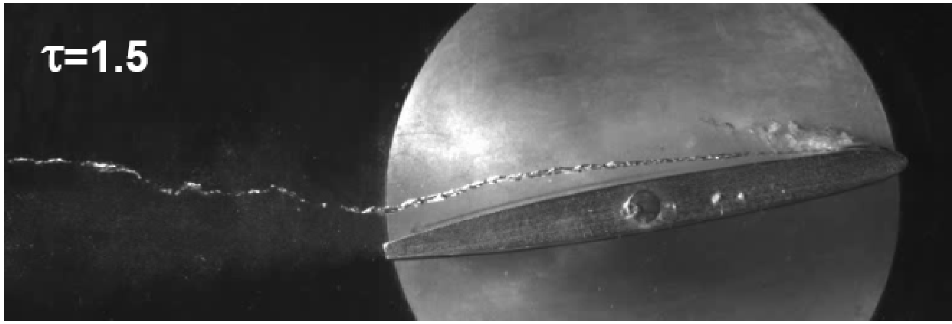


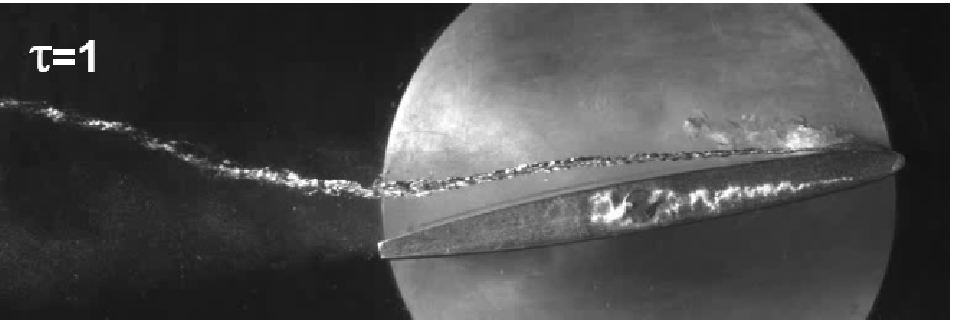


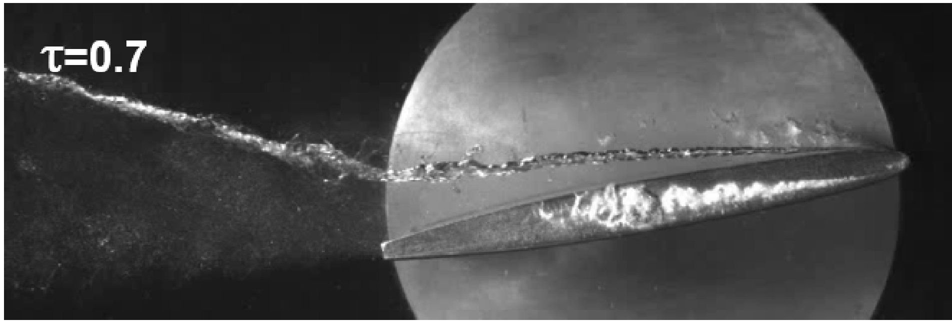
normalized tip clearance:

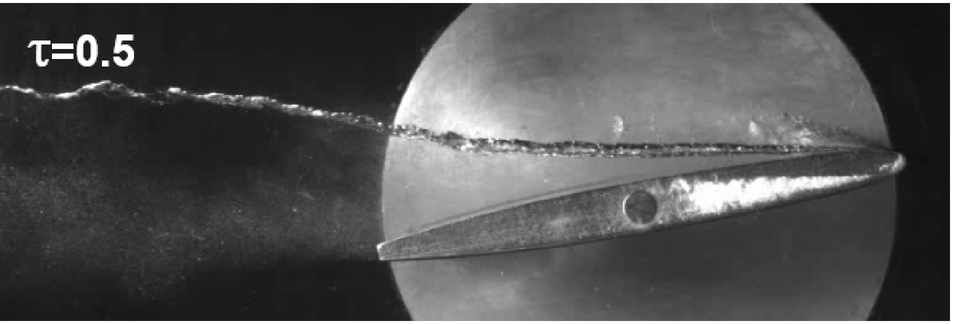
$$\boxed{\tau = \text{gap} / \text{h}}$$

