AEROELASTICITY AND FLUID-STRUCTURE INTERACTION

Chapter 7:
Vortex Induced Vibration
7.2: Flow Control

Flow Control

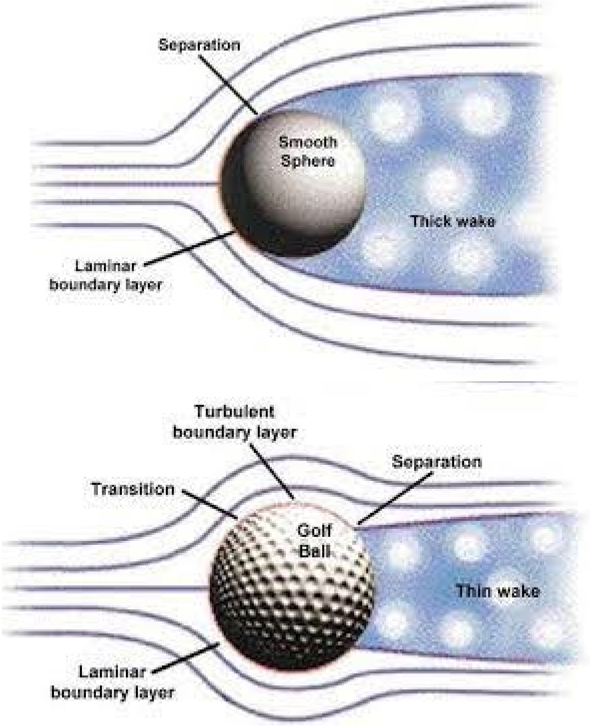
- **Flow control, what for ?**
  - Drag reduction (Energy saving)
  - Increase of stall angle (for an extended range of operation)
  - Reduction of Flow Induced Vibration (Prevention of mechanical failures and noise)
  - …
- **Two Types: Passive and Active**
  - *Passive Flow Control: does not require external energy or active intervention and relies on slight geometrical modifications to influence the flow.*
  - *Active Flow Control: Requires external energy or dynamic input to manipulate the flow. These methods include devices like blowing/suction and actuators, which can be turned on/off or adjusted during operation.*

Vortex Induced Vibration: Flow Control

Flow Control

- **Example: Gulf ball (surface texture):**
  - Flow separation delayed by turbulence
    - *Because laminar boundary layer tends to separate earlier than turbulent one*
  - Roughened ball experiences less drag and travels longer

- **Reminder on boundary layer separation:**
  - *Laminar Boundary Layer: The flow is smooth with low momentum near the surface. Because of this, it is less capable of resisting adverse pressure gradients. This makes it more prone to separation when the flow encounters regions of increasing pressure (adverse pressure gradients).*
  - *Turbulent Boundary Layer: The flow is chaotic but has higher momentum near the surface due to mixing of fluid layers. This helps it overcome adverse pressure gradients more effectively, delaying separation.*



Vortex Induced Vibration: Flow Control

Flow Control

- ***Golf Ball:*** *with a diameter of ~ 4.3 cm and speeds typically up to 60 m/s, can achieve Reynolds numbers from approximately 5×10^4 to 3×10^5. Its dimpled surface plays a critical role in reducing drag by promoting turbulent flow at lower Reynolds numbers compared to smooth balls.*
- ***Tennis Ball:*** *with a diameter of ~ 6.7 cm and typical velocities between 20 to 60 m/s, the Reynolds number ranges between 10^4 and 10^5, often reaching transitional or turbulent boundary layer conditions at higher speeds.*
- ***Soccer Ball:*** *With a larger diameter (~ 22 cm) and speeds up to 30 m/s, the Reynolds number for a soccer ball is often around 3×10^5. The stitching and texture ensurs earlier transition to turbulence compared to smooth spheres.*
- ***Ping Pong Ball:*** *With a smaller diameter (~ 4 cm) and lower speeds (up to 10 m/s), Reynolds numbers are in the range of 2×10^3 to 10^4, typically keeping the flow laminar or transitional due to the lower speeds involved.*

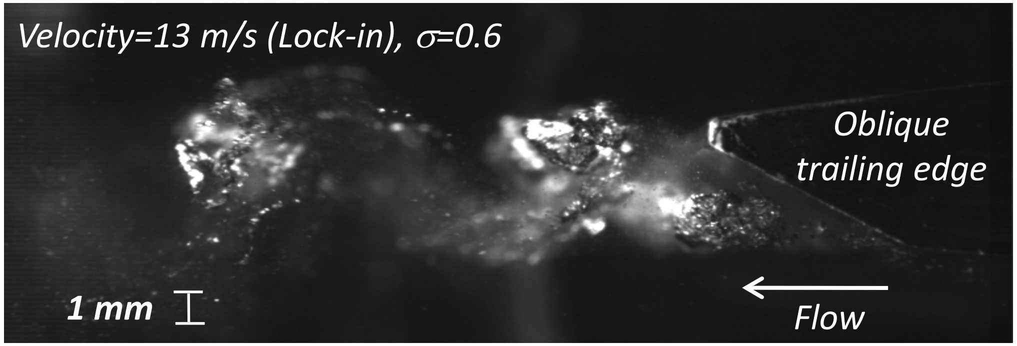
Vortex Induced Vibration: Flow Control

Flow Control

- **Example: Shape of the trailing edge of a foil**
  - Replace the blunt TE with an oblique truncation (30°) or Donaldson shape

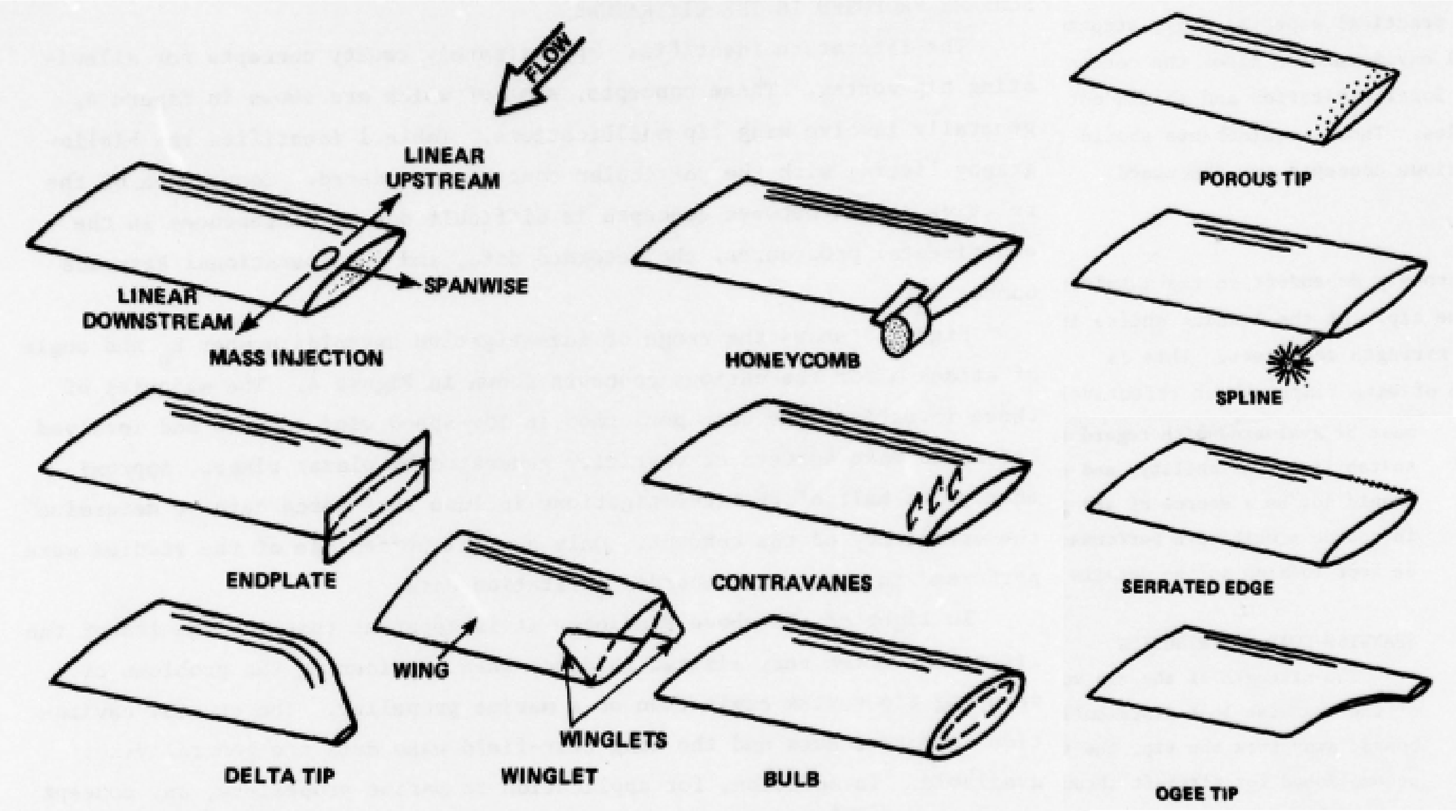
  → Significant decrease of vortex induced vibration: Upper and lower vortices are phase-shifted and collide leading to their partial cancelation

  → Lock-in suppressed with Donaldson trailing edge



Vortex Induced Vibration: Flow Control

- **Example: Control of tip vortex development:**
  - *A variety of passive and active techniques were developed in marine propulsion to manipulate the tip vortex formation and development*

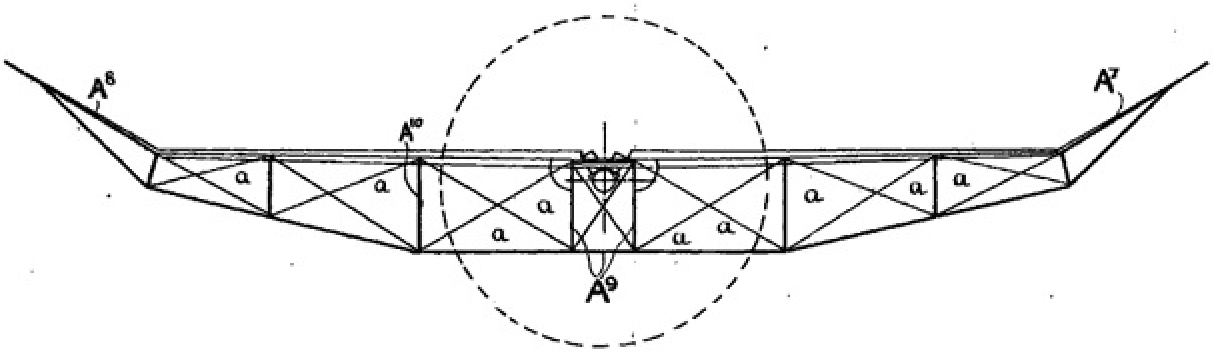


Platzer et al., (1971) Tip Vortex Cavitation Delay with Application to Marine Lifting Surfaces. A Litterature Survey

Vortex Induced Vibration: Flow Control

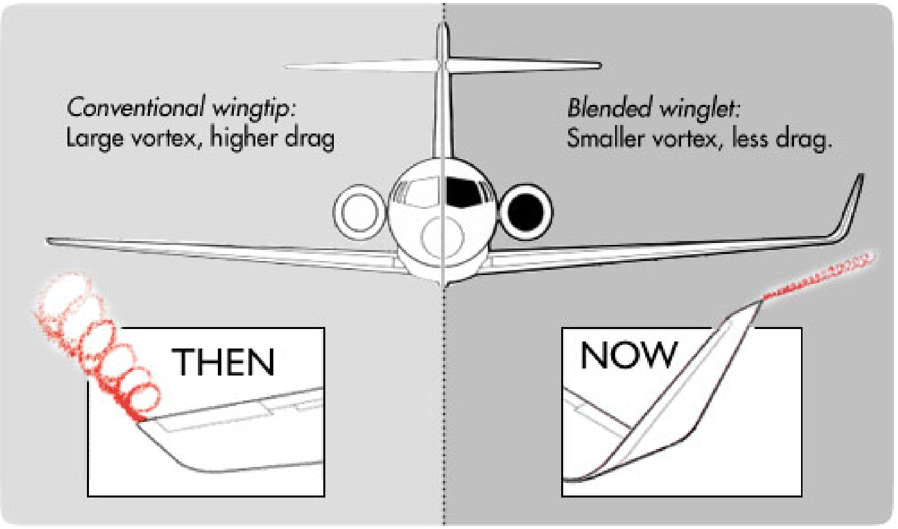
- **Example: Winglets at the tip of airplane wings**
  - *Tip vortices, a source of concern in aeronautics: Lift-induced drag & flight hazards)*
    - *A common remedy is appending winglets to wingtips*

