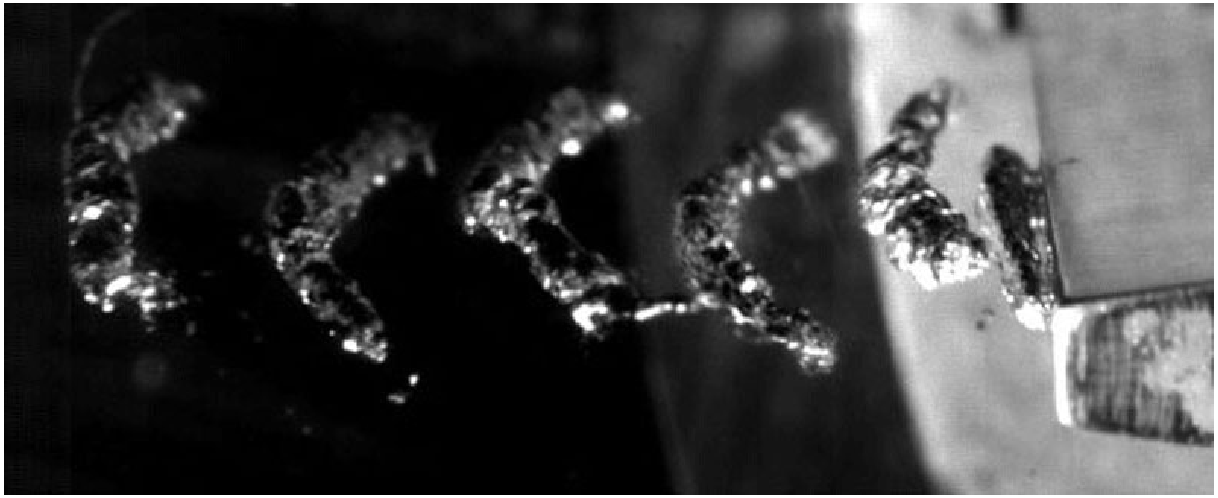
Common Chapter:

Cavitation and Interface Phenomena
Chapter 5.1: Vortex Cavitation - Introduction

Aeroelasticity & Fluid-Structure Interaction
Chapter 7.1: Vortex Induced Vibration - Introduction



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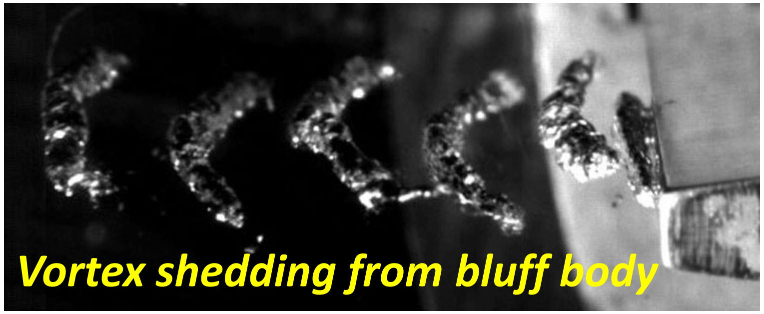
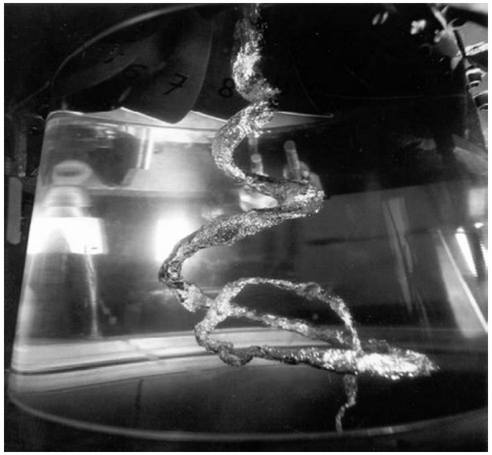
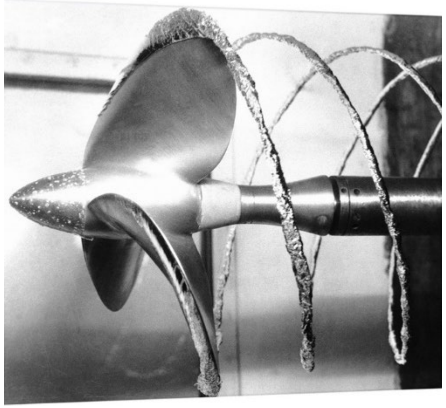
Vortices – Source of cavitation and vibration

Vortices are highly relevant for both Cavitation and Flow-induced Vibration
They are present in a variety of applications:





Part-load rope in a Francis Turbine



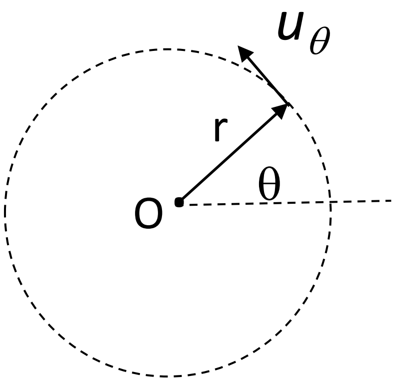
Tip vortex cavitation in a marine propeller

Vortex-induced vibration of soft coral → improve nutrition

Vortices – Source of cavitation and vibration

What is a vortex ?

- ***A vortex may be seen as region of a flow in which the fluid rotates around a straight or curved axis line***



- ***Free vortex (potential flow, incompressible):***

  - ***Velocity field:*** $\vec{u} = (u_r, u_\theta, u_z) = \left(0, \frac{\Gamma}{2\pi r}, 0\right)$

$$\Gamma = \oint_C u_\theta(r)dl = cste \quad \forall C, a\ closed\ contour\ around\ O$$

We may verify that the flow is incompressible $\left(\vec{\nabla}.\vec{u} = 0\right)$ ***and irrotational*** $\left(\vec{\nabla} \times \vec{u} = 0\right)$

$$\vec{\nabla}.\vec{u} = \frac{1}{r}\frac{\partial(ru_r)}{\partial r} + \frac{1}{r}\frac{\partial u_\theta}{\partial \theta} + \frac{\partial u_z}{\partial z} = 0$$

$$\vec{\nabla} \times \vec{u} = \left(\frac{1}{r}\frac{\partial u_z}{\partial \theta} - \frac{\partial u_\theta}{\partial z}, \frac{\partial u_r}{\partial r} - \frac{\partial u_z}{\partial r}, \frac{1}{r}\left(\frac{\partial(ru_\theta)}{\partial r} - \frac{\partial u_r}{\partial \theta}\right)\right) = (0,0,0) \ \ \forall r > 0$$

Vortices – Source of cavitation and vibration

- ***Free vortex (potential flow):***
  - ***Pressure field :***
    - ***Navier-Stokes in cylindrical coordinates (radial equilibrium):***

$$\frac{\partial p}{\partial r} = \rho \frac{u_\theta^2}{r} = \rho \frac{\Gamma^2}{4\pi^2 r^3}$$

Integration → $p(r) = p_\infty - \dfrac{\rho\Gamma^2}{8\pi^2 r^2}$

- ***Alternate method - Bernoulli equation:***

Since the flow is irrotational and steady, Bernoulli equation reads:

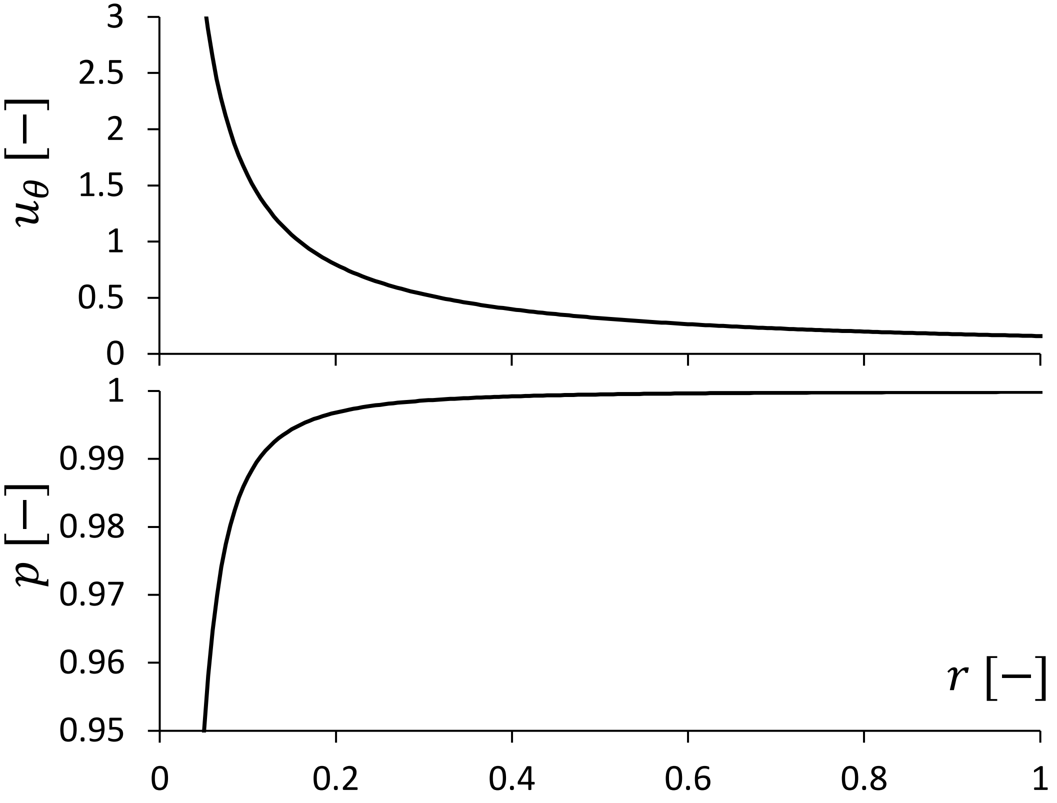
$$\forall r > 0, \qquad p(r) + \rho \frac{u_\theta^2}{2} = constant$$

$$\Longrightarrow \forall r > 0, \qquad p(r) = p_\infty - \rho \frac{u_\theta^2}{2} = p_\infty - \frac{\rho\Gamma^2}{8\pi^2 r^2}$$

Vortices – Source of cavitation and vibration

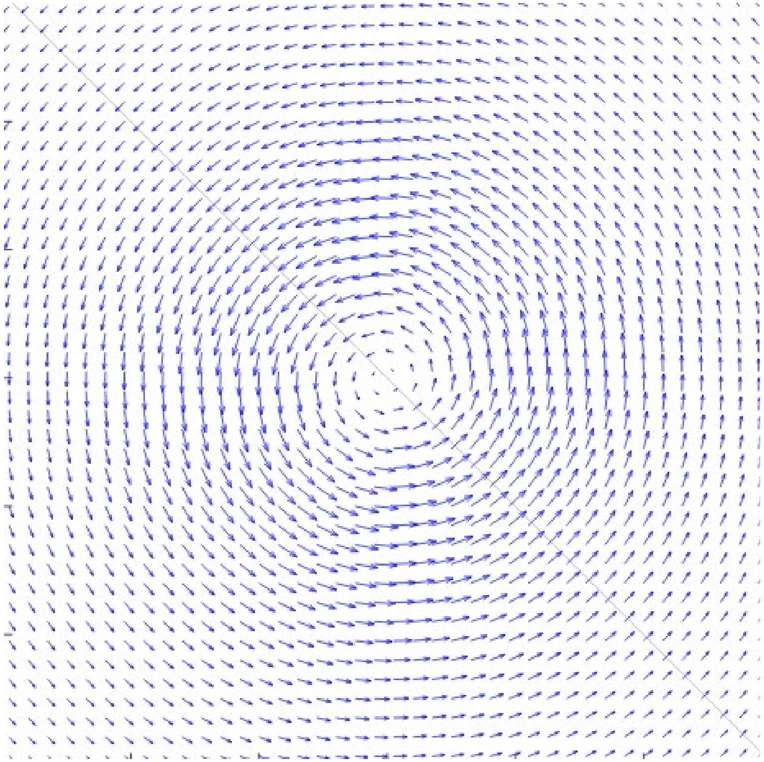
- ***Free vortex (potential flow):***
  - ***Pressure field :*** $\forall r > 0, \qquad p(r) = p_\infty - \rho \frac{u_\theta^2}{2} = p_\infty - \frac{\rho \Gamma^2}{8\pi^2 r^2}$

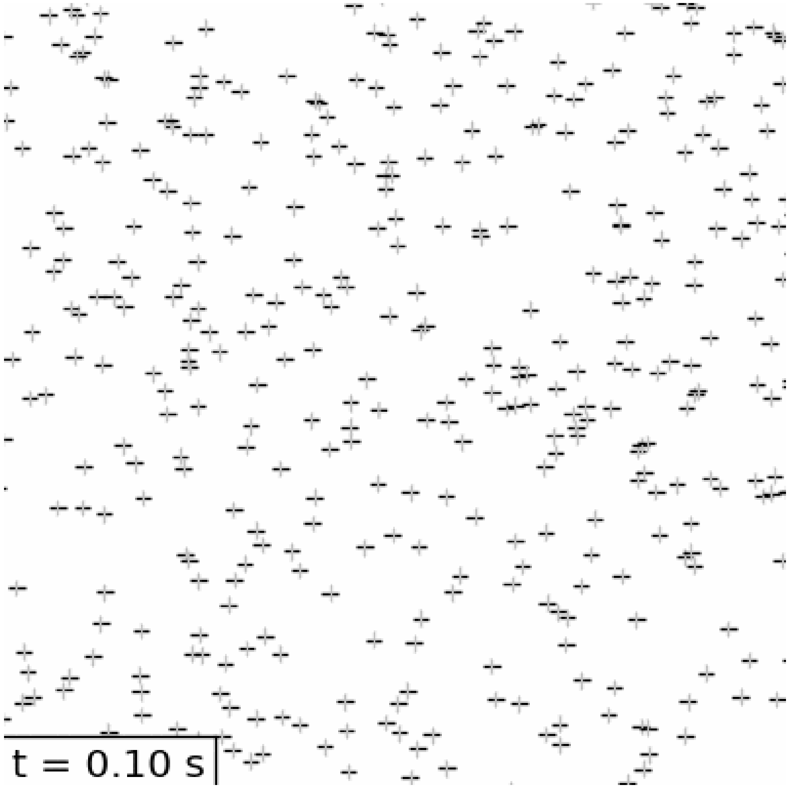
Limitations: $\lim_{r \to 0} u_\theta(r) = +\infty$ and $\lim_{r \to 0} p(r) = -\infty$



Vortices – Source of cavitation and vibration

- ***Observation of vortices in real life leads to the following:***
  - ***Far from the vortex axis, the flow is irrotational***
  - ***As we approach the axis, the flow becomes rotational and its velocity decreases gradualy to vanish on the axis.***
  - ***The maximum velocity is reached at the border between rotational and irrotational domains***





Vortices – Source of cavitation and vibration

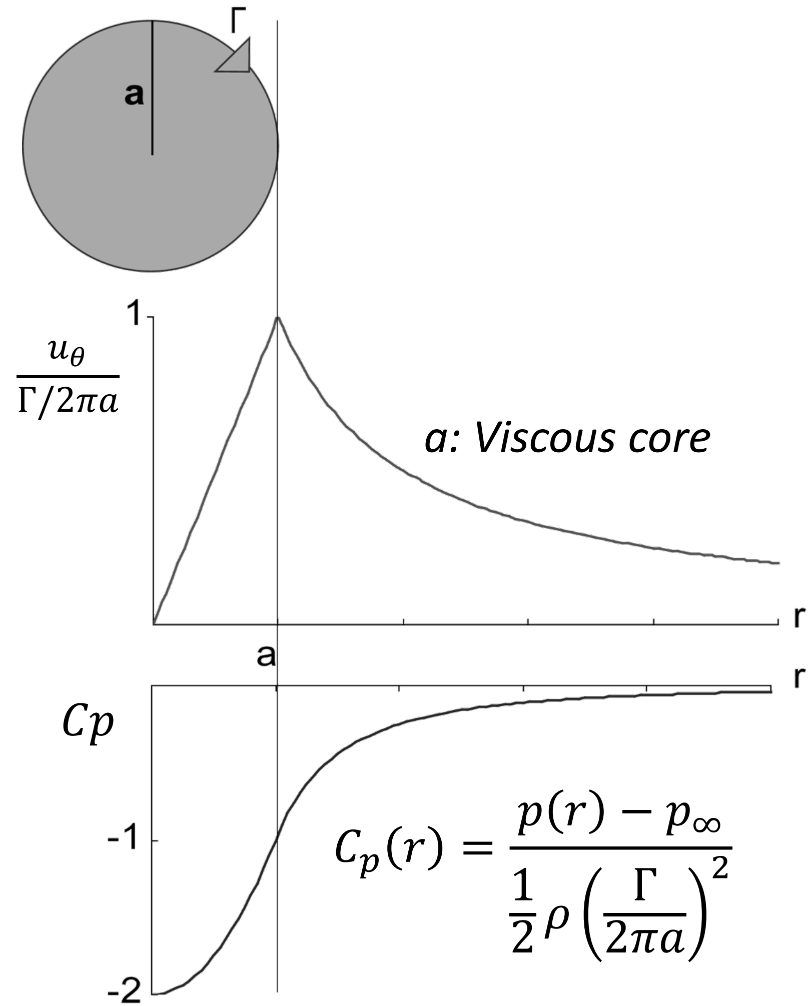
- ***Rankine model:***
  - ***Close to the axis, the viscous forces limits the velocity***
  - ***Velocity field:***

$$r \geq a, \qquad u_\theta = \frac{\Gamma}{2\pi r}$$

$$r \leq a, \qquad u_\theta = \omega r$$

where Γ is the circulation:

$$\Gamma = \int_0^{2\pi} u_\theta \, r d\theta$$



- ***Continuity of the velocity at $r = a$:*** $\omega a = \frac{\Gamma}{2\pi a} \quad \Rightarrow \quad \Gamma = 2\pi\omega a^2$

Vortices – Source of cavitation and vibration

- ***Rankine model:***
  - ***Pressure field (Navier Stokes)***

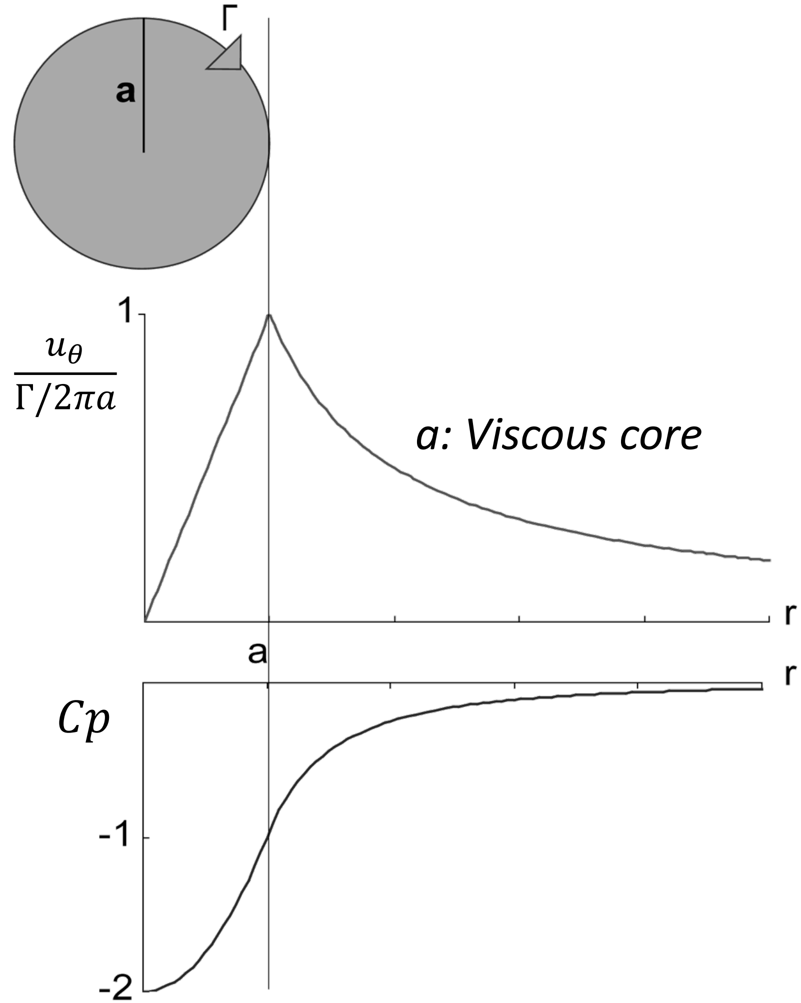
$$\frac{\partial p}{\partial r} = \rho \frac{u_\theta^2}{r}$$

  - ***Integration:***

$$r \geq a, \qquad p(r) = p_\infty - \frac{\rho \Gamma^2}{8\pi^2 r^2}$$

$$r \leq a, \qquad p(r) = p_\infty - \frac{\rho \Gamma^2}{8\pi^2 a^2}\left(2 - \frac{r^2}{a^2}\right)$$

$$C_p(r) = \frac{p(r) - p_\infty}{\frac{1}{2}\rho\left(\frac{\Gamma}{2\pi a}\right)^2} \qquad C_{p,min} = -2$$



  - ***Limitation: Discontinuity of the velocity derivative at $r = a$***
  - ***About Bernoulli equation: In the viscous core, the flow is rotational and Bernoulli equation is only valid along a streamline (useless)***

More realistic models for vortex flows

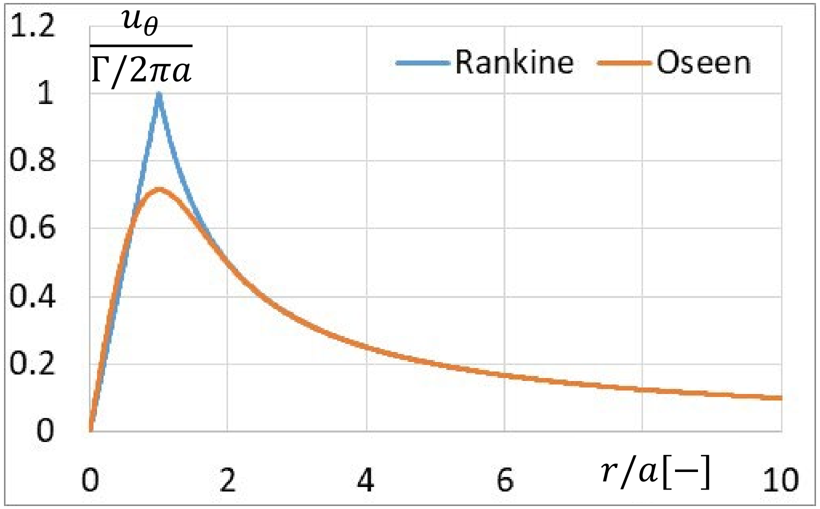
- ***Lamb-Oseen model:***
  - ***Velocity field:***