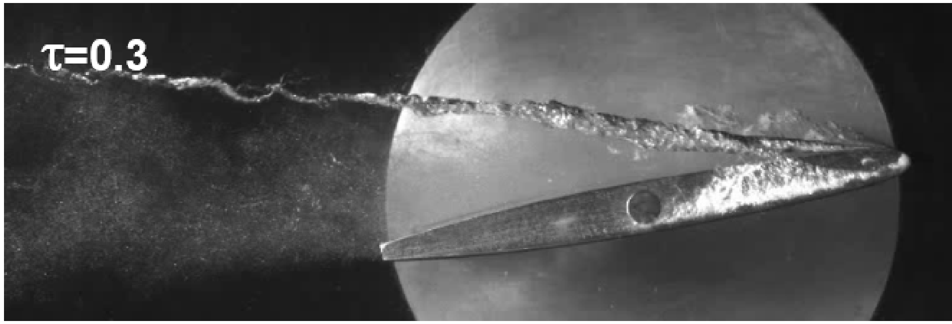

τ=2


τ=1.5

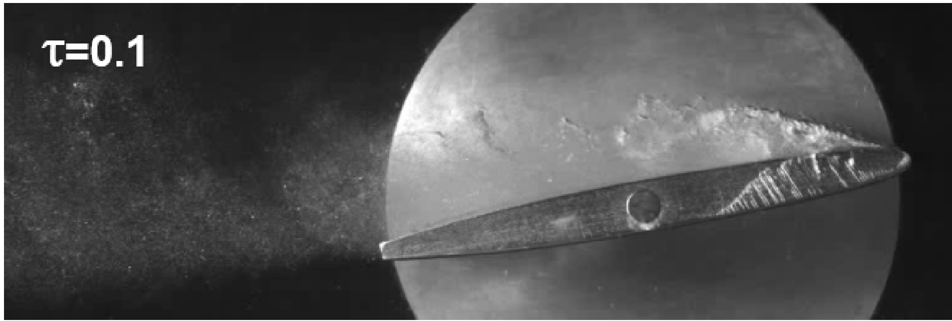

τ=1


τ=0.7


τ=0.5

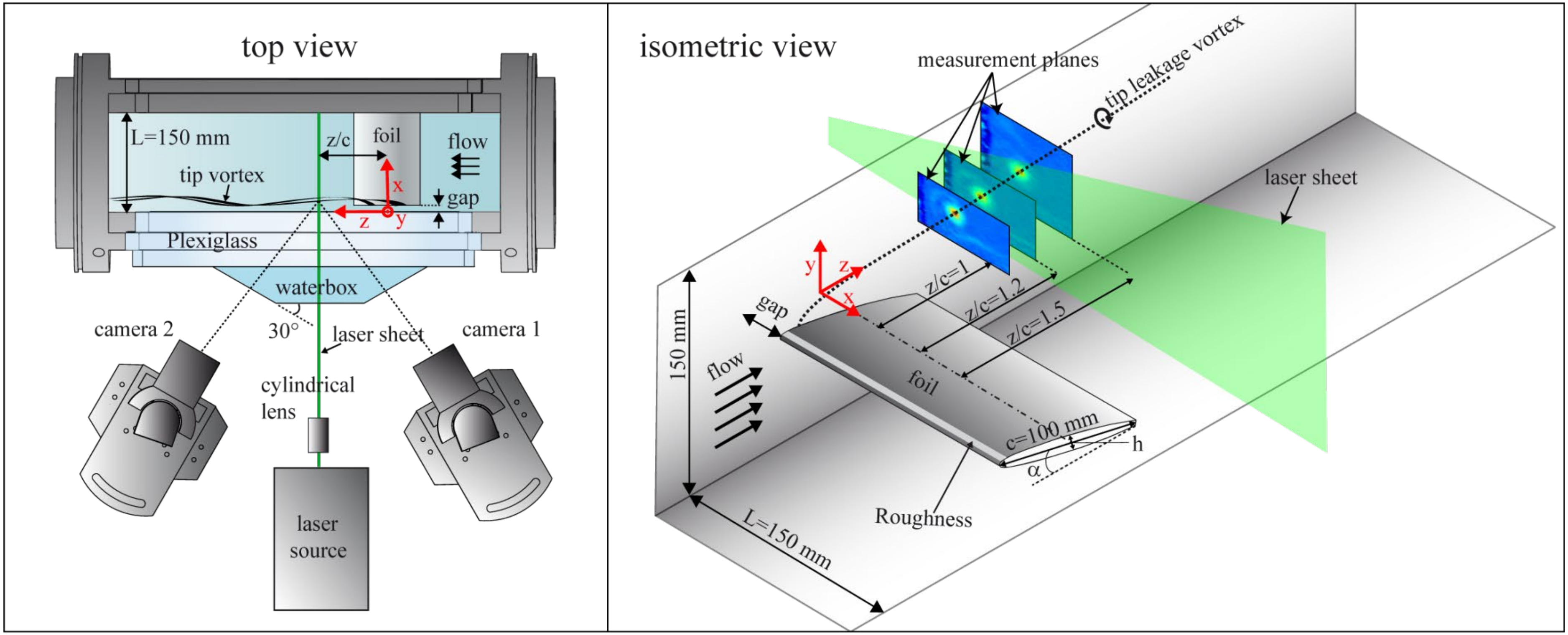

τ=0.3


τ=0.2


τ=0.1

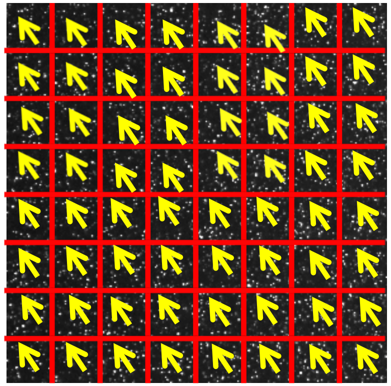
Effect of gap width on the TLV

- **Stereo PIV (SPIV)**
  - **Non-intrusive measurement of 3 components of the velocity in 3 planes $(z/c = 1, 1.2\ and\ 1.5)$**
  - **To minimize optical distortions, a water-filled box is fitted to the test section to minimize optical distortions**

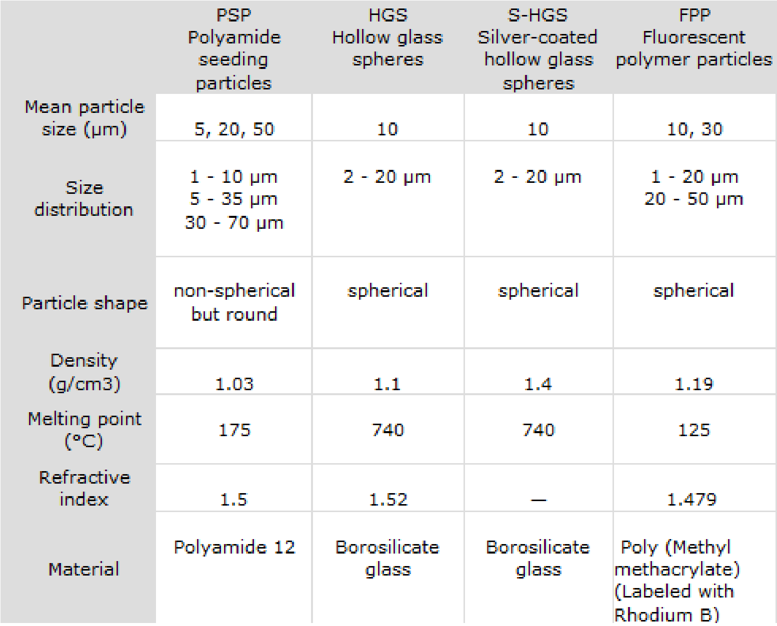


Effect of gap width on the TLV

- **PIV - Particle Image Velocimetry: working principle**
  - **Divide images in interrogation windows (e.g. 32x32 pixels)**



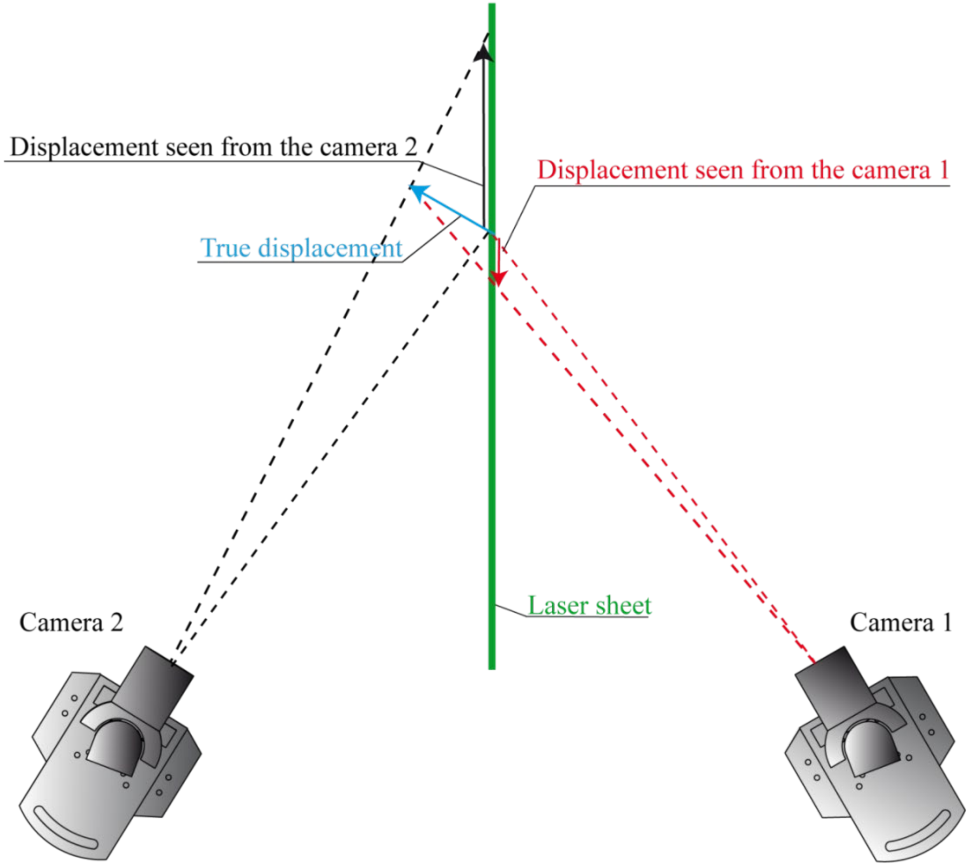
  - **Hypothesis:**
    - Particles travel with the flow at the same speed
    - Uniform motion within every interrogation window
    - Cross correlation → Velocity estimate
  - **Seeding particles:**
    - Density similar to water density
    - Typical size: ~5 µm to 50 µm