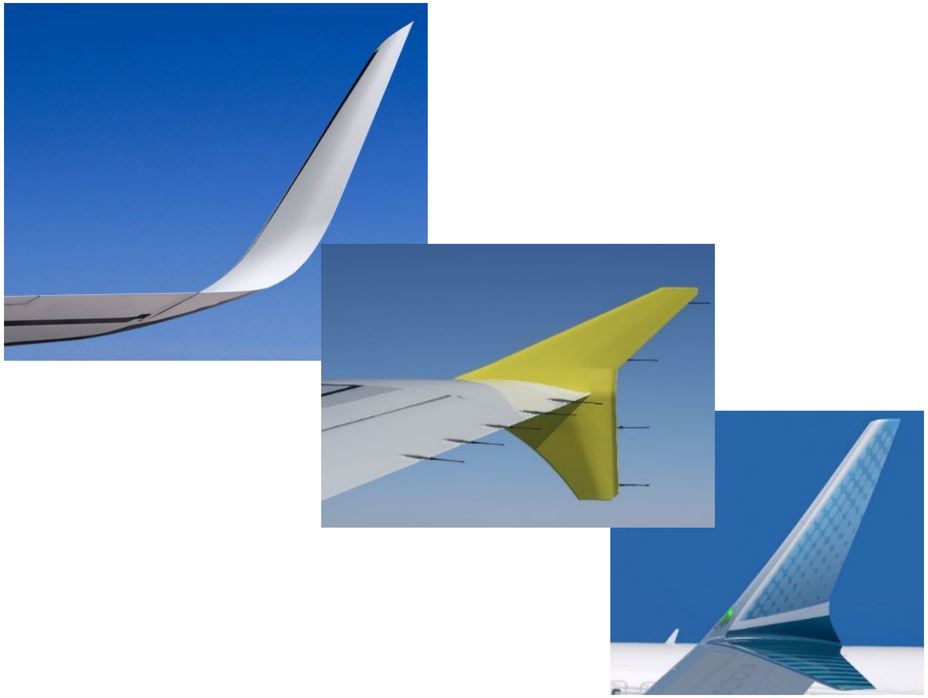
  - *Patented by Frederick W. Lanchester in 1887*
  - *First time used in aircrafts … one century later.*



Vortex Induced Vibration: Flow Control

- **Example: Winglets at the tip of airplane wings**
  - *Widely used in commercial airplanes*
  - *A large variety of winglets designs*
  - *May significantly reduce the fuel consumption (by typically 5-10 %)*





Vortex Induced Vibration: Flow Control

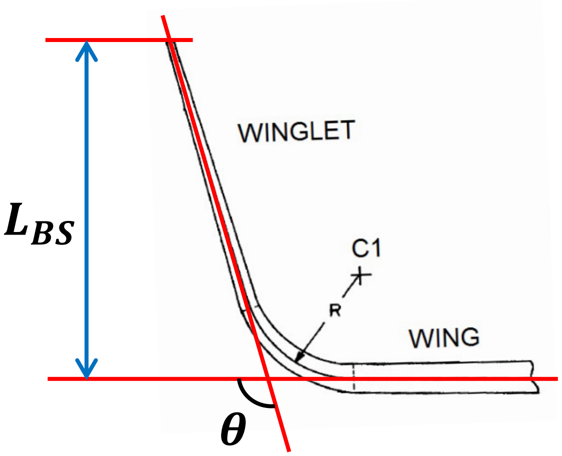
- **Example: Control of tip vortex development:**
  - Sometimes used in axial turbines (Kaplan) to mitigate tip vortex cavitation
  - The winglets (called anti-cavitation lips) are of simple design
    - A plate attached to the tip of the blades, towards suction side

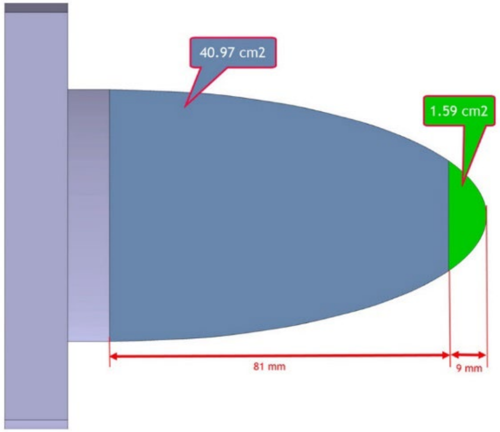
Vortex Induced Vibration: Flow Control

- **Example: Control of tip vortex development:**
  - Suppression of tip vortex cavitation by winglets

The winglets are realized by non-planar extensions of the original section of a Naca16-20 elliptical hydrofoil at various angles

- *Design variables:* θ *&* L_{BS}
- *Smooth transition of the geometry*





The affected area is max. 3.7% of the whole lifting surface.

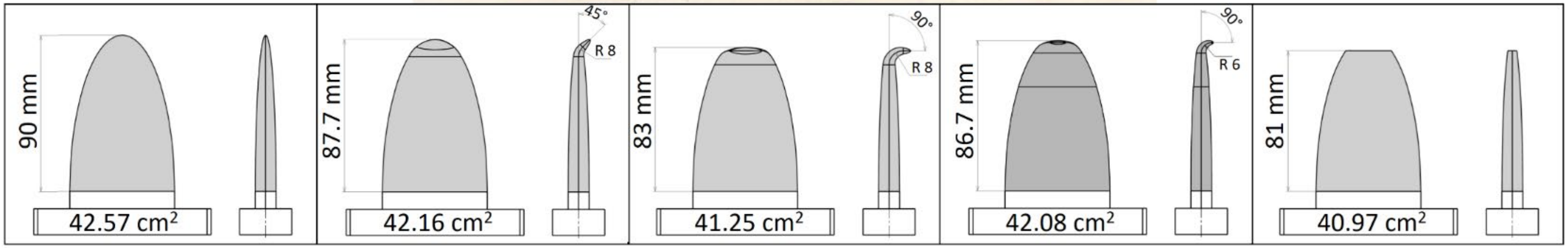
Dihedral angle: $\theta = 0°, \pm 45, \pm 90°$

Bent section length: $L_{BS} = 0.05S \; \& \; 0.1S$

$\boldsymbol{S}$*: span of the baseline hydrofoil (90 mm)*

Vortex Induced Vibration: Flow Control

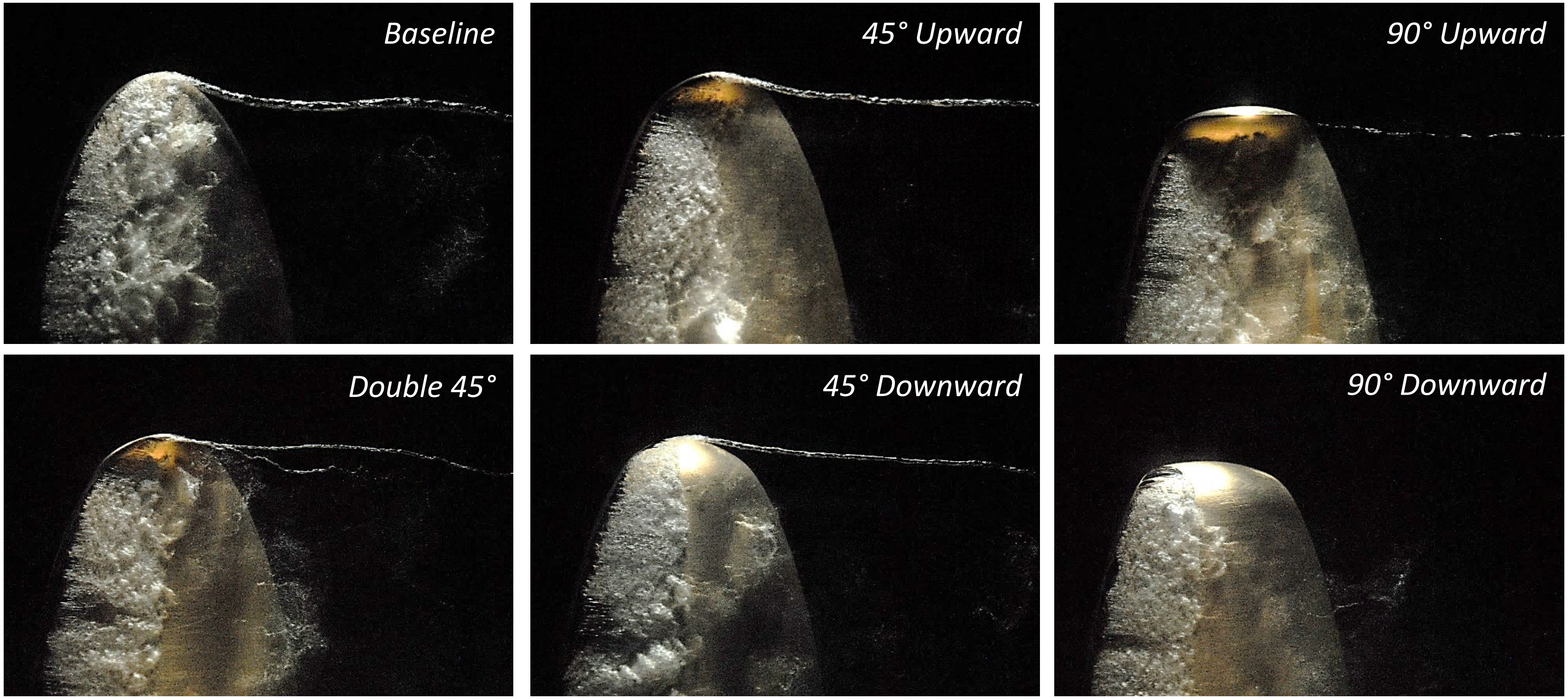
- **Example: Control of tip vortex development:**
  - Suppression of tip vortex cavitation by winglets
    - *Naca16-20 with different tips, tested in the EPFL cavitation tunnel*



Vortex Induced Vibration: Flow Control

- **Example: Control of tip vortex development:**
  - Suppression of tip vortex cavitation by winglets
    - *Naca16-20 with different tips, tested in the EPFL cavitation tunnel*

Effect of winglets shape on TVC $(\boldsymbol{U_\infty = 10\ \mathrm{m/s}}, \boldsymbol{\alpha = 12°}, \boldsymbol{\sigma = 1.2})$

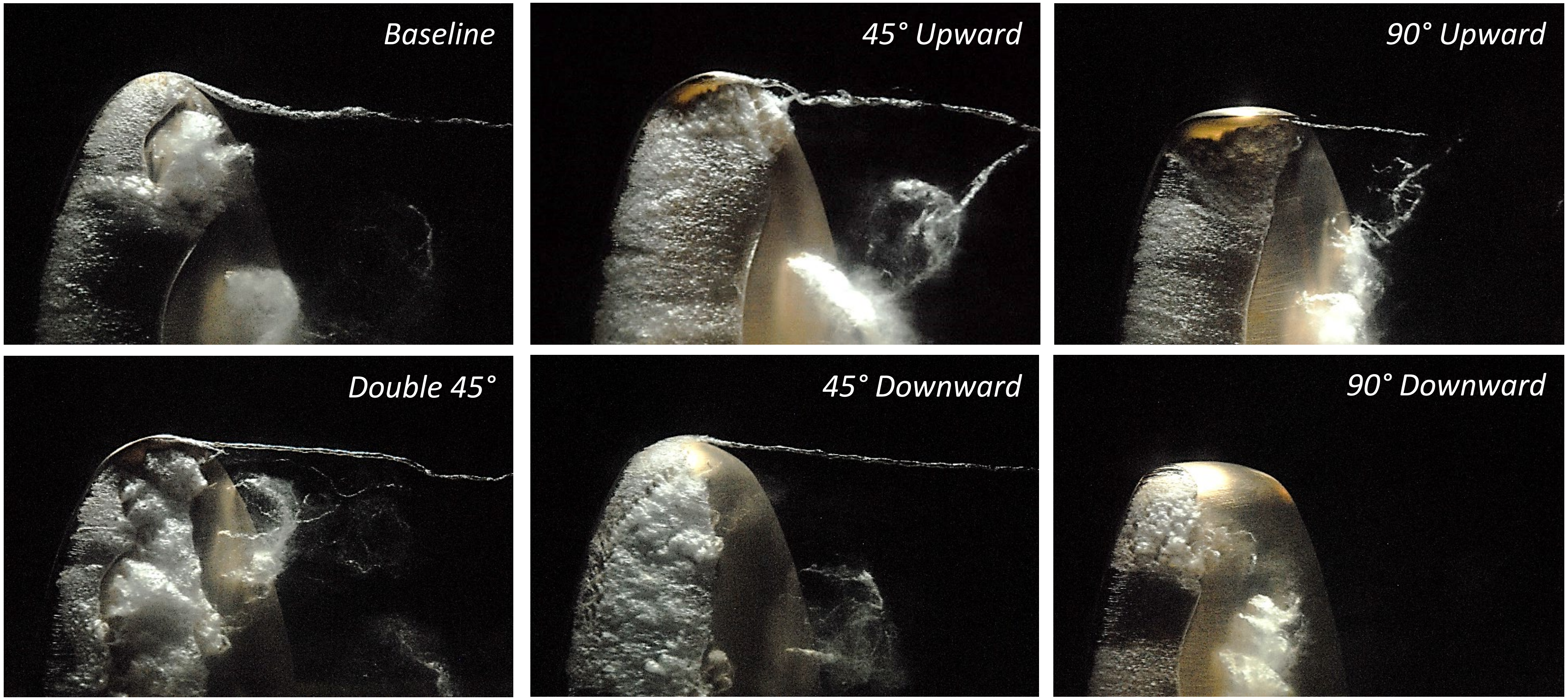


TVC suppressed with the hydrofoil bent 90° downward (towards pressure side)

Vortex Induced Vibration: Flow Control

- **Example: Control of tip vortex development:**
  - Suppression of tip vortex cavitation by winglets
    - *Naca16-20 with different tips, tested in the EPFL cavitation tunnel*

Effect of winglets shape on TVC $(\boldsymbol{U_\infty = 15\ \mathrm{m/s}}, \boldsymbol{\alpha = 12°}, \boldsymbol{\sigma = 1.2})$