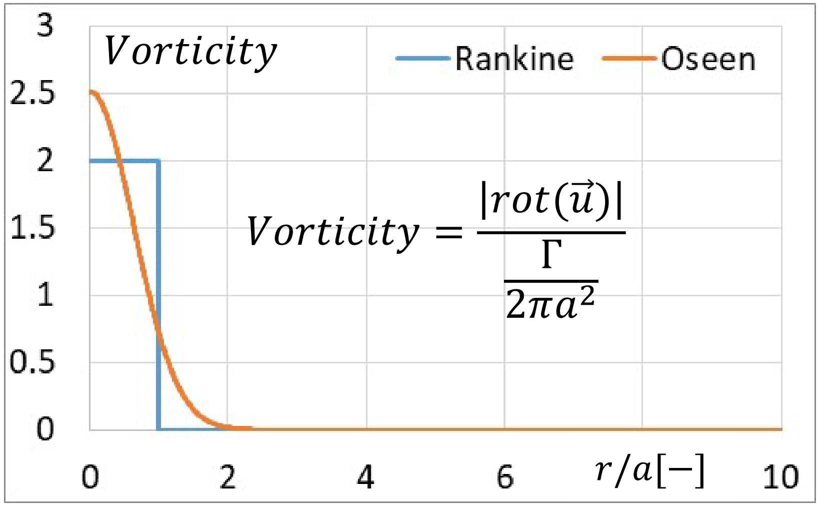
$$\forall r > 0, \qquad u_\theta = \frac{\Gamma}{2\pi r}\left(1 - e^{-\lambda r^2/a^2}\right)$$

Where λ *is a constant* $(\lambda \approx 1.256)$

$$u_{\theta,max} \approx 0.715\,\frac{\Gamma}{2\pi a}$$

→ *Smooth transition from rotational to irrotational flow*





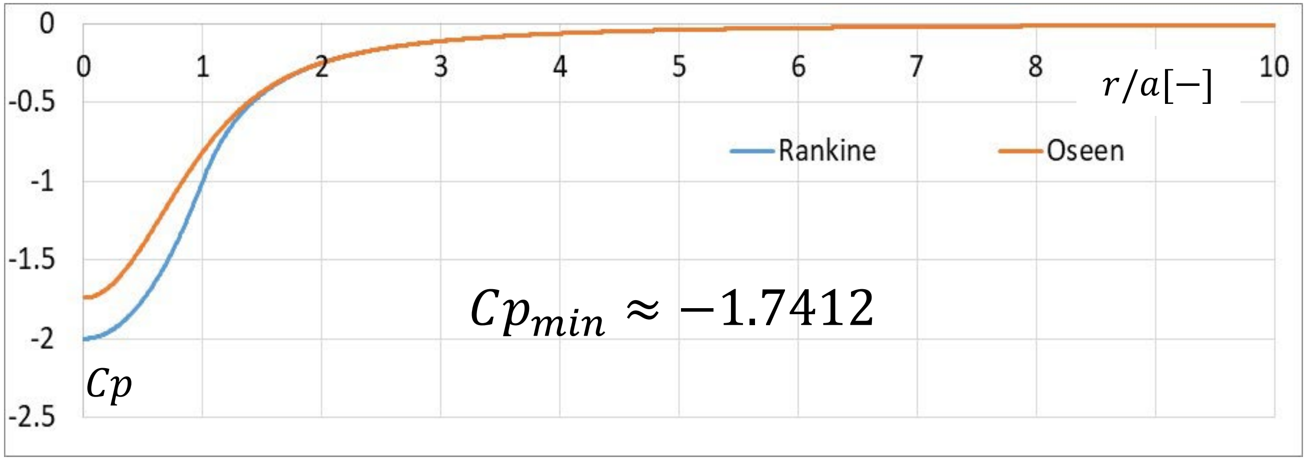
Vortices – Source of cavitation and vibration

- ***Lamb-Oseen model:***
  - ***Pressure field: integration of*** $\dfrac{\partial p}{\partial r} = \rho \dfrac{u_\theta^2}{r}$

$$p(r) = p_\infty - \int_r^{+\infty} \rho \frac{u_\theta^2}{r} dr = p_\infty - \rho \left(\frac{\Gamma}{2\pi a}\right)^2 \int_{r/a}^{+\infty} \frac{\left(1 - e^{-\lambda s^2/a^2}\right)^2}{s^3/a^3} ds$$

$$\ldots\ Cp(r^*) = \frac{p(r^*) - p_\infty}{\frac{1}{2}\rho\left(\frac{\Gamma}{2\pi a}\right)^2} = 2\lambda Ei(-\lambda r^{*2}) - 2\lambda Ei(-2\lambda r^{*2}) + \frac{2e^{-\lambda r^{*2}} - e^{-2\lambda r^{*2}} - 1}{r^{*2}}$$

Where Ei *stands for the Exponential Integral, defined by:* $Ei(x) = \int_{-\infty}^{x} \frac{e^s}{s} ds$ *and* $r^* = r/a$

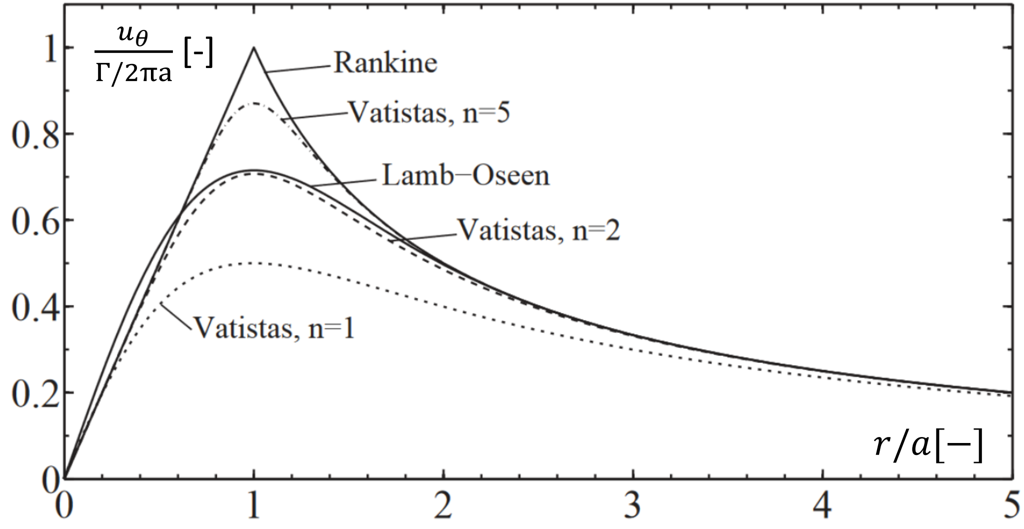


- **Vatistas Model**
  - **Velocity field:**

$$\forall r \geq 0, \qquad u_\theta = \frac{\Gamma}{2\pi} \frac{r}{(a^{2n} + r^{2n})^{1/n}}$$

Where n is a shape parameter

  - **Key parameters of the vortex**
    - **a: Viscous core radius**
    - **Γ: Circulation**



- **Other models are available (e.g. Batchelor, VM2, …)**

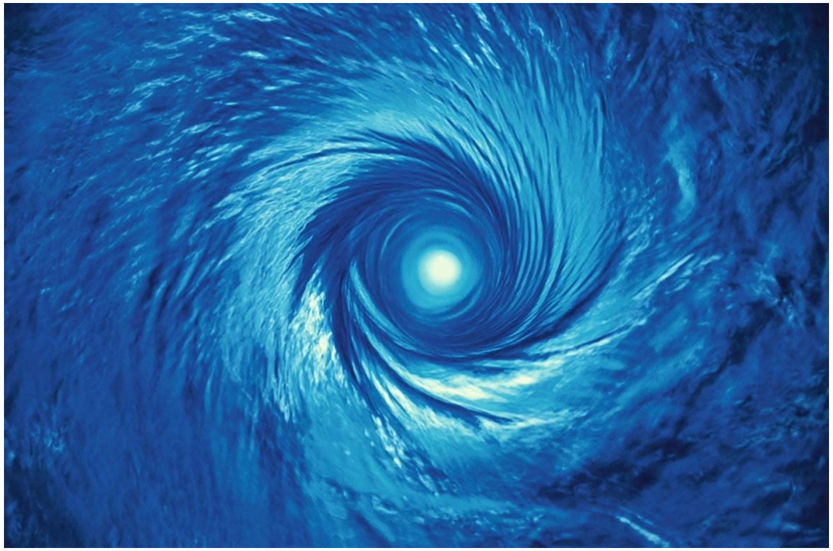
Vortices – Source of cavitation and vibration

Similarity with astrophysics

- *The motion of stars in a galaxy looks like a vortex*
  - *It is possible to fit a vortex model to describe the motion of stars ?*

Milky way

Sink (Lavabo)



Example: Tip Vortex Cavitation

Tip vortex cavitation (TVC) on an elliptic hydrofoil

Upstream velocity (U_∞): 13.5 m/s, Incidence: 10°

σ = 2 σ = 1.5 σ = 1.3 σ = 1 σ = 0.8

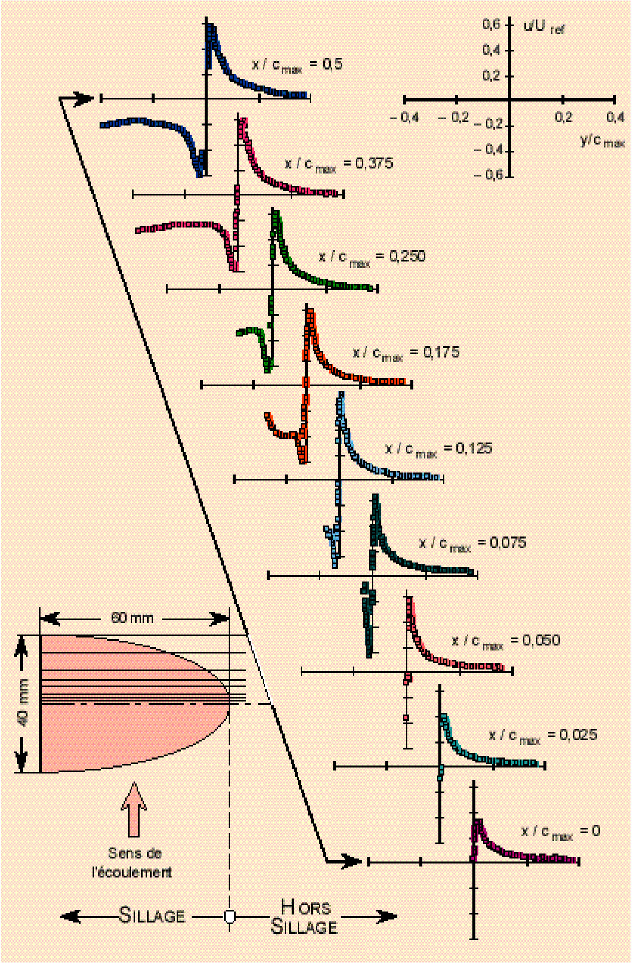
Where σ is the cavitation number, defined as:
With p_v is the vapor pressure

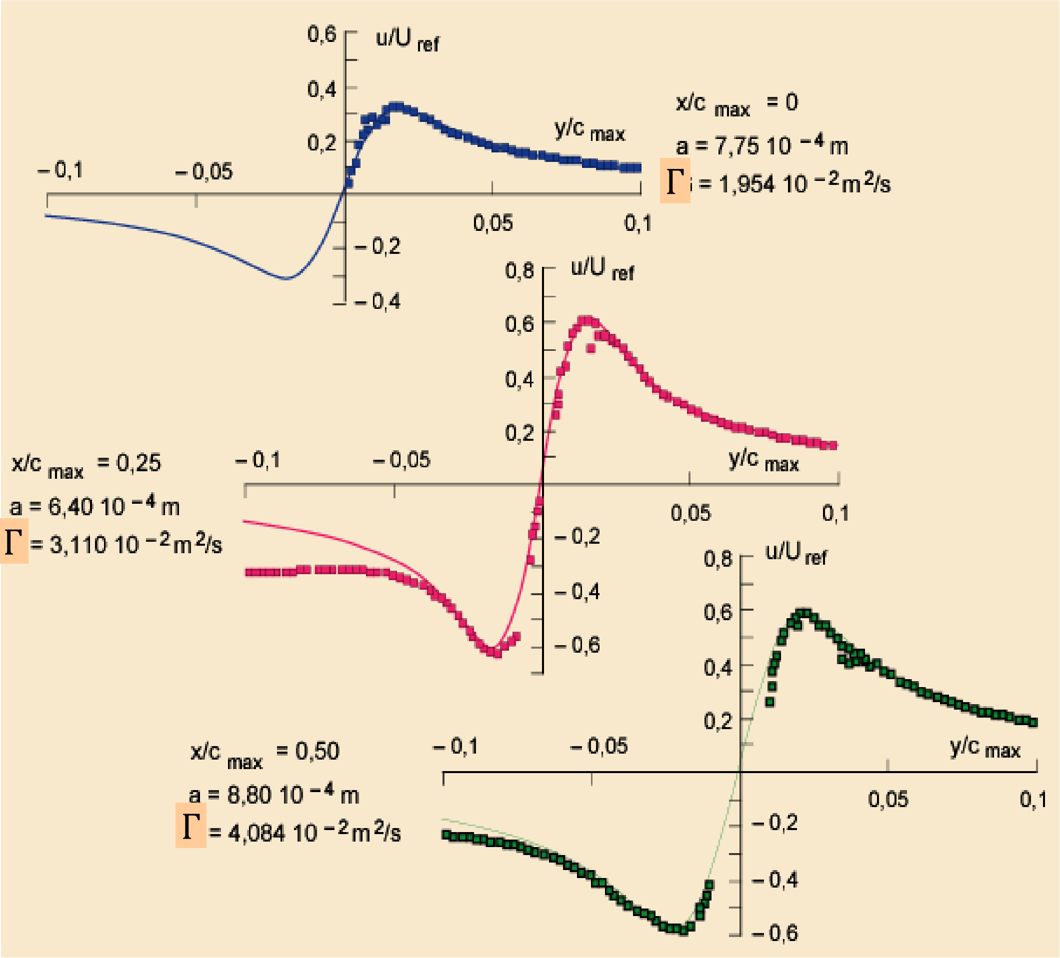
$$\sigma = \frac{p_\infty - p_v}{\frac{1}{2}\rho U_\infty^2}$$

Example: Tip Vortex Cavitation

Velocity profiles downstream an elliptic foil, measured with LDV

Lamb-Oseen model is used to fit the experimental data



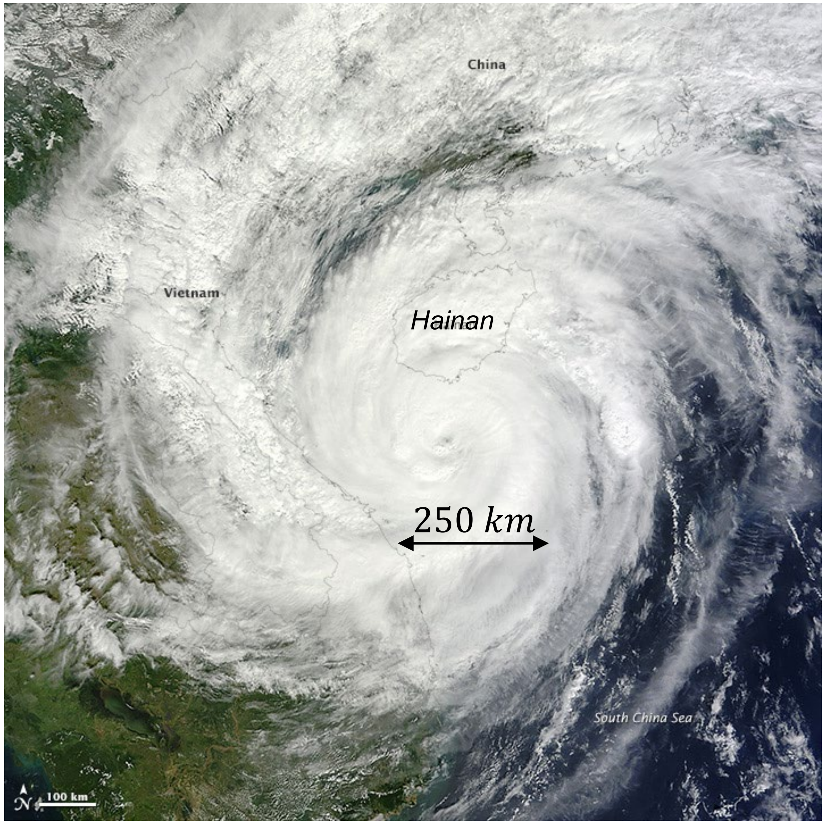


Vortices – Source of cavitation and vibration

Example: Super Typhoon Haiyan, Philippines, November 2013

- **Maximum wind speed ~ 360 km/h**
  - **Pressure in the vortex axis ?**

  - **Assumptions:**
    - Air density $\rho = 1$ kg/m^3
    - Atm. pressure = $1000\ hPa$
    - *2D flow*



  - **Rankine model:**

$$p(r=0) = p_\infty - \frac{\rho\Gamma^2}{4\pi^2 a^2} = p_\infty - \rho u_{\theta,max}^2 \approx 900\ hPa$$

Example: Super Typhoon Haiyan, Philippines, November 2013

Le Nouvelliste

VALAIS SUISSE SPORTS ECONOMIE MONDE SORTIR LIFESTYLE DOSSIERS PREMIUM

DÉFINITION Typhons, ouragans et cyclones sont autant de déclinaisons pour désigner le même phénomène météorologique: une dépression tropicale capable de dégager une puissance équivalente à dix bombes nucléaires.

Typhons, ouragans et cyclones sont un même phénomène Météo désignant la plus violente manifestation des dépressions tropicales. Elles sont capables de dégager une puissance équivalente à dix fois la bombe d'Hiroshima.

Le typhon qui s'est abattu sur les Philippines, où les autorités évoquent plus de 10'000 morts et 2000 disparus, est le mot asiatique pour un phénomène qualifié d'ouragan dans les Caraïbes et de cyclone dans les régions tropicales.

Echelle de Saffir-Simpson

Les cyclones, terme générique pour ces phénomènes tourbillonnaires, sont mesurés par l'échelle de Saffir-Simpson en cinq catégories selon la force des vents maximum et l'ampleur des dégâts potentiels.

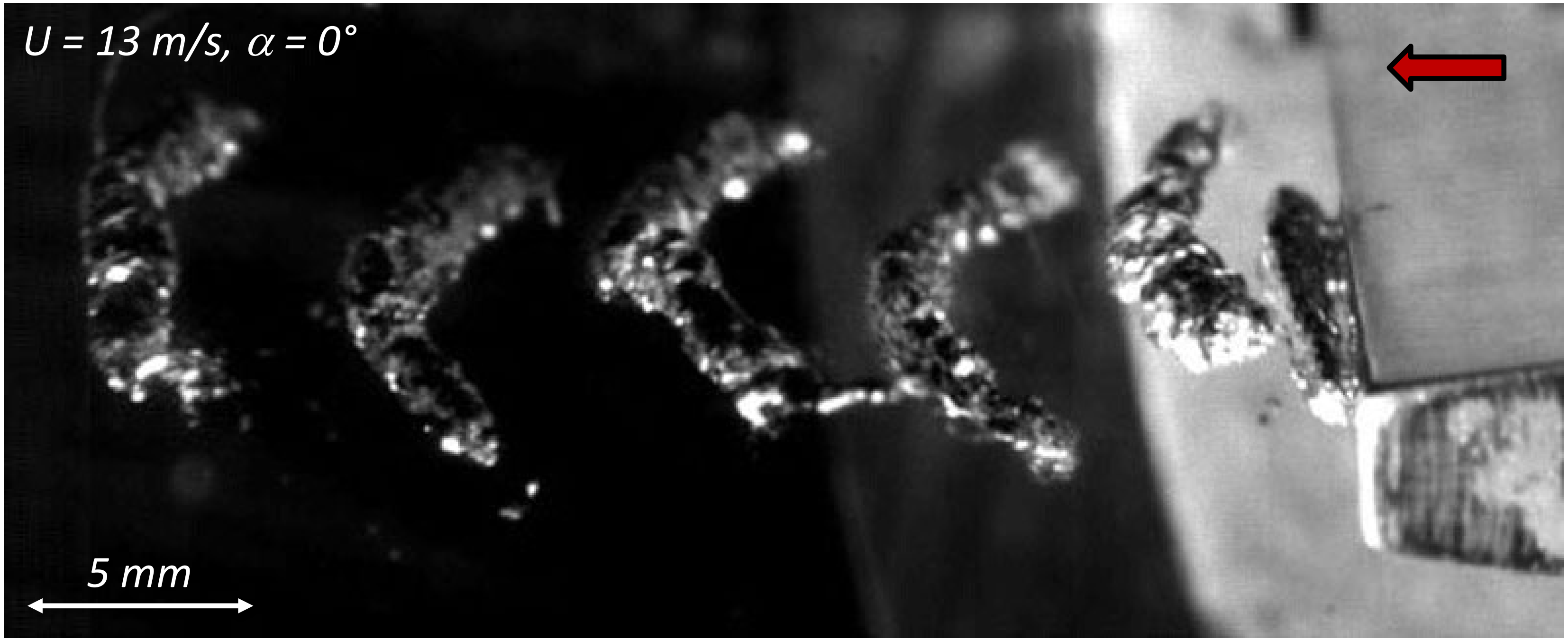
Le super typhon Haiyan est un typhon de catégorie 5, la plus élevée, avec des vents maximum estimés à 315 km/h et des rafales atteignant 380 km/h selon l'agence météo japonaise et le centre américain inter-armes de prévision des cyclones tropicaux.

Au plus fort de son intensité, la pression en son centre était comprise, selon les estimations, entre 870 et 895 hectoPascal. Il pourrait s'avérer le plus violent mesuré à ce jour. Le précédent record est détenu par Tip, dans l'océan Pacifique, avec 870 hPa mesurés le 12 octobre 1979 et des vents maximum alors estimés à 305 km/h, selon le site de Météo France.