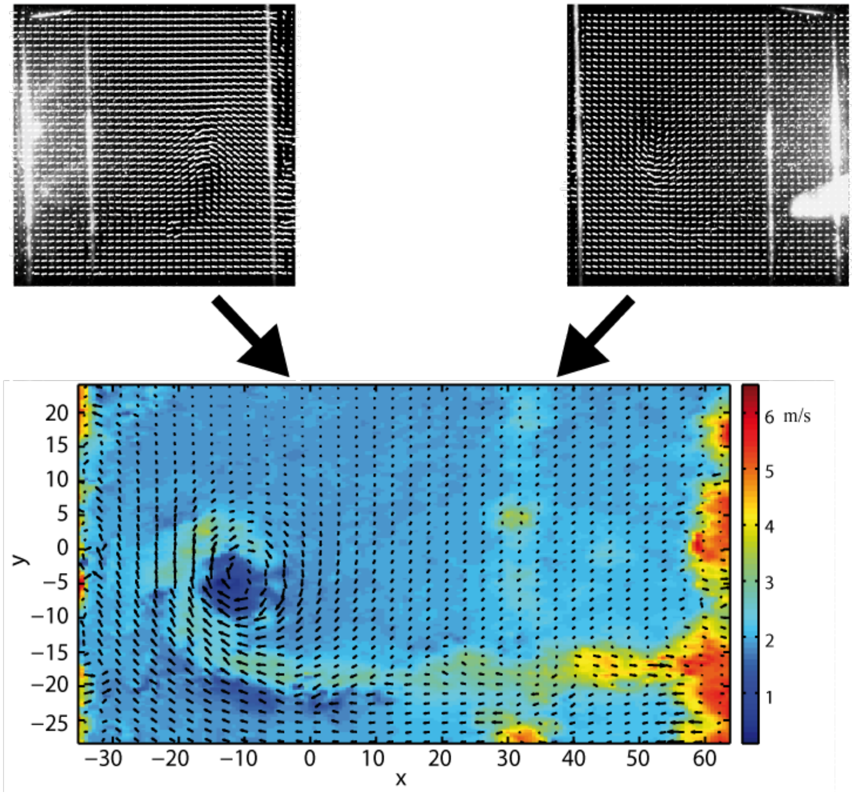


	PSP Polyamide seeding particles	HGS Hollow glass spheres	S-HGS Silver-coated hollow glass spheres	FPP Fluorescent polymer particles
Mean particle size (µm)	5, 20, 50	10	10	10, 30
Size distribution	1 - 10 µm 5 - 35 µm 30 - 70 µm	2 - 20 µm	2 - 20 µm	1 - 20 µm 20 - 50 µm
Particle shape	non-spherical but round	spherical	spherical	spherical
Density (g/cm3)	1.03	1.1	1.4	1.19
Melting point (°C)	175	740	740	125
Refractive index	1.5	1.52	—	1.479
Material	Polyamide 12	Borosilicate glass	Borosilicate glass	Poly (Methyl methacrylate) (Labeled with Rhodium B)

Effect of gap width on the TLV

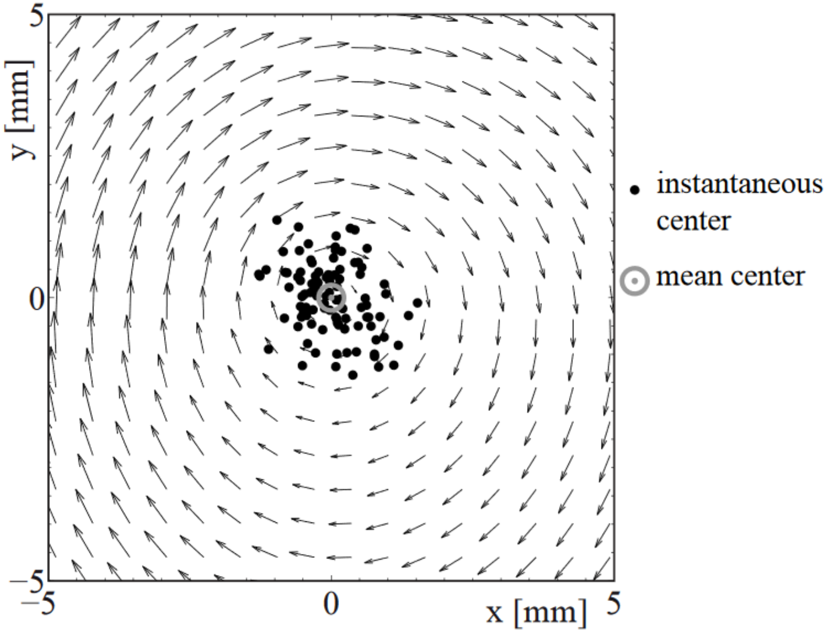
- **Stereo PIV (SPIV)**
  - ***Use of 2 cameras → Measurement of 3 components of the velocity***
    - *Requires a precise calibration*

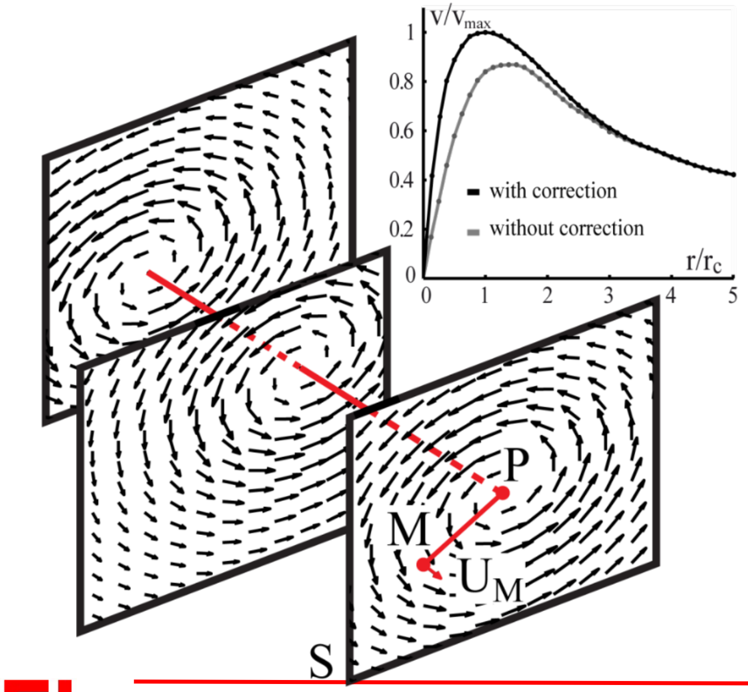




Effect of gap width on the TLV

- **SPIV - data processing**
  - *Issue: Wandering (random displacement of the vortex axis due to turbulence)*
  - *Correction of vortex wandering*
    - *Vortex center identification*
    - *Shifting and aligning velocity maps*
    - *Mean and statistic computation*





$$\Pi(P) = \frac{1}{S}\int_{M\in S}\frac{(PM \wedge U_M)\cdot z}{\|PM\|\cdot\|U_M\|}\,dS$$

Graftieaux criteria: Min(Π) = Vortex Axis

Effect of gap width on the TLV

- **SPIV - data processing**
  - Key vortex parameters
    - Vortex model best fit
      → Viscous core size estimation (r_c)
      → Circulation (Γ)

Lamb-Oseen model

$$v_\theta(r) = \frac{\Gamma}{2\pi r}\left(1 - e^{-\alpha r^2/r_c^2}\right)$$

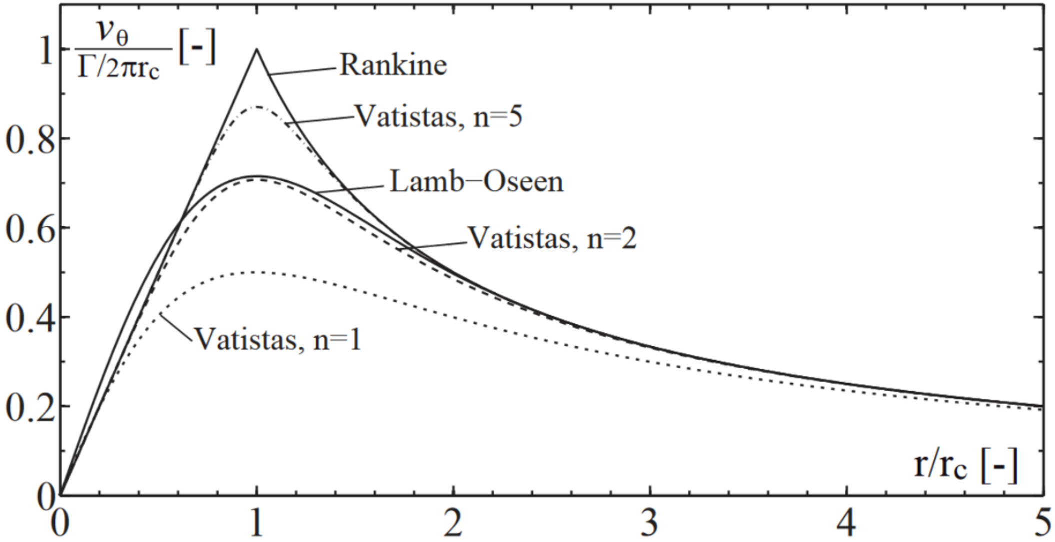
Vatistas model

$$v_\theta(r) = \frac{\Gamma}{2\pi}\left(\frac{r}{(r_c^{2n} + r^{2n})^{1/n}}\right)$$