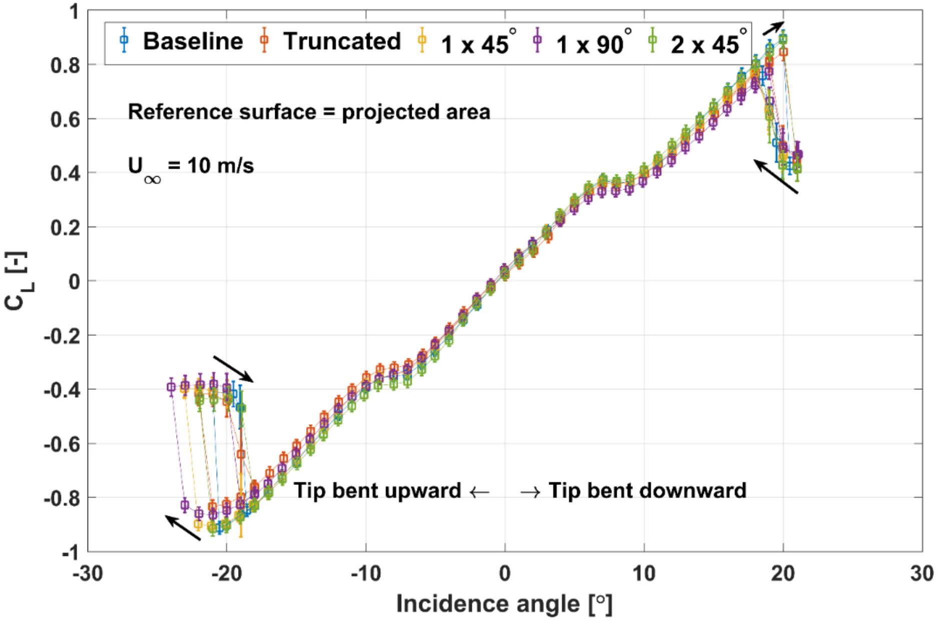


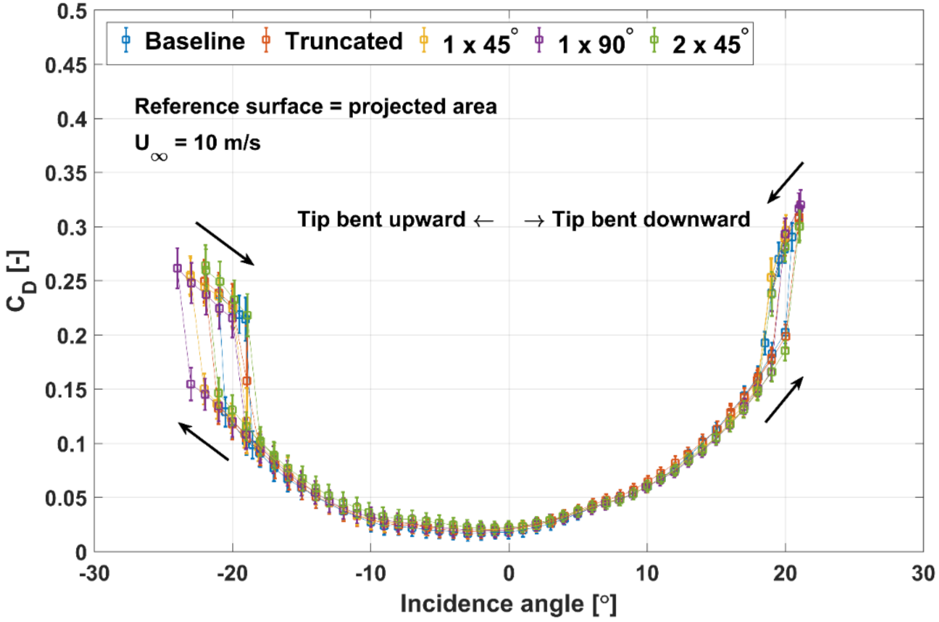
TVC suppressed with the hydrofoil bent 90° downward (towards pressure side)

Vortex Induced Vibration: Flow Control

- **Example: Control of tip vortex development:**
  - Suppression of tip vortex cavitation by winglets
    - *Naca16-20 with different tips, tested in the EPFL cavitation tunnel*

Measurements of lift and drag coefficients in cavitation free regime $(U_\infty = 10\ \mathrm{m/s})$



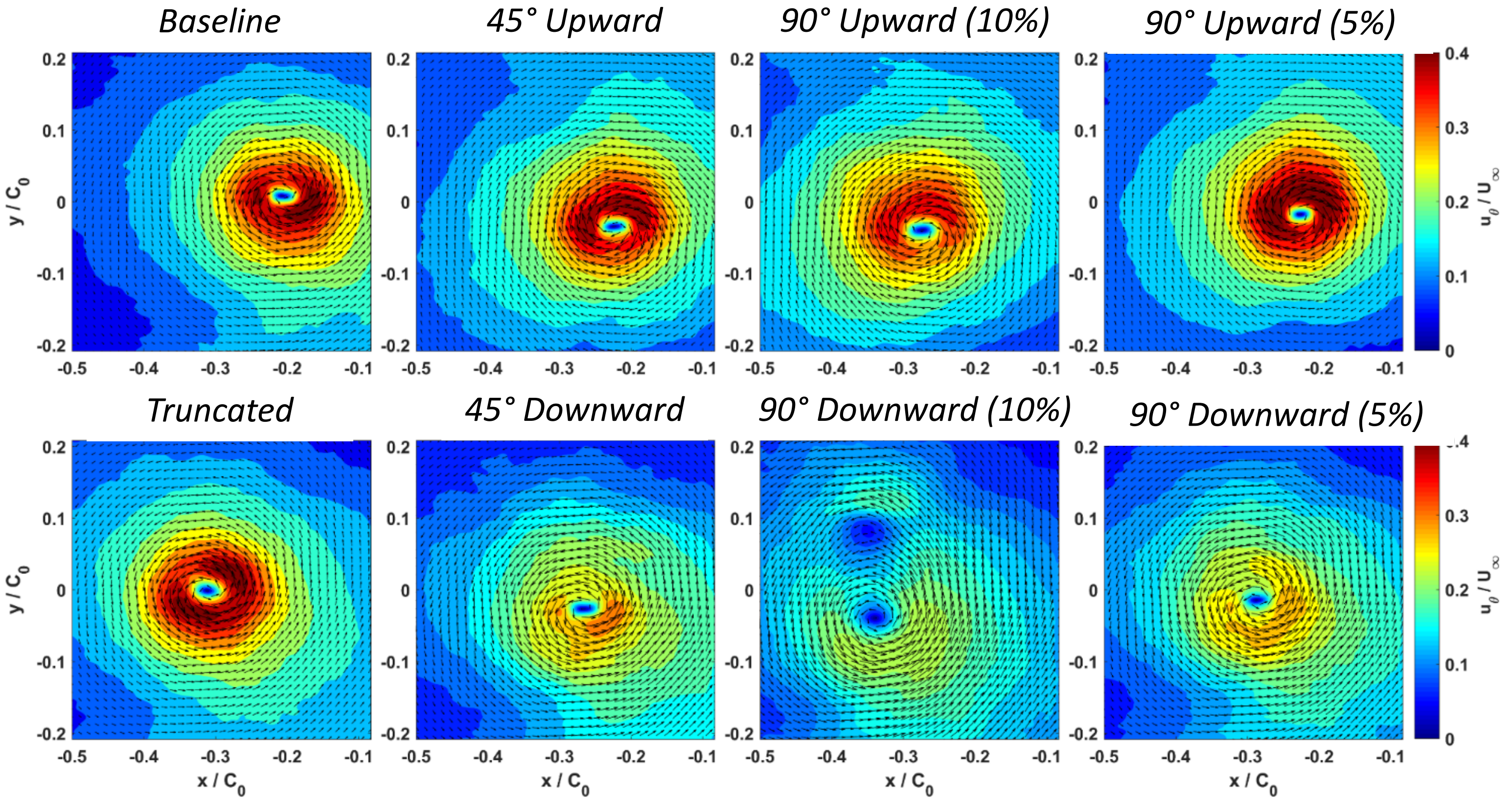


Almost no effects of winglets on hydrodynamic performances

Vortex Induced Vibration: Flow Control

- **Example: Control of tip vortex development:**
  - Suppression of tip vortex cavitation by winglets
    - *Naca16-20 with different tips, tested in the EPFL cavitation tunnel*

Contours of the tangential velocity by Stereo-PIV $(U_\infty = 10\ \mathrm{m/s}, \alpha = 12°)$



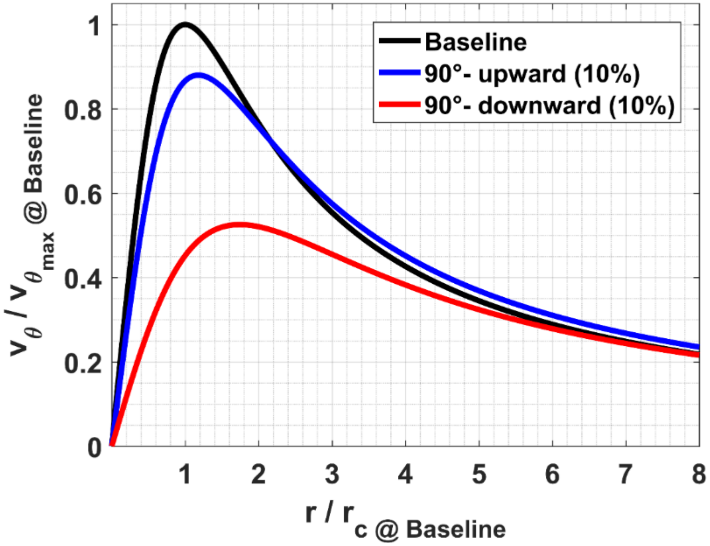
Vortex Induced Vibration: Flow Control

- **Example: Control of tip vortex development:**
  - Suppression of tip vortex cavitation by winglets
    - *Naca16-20 with different tips, tested in the EPFL cavitation tunnel*

Comparison of the tangential velocity profiles:

- *Flow conditions:* $U_\infty = 10 \ \mathrm{m/s}, \alpha = 12°$

- *90°-downward (10%)*
  - ➢ *Most effective case*
  - ➢ *Increase of the viscous radius (*r_c*) by 70 %*
  - ➢ *Decrease of* $v_{\theta_{max}}$ *by almost 50 %*



✓ Γ *remains constant while* r_c *increases*

✓ *Viscous core thickening is likely the dominant mechanism of TVC mitigation*

Vortex Induced Vibration: Flow Control

- **Example: Control of vortex induced vibration of cylindrical structures:**
  - *Various shapes, intended to suppress the formation of coherent structures in the wake of cylindrical structures.*

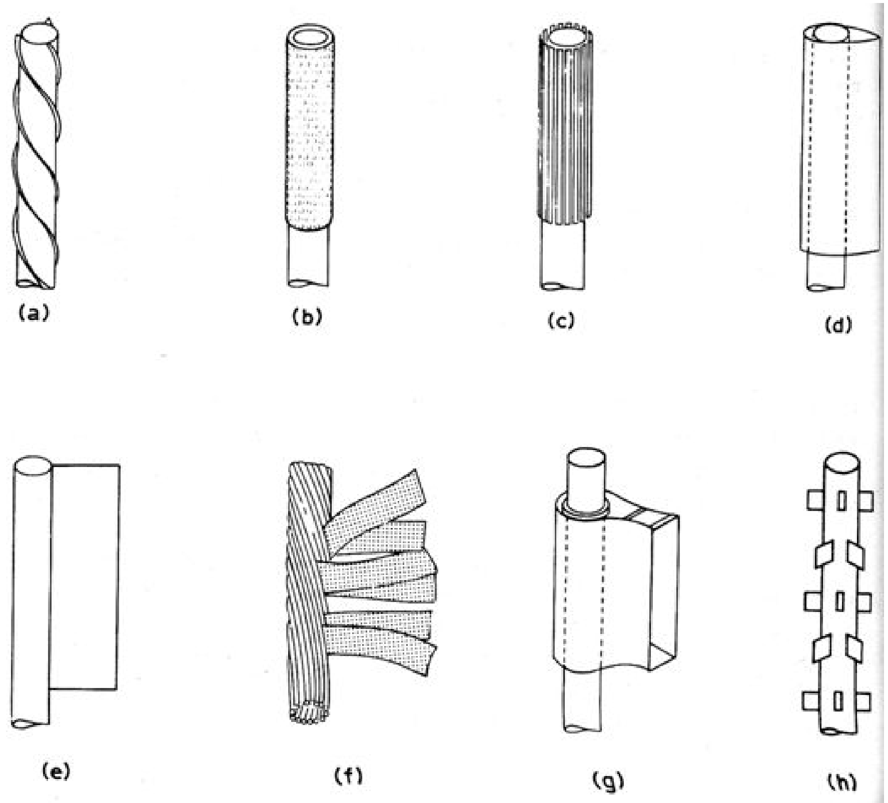
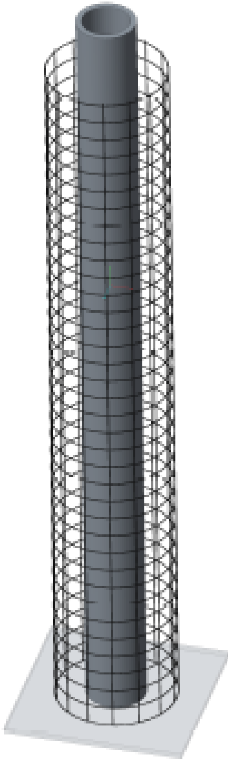
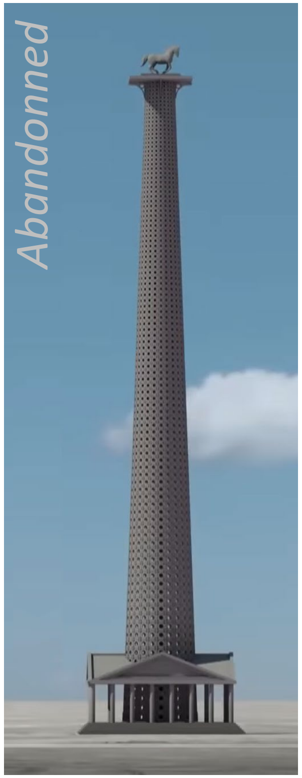


Fig. 3-23 Add-on devices for suppression of vortex-induced vibration of cylinders: (a) helical strake; (b) shroud; (c) axial slats; (d) streamlined fairing; (e) splitter; (f) ribboned cable; (g) pivoted guiding vane; (h) spoiler plates.