Vortices – Source of cavitation and vibration

Wake dynamics:

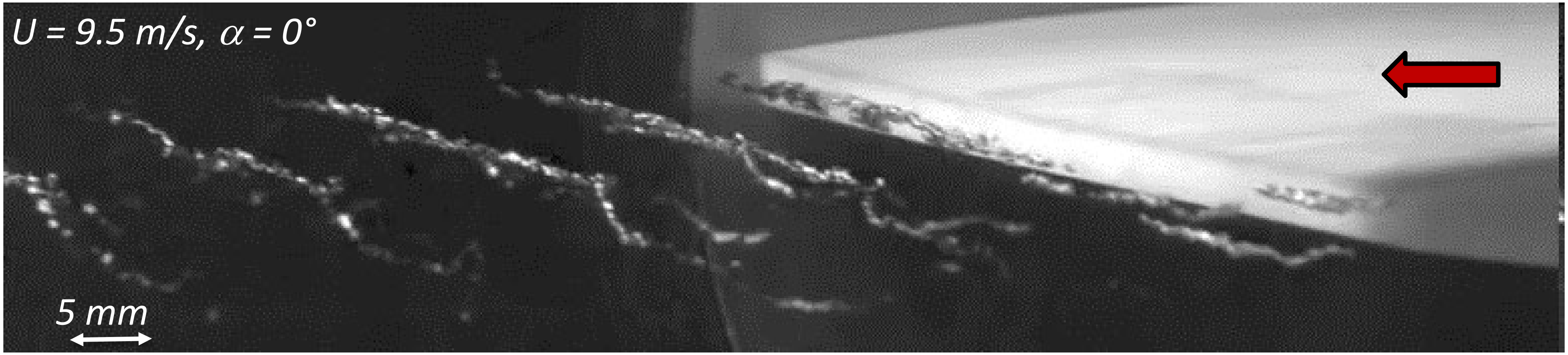
- ***Placed in a fluid stream, bodies generate separated flow that extends to their wake with a possible formation of alternate vortices (Kàrman vortices)***
  → Fluctuating lift → Vibration
- ***Example of Karman vortices in the wake of a stainless steel Naca0009 hydrofoil with a blunt trailing edge***
  Velocity: 13 m/s; 0° incidence angle; resonance (first torsional mode)



Vortices – Source of cavitation and vibration

Wake dynamics:

- ***Placed in a fluid stream, bodies generate separated flow that extends to their wake with a possible formation of alternate vortices (Kàrman vortices)***
  → Fluctuating lift → Vibration
- ***Example of Karman vortices in the wake of a POM Naca0009 hydrofoil with a blunt trailing edge***
  Velocity: 9.5 m/s; 0° incidence angle; resonance (second torsional mode)



Vortices – Source of cavitation and vibration

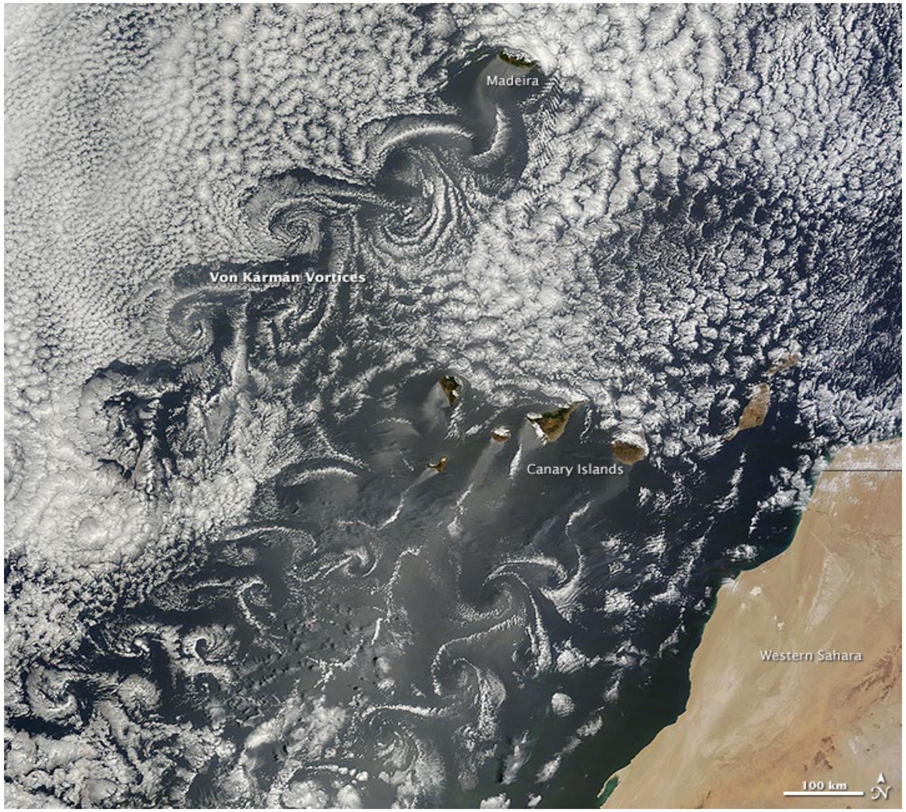
Wake dynamics:

- ***Placed in a fluid stream, bodies generate separated flow that extends to their wake with a possible formation of alternate vortices (Kàrman vortices)***
  → Fluctuating lift → Vibration
- ***Example: Karman vortices in the wake of a Kaplan turbine blades***
  The vortices are visible because of cavitation occurrence

Vortices – Source of cavitation and vibration

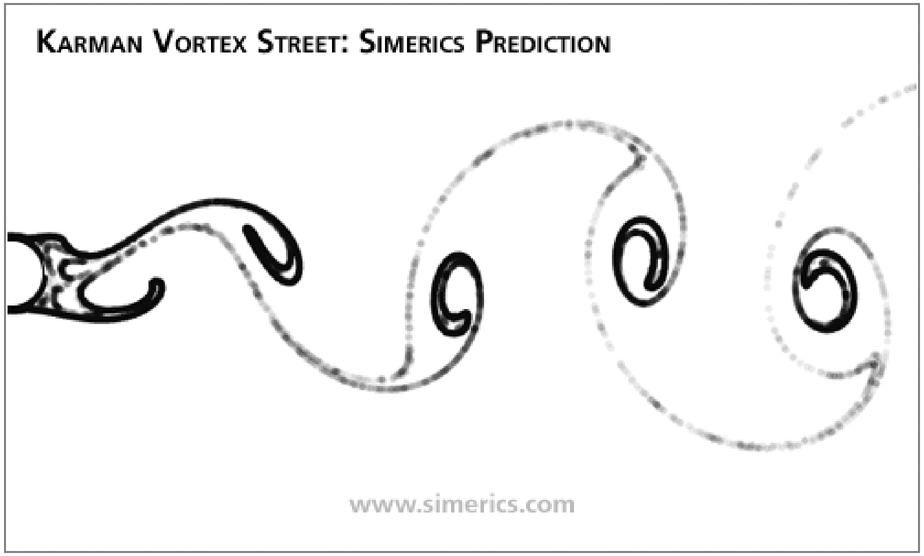
Wake dynamics:

- *Placed in a fluid stream, bodies generate separated flow that extends to their wake with a possible formation of alternate vortices (Kàrman vortices)*
  → Fluctuating lift → Vibration
- *Example: Karman vortices in the wake of Madeira and Canary islands*



Vortices – Source of cavitation and vibration

Wake dynamics: The case of a flow over a cylinder



- *Shedding Frequency f_s ?*
  - *Dimensional analysis →*

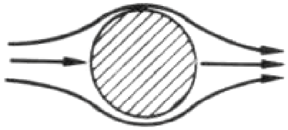
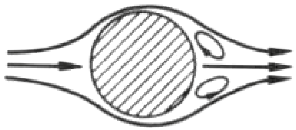
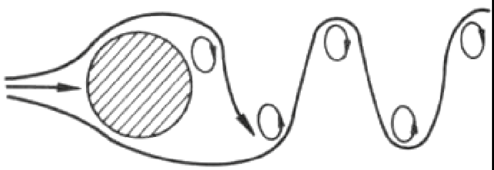
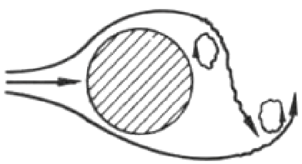
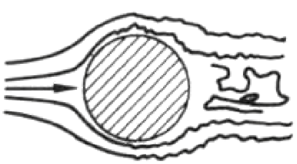
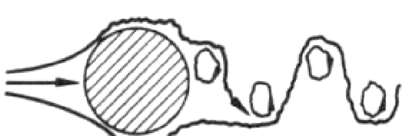
$$F\left(\frac{f_s D}{U_\infty}, \frac{\rho U_\infty D}{\mu}\right) = 0$$

$\frac{f_s D}{U_\infty}$ → **St** — **Strouhal Number**

$\frac{\rho U_\infty D}{\mu}$ → **R_e** — **Reynolds Number**

Vortices – Source of cavitation and vibration

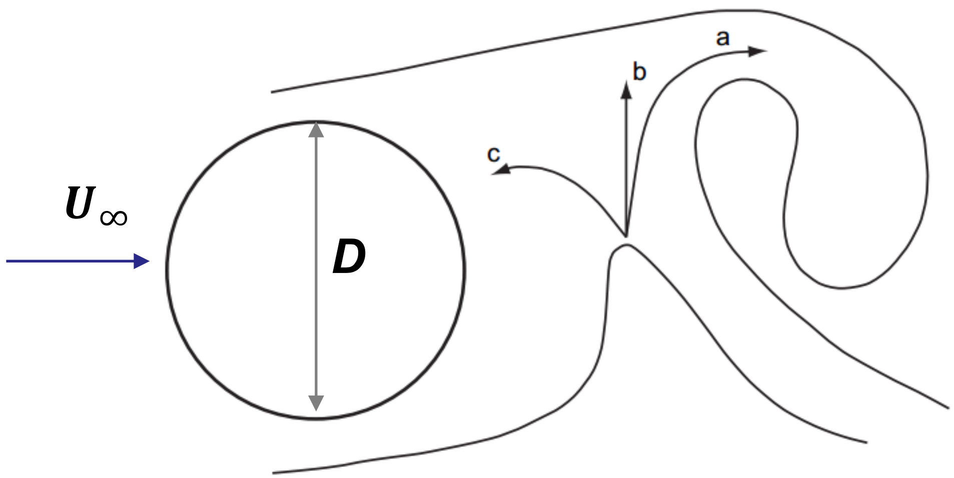
Wake dynamics: The case of a flow over a cylinder

	$R_e < 5$: Laminar flow with 2 stagnation points. The flow moves smoothly around the obstacle without separation.
	$5\ to\ 15 < R_e < 40$: Laminar flow with the formation of fixed pair of vortices in the wake
	$40 < R_e < 90\ \ AND\ \ 90 < R_e < 150$: Two regimes in which vortex street is laminar
	$150 < R_e < 300$: Transition range to turbulent shedding $300 < R_e < 3\ 10^5$: Vortex street is fully turbulent
	$3\ 10^5 < R_e < 3.5\ 10^6$: Laminar boundary layer has undergone turbulent transition and wake is narrower and disorganized. This coincides with the so-called drag crisis
	$R_e > 3.5\ 10^6$: Re-establishment of turbulent vortex street

Vortices – Source of cavitation and vibration

Wake dynamics: The case of a flow over a cylinder

- ***The mutual interaction between the two separating shear layers leads to the formation of a vortes, which continues to grow, fed by circulation from its connected shear layer, until it is strong enough to draw the opposing shear layer across the wake.***



Vortex-formation model, Gerrard (1966)

- ***The alternate shedding of vortices is the result of a complex interaction between 3 shear layers: (i) The boundary layer, (ii) the formation region and (iii) the wake.***

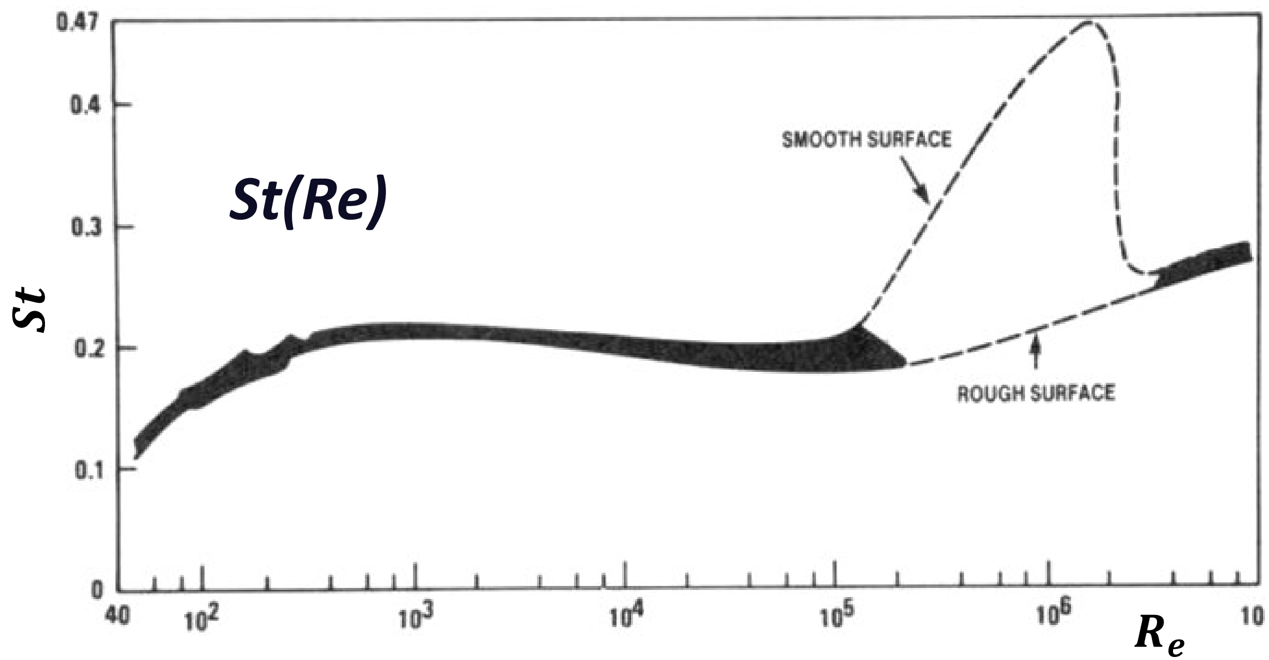
Vortices – Source of cavitation and vibration

Wake dynamics: The case of a flow over a cylinder

- *Shedding frequency (f):*
  - *Function of Reynolds and Strouhal numbers:*

$$St = \frac{f_s D}{U_\infty}, R_e = \frac{\rho U_\infty D}{\mu}$$

  - *Empirical relation :*



Vortices – Source of cavitation and vibration

- ## *Vortex shedding, Initial Theory by Von Karman, 1911*

… Perhaps I should tell how I became interested in the problem. In 1911 I was a graduate assistant in Göttingen. At that time Prandtl's main interest was in the theory of the boundary layer (which we will take up later), i.e., the flow of the fluid very close to the surface of a body. Prandtl had a doctoral candidate, Karl Hiemenz (Ref. 6), to whom he gave the task of constructing a water channel in which he could observe the separation of the flow behind a cylinder. The object was to check experimentally the separation point calculated by means of the boundary-layer theory. For this purpose, it was first necessary to know the pressure distribution around the cylinder in a steady flow. Much to his surprise, Hiemenz found that the flow in his channel oscillated violently.

When he reported this to Prandtl, the latter told him: "Obviously your cylinder is not circular."

However, even after very careful machining of the cylinder, the flow continued to oscillate. Then Hiemenz was told that possibly the channel was not symmetric, and he started to adjust it.

I was not concerned with this problem, but every morning when I came in the laboratory I asked him, "Herr Hiemenz, is the flow steady now?"

He answered very sadly, "It always oscillates." [1]

Now, I thought, if the flow always oscillates, this phenomenon must have a natural and intrinsic reason. One weekend I tried to calculate the stability of the system of vortices, and I did it in a very primitive way. I assumed that only one vortex was free to move, while all the other vortices were fixed, and calculated what would happen if this vortex were displaced slightly. The result I got was that, provided a symmetric arrangement was assumed, the vortex always went off from its original position. I obtained the same result for asymmetric arrangements but found that, for a definite ratio of the distances between the rows and between two consecutive vortices, the vortex remained in the immediate neighborhood of its original position, describing a kind of small closed circular path around it.

I finished my work over the weekend and asked Prandtl on Monday, "What do you think about this?"

"You have something," he answered. "Write it up and I will present your paper in the Academy."

This was my first paper on the subject. Then because I thought my assumption was somewhat too arbitrary, I considered a system in which all vortices were movable. This required a little more complicated mathematical calculation, but after a few weeks I finished the calculation and wrote a second paper.

Some people asked, "Why did you publish two papers in three weeks? One of them must be wrong." Not exactly wrong, but I first gave a crude approximation and afterward refined it. The result was essentially the same; only the numerical value of the critical ratio was different.

Now these vortices have many physical applications. Shortly after the publication of my paper, Rayleigh (Ref. 7) got the idea that the alternating vortices must give the explanation of the Aeolian harp—the singing wires. Some people will still remember the singing wires of the biplane cellules. The singing comes from the periodical shedding of vortices. When certain struts used on an underwater vehicle sang a high tune, Gongwer (Ref. 8) showed experimentally that the vibration was caused by the periodical shedding of vortices, which occurred when the trailing edges were not properly sharp. This also explains the singing of marine propellers, as was previously found by Gutsche (Ref. 9).

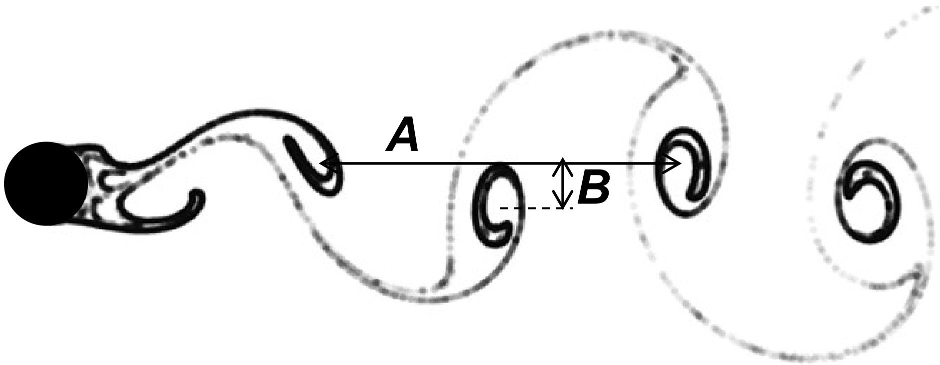
A French naval engineer told me of a case where the periscope of a submarine was completely useless at speeds over 7 knots under water, because the rod of the periscope produced periodic vortices whose frequency at a certain speed was in resonance with the natural vibration of the rod. Radio towers have shown resonant oscillations in natural wind. The galloping motion of power lines also has some connection with the shedding of vortices. The collapse of the bridge over the Tacoma Narrows was also caused by resonance due to periodic vortices. The designer wanted to …

From Aerodynamics, By Theodor Von Karman,Oxford Univ. Press, 1963

Vortices – Source of cavitation and vibration

Wake dynamics: The case of a flow over a cylinder

- ***Initial Theory, by Von Karman, 1911***
  - ***Stability conditions:***
    - ***Alternate shedding***



    - ***Constant ratio between streamwise and spanwise vortex spacings***

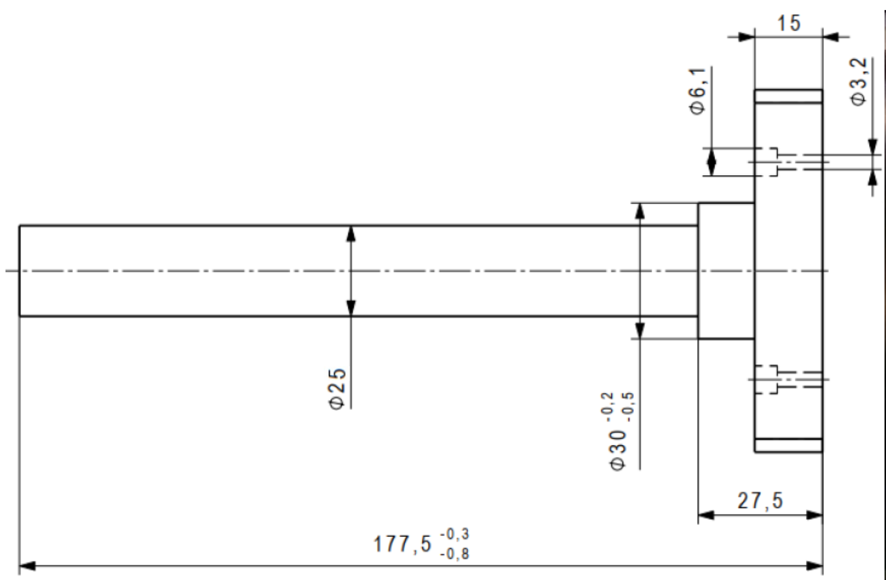
$$\frac{B}{A} = 0.281$$

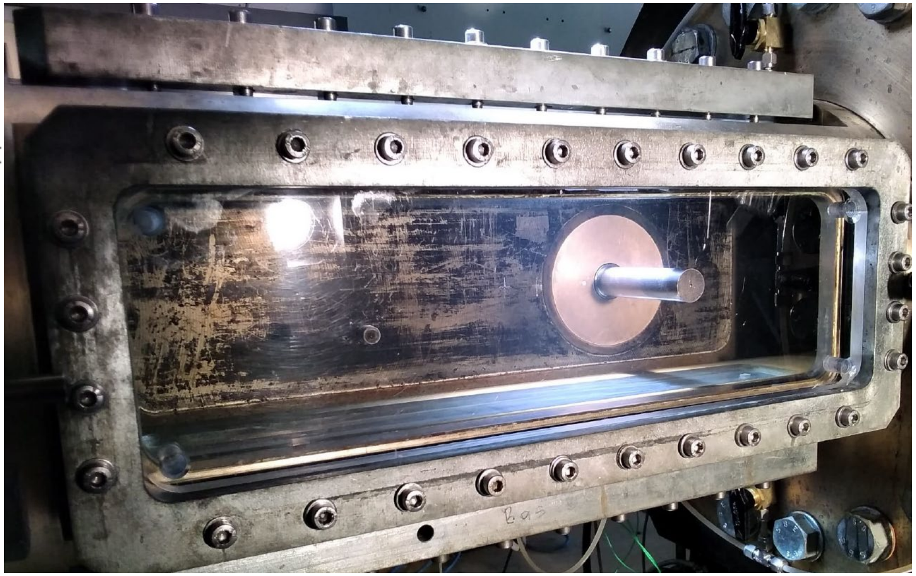
    - ***Relationship between advection velocity, vortex intensity and spacing***

$$V_{adv} = -\frac{\Gamma}{2A}\tanh\left(\frac{\pi B}{A}\right)$$

Vortex Induced Vibration

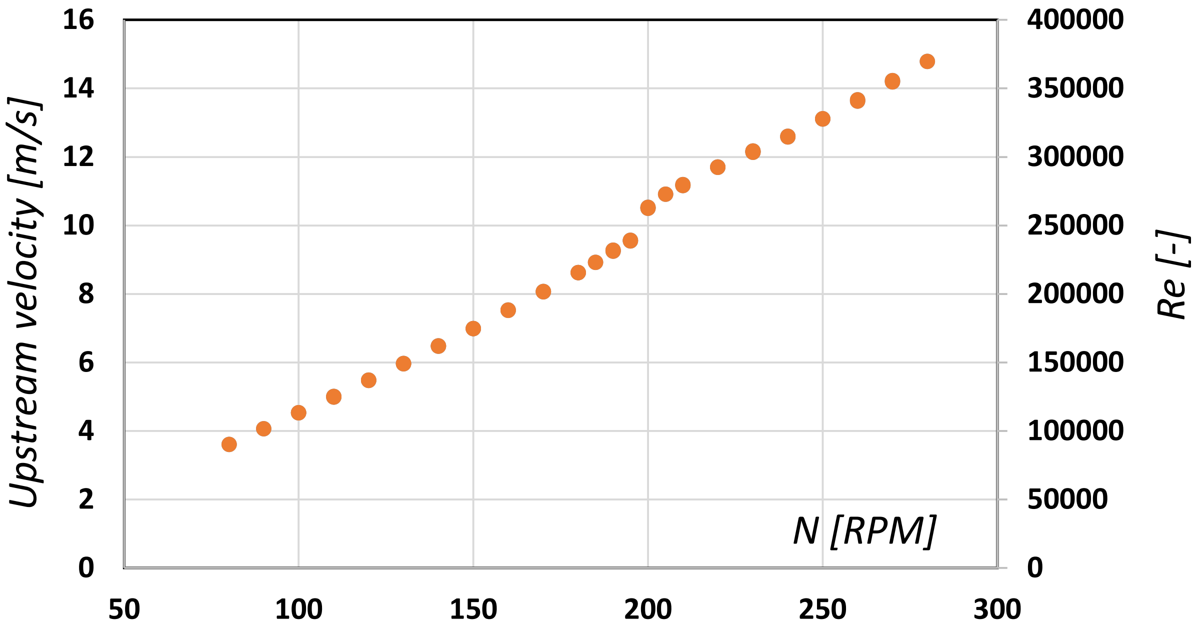
- *Case f a cylinder in EPFL Cavitation Tunnel (semester project 2021)*
  - *Stainless steel, made from one bloc of metal*
    - *Several cylinders made of assembly of 2 parts were destroyed because of too much vibration !!*
  - *25 mm diameter, 150 mm span*
  - *Measurement of vibration, Lift&Drag, High-speed visulization*