$$\partial p/\partial r = \rho v_\theta^2/r$$

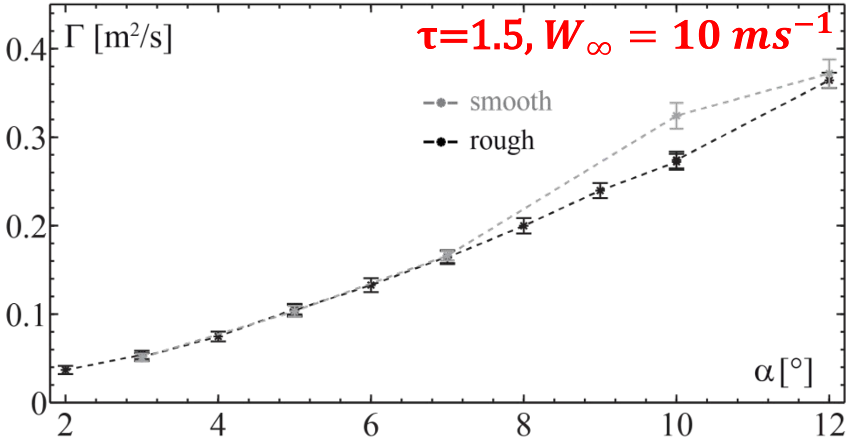
$$C_{p_{min}} = -\beta\left(\frac{\Gamma}{W_\infty r_c}\right)^2$$

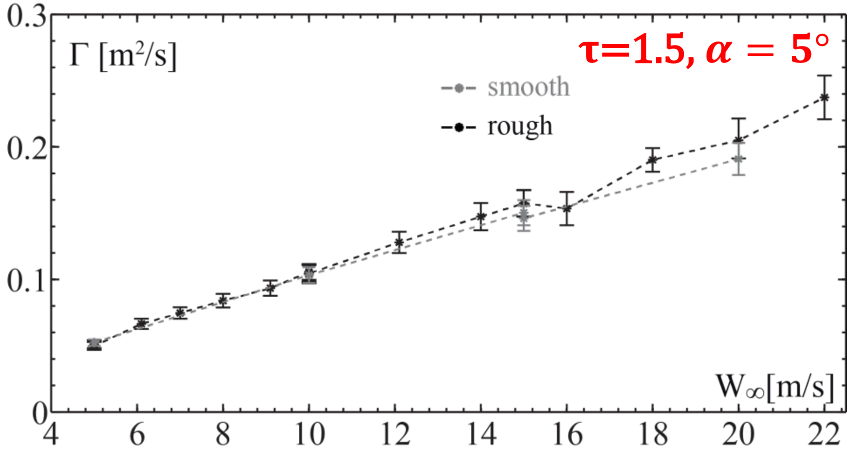
$$\Gamma = \int_A \vec{\omega}\cdot\vec{n}\cdot dS$$



TLV Characteristics

- **Circulation $(\boldsymbol{\Gamma})$:**
  - *Estimated from velocity fields by fitting the Lamb-Oseen model*
  - *Almost linear relationship with incidence angle and upstream velocity*
  - *No significant influence of leading edge roughness*

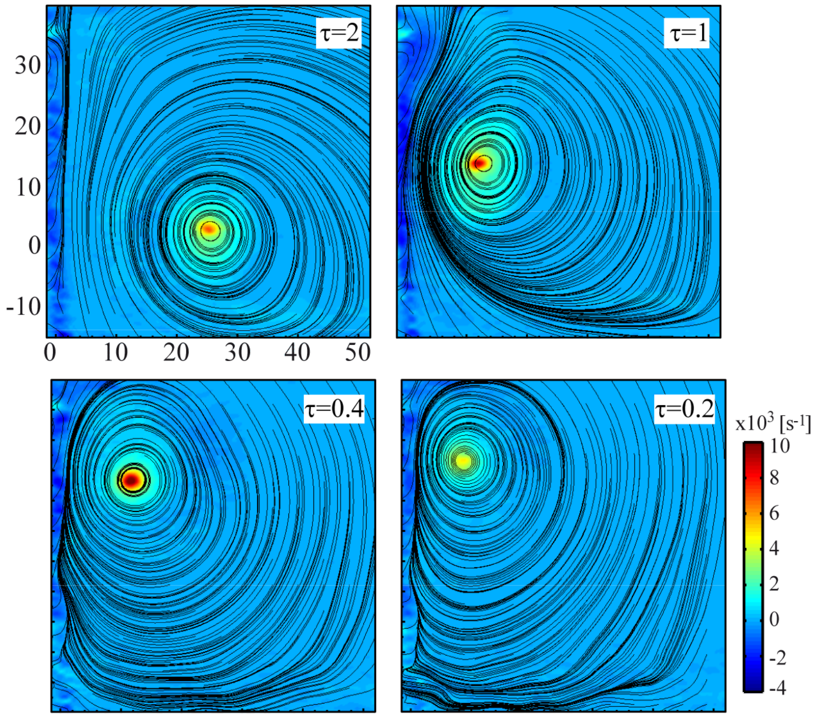




TLV Characteristics

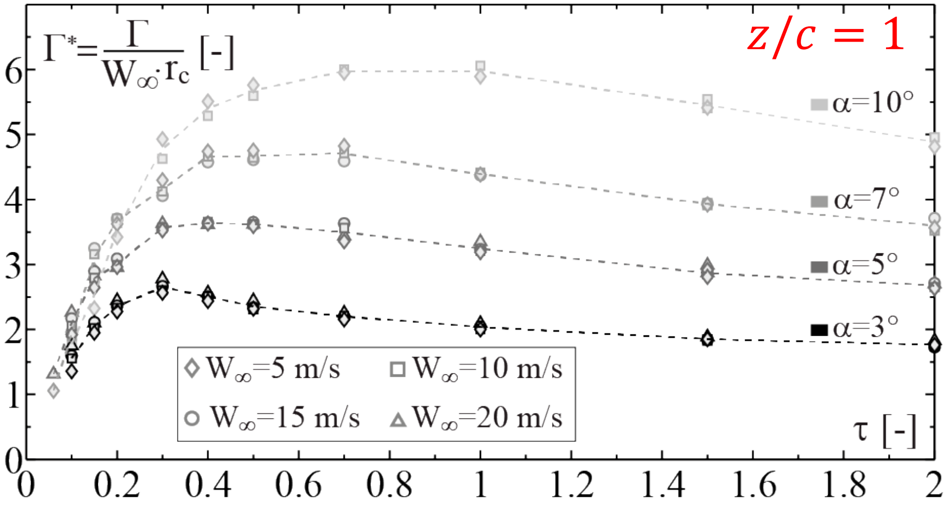
- **Influence of gap width (τ) on vortex intensity**
  - *Non-dimensional circulation Γ^* at $z/c = 1$ (roughened leading edge)*
  - $\Gamma^*(\tau)$ highly dependent on incidence angle