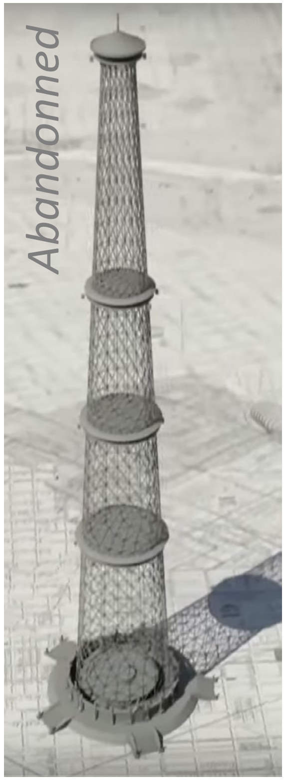


Vortex Induced Vibration: Flow Control

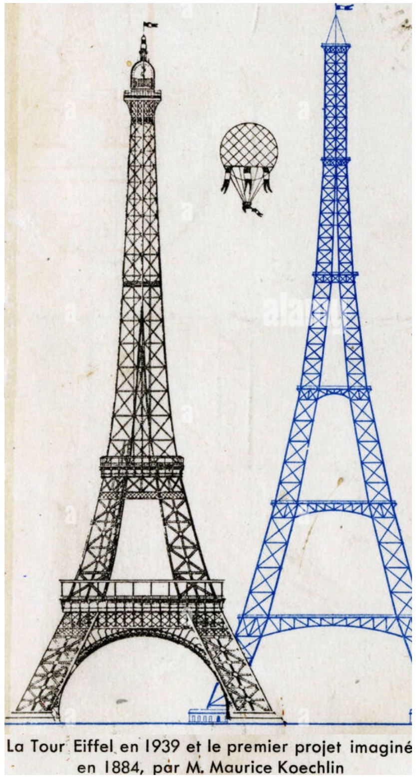
- **Example: Control of vortex induced vibration of cylindrical structures:**
- **19th century: the race to build the first tower exceeding 1000 feet led to various designs, all characterized by their porosity to better resist the wind.**



Richard Trevithick
London, 1832



Clarke, Reeves & Co.
Philadelphia,1876


La Tour Eiffel en 1939 et le premier projet imaginé en 1884, par M. Maurice Koechlin

G. Eiffel & M. Koechlin,
Paris, 1889

Vortex Induced Vibration: Flow Control

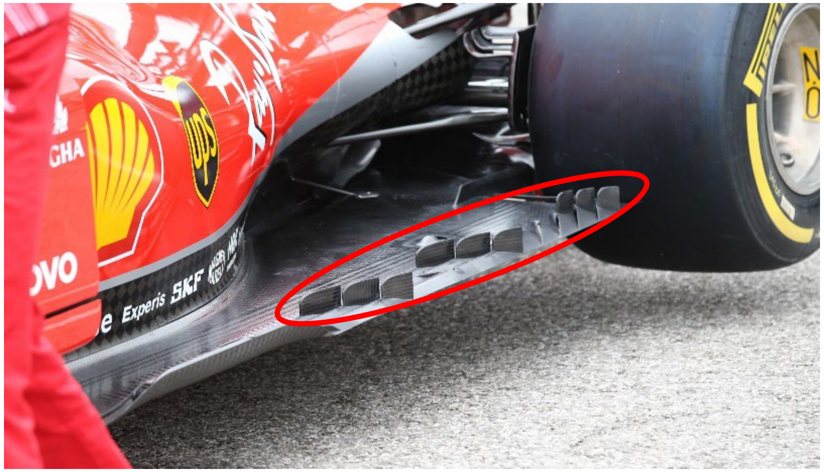
Vortex Generators

- *Introduced in 1947 by Taylor HD*
  (Suppression of diffuser separation by vortex generators, United Aircraft Corporation Report)
- *Made of isolated obstacles (vanes), of various shapes, distributed along the span*
  - *Mainly used in aerodynamic applications to delay flow separation*
    → Reduction of Drag & Flow induced vibration
  - *Recently introduced to control cavitation in hydro turbine (mixed results)*

Vortex Induced Vibration: Flow Control

Vortex Generators

- Various applications (airspace, automotive, wind turbines, …):



Vortex Induced Vibration: Flow Control

Vortex Generators

- **Conventional Vortex Generators:**
    - Device height ~ Boundary layer thickness
    - Device angle: β vs local flow direction

    → to produce an array of stream wise trailing vortices

- **Advantage**:
    - Suitable for flow separation control in aircrafts
        - Lower drag, Increase of maximum take-off weight

          Reduction of noise and vibration

- **Disadvantage**:
    - Limited to applications where BL separation location is fixed

    Otherwise, when VG's cover a large downstream area, they may produce residual drag (turbulent wake)

Flow Control: Vortex Generators

- **Modern Vortex Generators**
    - Device Height ~ 10 – 50 % of boundary layer thickness
    - Known as:
        - Micro VG's – Low profile VG's – Submerged VG's –MEMS-scale effectors – Microvanes
- **Advantages of Micro VG's**
    - Similar effects as conventional VG's
    - Almost no drag induced
    - Small size → may be stowed within the wing when not needed

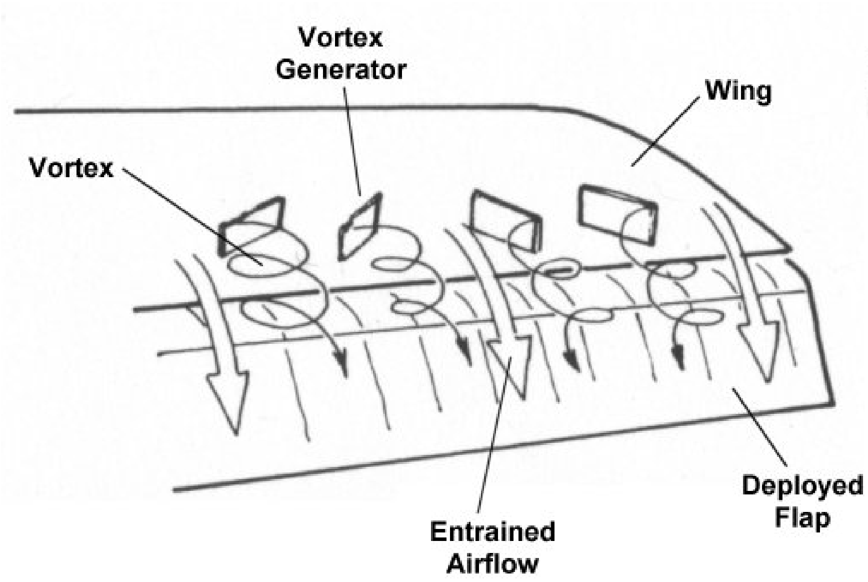
Vortex Induced Vibration: Flow Control

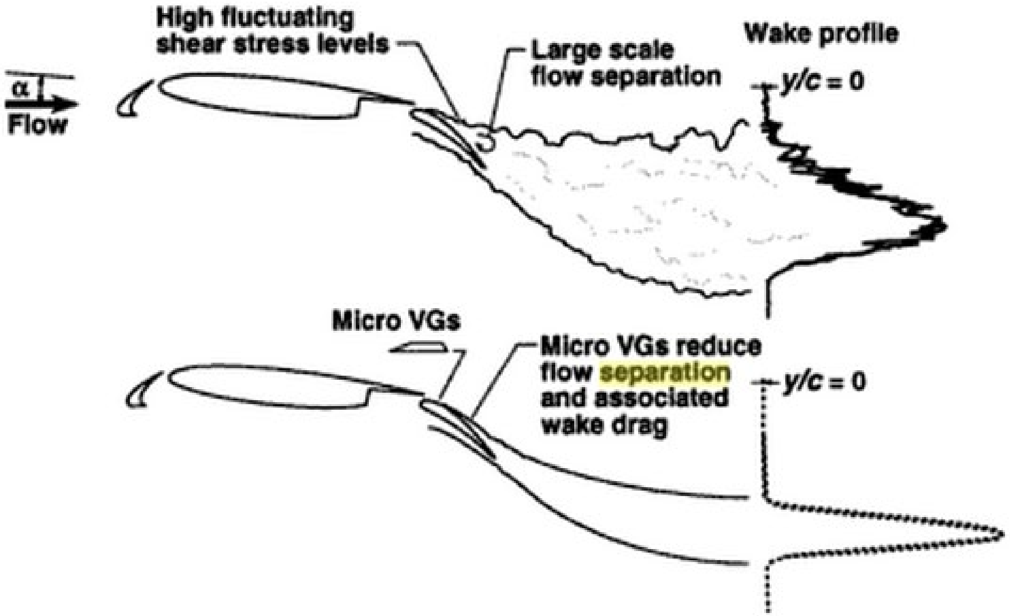
Flow Control: Vortex Generators

- **How VG's work ?**
  - Not fully understood (empirical optimization)
  - Generation of streamwise vortices

  → Fluid is pumped in & out of the boundary layer leading to its re-energizing

  → Improved mixing → BL remains attached on a longer distance

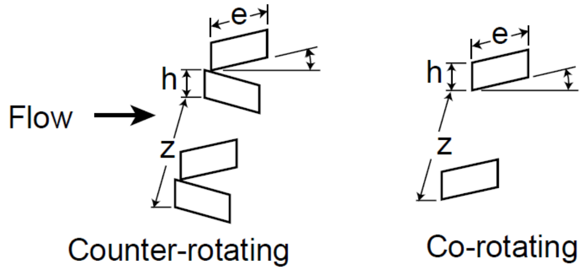




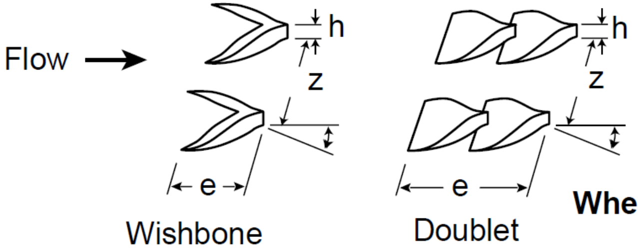
Vortex Induced Vibration: Flow Control

Flow Control: Vortex Generators

- **Various VG's shapes:**
  - Doublets, wishbones (Y-shaped), Counter-rotating rectangular vanes, Counter rotating delta vanes, Forward wedges, …



Vane-type VGs



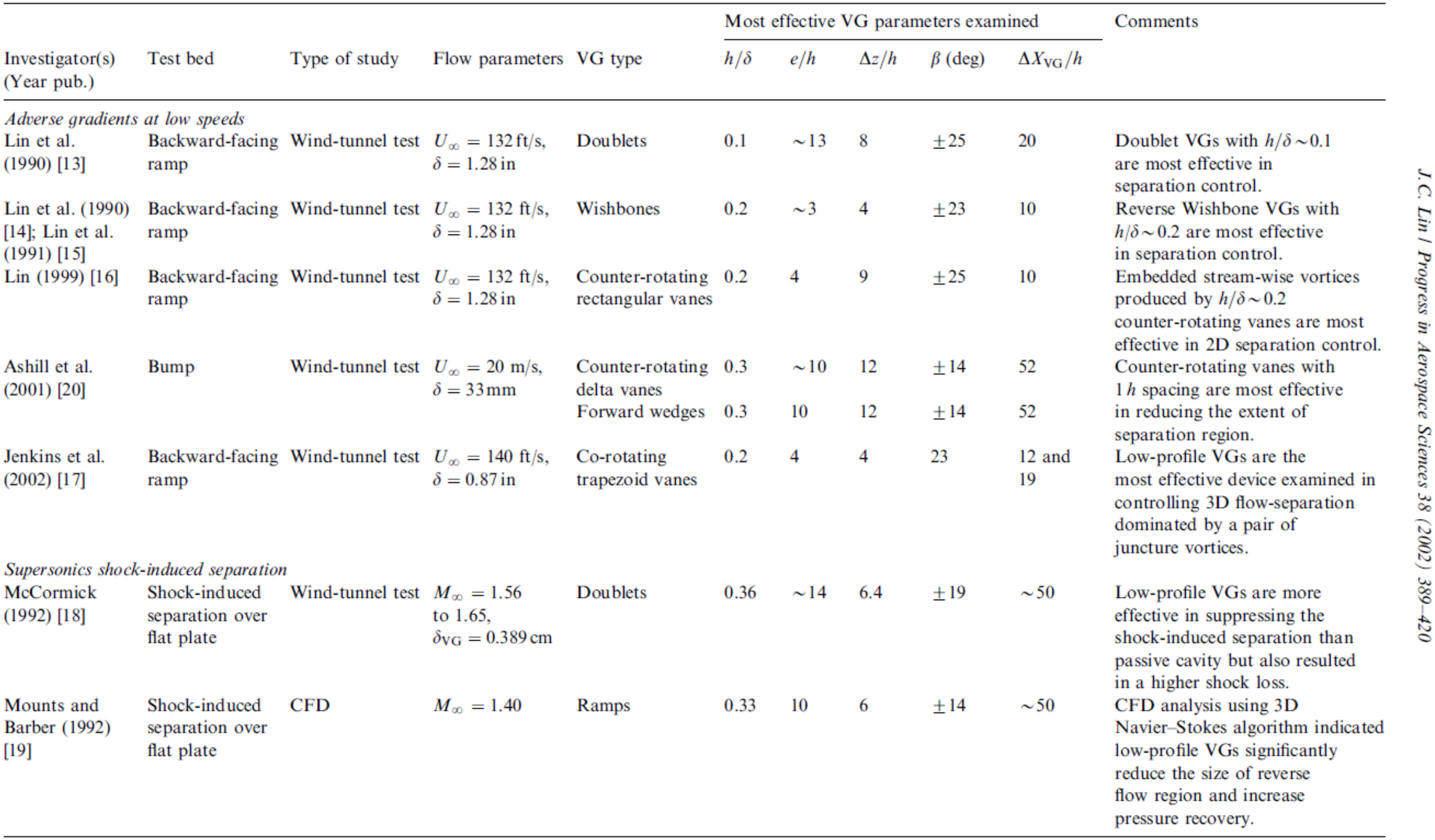
Wheeler VGs

- **VG's parameters:**
  - h/δ, e/δ: height and length, reported to BL thickness
  - $\Delta z/h$: Span wise Spacing
  - β : Incidence angle vs main stream
  - $\Delta X_{VG}/h$: Streamwise distance between VG's and baseline separation