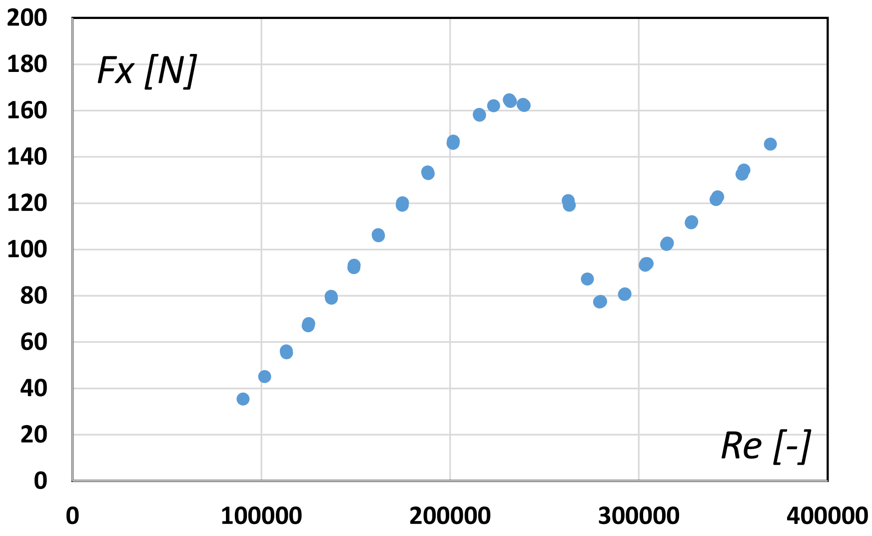
Vortex Induced Vibration

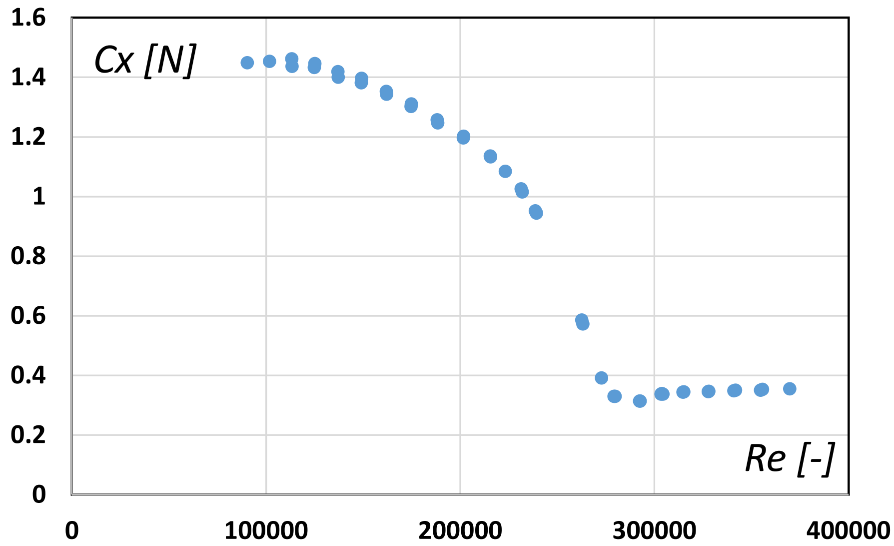
- Case f a cylinder in EPFL Cavitation Tunnel (semester project 2021)
  - Evidence of drag crisis (Cavitation free)
    - Upstream velocity vs Rotation speed of the pump
      - Constant acceleration of the pump during 3 minutes
    - Sudden increase around Re=250’000
      - Due to a sudden drop of the cylinder drag



Vortex Induced Vibration

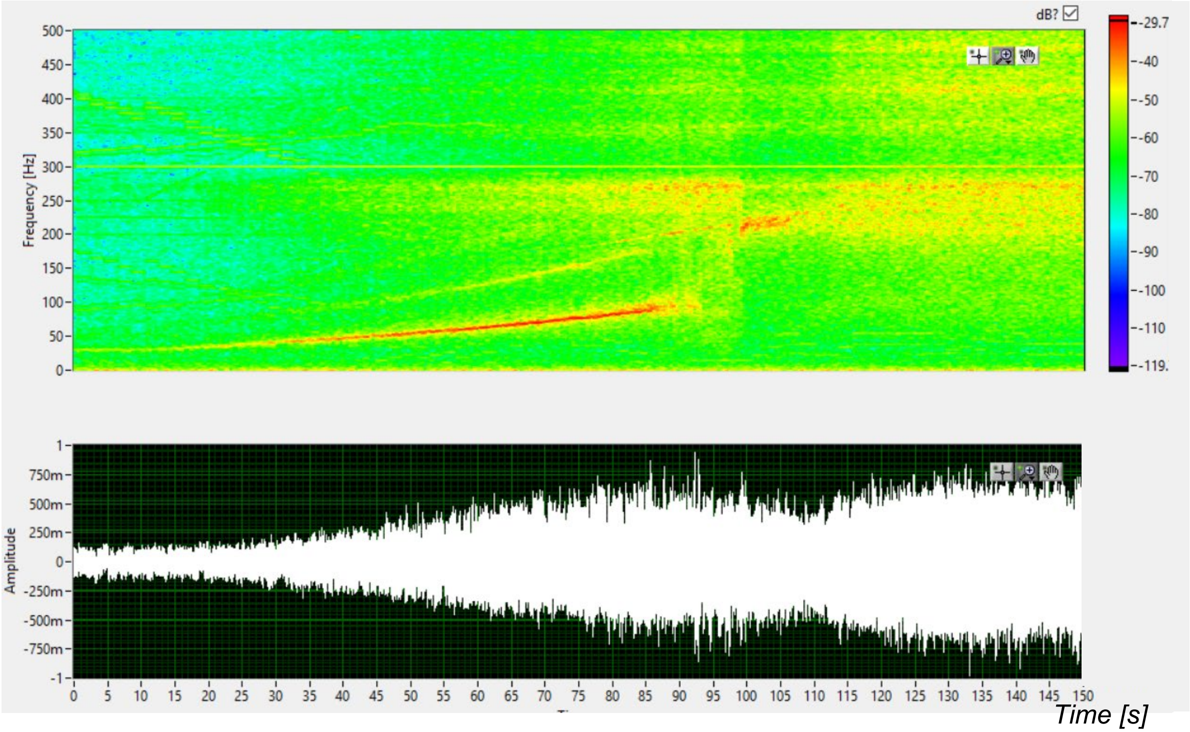
- *Case f a cylinder in EPFL Cavitation Tunnel (semester project 2021)*
  - *Evidence of drag crisis*
    - *Drag force and drag coefficient vs Reynolds number*
    - *Significant decrease of the drag force around Re=250’000*
      - *Due to a delay in boundary layer separation*





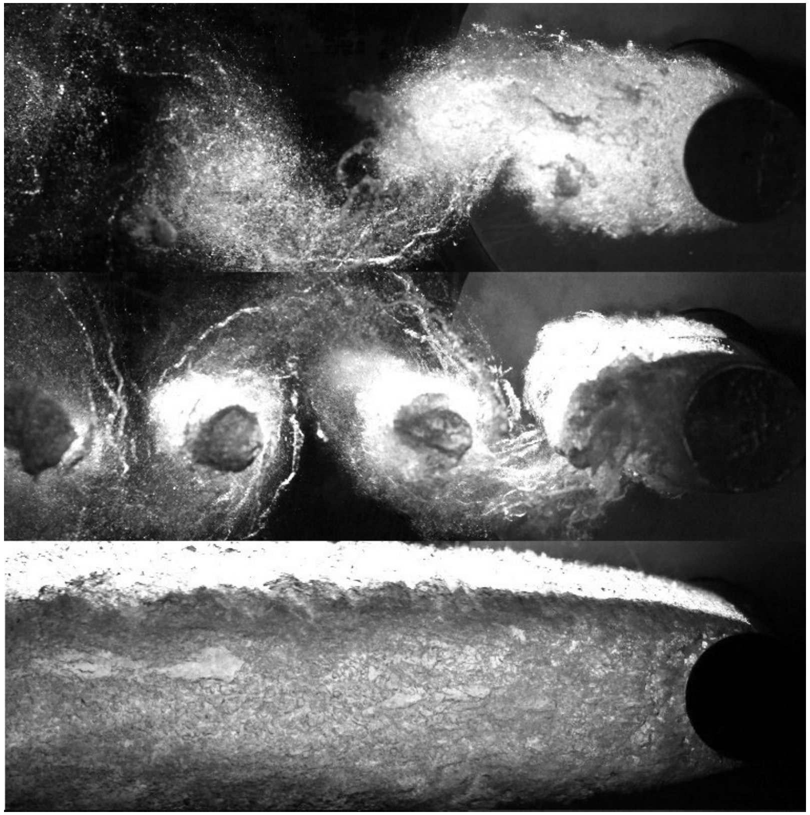
Vortex Induced Vibration

- *Case f a cylinder in EPFL Cavitation Tunnel (semester project 2021)*
  - *Flow induced vibration (upstream velocity 3.6 → 13 m/s)*
    - *No significant increase of vibration at onset or beyond drag crisis*
    - *Strouhal frequency dominant before drag crisis (St~0.2)*
    - *Wake less organized beyond drag crisis*



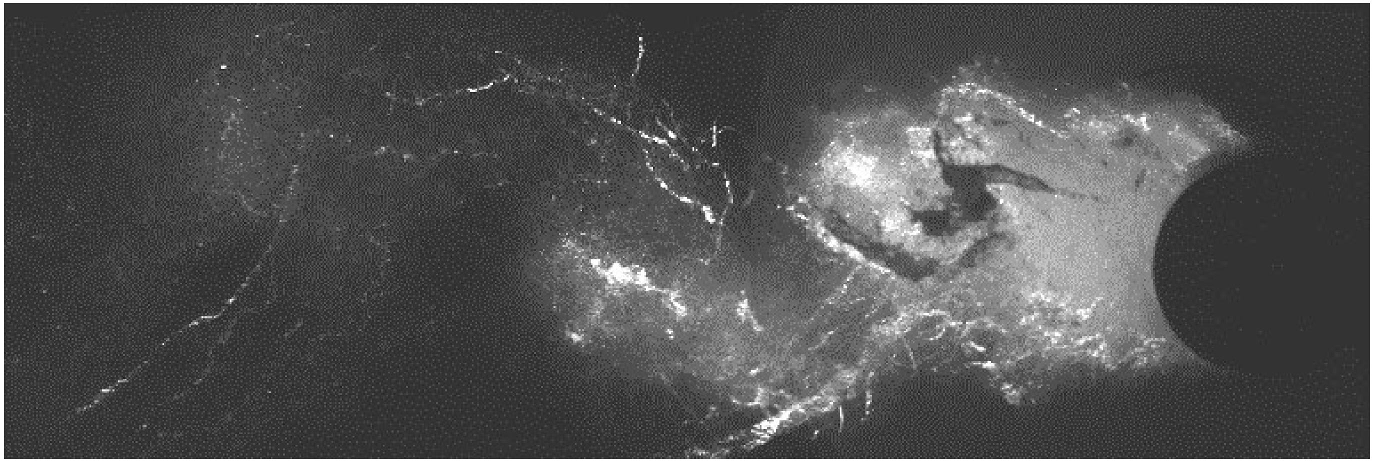
Vortex Induced Vibration

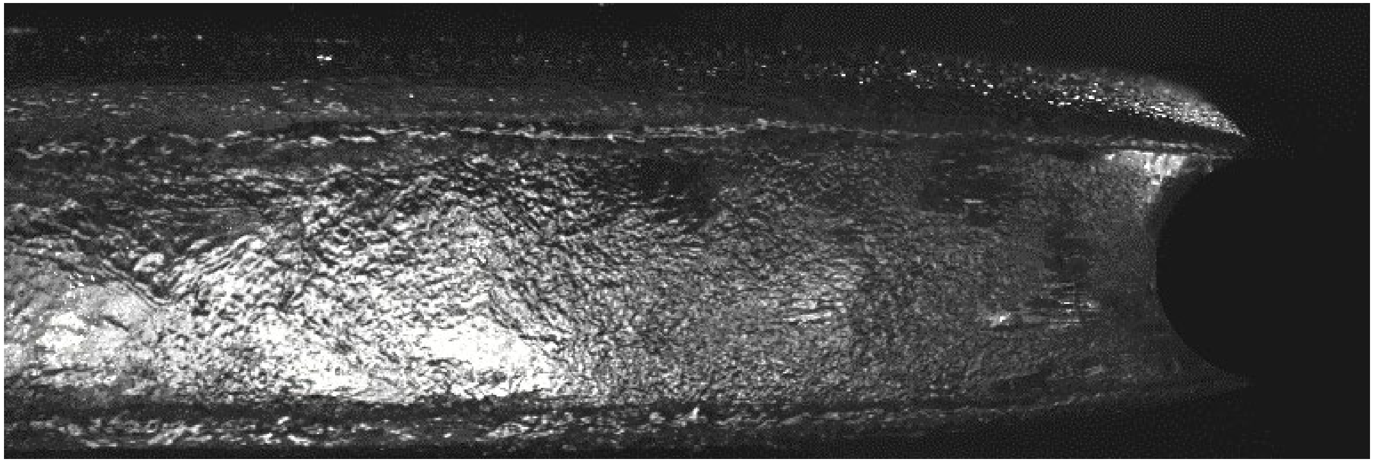
- *Case f a cylinder in EPFL Cavitation Tunnel (semester project 2021)*
  - *Effect of cavitation on fluid-structure vibration:*
    - *Cavitation occurrence in the wake*
      → *the vortices are more coherent*
      → *A tremendous increase of vibration*
    - *Supercavitation:*
      → *No vortex shedding*
      → *Minimum vibration*
      → *Minimum drag*
    - *Further research is underway to understand these peculiar effects*



Drag induced instability : Drag Crisis

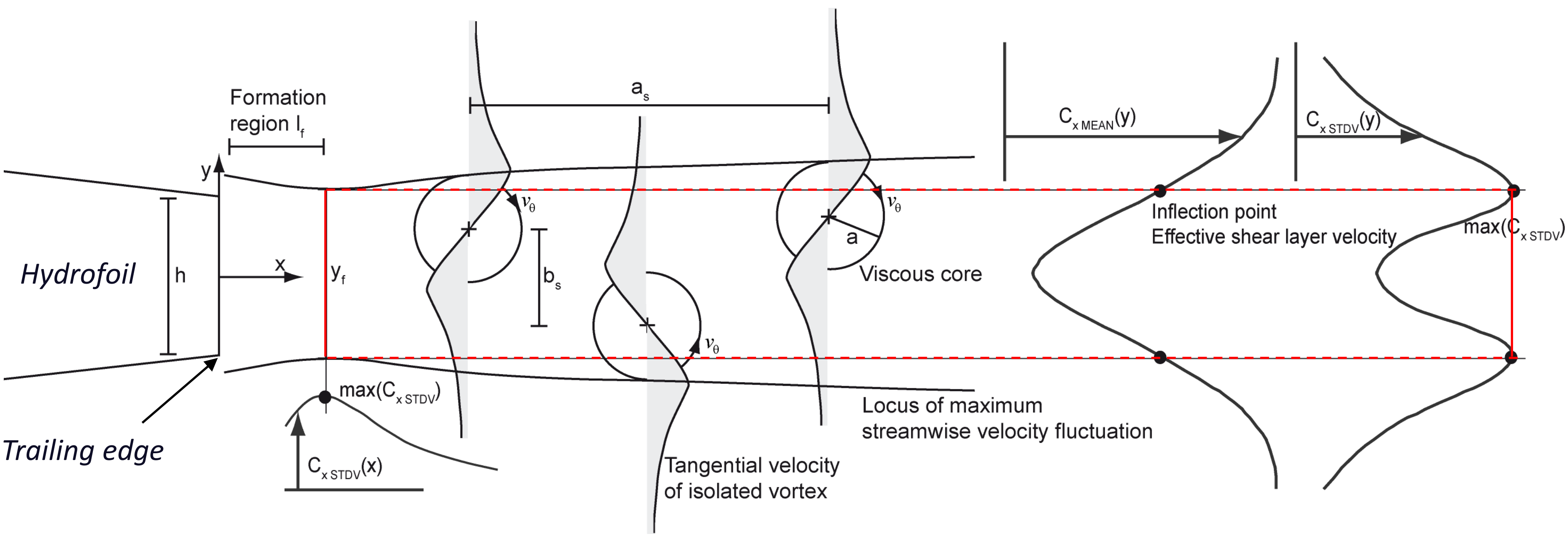
- ***Case f a cylinder in EPFL Cavitation Tunnel (semester project 2021)***
  - ***Effect of cavitation on fluid-structure interaction:***





The case of a flow over a hydrofoil

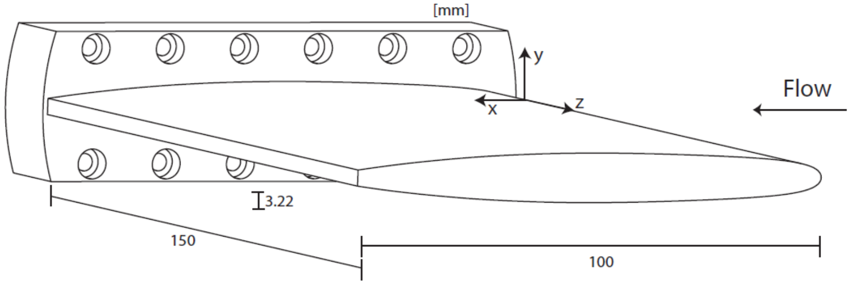
- **Wake structure (similar to the Cylinder case)**
  - **Vortex formation region (l_f):**
    - **bound by X-Position of maximum streamwise velocity fluctuation**
  - **Wake width (y_f) :**
    - **Distance between the streamwise velocity fluctuations maxima**
    - **$y_f = 4a$, where a is the viscous core of karman vortices**

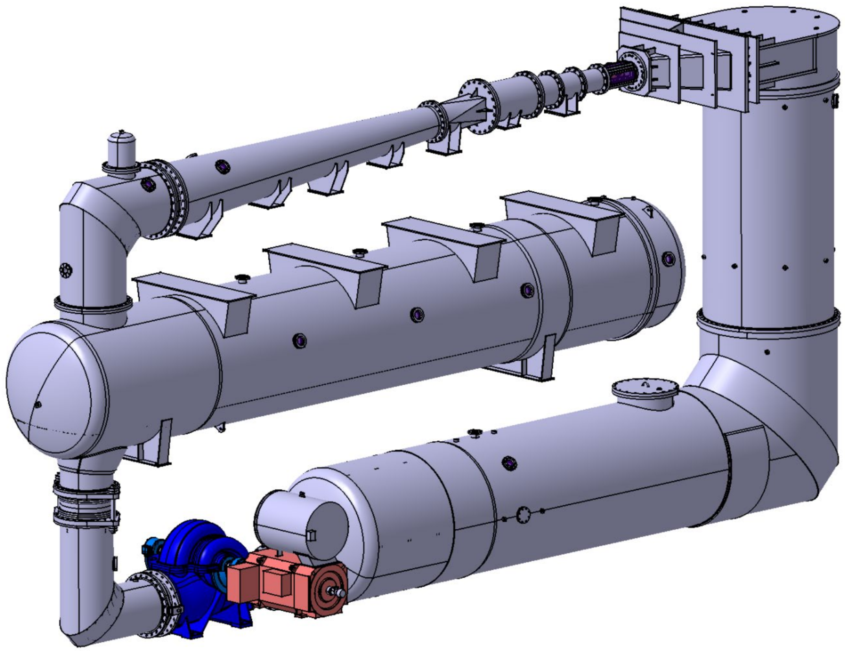


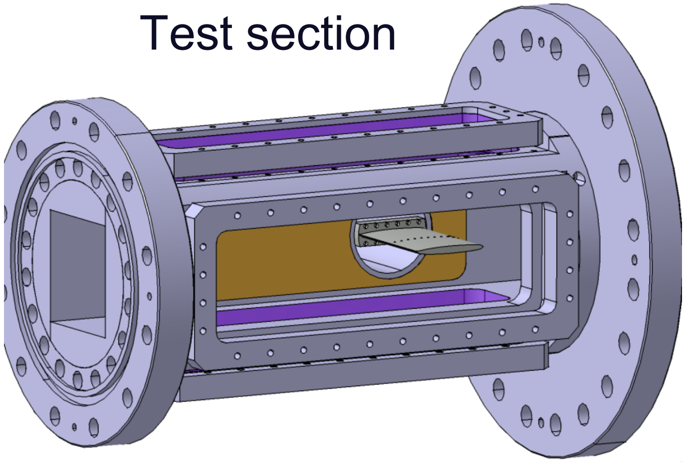
Vortices – Source of cavitation and vibration

The case of a flow over a hydrofoil

- ***Experimental investigations***
  - ***2D NACA0009 hydrofoil in the EPFL high speed cavitation tunnel***
  - ***Blunt trailing edge***
  - ***Smooth and rough leading edge***