Streamwise vorticity (W_∞ =10 ms^{-1}, $\alpha = 10°$)



$$\Gamma^* = \frac{\Gamma}{W_\infty r_c}$$

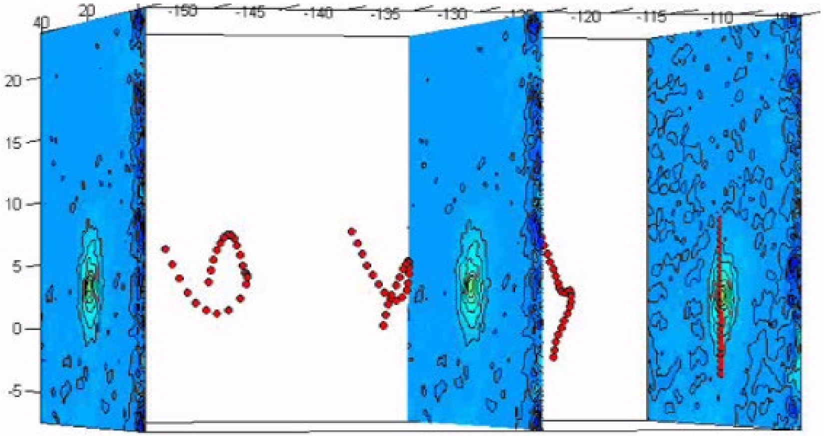
r_c is the viscous core radius



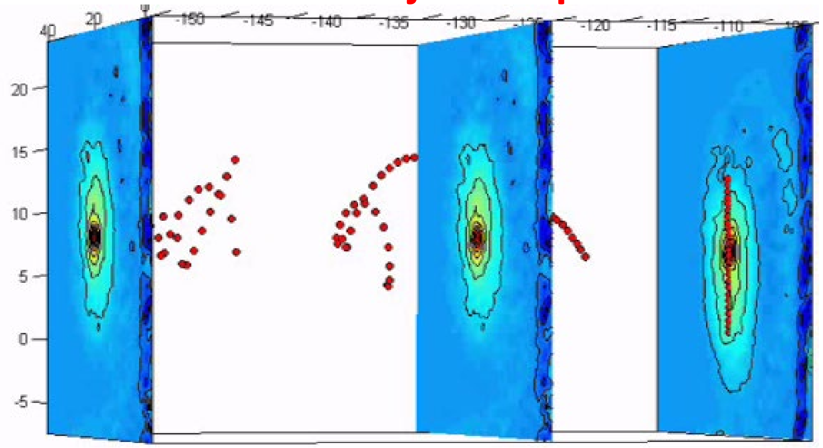
TLV Characteristics

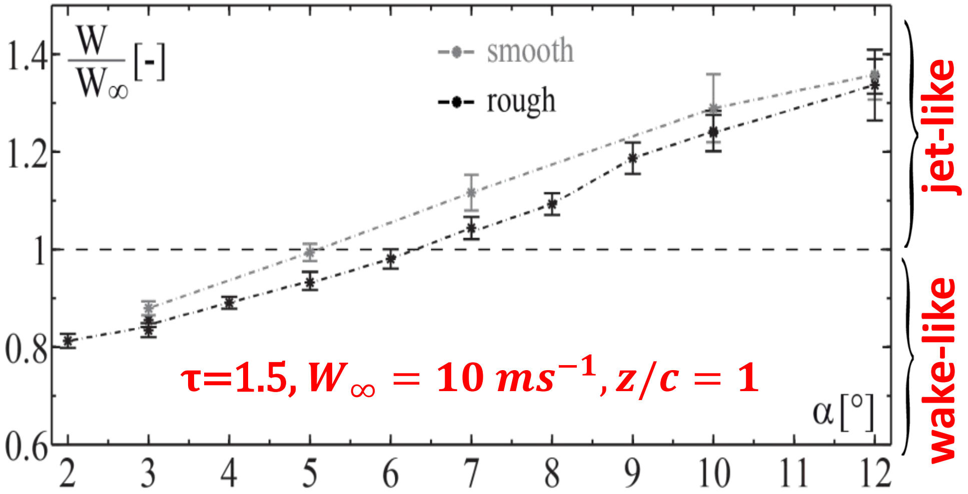
- **Influence of incidence angle (α) on axial velocity**
  - 2 regimes:
    - $\alpha \lesssim 6°$: wake-like profile $(W < W_\infty)$
    - $\alpha \gtrsim 6°$: Jet-like profile $(W < W_\infty)$ fluid particles, close to the vortex axis, travel faster in the stream-wise direction than the mean flow