Vortex Induced Vibration: Flow Control

Vortex Generators

- ***Optimum VG's parameters:***



Investigator(s) (Year pub.)	Test bed	Type of study	Flow parameters	VG type	Most effective VG parameters examined					Comments
					h/δ	e/h	$\Delta z/h$	β (deg)	$\Delta X_{VG}/h$	
Adverse gradients at low speeds										
Lin et al. (1990) [13]	Backward-facing ramp	Wind-tunnel test	$U_\infty = 132\,\text{ft/s}$, $\delta = 1.28\,\text{in}$	Doublets	0.1	~13	8	±25	20	Doublet VGs with $h/\delta \sim 0.1$ are most effective in separation control.
Lin et al. (1990) [14]; Lin et al. (1991) [15]	Backward-facing ramp	Wind-tunnel test	$U_\infty = 132$ ft/s, $\delta = 1.28\,\text{in}$	Wishbones	0.2	~3	4	±23	10	Reverse Wishbone VGs with $h/\delta \sim 0.2$ are most effective in separation control.
Lin (1999) [16]	Backward-facing ramp	Wind-tunnel test	$U_\infty = 132$ ft/s, $\delta = 1.28\,\text{in}$	Counter-rotating rectangular vanes	0.2	4	9	±25	10	Embedded stream-wise vortices produced by $h/\delta \sim 0.2$ counter-rotating vanes are most effective in 2D separation control.
Ashill et al. (2001) [20]	Bump	Wind-tunnel test	$U_\infty = 20$ m/s, $\delta = 33\,\text{mm}$	Counter-rotating delta vanes Forward wedges	0.3 0.3	~10 10	12 12	±14 ±14	52 52	Counter-rotating vanes with 1 h spacing are most effective in reducing the extent of separation region.
Jenkins et al. (2002) [17]	Backward-facing ramp	Wind-tunnel test	$U_\infty = 140$ ft/s, $\delta = 0.87\,\text{in}$	Co-rotating trapezoid vanes	0.2	4	4	23	12 and 19	Low-profile VGs are the most effective device examined in controlling 3D flow-separation dominated by a pair of juncture vortices.
Supersonics shock-induced separation										
McCormick (1992) [18]	Shock-induced separation over flat plate	Wind-tunnel test	$M_\infty = 1.56$ to 1.65, $\delta_{VG} = 0.389\,\text{cm}$	Doublets	0.36	~14	6.4	±19	~50	Low-profile VGs are more effective in suppressing the shock-induced separation than passive cavity but also resulted in a higher shock loss.
Mounts and Barber (1992) [19]	Shock-induced separation over flat plate	CFD	$M_\infty = 1.40$	Ramps	0.33	10	6	±14	~50	CFD analysis using 3D Navier–Stokes algorithm indicated low-profile VGs significantly reduce the size of reverse flow region and increase pressure recovery.

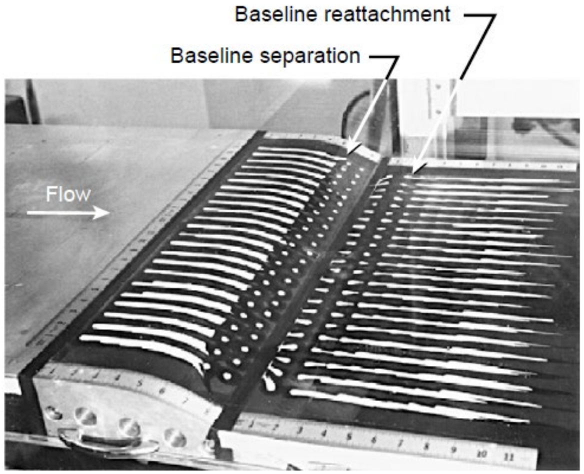
J.C. Lin / Progress in Aerospace Sciences 38 (2002) 389–420

Vortex Induced Vibration: Flow Control

Vortex Generators

- ***Conventional VG's compared to micro VG's:***
  - *Case study : backward facing ramp*

Baseline, No VG's

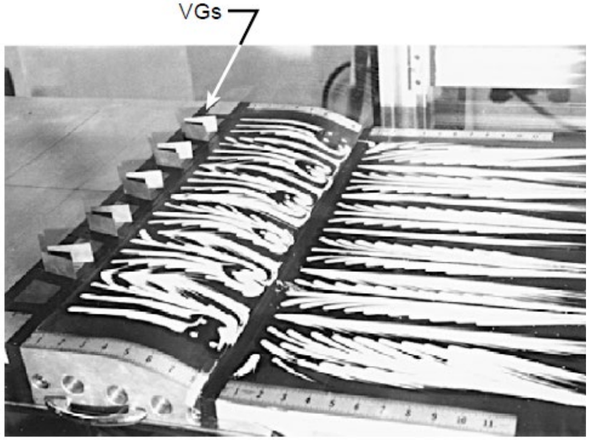


(a) Baseline (VG off) case.

Flow separation with reattachment

Conventional VG's

$$\frac{h}{\delta}=0.8\,;\frac{e}{h}=2\,;\frac{\Delta z}{h}=4\,;\beta=\pm 15^\circ$$

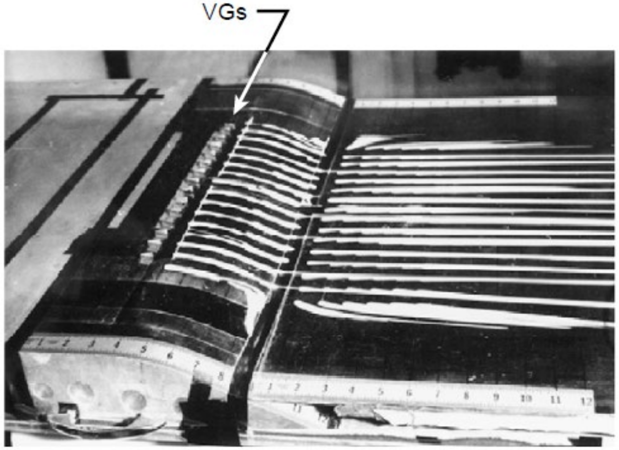


(b) 0.8δ-high vane-type counter-rotating VGs at 6 h upstream of baseline separation.

Attached flow, but 3D strong vortices

Micro VG's

$$\frac{h}{\delta}=0.2\,;\frac{e}{h}=4\,;\frac{\Delta z}{h}=9\,;\beta=\pm 25^\circ$$



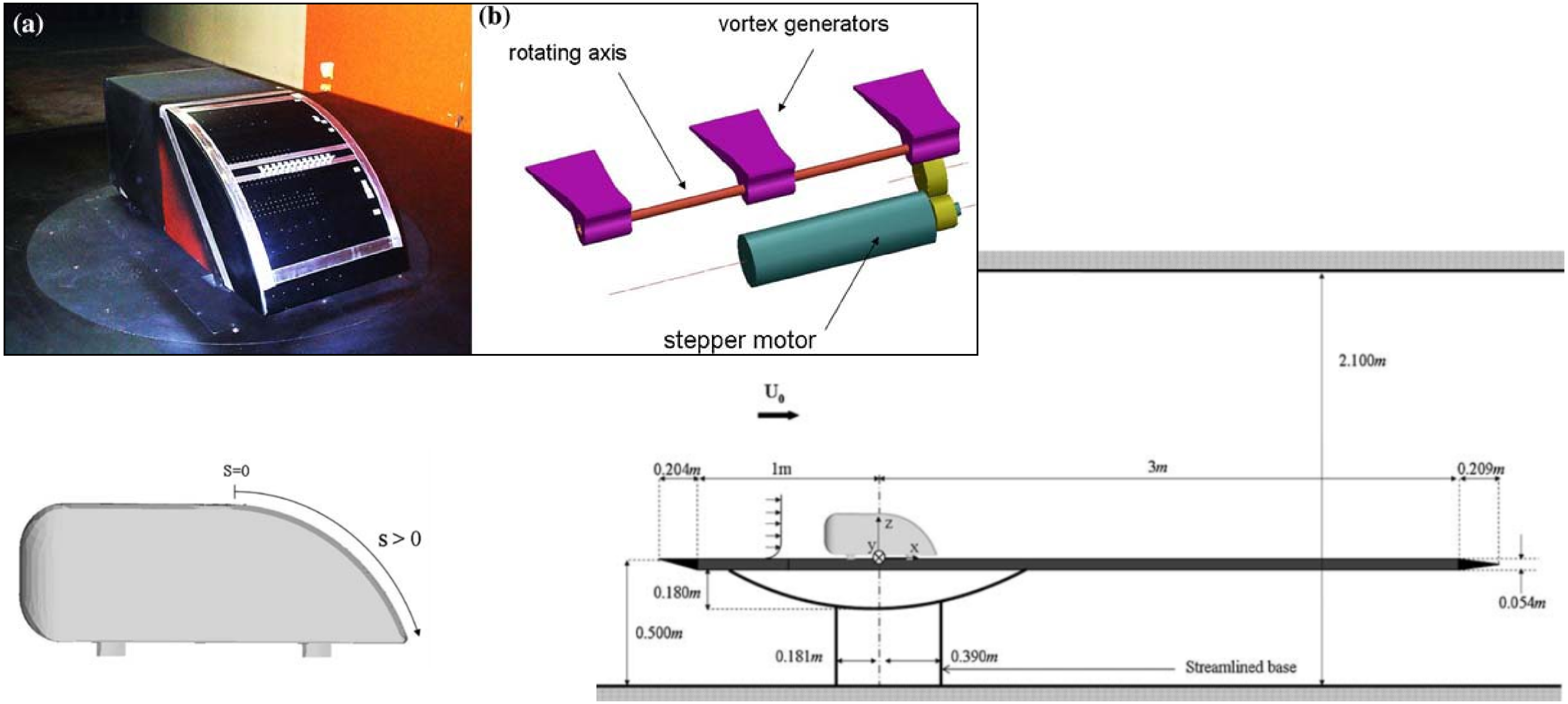
(c) 0.2δ-high vane-type counter-rotating VGs at 10 h upstream of baseline separation.

Attached 2D flow with μ–VG's

Vortex Induced Vibration: Flow Control

Flow Control: Vortex Generators

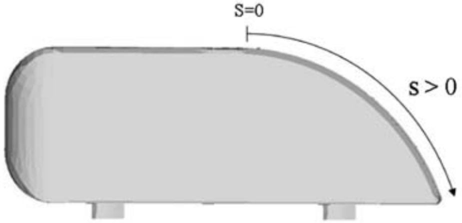
- ***Active Vortex Generators***
  - *J. L. Aider et. al., Experiments in fluids, 2010*
  - *Case study: a modified Ahmed bluff body with motorized VG's*



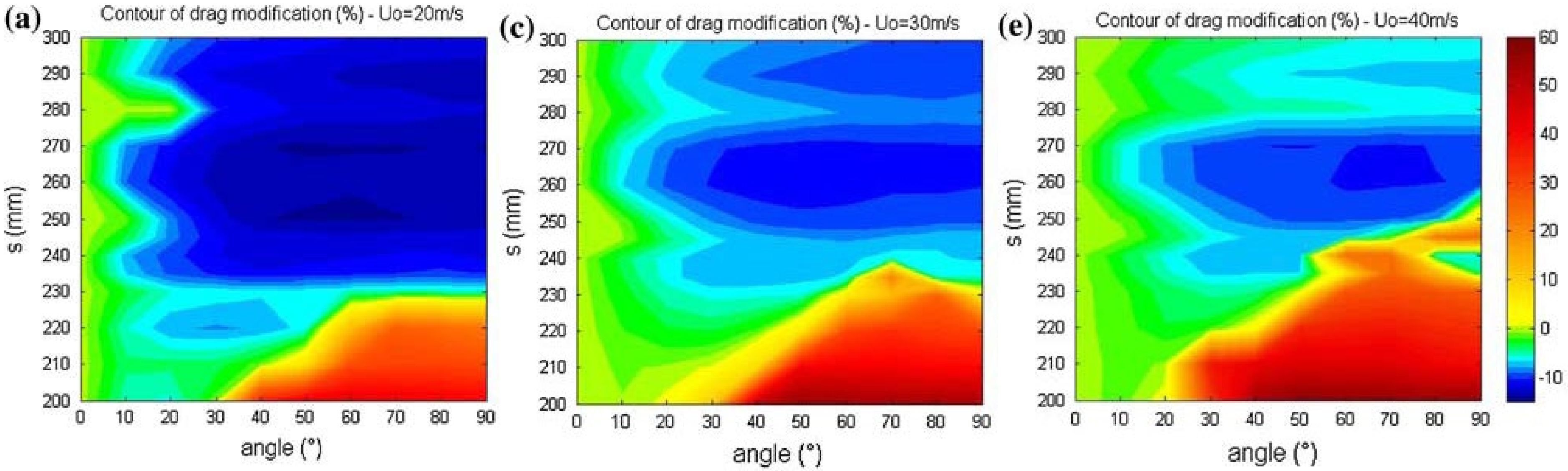
Vortex Induced Vibration: Flow Control

Flow Control: Vortex Generators

- ***Recent development : Active Vortex Generators***
  - *J. L. Aider et. al., Experiments in fluids, 2010*