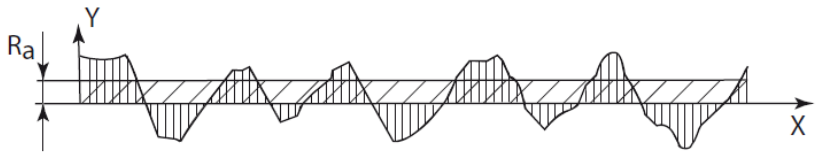




The case of a flow over a hydrofoil

- ***Boundary layer tripping through leading edge roughness***
  - ***Surface roughness – Definition***
    - ***Ra: Arithmetic Mean Roughness***
      Ra is the average value of all absolute distances of the roughness profile from the center line within the measuring length

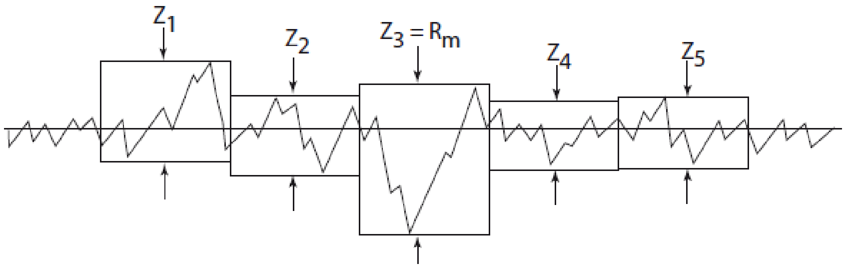
$$R_a = \frac{1}{l_r}\int_{x=0}^{x=l_r} |\, y \,|\, dx$$



- ***Rz: Average Maximum Peak to Valley***

Rz is the average maximum peak-to-valley of five consecutive sampling lengths within the measuring length

$$Rz = 1/5(Z_1 + Z_2 + Z_3 + Z_4 + Z_5) = 1.5\ \mu\text{m}$$

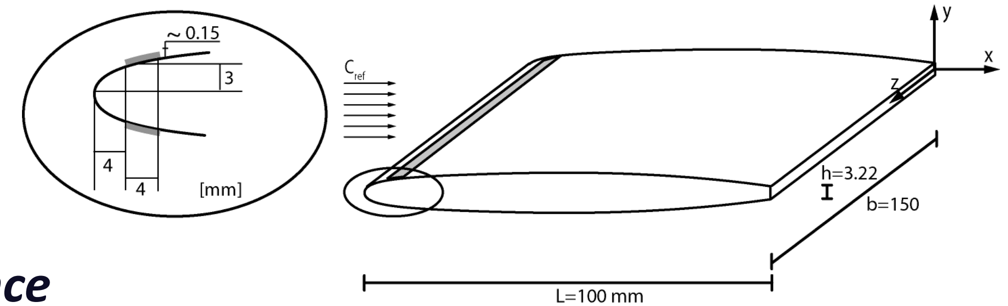


Vortices – Source of cavitation and vibration

The case of a flow over a hydrofoil

- ***Boundary layer tripping through leading edge roughness***
  - ***Natural transition to turbulence***
    - ✓ ***Polished surface (R_Z~2 μm)***
    - ✓ ***Foil hydraulically smooth (H. Schlichting)***

$$\frac{C_{ref} R_z}{\upsilon} < 100$$
$$\Rightarrow C_{ref} < 50\ m/s$$



  - ***Tripped transition to turbulence***
    - ✓ ***Glue + 125 μm diameter sand***
    - ✓ ***Transition to turbulence (H.L. Dryden:) :***

$$\frac{C_{ref} k}{\upsilon} > 900$$

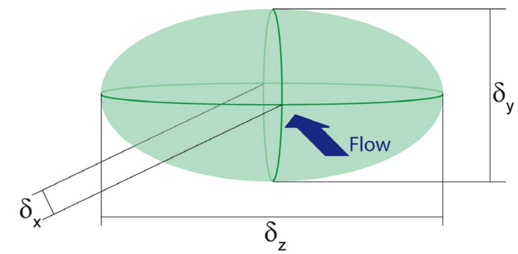
k is the mean of roughness height ~ 150 μm

→ transition to turbulence occurs for upstream velocity above 6 m/s

Vortices – Source of cavitation and vibration

The case of a flow over a hydrofoil

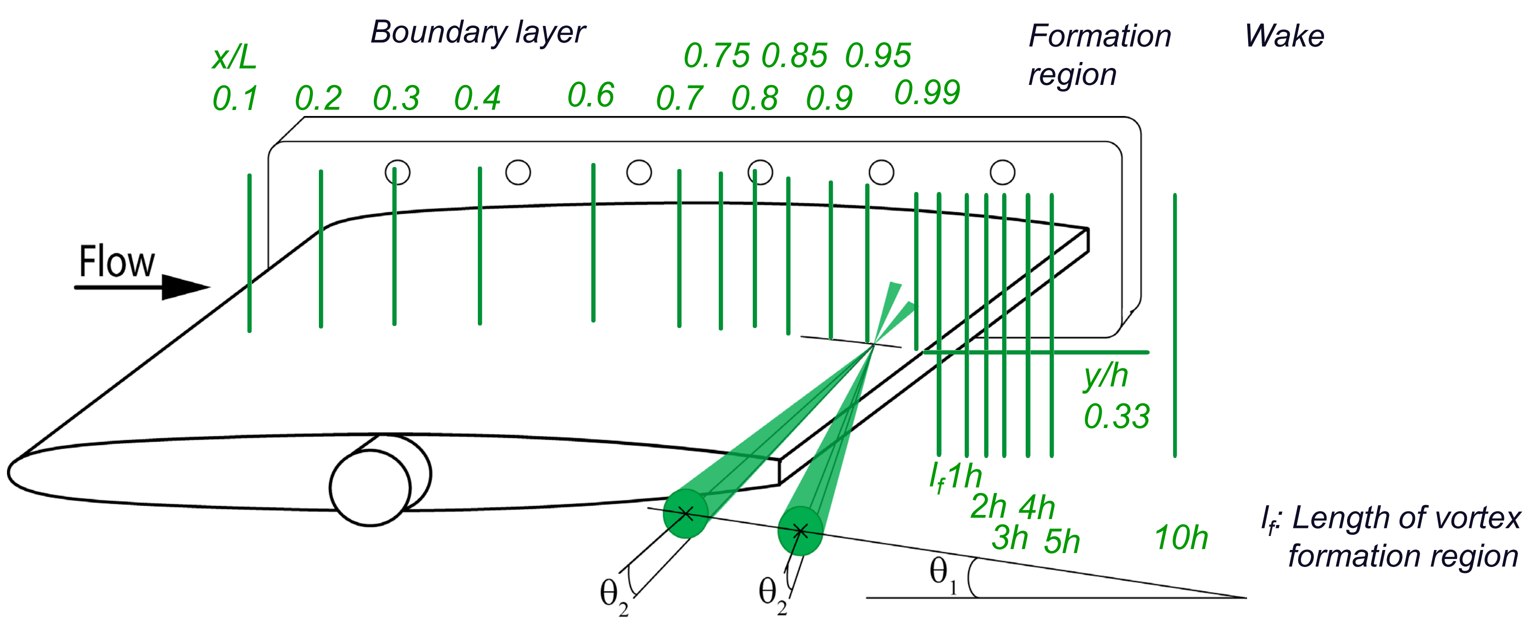
- *Laser Doppler Velocimetry (LDV)*
  - *Seeding: 10 µm diameter hollow glass spheres*
  - *Laser light: 10 W argon-ions source*
  - *Ellipsoidal measurement volume: diameter: 0.074 mm; length: 1.3 mm*



$$\delta_x = \delta_y = 0.074mm$$

$$\delta_z = 1.307mm$$

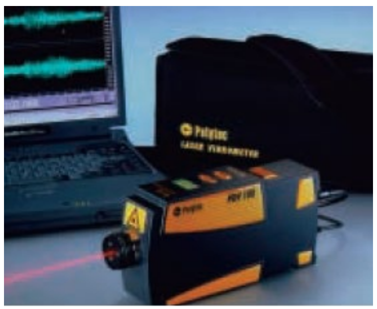
  - *Velocity profiles:*



Vortices – Source of cavitation and vibration

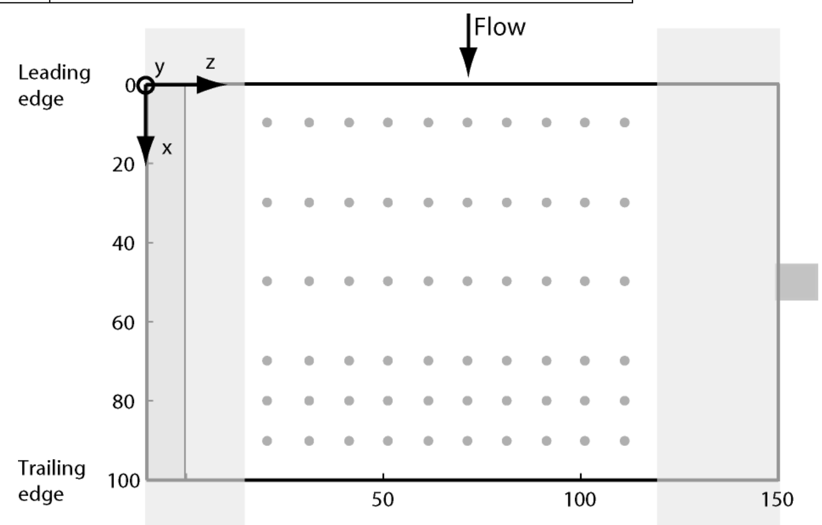
The case of a flow over a hydrofoil

- **Vibration measurements:**
  - **Piezoelectric accelerometer fitted on the hydrofoil support**
  - **Non intrusive Laser Doppler Vibrometer (Polytec PDV100)**



Specification	
Laser type and class	$HeNe$, class II
Velocity range	$20, 100, 500$ mm/s
Frequency range	22 kHz
Low pass filter	$1, 5, 22$ kHz digital FIR type
High pass filter	100 Hz analog, 3^{rd} order Butterworth
Working distance	> 0.1 m

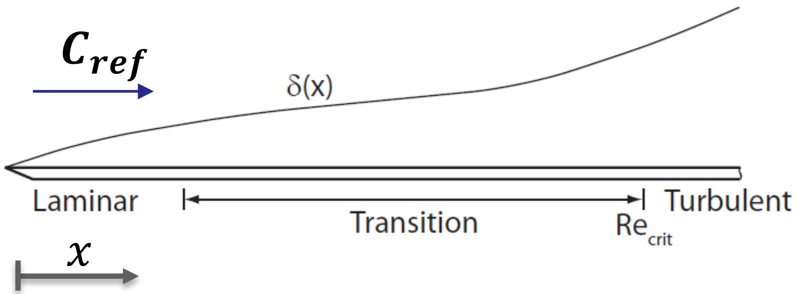
- ***Hydrofoil eigen mode identification:***
  - ***Accelerometer: Fixed position***
    - ***Reference signal***
  - ***Laser vibrometer:***
    - ***Multiple measurement points***



Boundary layer properties

Definition: "A thin layer of the fluid close to a boundary surface where the viscous forces are dominant"

- **99% boundary layer thickness:**



$$\delta = y|_{C_x=0.99C_{ref}}$$

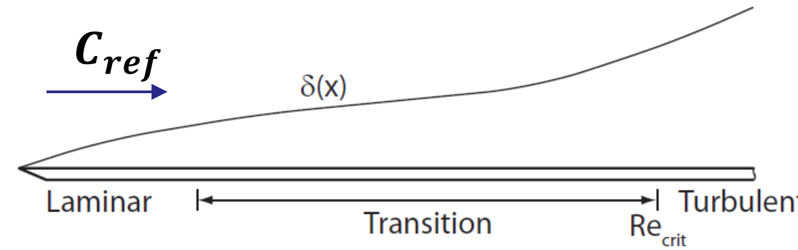
- **Displacement thickness:** $$\delta_1 = \int_0^{\delta}\left(1-\frac{C_x}{C_{ref}}\right)dy$$

- **Momentum thickness:** $$\delta_2 = \int_0^{\delta}\left(1-\frac{C_x}{C_{ref}}\right)\frac{C_x}{C_{ref}}dy$$

- **Form (or Shape) factor:** $$H_{12} = \frac{\delta_1}{\delta_2}$$

Provides an indication of the boundary layer state (laminar or turbulent)

Boundary layer properties



Boundary layer on a flat plate

	Symbol	Laminar flow[1]	Turbulent flow[2]
Boundary layer thickness	$\delta(x)$	$5.0\, x\, Re_x^{-1/2}$	$0.37\, x\, Re_x^{-1/5}$
Boundary layer displacement thickness	$\delta_1(x)$	$0.344\, \delta(x)$	$0.125\, \delta(x)$
Boundary layer momentum thickness	$\delta_2(x)$	$0.133\, \delta(x)$	$0.097\, \delta(x)$
Form factor	$H_{1,2}$	2.59	$1.3 - 1.4$
Skin friction coefficient	c_f	$0.664\, Re_x^{-1/2}$	$0.0576\, Re_x^{-1/5}$

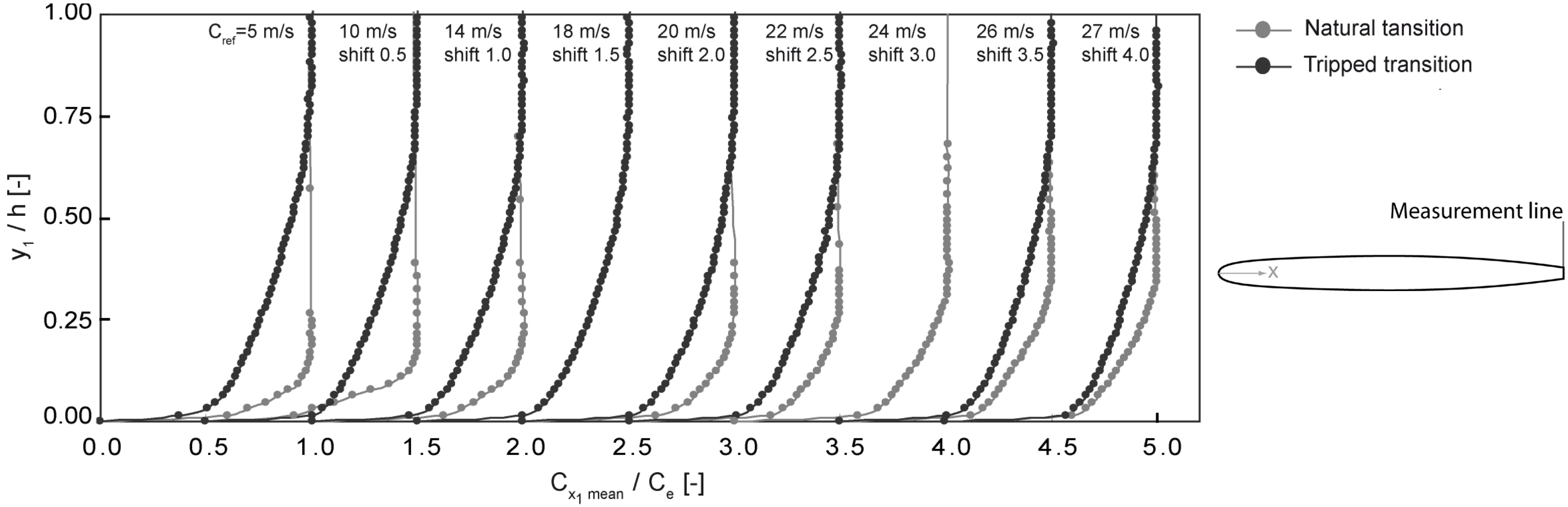
Where Re_x is defined by: $Re_x = \dfrac{\rho C_{ref} x}{\mu}$

[1] ***Blasius Theory;*** [2] ***Empirical***

Vortices – Source of cavitation and vibration

Effect of the boundary layer on vortex shedding

- ***Boundary layer vs Reynolds number***
  - ***Time-averaged velocity profiles: Trailing edge***
    - ✓ ***Velocity profiles: shifted on the horizontal axis for clarity***



✓ ***Tripped transition: δ significantly increases***

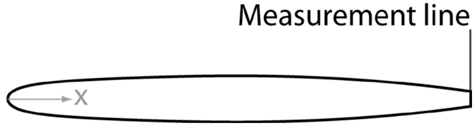
✓ ***Reynolds effects: For increasing C_{ref}***

- Natural transition: δ increases (transition point moves upstream)

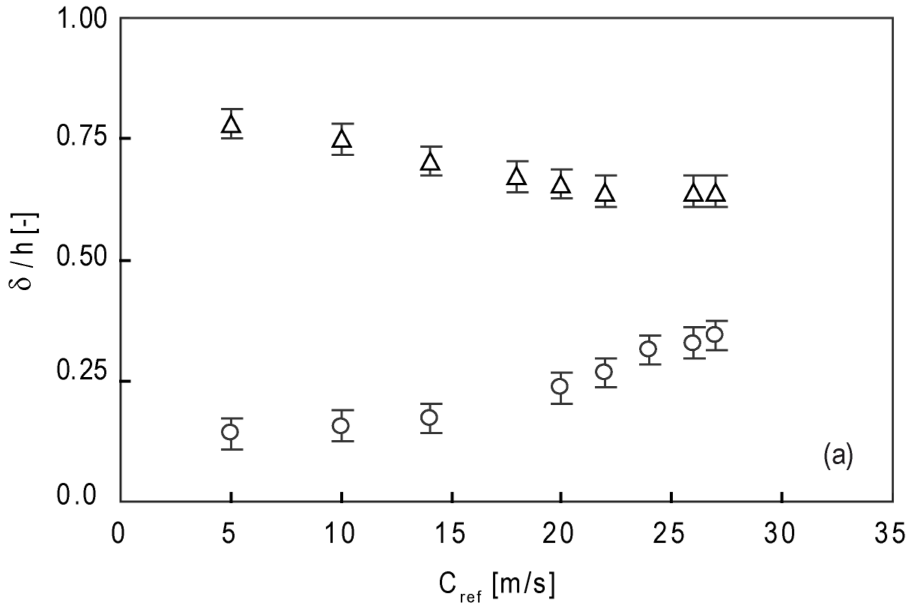
- Tripped transition: δ decreases

Effect of the boundary layer on vortex shedding

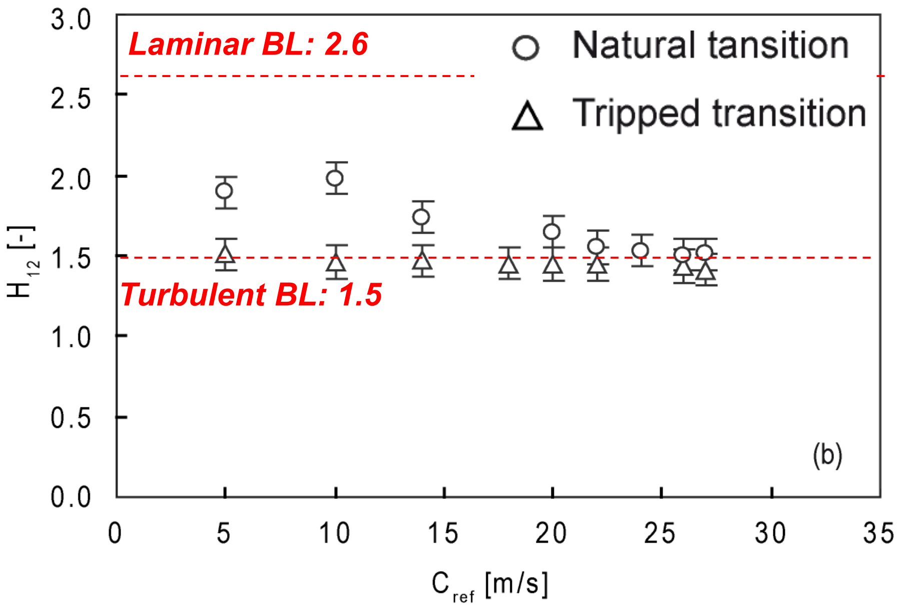
- **Boundary layer flow**
  - **Time-averaged velocity profiles: Trailing edge**



Boundary layer thickness (δ)



Form factor (H_{12})



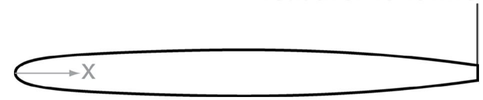
✓ ***Natural transition: up to 14 m/s , H_{12} transitional boundary layer then, H_{12} tends to turbulent value → A natural transition occurs along the chord***

✓ ***Tripped transition: Turbulent BL at the leading edge for all tested velocities***

Effect of the boundary layer on vortex shedding

Boundary layer flow

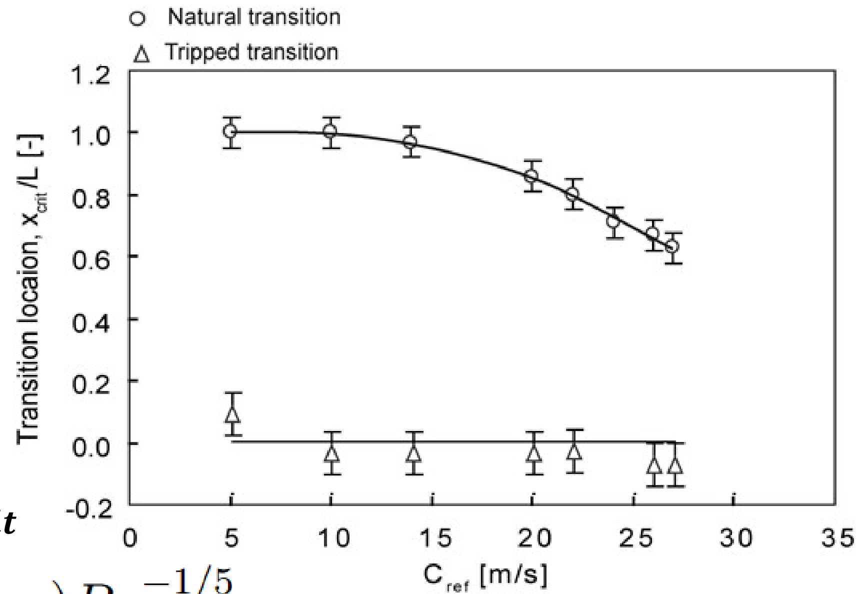
- ***Natural transition (Location of the transition point ?)***



Flat plate boundary layer, Schlichting (1979)

	Laminar flow	Turbulent flow
$\delta(x)$	$5.0\ x\ Re_x^{-1/2}$	$0.37\ x\ Re_x^{-1/5}$

x_{crit} : *Location of BL transition to turbulence*
$\delta_{T.E.}$: *Boundary layer thickness at the trailing edge*



  - ***Measurement of $\delta_{T.E.}$ → Evaluation of x_{crit}***

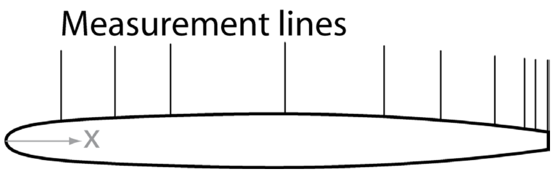
$$\delta_{T.E.} = 5.0 x_{crit} Re_{x_{crit}}^{-1/2} + 0.37(L - x_{crit}) Re_{L-x_{crit}}^{-1/5}$$