α=3°: wake-like profile



α=10°: jet-like profile

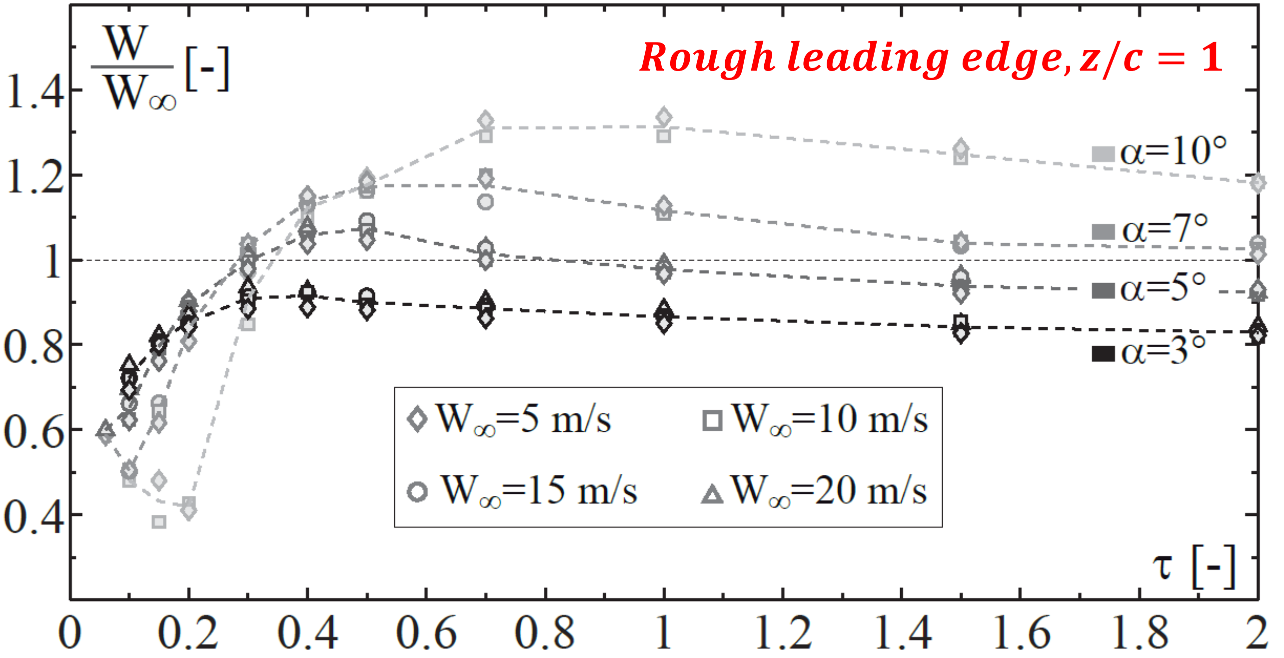




τ=1.5, $W_\infty = 10\ ms^{-1}, z/c = 1$

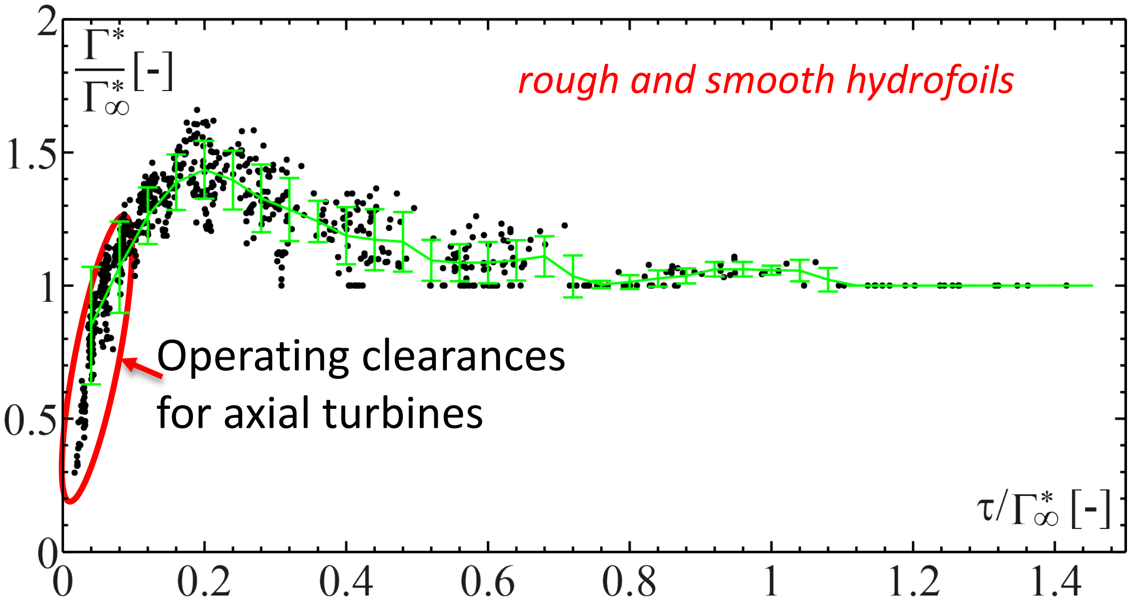
TLV Characteristics

- **Influence of gap width(τ) on axial velocity**
  - The flow around the vortex axis tends to switch from wake-like to jet-like flow as the gap increases
  - $W^*(\tau)$ highly dependent on incidence angle



Scaling law for TLV intensity

- **Dimensionless coefficients**
  - Scaling of the gap width: τ/Γ_∞^* , with $\Gamma_\infty^* = \lim_{\tau\to\infty}(\Gamma^*) \approx \Gamma^*(\tau = 2)$
  - Scaling of the TLV intensity: Γ^*/Γ_∞^*



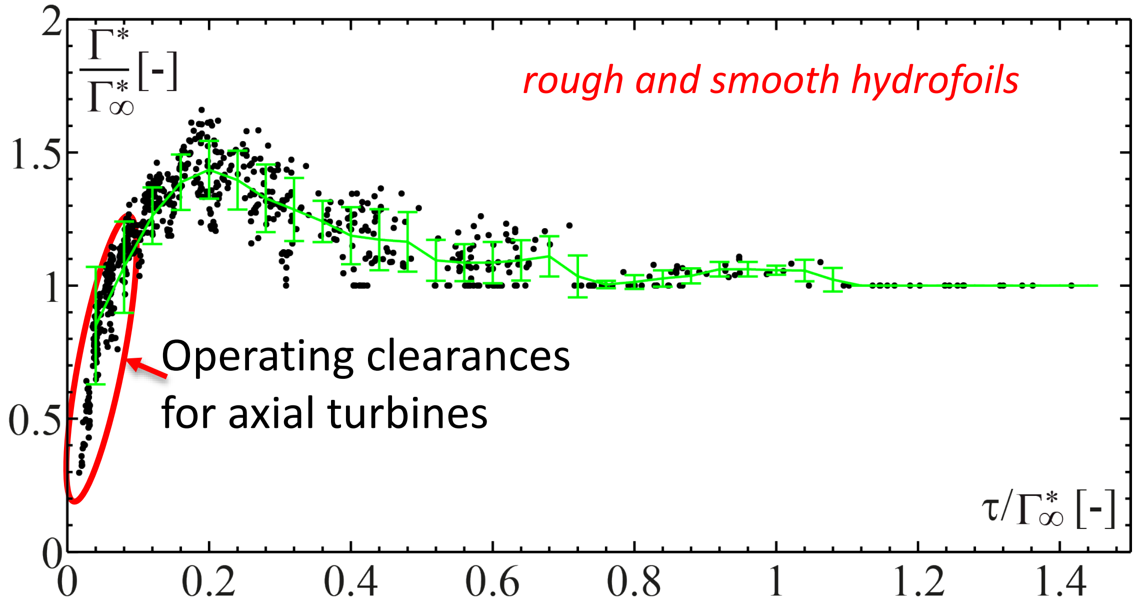
  - Cp_{min}: We can easily show in the case of Lamb-Oseen model, that:

$$Cp_{min} \approx -0.044 \left(\frac{\Gamma}{W_\infty r_c}\right)^2$$

→ As the gap reduces, Γ increases and so does the cavitation risk

New scaling law for TLV intensity

- **Dimensionless coefficients**
  - Scaling of the gap width: τ/Γ_∞^* , with $\Gamma_\infty^* = \lim_{\tau\to\infty}(\Gamma^*) \approx \Gamma^*(\tau = 2)$
  - Scaling of the TLV intensity: Γ^*/Γ_∞^*



- For $\tau/\Gamma_\infty^* \lesssim 0.2$, Γ^*/Γ_∞^* is highly dependent on the gap width
- This corresponds to typical clearances of axial turbines and may explain the discrepancy between model tests and full scale results.

Effect of gap width - Summary

- Vortex trajectory & intensity significantly influenced by the proximity of a neighboring wall.
- The axial flow may be wake-like or jet-like, depending on incidence angle and gap
- Existence of a critical gap width for which the TLV intensity is maximum, with an increase risk of cavitation.
- New dimensionless parameters $(\Gamma^*/\Gamma^*_\infty \; and \; \tau/\Gamma^*_\infty)$ allows to merge the data in almost a single curve.
- Sensitivity of TLV intensity to gap width explains the discrepancies of cavitation occurrence between models and prototypes.

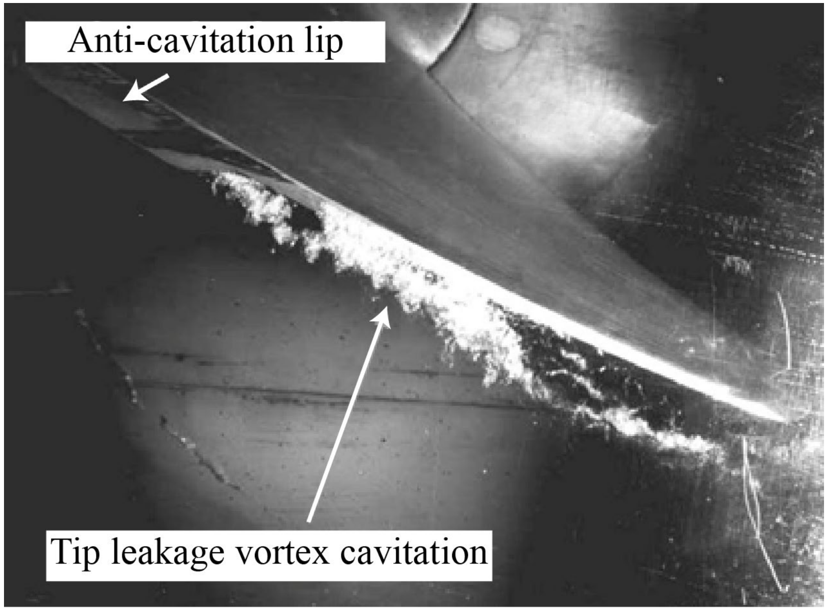
Related publications:

- M. Dreyer, J. Decaix, C. Münch-Alligné, and M. Farhat (2014) “Mind the Gap: A New Insight into the Tip Leakage Vortex Using Stereo-PIV.” Experiments in Fluids 55 (11): 1–13.
- J. Decaix, G. Balarac, M. Dreyer, M. Farhat, and C Münch (2015) “RANS and LES Computations of the Tip-Leakage Vortex for Different Gap Widths.“ Journal of Turbulence 16(4):309-341