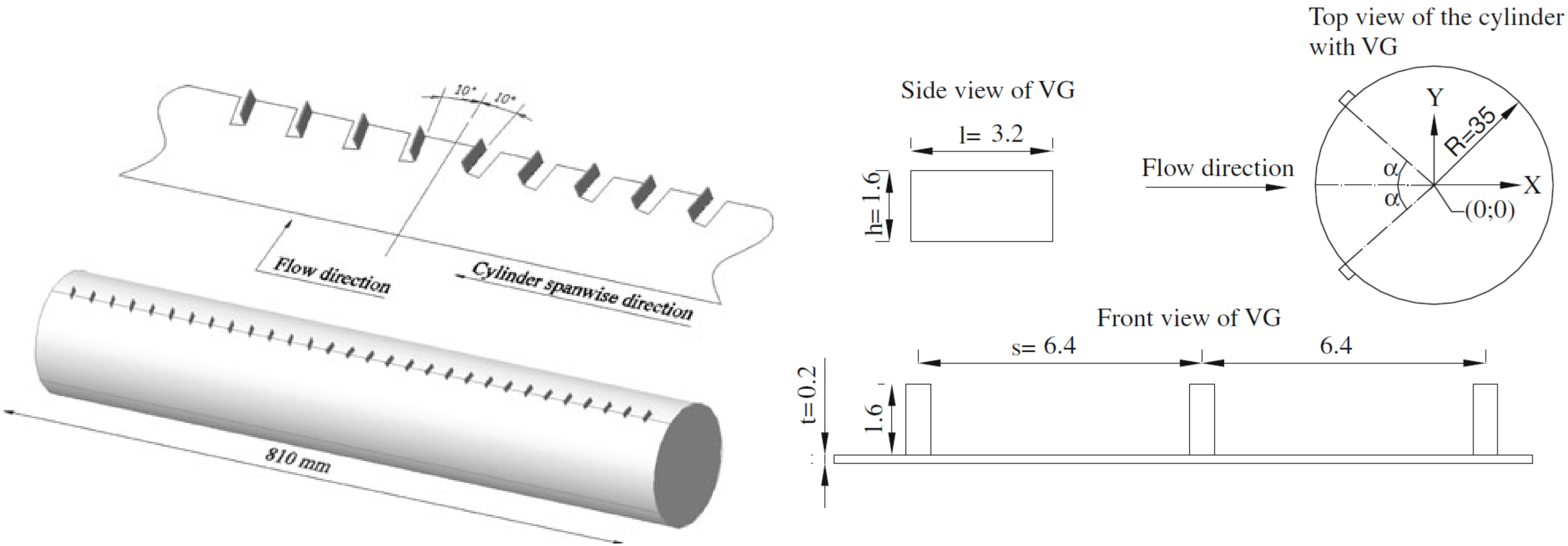
- *Effect of Reynolds number on optimum angle and location of vortex generators leading to maximum drag & noise reduction*



Vortex Induced Vibration: Flow Control

Flow Control: Vortex Generators

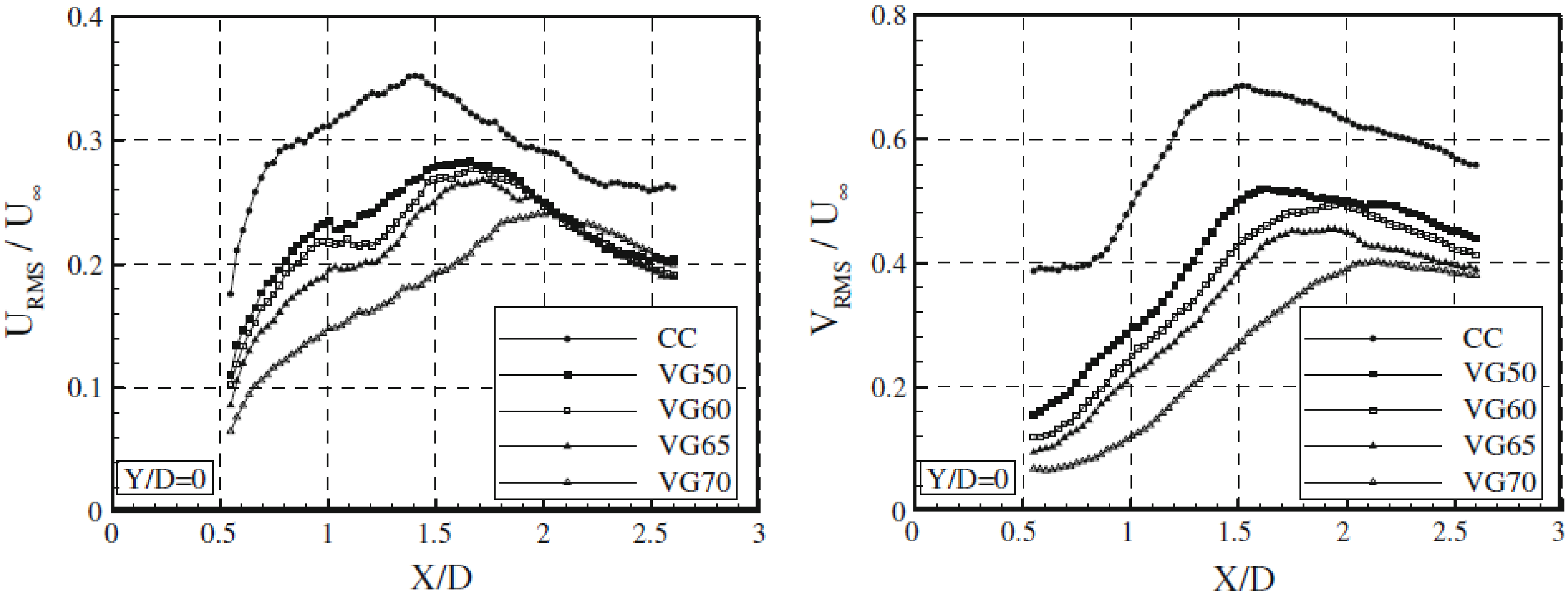
- ***Effect of VG's on the near wake flow of a cylinder:***
  - *Unal et. al., Experiments in Fluids, 2010*



Vortex Induced Vibration: Flow Control

Flow Control: Vortex Generators

- ***Effect of VG's on the near wake flow of a cylinder:***
  - *Unal et. al., Experiments in Fluids, 2010*
  - *Significant decrease of non dimensional RMS streamwise (left) and transverse velocity (right) with VG's*
  - *Effect of VG's location: Velocity fluctuation decreases with increasing α*



Flow Control: Vortex Generators

- ***Engineering applications:***
  - *Extensively used in aircrafts*
  - *Increasingly used in wind turbines*
  - *Still under development for automotive applications !*
  - *Completely absent in hydropower turbines !*

- ***Fundamental research:***
  - *Still empirical*
  - *A lot of research is underway*

Vortex Induced Vibration: Flow Control

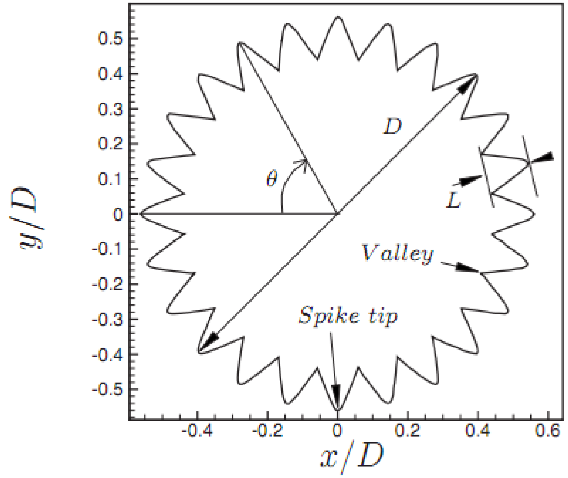
- ***Manipulation of wake dynamic through distributed roughness:***
  - *Noise and dynamic load reduction*
  - *Example : Cactus*

Cactus inspired building

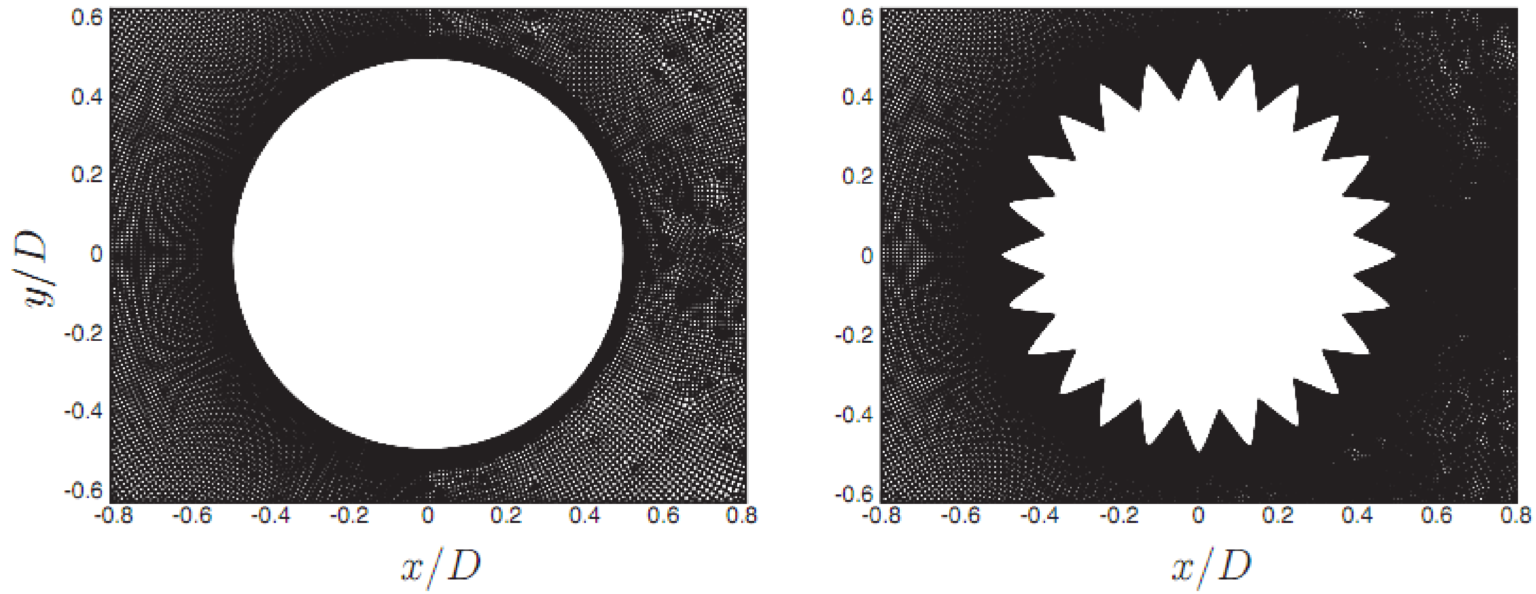
Vortex Induced Vibration: Flow Control

Flow Control: Vortex Generators

- *Case of Cactus shaped cylinder:*
    - *Direct Numerical simulation*

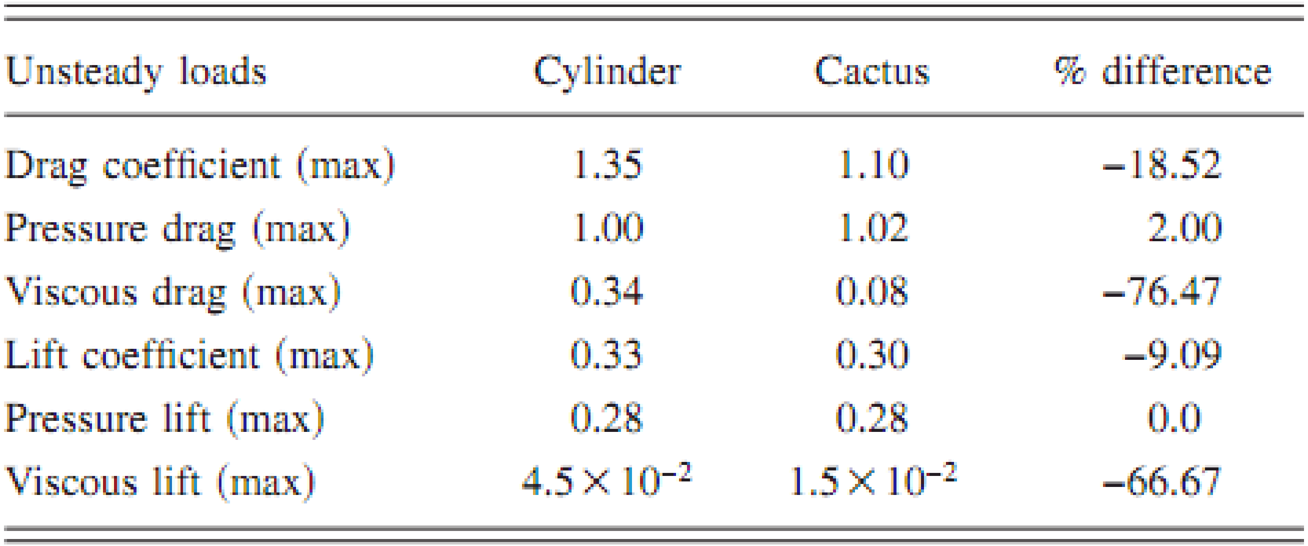


(a)