L: Chord length

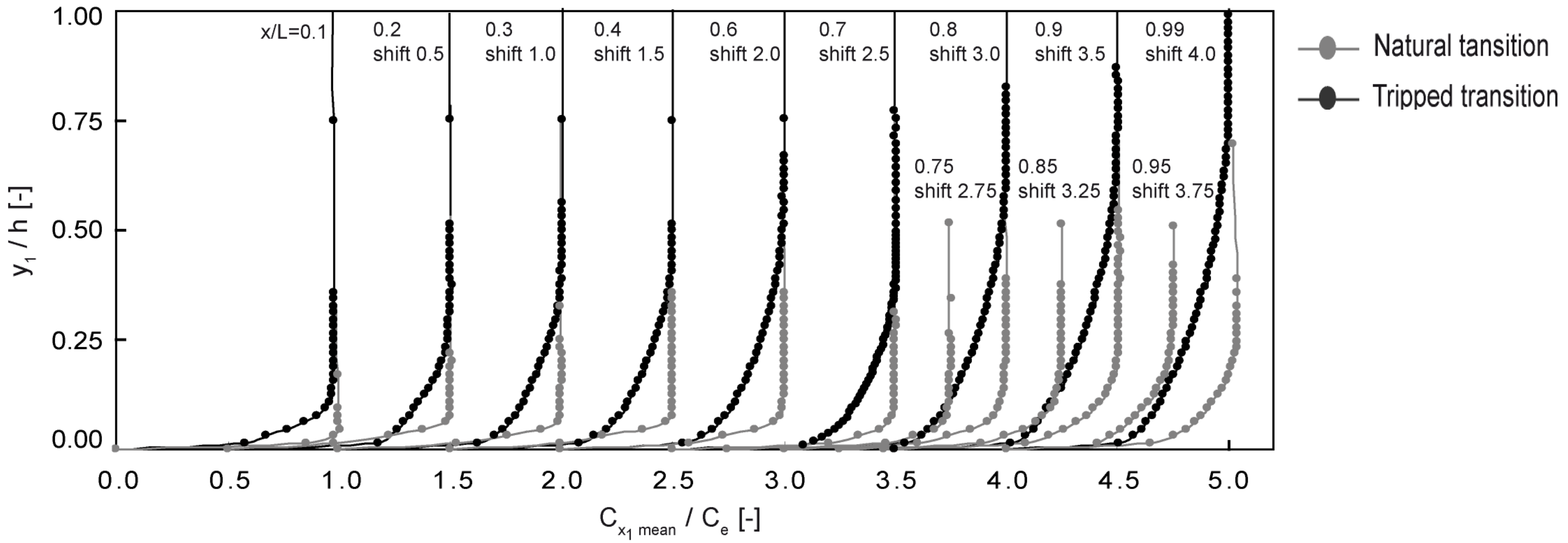
$$Re_x = \frac{\rho C_{ref} x}{\mu}$$

  - ***Benchmark condition: Cref = 20 m/s, transition at 0.85L***
  - ***Extrapolation → Natural transition at leading edge for Cref = 40 m/s***
- ***Tripped transition: Fully turbulent flow at leading edge***

Effect of the boundary layer on vortex shedding



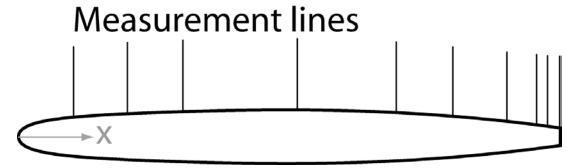
- ***Boundary layer flow***
  - ***Development along the hydrofoil chord***
  - ***Time-averaged velocity profiles (C_{ref}=20 m/s)***
    - ✓ ***Velocity profiles: shifted on the horizontal axis for clarity***



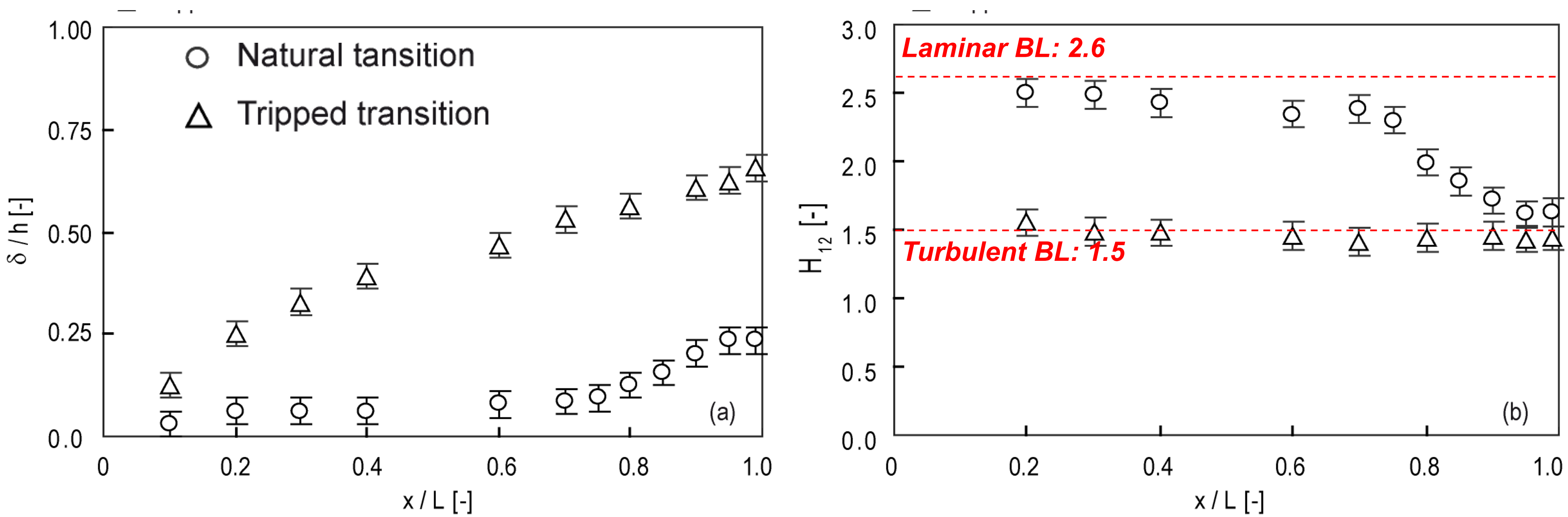
✓ ***Natural transition: δ increases with increasing distance from leading edge***

✓ ***Tripped transition: Larger growth of the BL thickness compared to natural case***

Effect of the boundary layer on vortex shedding



- ***Boundary layer flow***
  - ***Development along the hydrofoil chord***
  - ***Natural and tripped transitions (C_{ref}=20 m/s)***



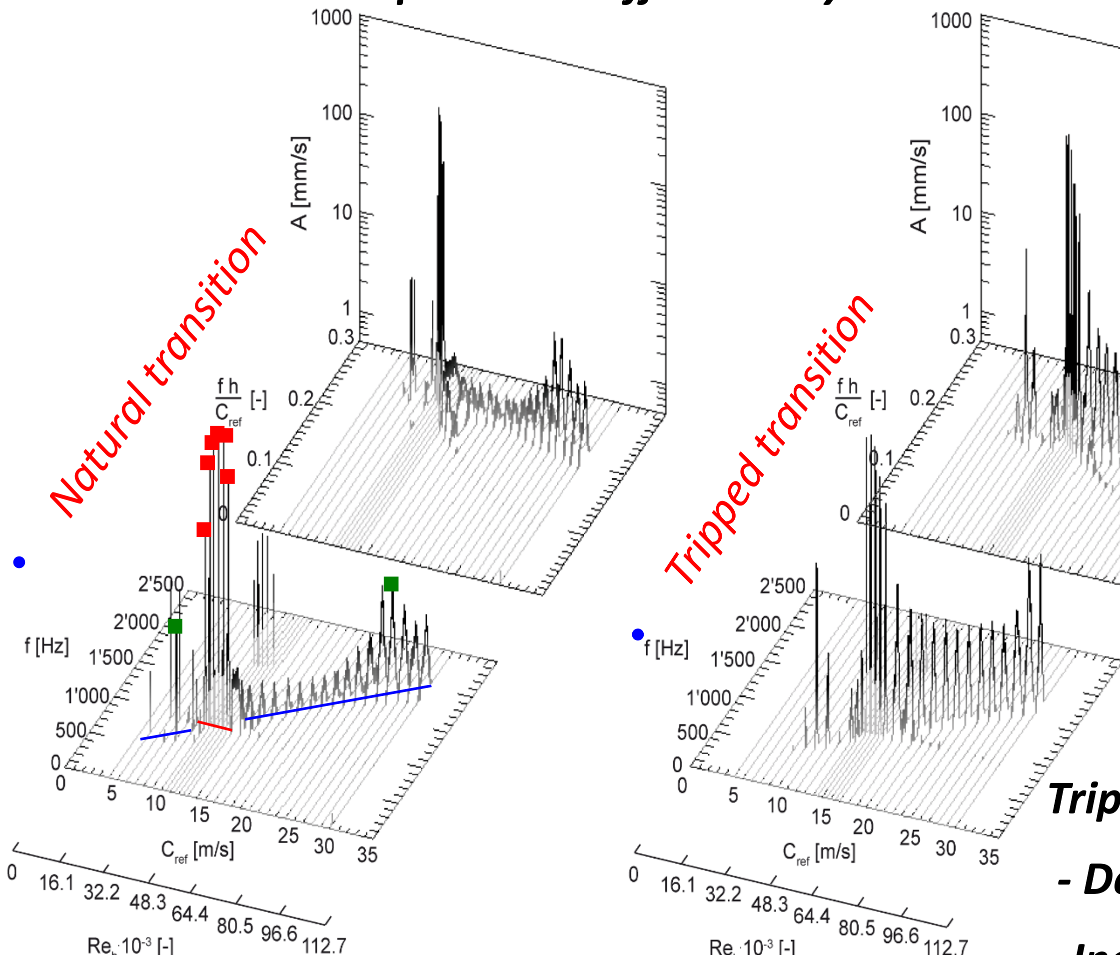
✓ ***Natural transition:***

✓ ***Form factor decreases from 2.5 (Laminar BL) to 1.6 (Turbulent BL)***
Natural turbulent boundary layer transition @ 0.8 L

✓ ***Tripped transition: Mean H_{12} ~ 1.46 : Turbulent BL develops along the entire chord***

Effect of the boundary layer on vortex shedding

- ***Vortex-induced vibration and vortex shedding frequency***
  - ***Vibration spectra at different Reynolds numbers (natural and tripped transition)***



✓ Strouhal behavior

f_s evolves linearly with C_{ref}

✓ Resonance

✓ Lock-in

Tripped vs. Natural transition

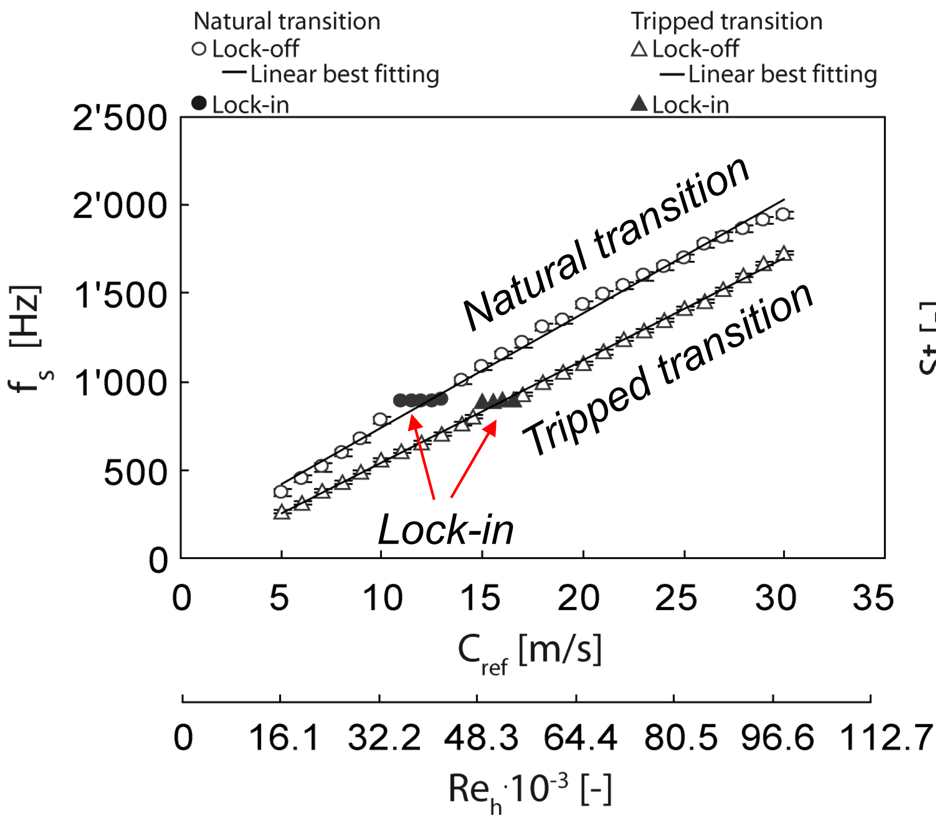
- Decrease of shedding frequency (22%)

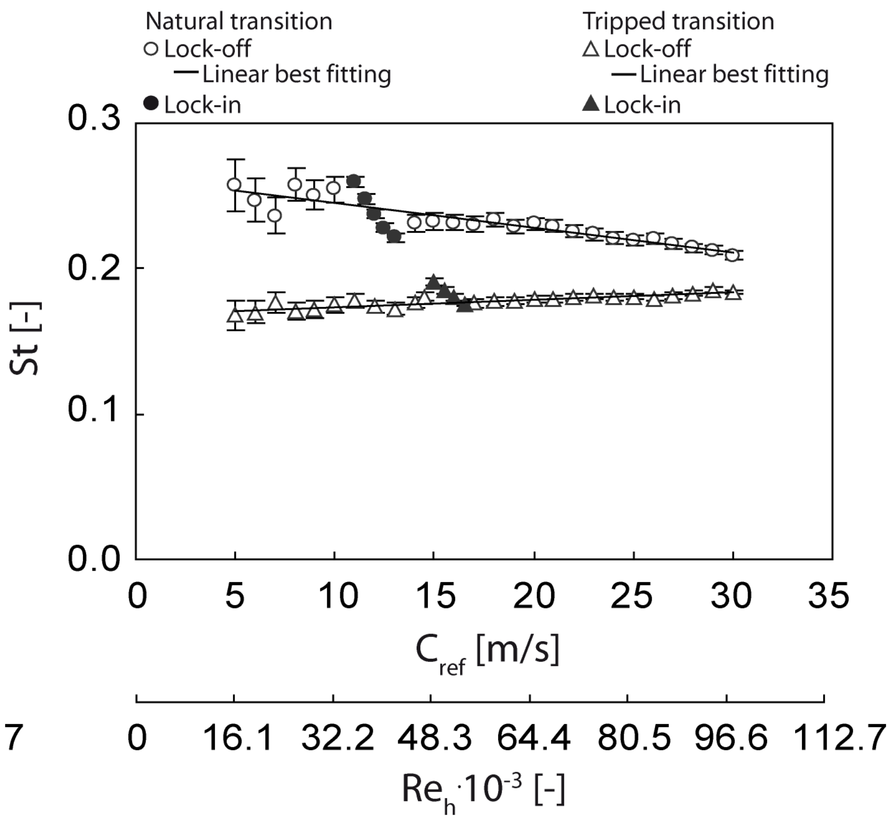
- Increase of the vortex-induced vibration

Effect of the boundary layer on vortex shedding

- **Vortex shedding frequency and Strouhal number**

$$St_h = \frac{f_s h}{C_{ref}}$$

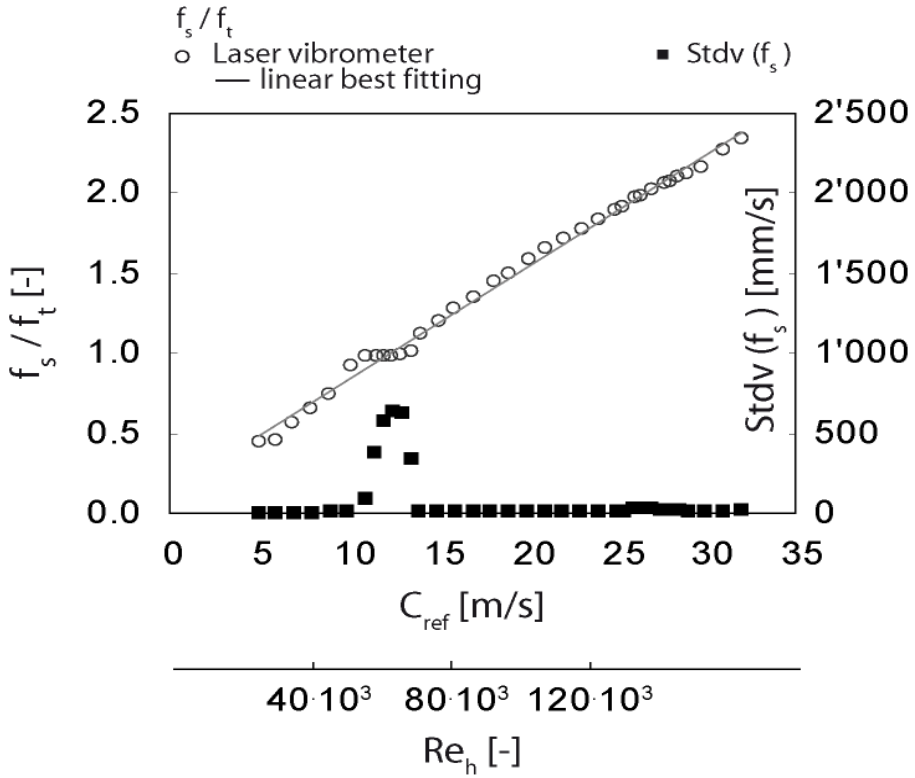


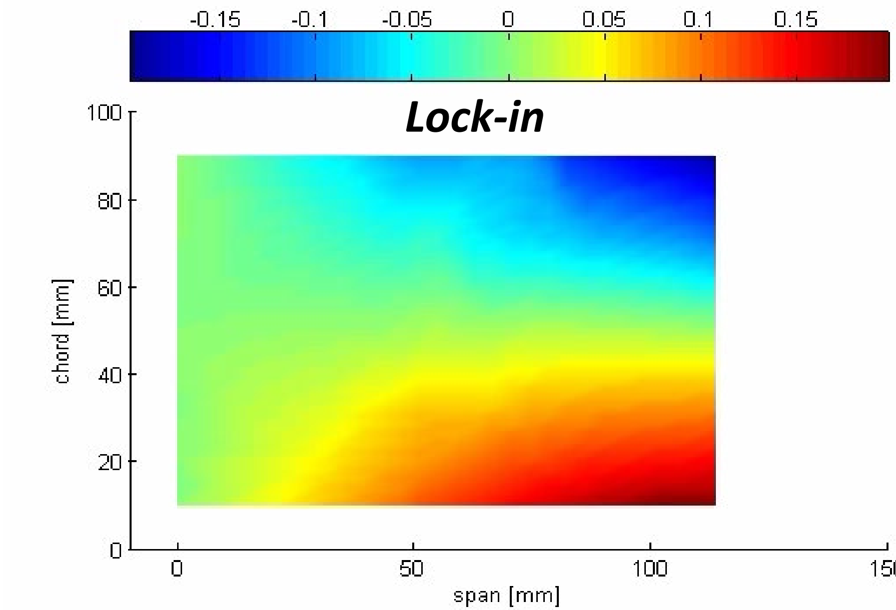


$$\overline{St}_{Smooth} = 0.24 \qquad \overline{St}_{Rough} = 0.18$$

Effect of the boundary layer on vortex shedding

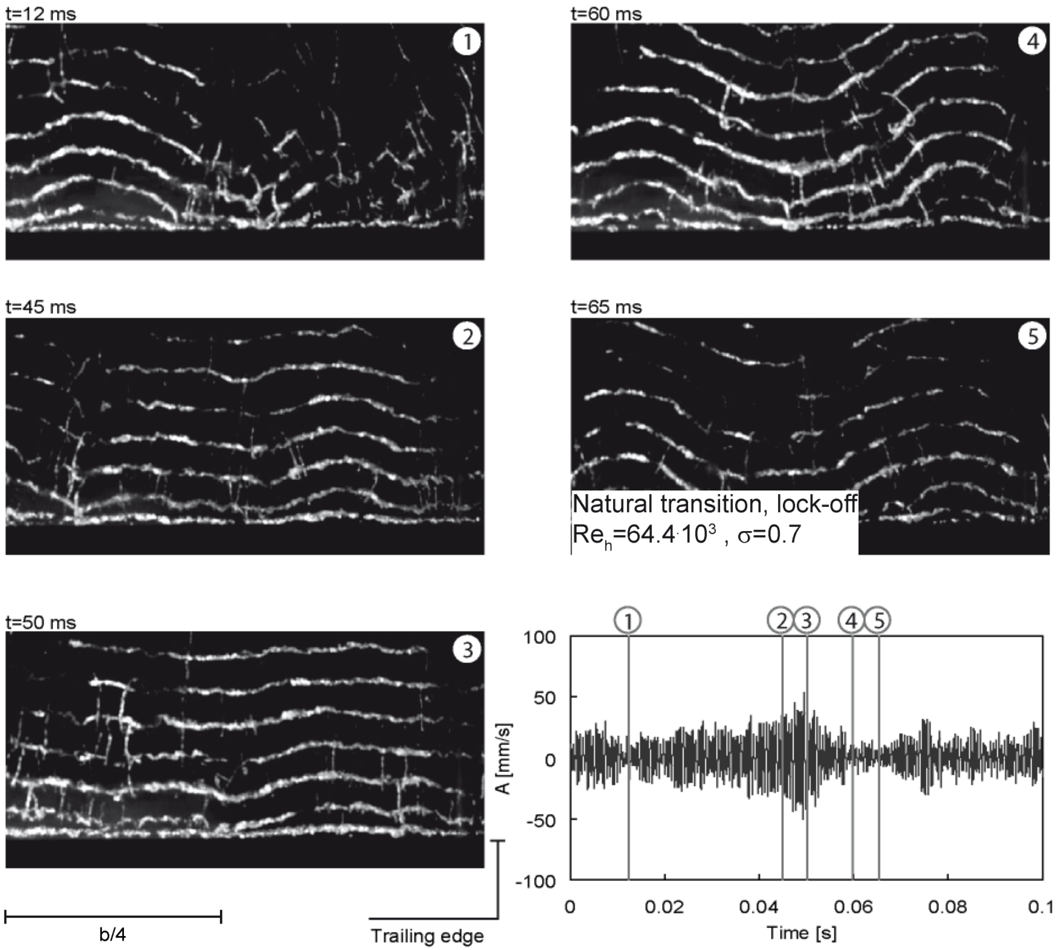
- ***Smooth leading edge – Lock-in***
  - ***1st torsional mode : Large vibration amplitude***