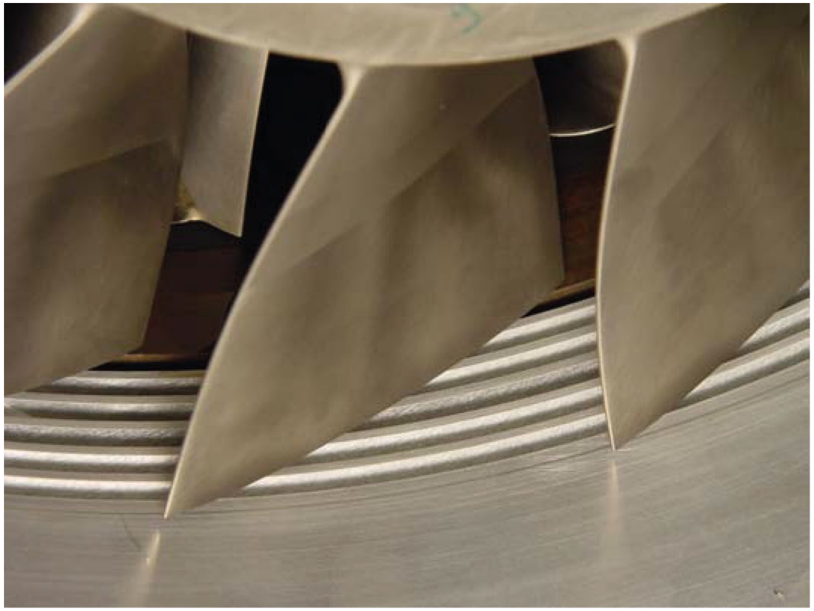
Mitigation of tip leakage vortex cavitation by grooves

- **MOTIVATION AND CONTEXT**

in hydraulic turbines



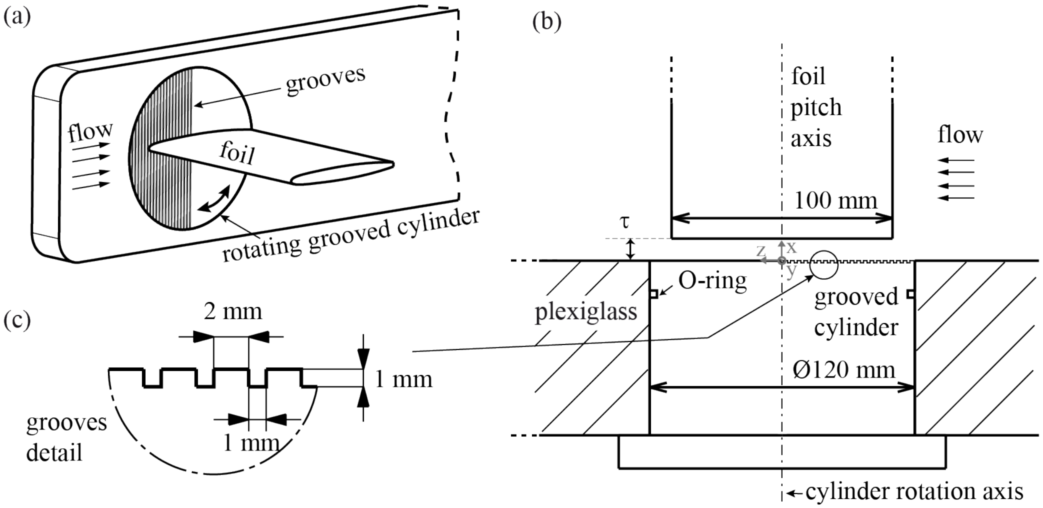
Grooves are used in gas compressors



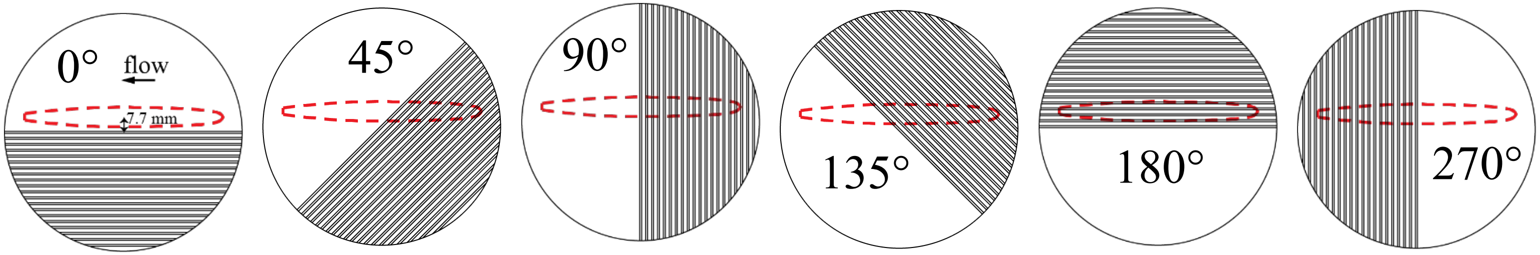
Muller et al. 2007. In ASME Turbo Expo 2007: Power for Land, Sea, and Air, 115–24.

Mitigation of tip leakage vortex cavitation by grooves

- **Case study – Experimental Setup**
  - Naca0009 hydrofoil
  - Grooves implementation: on the lateral window, with adjustable orientation
  - Grooves size of the order of the wall boundary layer thickness (~1 mm)

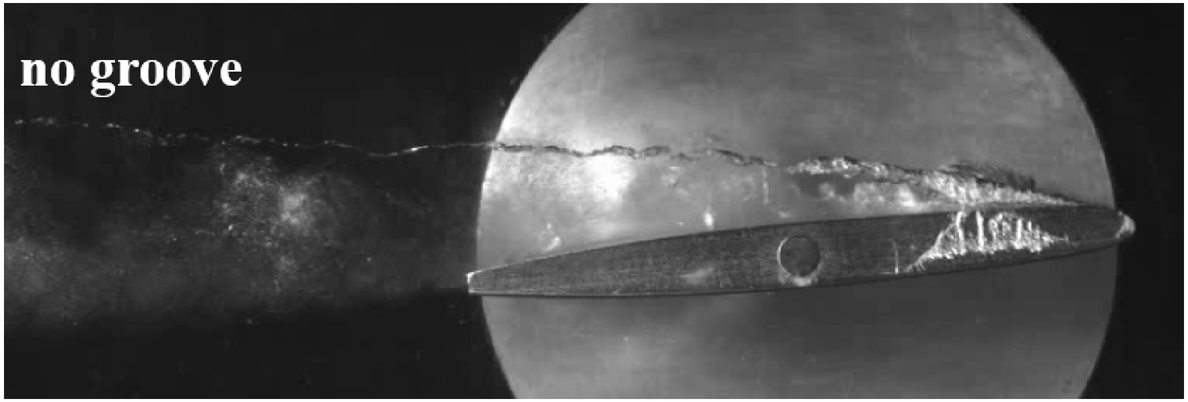


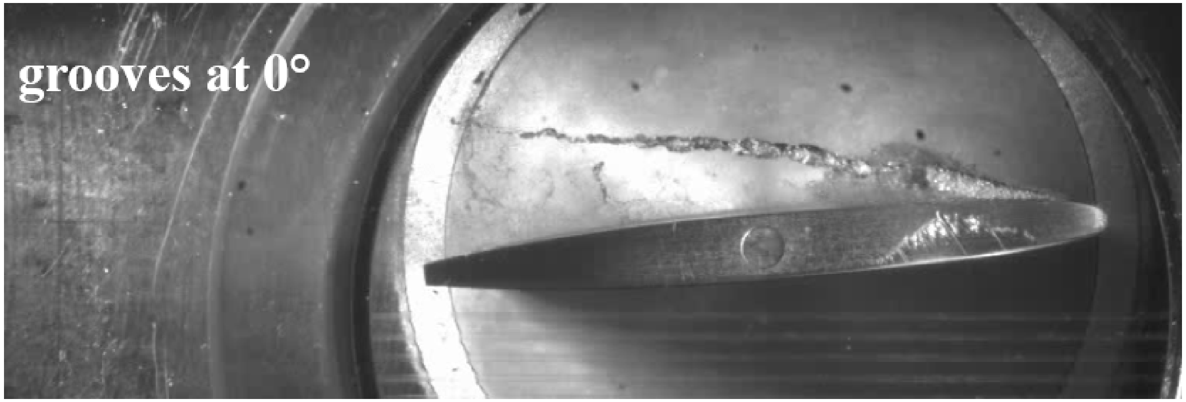
  - Grooves orientations:



Mitigation of tip leakage vortex cavitation by grooves

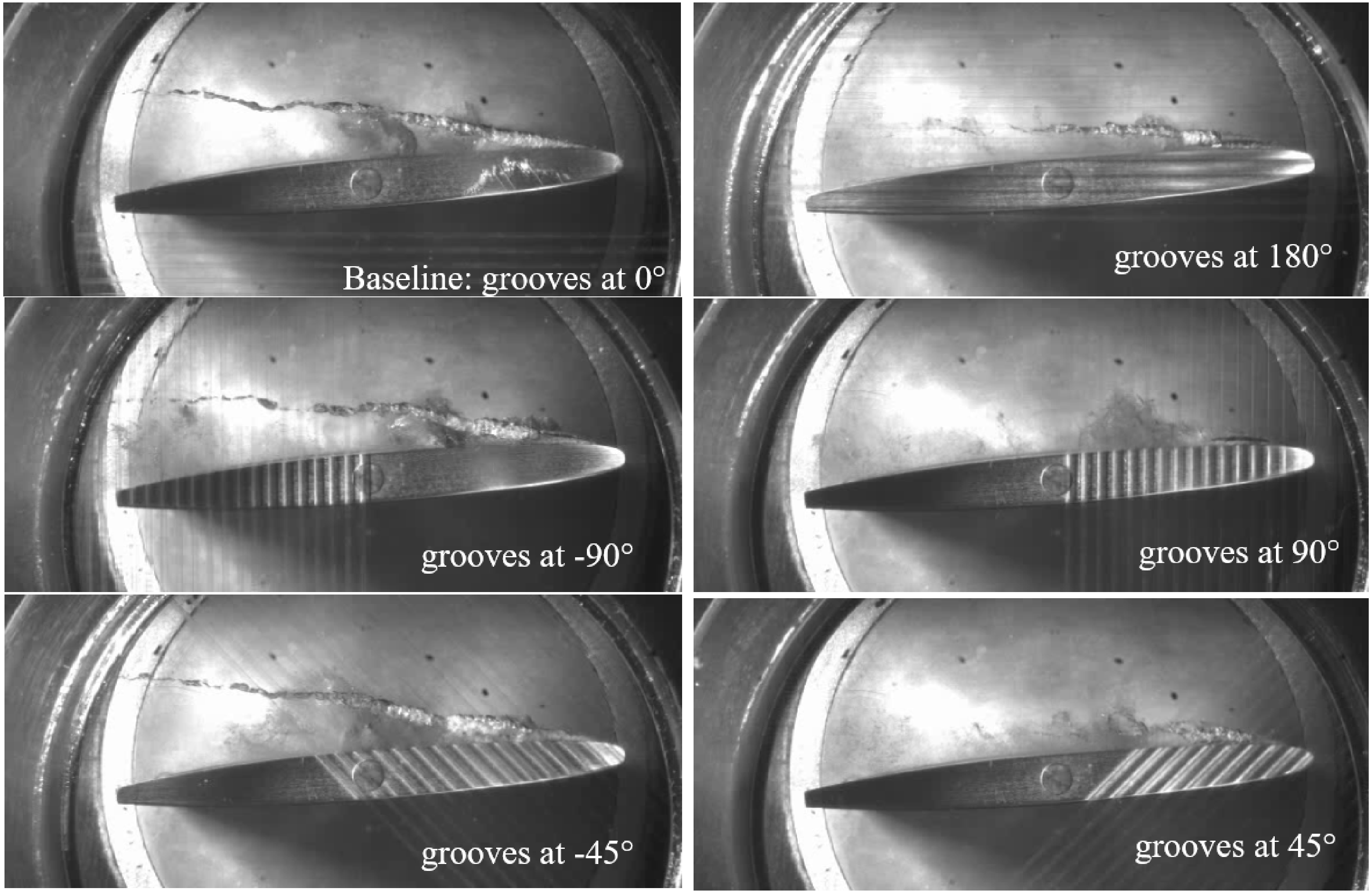
- **No groove vs grooves below the foil**
  - $\tau=0.1, W_\infty = 10\ ms^{-1}, \alpha = 5°$
  - *No significant effect → this case may be used as baseline for comparison*





Effect of grooves orientation on TLV cavitation development

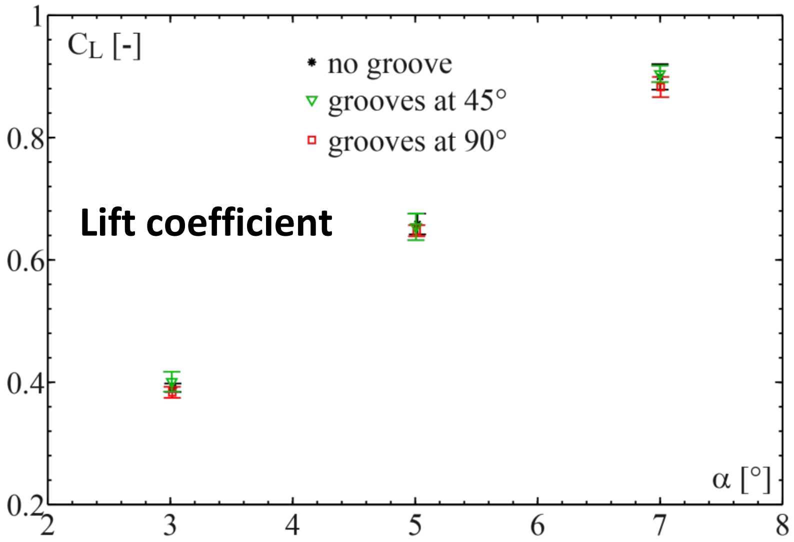
$\tau=0.1, W_{\infty} = 10\ ms^{-1}, \sigma = 1.2, \alpha = 5^{\circ}$



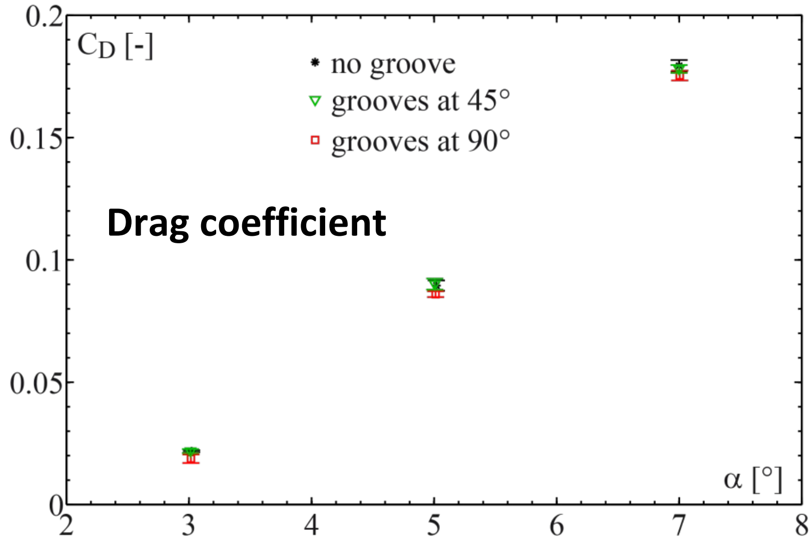
Optimum is obtained with grooves at ~ 45° to 90°

Effects on hydrodynamic performances

- **Lift and drag measurements**
  - **Cavitation-free conditions, $\tau=0.1$, $W_\infty = 10\ ms^{-1}$**



Lift coefficient



Drag coefficient

- **TLV control with grooves - summary**
  - Significant reduction of cavitation with grooves near the leading edge, oriented at 45° or 90°, without alteration of hydrodynamic performances (lift and drag)