Vortex Induced Vibration: Flow Control

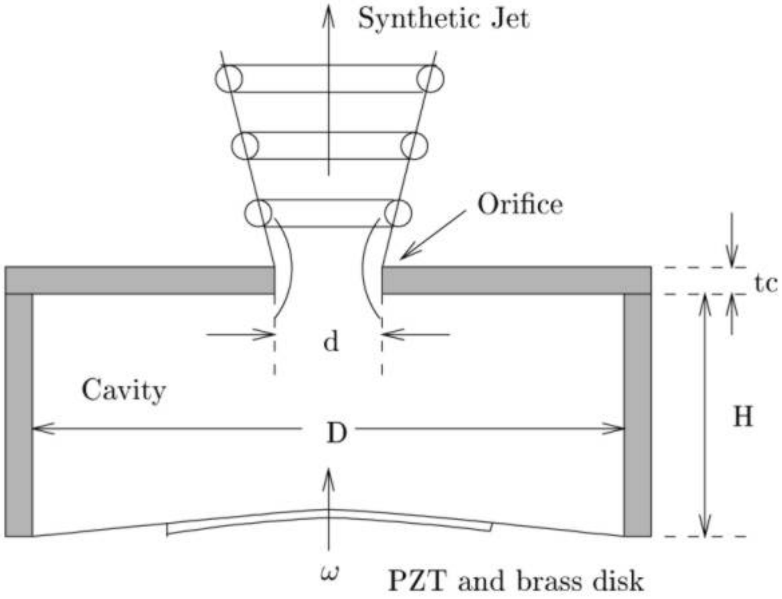
- *Cactus shaped cylinder:*
  - *Direct Numerical simulation*
    - *Comparison of unsteady loads acting on smooth cylinder and cactus shaped cylinder at Re=100*
    - *Significant reduction of total drag coefficient*
      - *Increase of pressure drag and decrease of viscous drag*
    - *For high Reynolds Nb, drag reduction is less pronounced*



Unsteady loads	Cylinder	Cactus	% difference
Drag coefficient (max)	1.35	1.10	−18.52
Pressure drag (max)	1.00	1.02	2.00
Viscous drag (max)	0.34	0.08	−76.47
Lift coefficient (max)	0.33	0.30	−9.09
Pressure lift (max)	0.28	0.28	0.0
Viscous lift (max)	4.5×10^{-2}	1.5×10^{-2}	−66.67

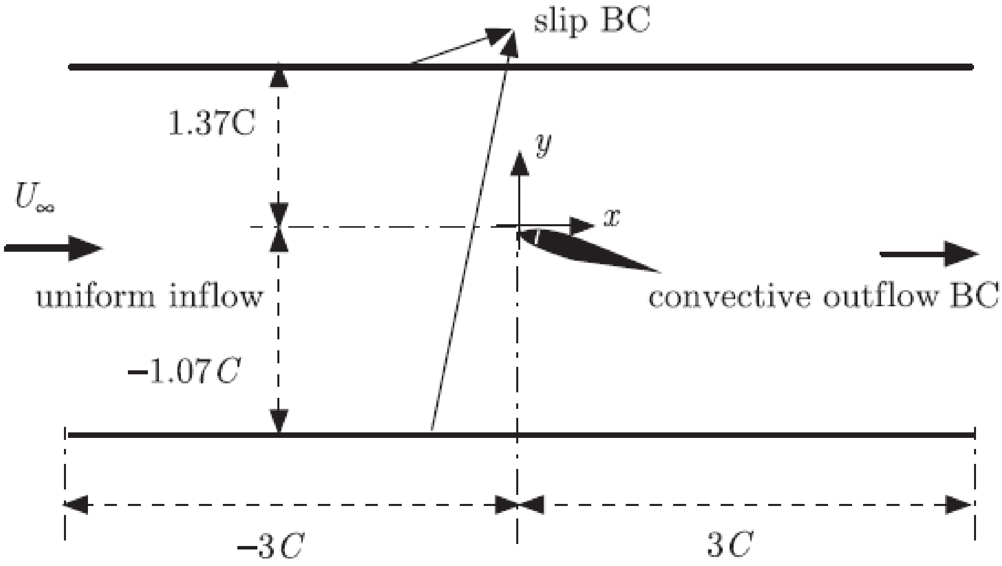
Vortex Induced Vibration: Flow Control

- ***Synthetic jets actuators for flow separation control:***
  - *Principle: Inject fluid momentum into a flow with the help of an oscillating diaphragm/piston . Air is forced in and out of a chamber via a sharp edged orifice.*
  - *The device generates discrete vortices which displace the local streamlines and induce a virtual change of the surface*
  - *A promising technique*



Vortex Induced Vibration: Flow Control

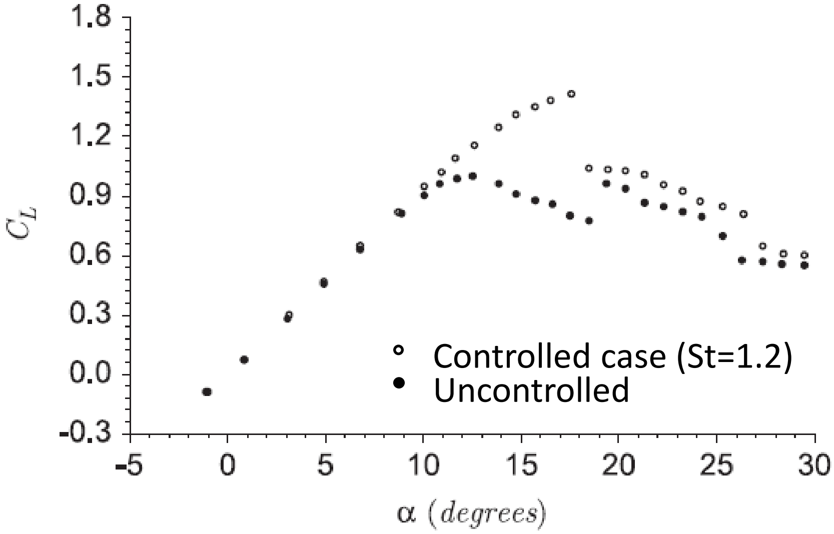
- ***Example: Synthetic jets actuators on a Naca 0015 airfoil***
    - *Chord length: C=375 mm*
  - *Synthetic jet :*
    - *A slot across the entire span with 2 mm width*
    - *Located on the suction side at 12 % of the chord (from leading edge).*
    - *Actuation frequency,* $f: \ 60 - 130\ Hz\ (fC/U = 0{,}65 - 1{,}40\ )$
  - *Large Eddy Simulation & Experimentation*

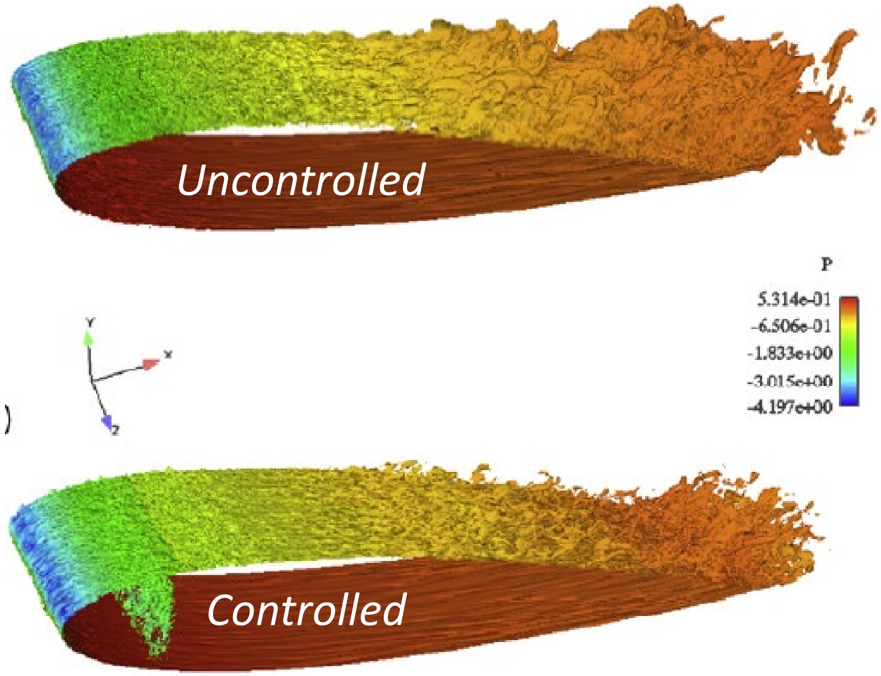


D. You et al., J. of Fluids and Structures, 2008

Vortex Induced Vibration: Flow Control

- ***Example: Synthetic jets actuators on a Naca 0015 airfoil (LES)***
  - *Effect of synthetic jet on the lift curve (Incidence: 16.5°, Re: 8.96 10^5, f: 120 Hz)*



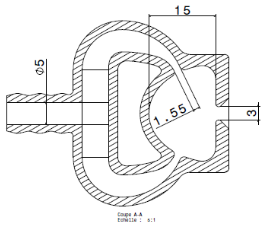


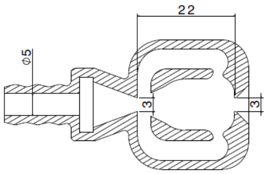
D. You et al., J. of Fluids and Structures, 2008

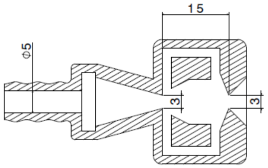
Vortex Induced Vibration: Flow Control

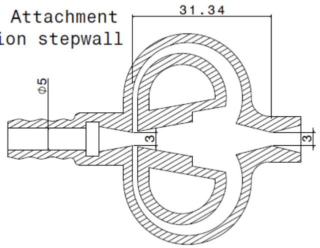
Flow Control: Sweeping Jet

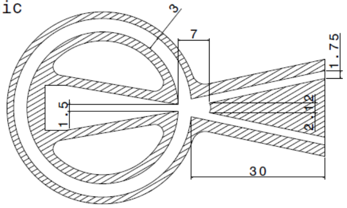
- *Working principles:*
    - *Generation of a sweeping jet without moving parts (Flow instability)*
- *Various shapes:*


FO Jet Interaction


FO Wall Attachment
Relaxation Curved


FO Wall Attachement
Relaxation Angled


FO Wall Attachment
Relaxation stepwall

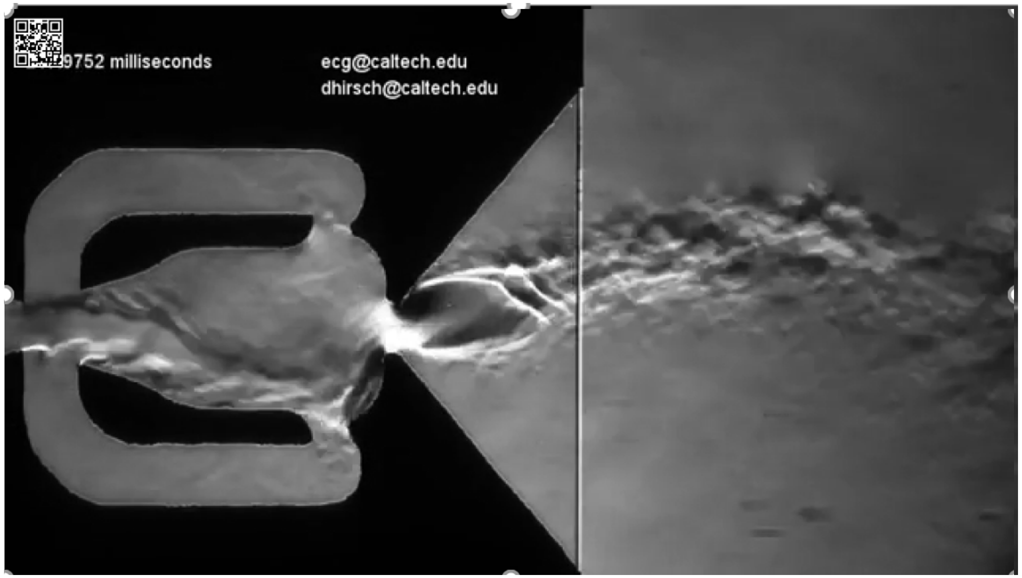

FO Wall Attachement
Sonic

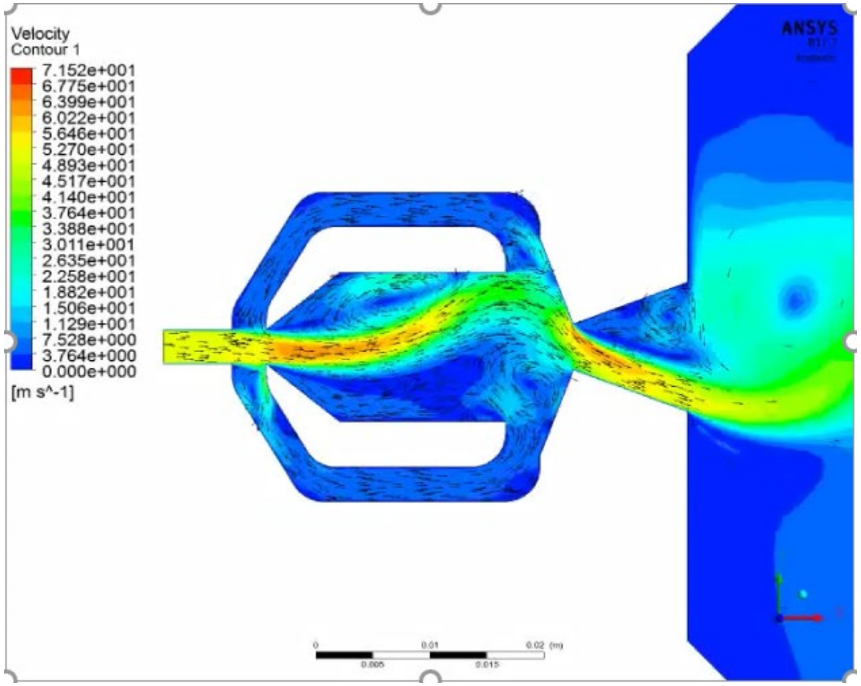
- *Old technology, used for irrigation purposes*
- *Nowadays, miniaturized for flow control purposes:*
    - *Design tool for high lift generation*
    - *Promising results obtained for Boeing 747 tail wing*
- *Ongoing research for broader applications of sweeping jets*
    - *Drag reduction, Vortex induced vibration, …*