Effect of the boundary layer on vortex shedding

- ***Wake structure – Natural transition – Lock-off***

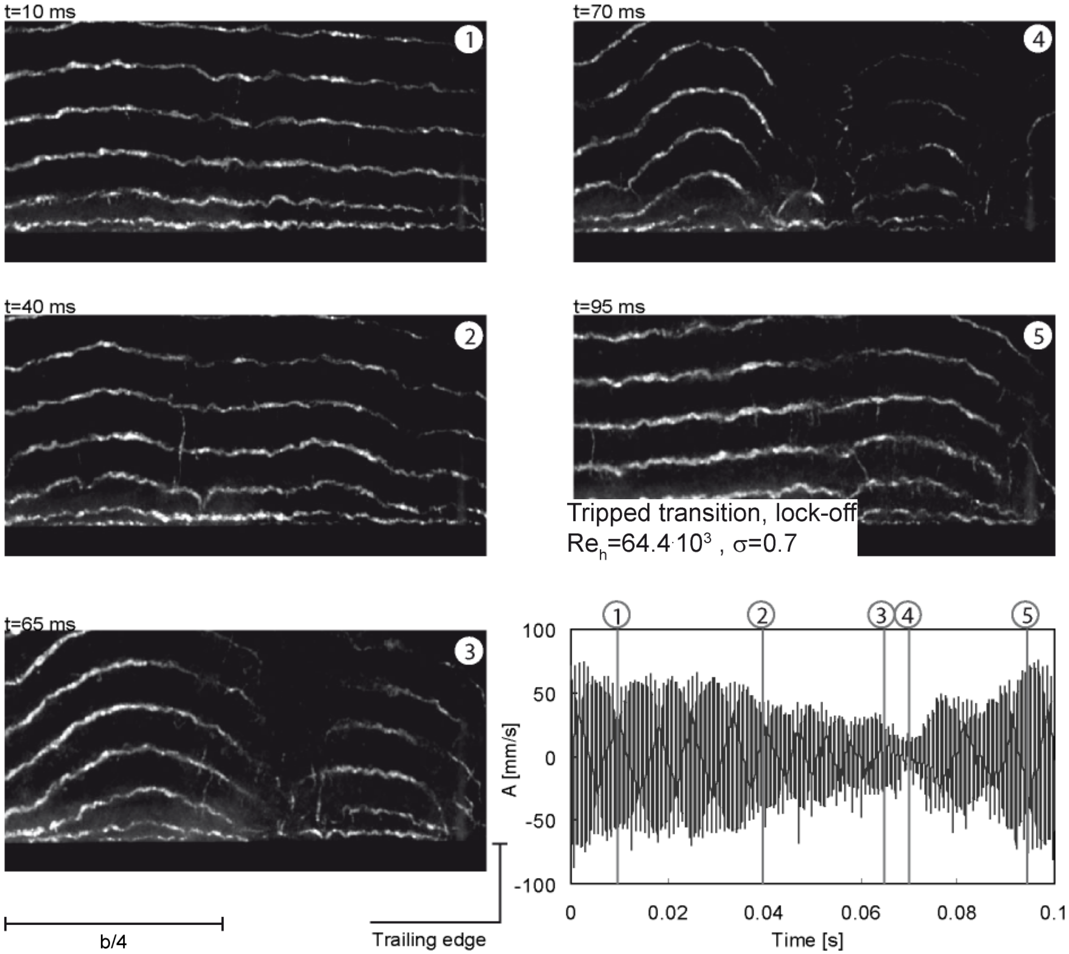


Vibration amplitude correlates well with vortex patterns:

- ***3D pattern → lower vibration***
  - ***Loss of coherence***
- ***2D pattern → Higher vibration***
  - ***More coherent structures***

Effect of the boundary layer on vortex shedding

- ***Wake structure – Tripped transition – Lock-off***



Tripped transition:

→ Larger vibration amplitude

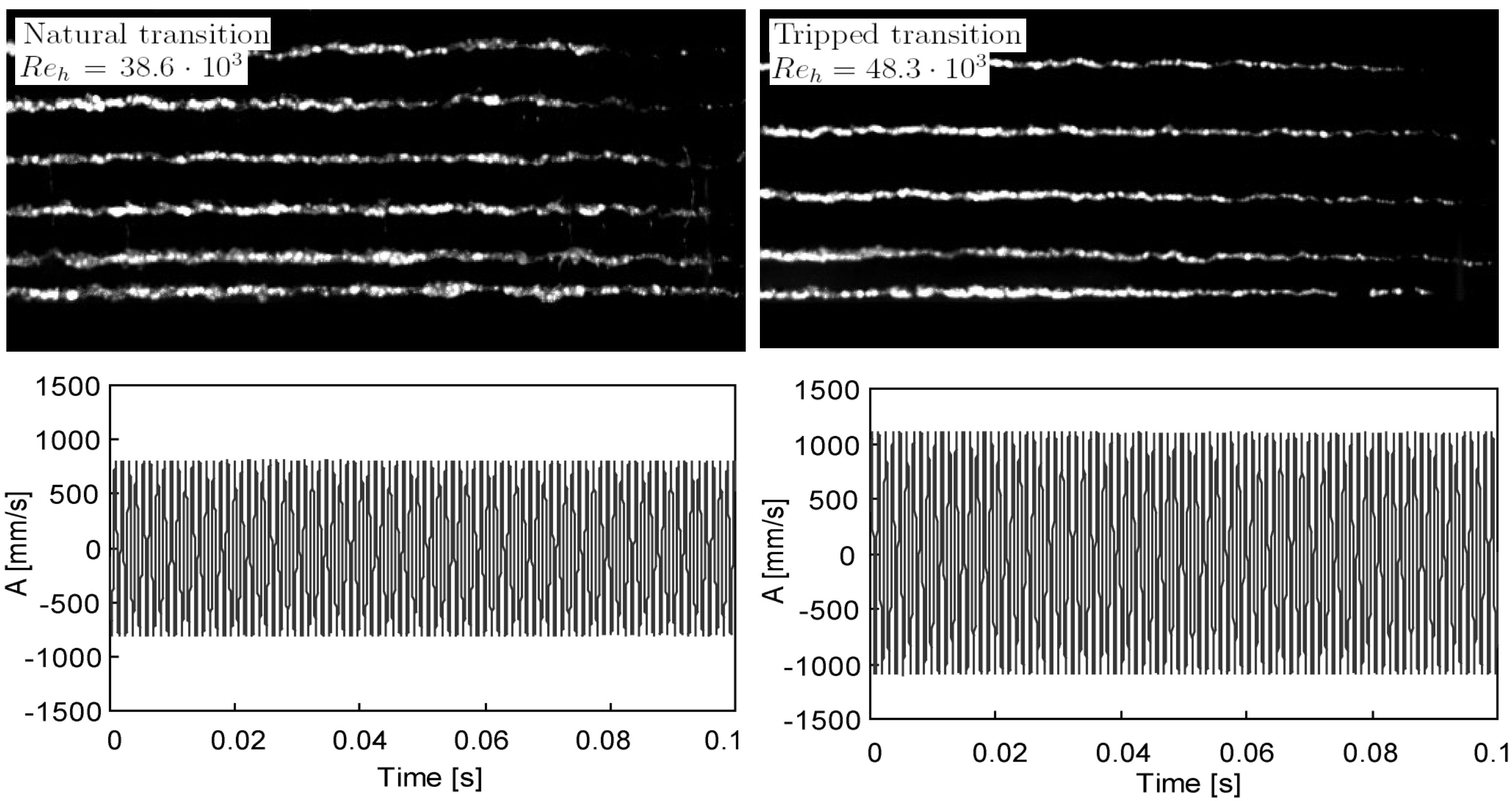
→ Enhance vortex spanwise organization

→ Promotes parallel vortex shedding

Vortices – Source of cavitation and vibration

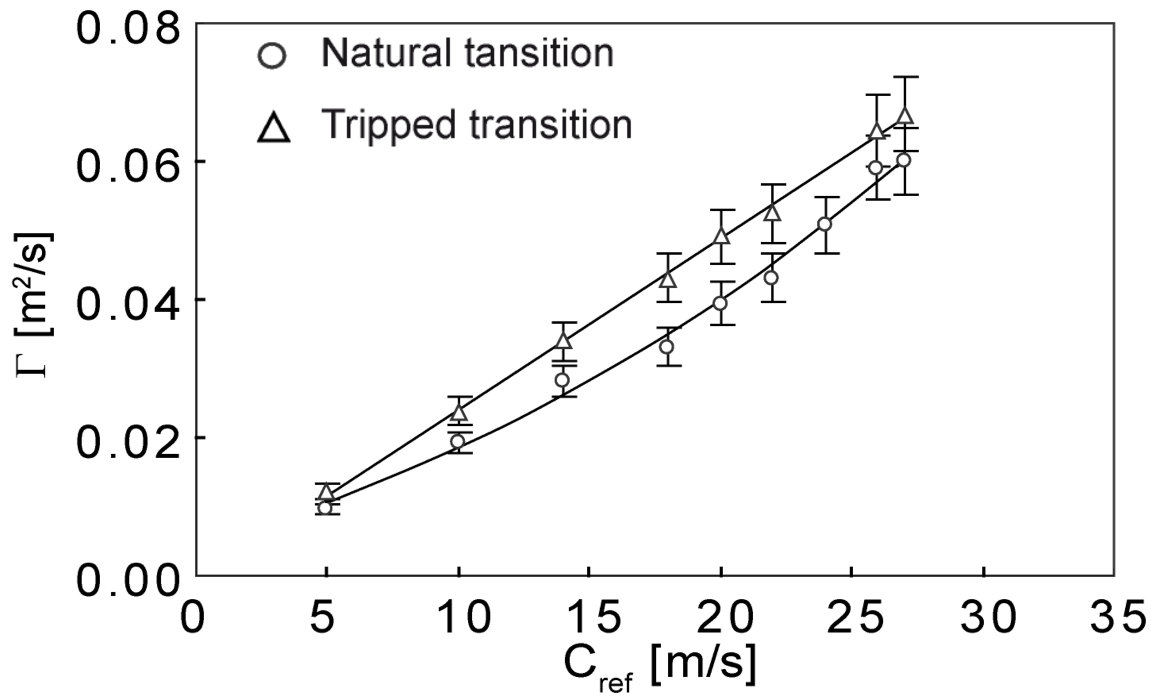
Effect of the boundary layer on vortex shedding

- ***Wake structure – Lock-in - Natural vs. Tripped transition:***
  - ***Vibration signal almost sinusoidal and parallel vortex shedding for both BL transitions***
  - ***Vibration amplitude larger for tripped transition***



Effect of the boundary layer on vortex shedding

- ***Vortex strength:***
  - ***Using Rankine model for vortex velocity distribution***

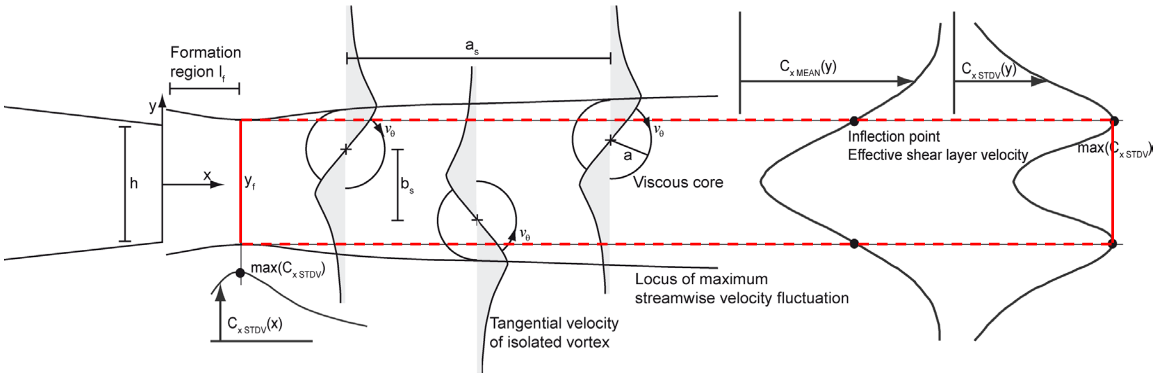


  - ***Tripped transition: Vortices have more strength because of the enhanced spanwise organization → increased vibration***

Effect of the boundary layer on vortex shedding

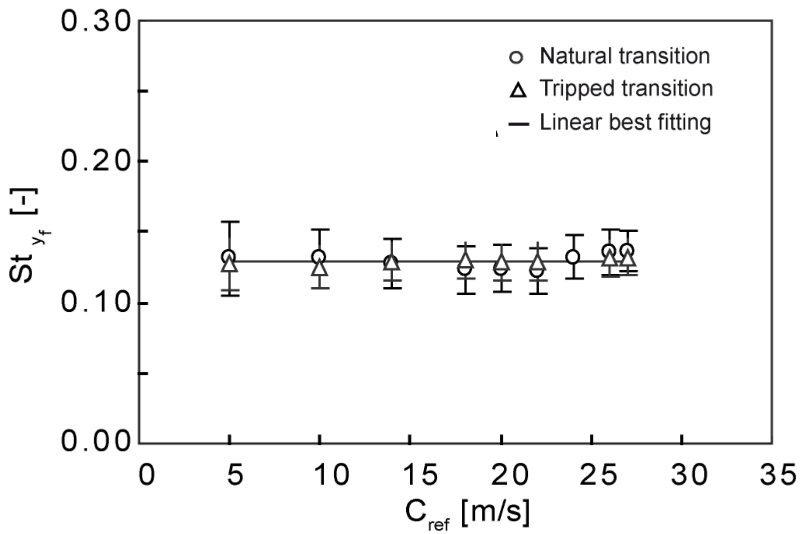
- ***Universal scaling law (Griffin Number):***
  - ***Based on vortex formation length:***

$$St_{yf} = \frac{f_s y_f}{C_{ref}}$$



- ***For natural and tripped transitions:***
  - ***Constant Griffin number:***

$$St_{yf} \approx 0.13$$

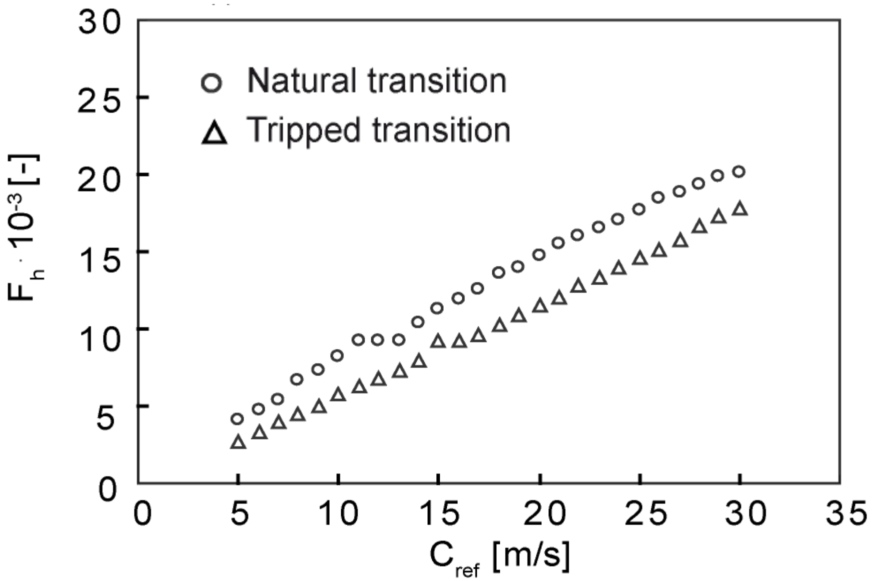


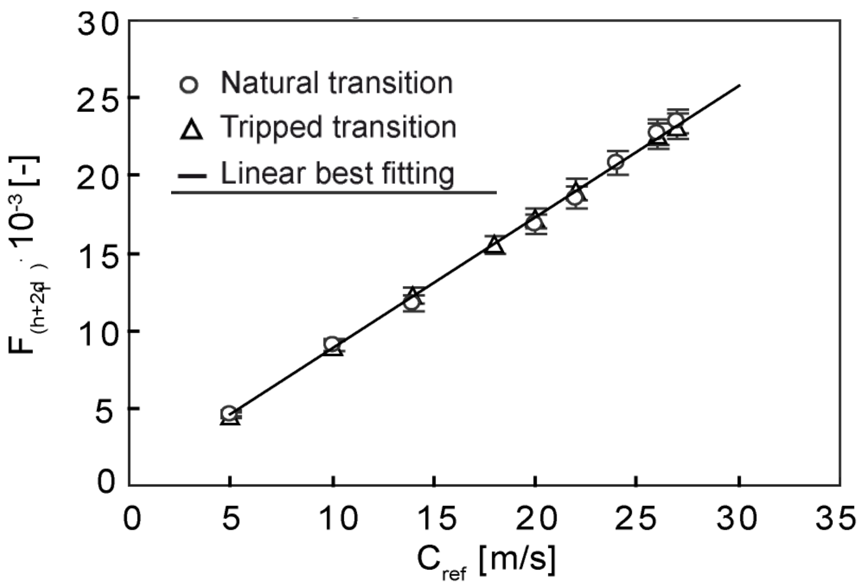
Effect of the boundary layer on vortex shedding

- ***Universal scaling law (Roshko Number):***
  - ***Replace the inertia time (h/C_{ref}) by diffusion time (h^2/ν)***

$$F_h = \frac{f_s h^2}{\nu}$$

$$F_{(h+2\delta_1)} = \frac{f_s (h + 2\delta_1)^2}{\nu}$$

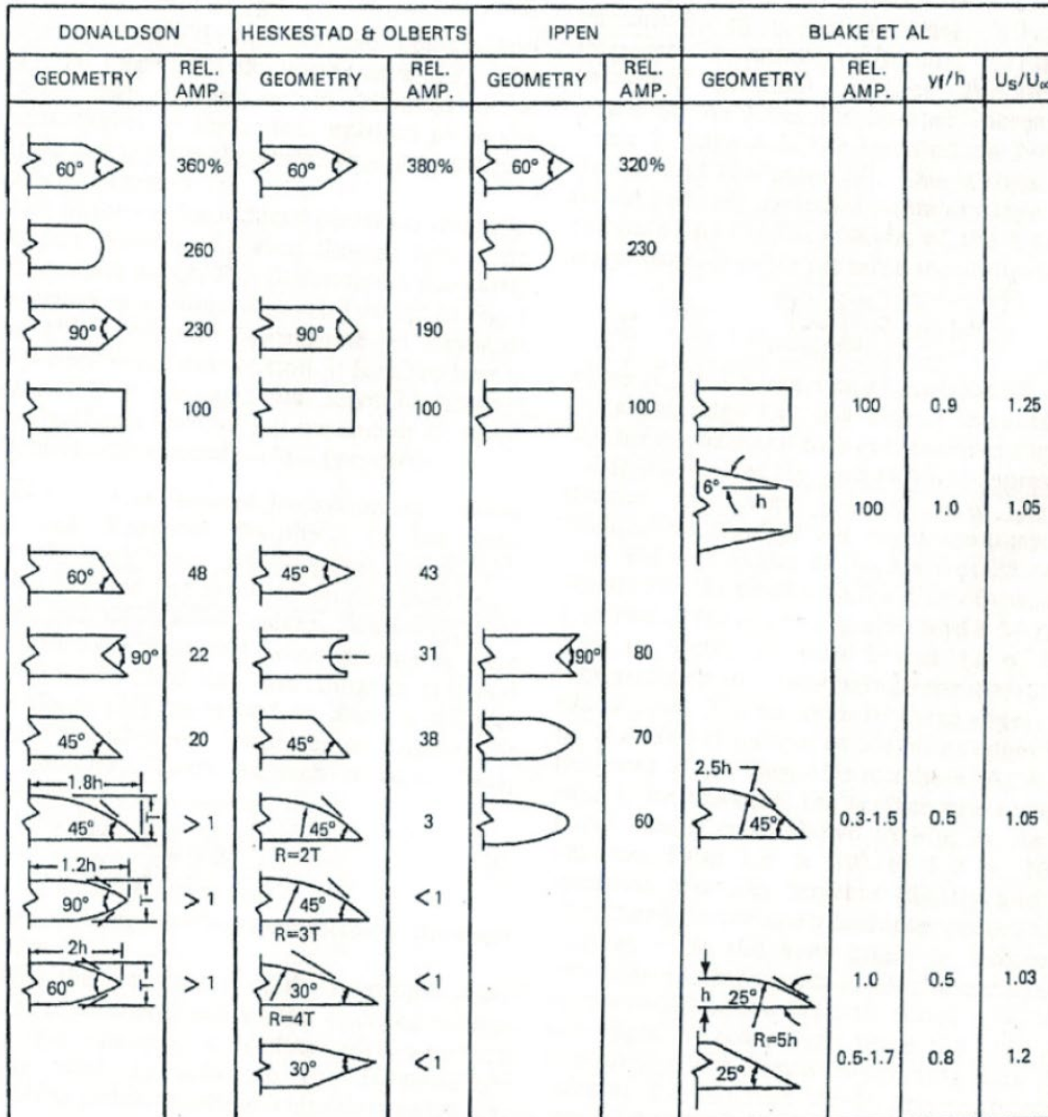




✓ ***Natural and tripped transitions: Single linear law when d_1 is taken into account***
✓ ***Rosko number more appropriate for the scaling than Strouhal number***
  ✓ ***But not straightforward (boundary layer thickness is not always known)***

Effect of trailing edge shape on vortex induced vibration

- **A variety of trailing edge (T.E.) geometries have been tested**
- **Relative vibration amplitude is reported in comparison with baseline hydrofoil with blunt T.E.**
- **Some of the shapes cut the vibration amplitude by 2 orders of magnitude**



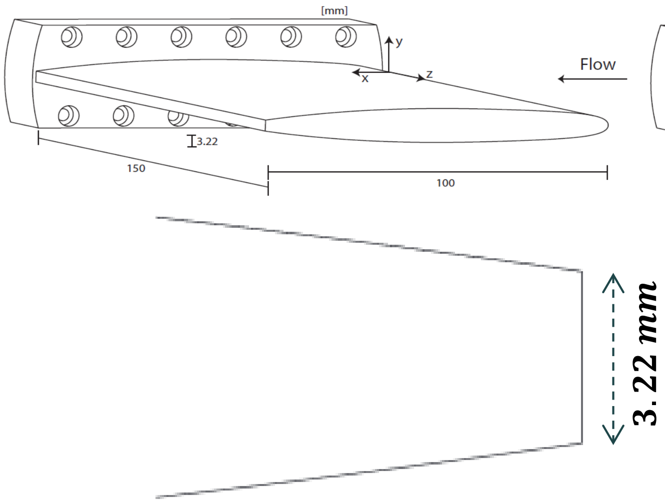
DONALDSON		HESKESTAD & OLBERTS		IPPEN		BLAKE ET AL			
GEOMETRY	REL. AMP.	GEOMETRY	REL. AMP.	GEOMETRY	REL. AMP.	GEOMETRY	REL. AMP.	y_f/h	U_s/U_∞
60°	360%	60°	380%	60°	320%				
	260				230				
90°	230	90°	190						
	100		100		100		100	0.9	1.25
						6°, h	100	1.0	1.05
60°	48	45°	43						
90°	22		31	90°	80				
45°	20	45°	38		70				
1.8h, 45°, T	> 1	45°, R=2T	3		60	2.5h, 45°	0.3-1.5	0.5	1.05
1.2h, 90°, T	> 1	45°, R=3T	<1						
2h, 60°, T	> 1	30°, R=4T	<1			h, 25°, R=5h	1.0	0.5	1.03
		30°	<1			25°	0.5-1.7	0.8	1.2

Ref.: Donaldson, J. of Eng. for Power, 1956

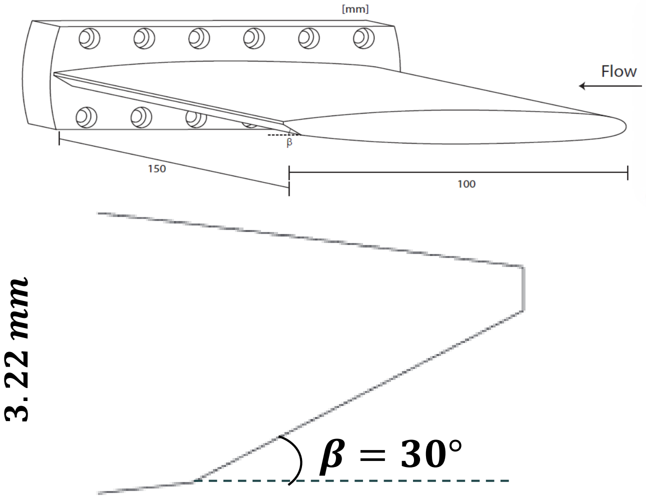
Effect of trailing edge shape on vortex induced vibration

- **Experimental Setup – Case study**
  - **3 NACA0009 hydrofoils with:**
    1. **Blunt (truncated) trailing edge**
    2. **Oblique trailing edge**
    3. **Rounded (Donaldson) trailing edge**
  - **Natural and tripped boundary layer transition**

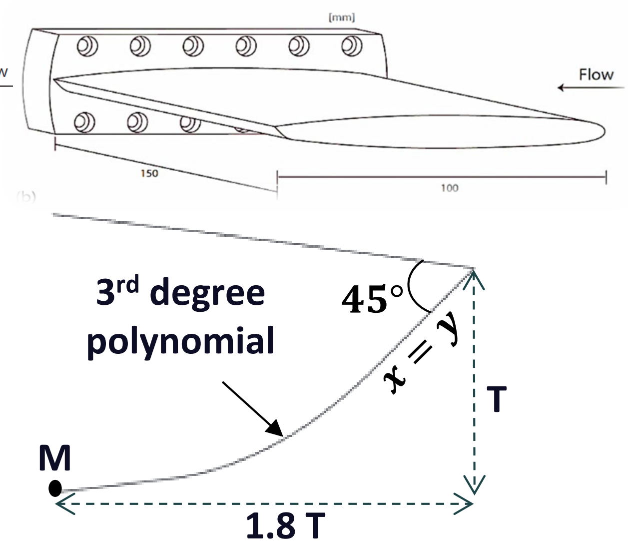
1. Blunt T.E.



2. Oblique T.E.



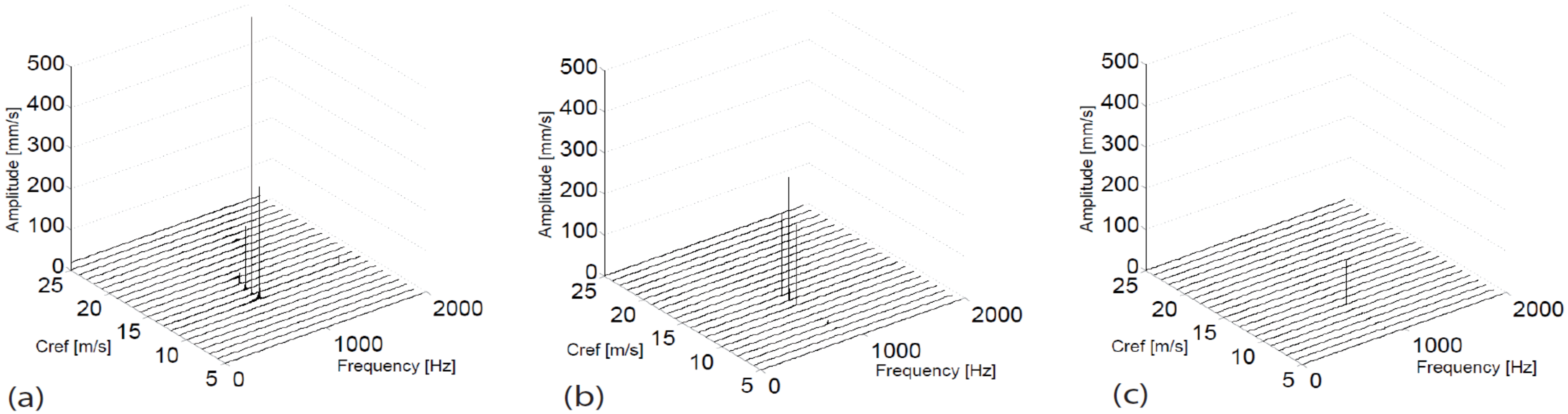
3. DonaldsonT.E.



Vortices – Source of cavitation and vibration

Effect of trailing edge shape on vortex induced vibration

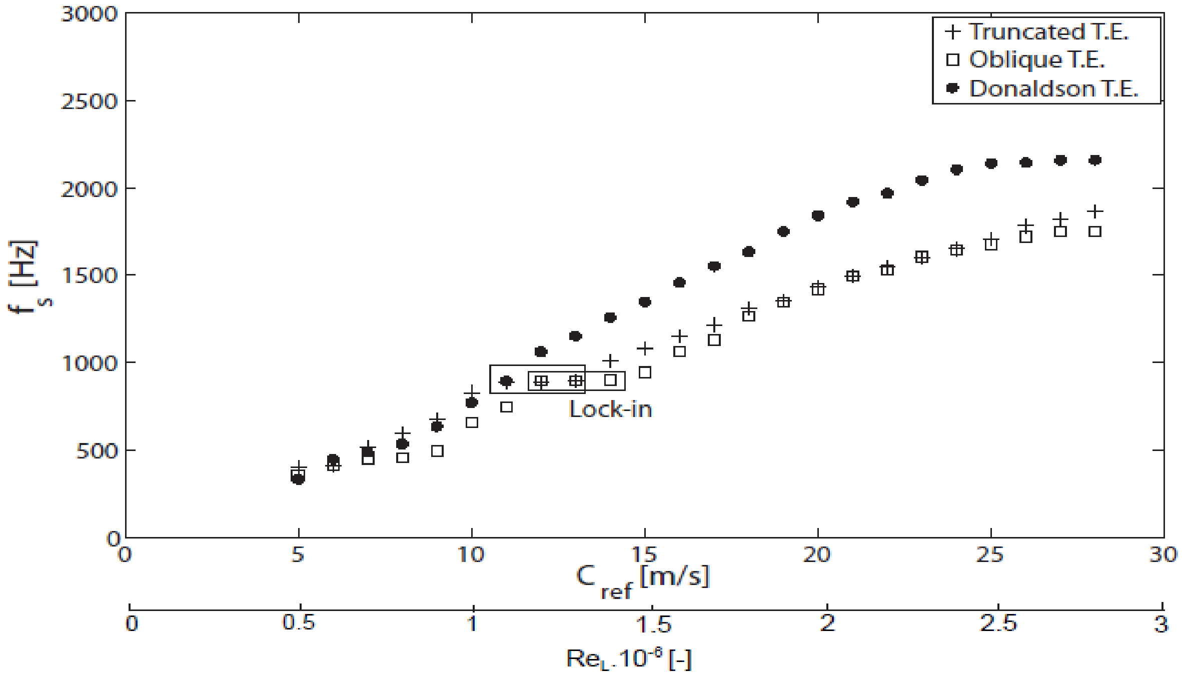
Truncated Trailing Edge ***Oblique Trailing Edge*** ***Donaldson Trailing Edge***



- **Maximum vibration with the truncated trailing edge**
- **Minimum vibration with Donaldson Trailing Edge**
- **No lock-in (Hydro-elastic coupling) with Donaldson trailing edge**

Effect of trailing edge shape on flow shedding frequency

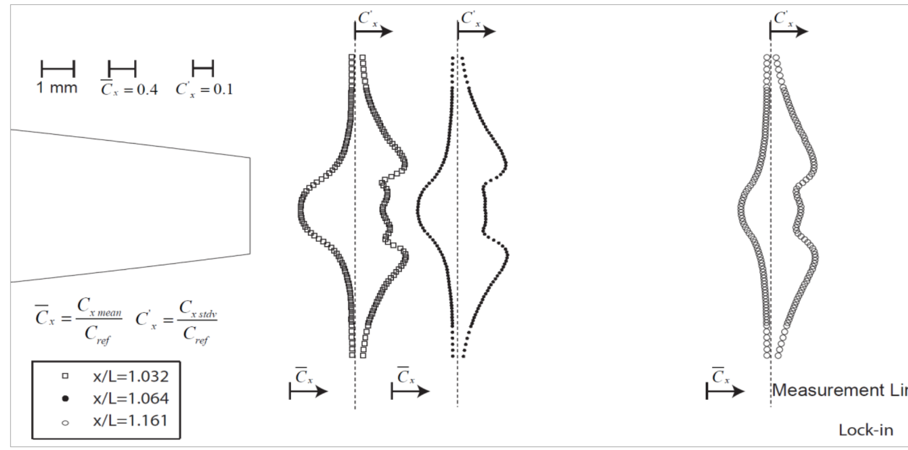
- **Linear relationship between shedding frequency and upstream velocity, except under Lock-in condition for truncated and oblique T. E.**
- **Lock-in (shedding frequency locked on the torsion mode of the hydrofoil) :**
  - **Truncated TE: 11- 14 m/s**
  - **Oblique TE : 12-15 m/s**
  - **Donaldson TE: No lock-in**



Vortices – Source of cavitation and vibration

Effect of trailing edge shape on wake dynamics

Velocity Profiles along the wake (Lock-in)

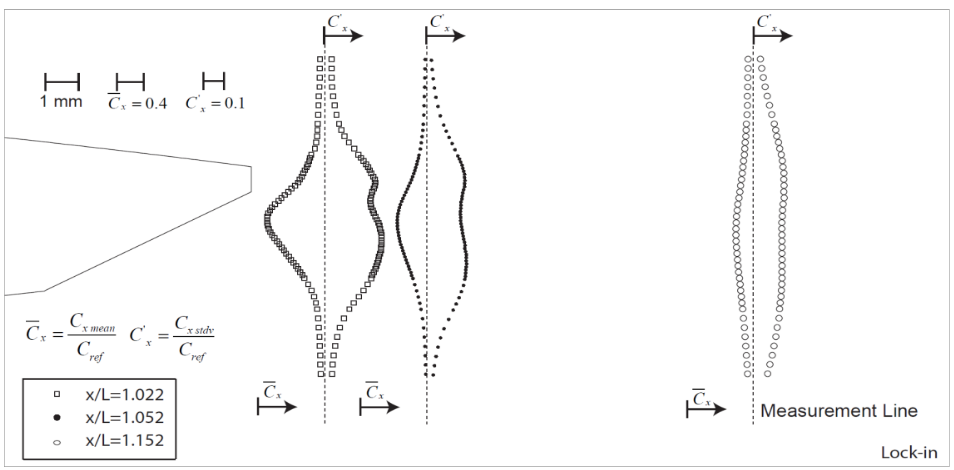


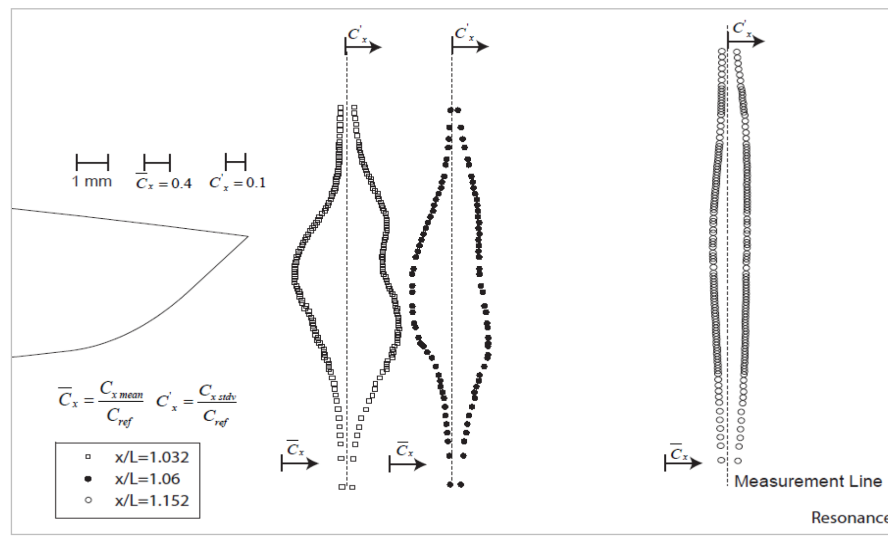
For all trailing edges:

- *Decrease of velocity deficit along the wake more pronounced with Donaldson TE*

Truncated TE: Symmetric wake

Oblique and Donaldson TE: Asymmetric wake





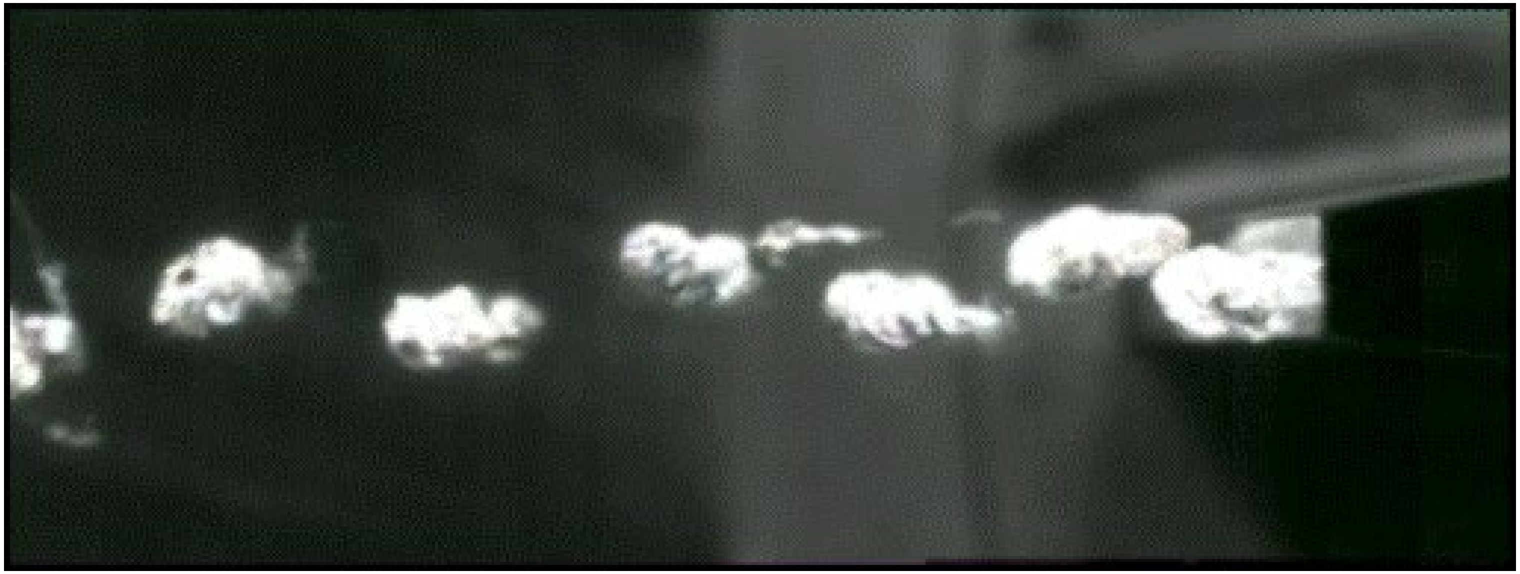
Vortices – Source of cavitation and vibration

Effect of trailing edge shape on wake dynamics

High speed visualization of cavitating vortices (Truncated TE., Lock-in)

- **Alternate shedding with lower and upper vortices of the same size.**

Cref=12 m/s, σ = 0.87



Vortices – Source of cavitation and vibration

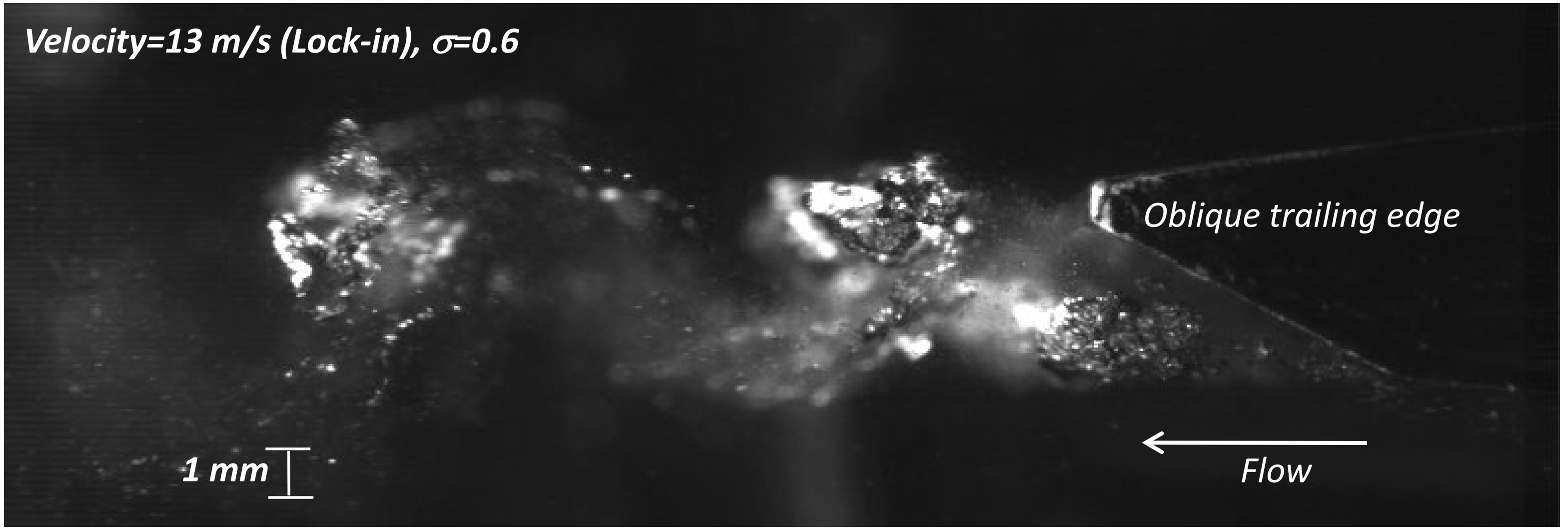
Effect of trailing edge shape on wake dynamics

High speed visualization of cavitating vortices (Oblique T. E., Lock-in)

- **Upper vortex coincides with the passage of lower vortex during the rolling up**
  Spatial shift → collision between upper and lower vortices (cancellation)

- **The vorticity less concentrated within the core of Karman vortices.**

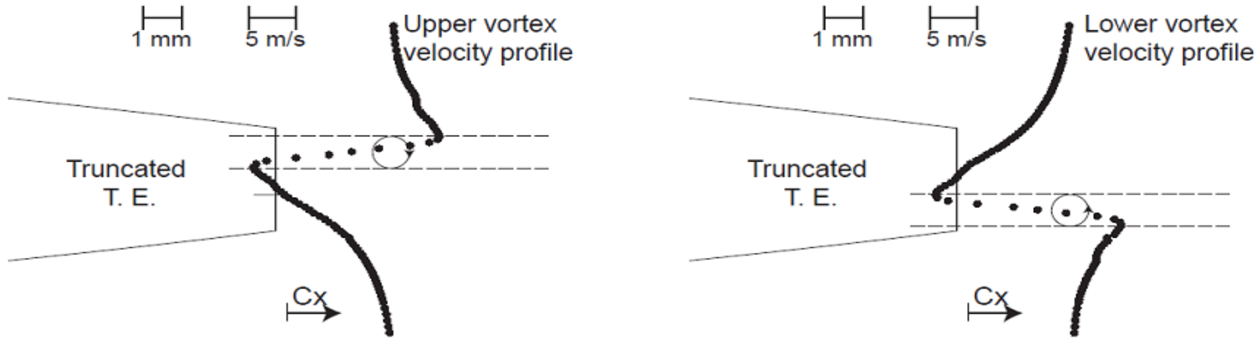
→ Decrease of induced vibration level



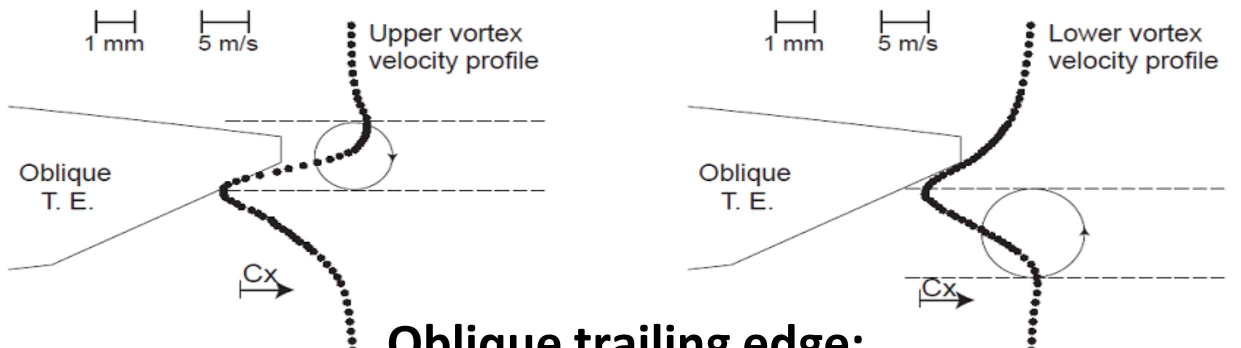
Vortices – Source of cavitation and vibration

Effect of trailing edge shape on wake dynamics

- **Instantaneous velocity profiles (LDV)**



Truncated TE: Similarity of upper and lower vortices



Oblique trailing edge:

Larger vortex core diameter in comparison with truncated T. E.

Larger vortex core of lower vortices compared to upper vortices

Effect of trailing edge shape on wake dynamics

High speed visualization of the wake dynamic for Donaldson TE

- **Strong collision between upper and lower vortices**
- **Most part of the lower vortex is destroyed by upper vortex**
- **Less vorticity concentration within the core of vortices**
- **Very efficient in reducing flow induced vibration**