Vortex Induced Vibration: Flow Control

Flow Control: Sweeping Jet

- ***Working Principle: Self-excitation of the jet → Periodic oscillations***



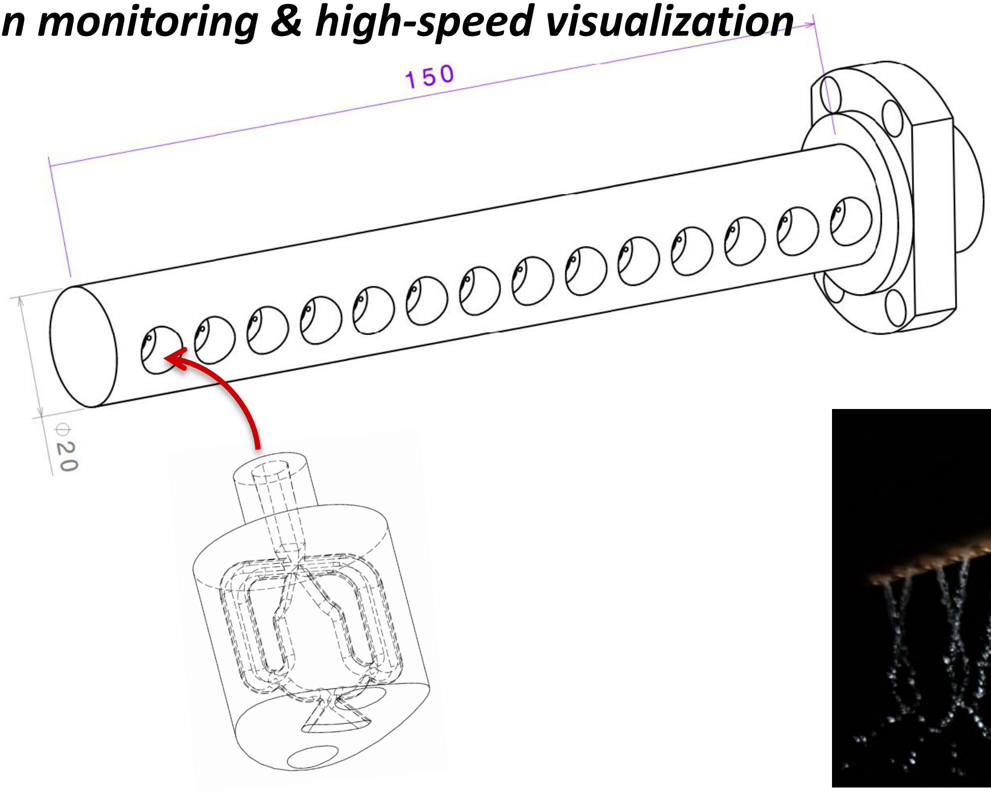


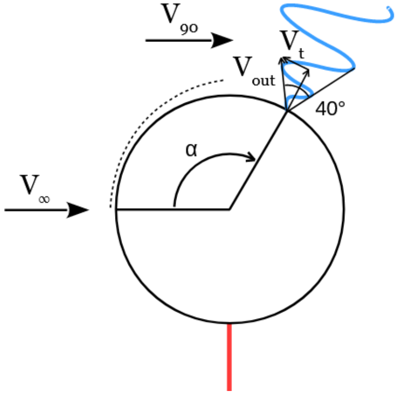
Vortex Induced Vibration: Flow Control

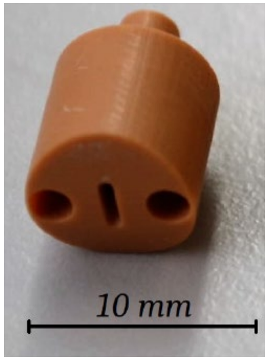
Flow Control: Sweeping Jet

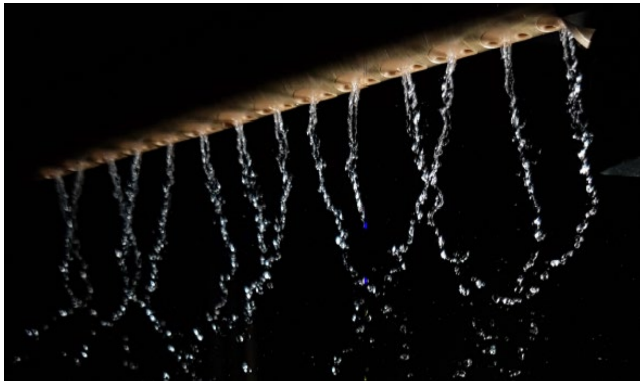
Application: Mitigation of vortex induced vibration on a cylinder in EPFL Cavitation tunnel (Master projects E. Boutillon 2017, J. Gildas, 2019)

- *Implementation of 14 miniaturized sweeping jets (3D printing)*
- *Angular position easilly adjusted*
- *Vibration monitoring & high-speed visualization*







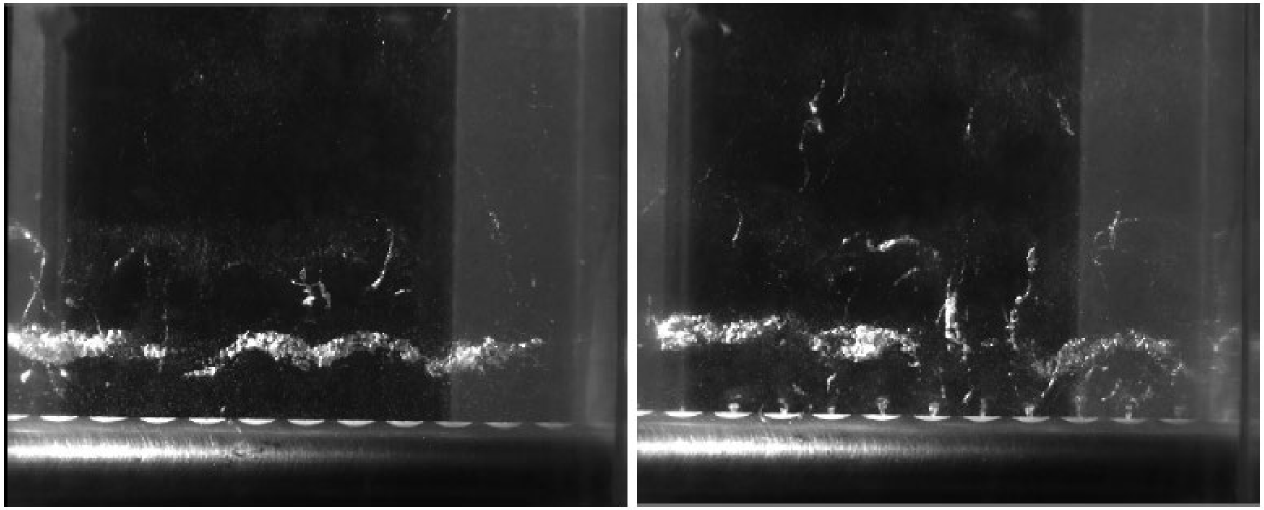


Vortex Induced Vibration: Flow Control

Flow Control: Sweeping Jet

Application: Mitigation of vortex induced vibration on a cylinder in EPFL Cavitation tunnel (Master projects E. Boutillon 2017, J. Gildas, 2019)

- ***Main Results:***
  - ***Sweeping jets at 180° : Almost no effects of SJ on wake instability***
  - ***Similar cavitating vortices***



(A) SWJ OFF (B) SWJ ON

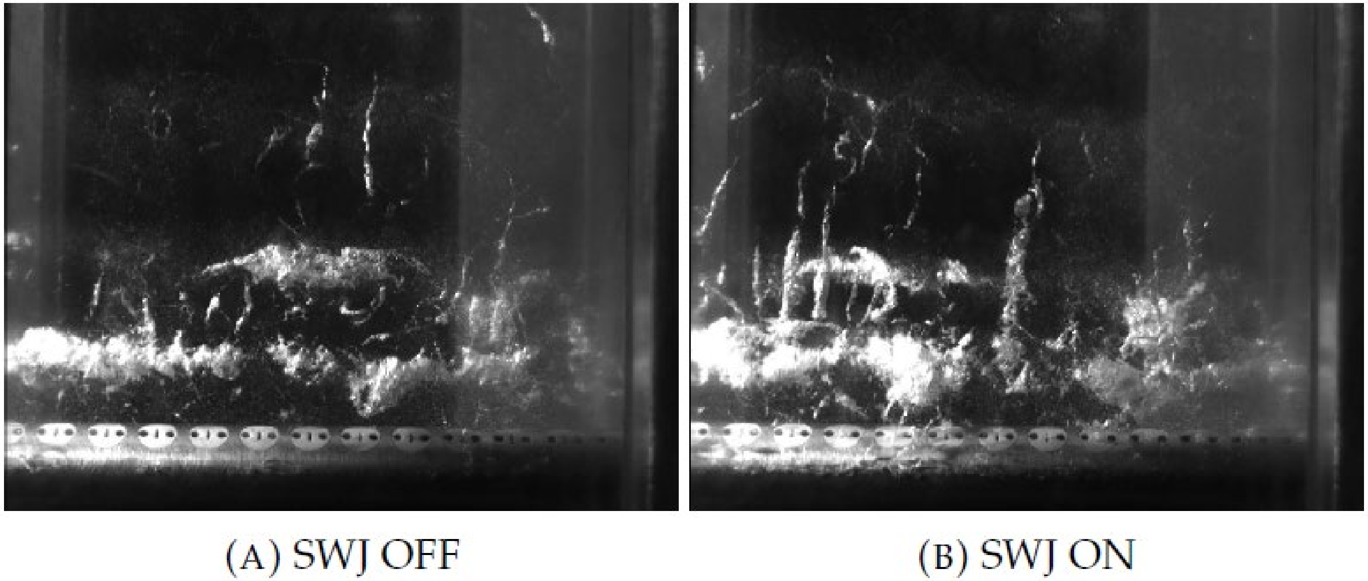
FIGURE 4.8: Cavitating wake vortex $\alpha = 180°, V_\infty = 6.5$ m/s, $\sigma = 3.52$

Vortex Induced Vibration: Flow Control

Flow Control: Sweeping Jet

Application: Mitigation of vortex induced vibration on a cylinder in EPFL Cavitation tunnel (Master projects E. Boutillon 2017, J. Gildas, 2019)

- ***Main Results:***
  - ***Sweeping jets at 145° : Almost no effect of SJ on wake instability***
  - ***Similar cavitating vortices***


(A) SWJ OFF

(B) SWJ ON

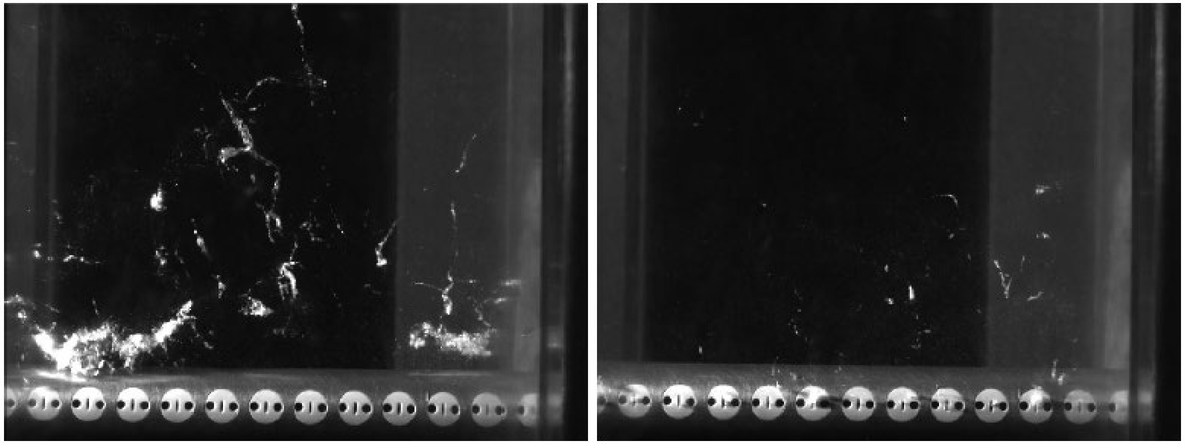
FIGURE 4.9: Cavitating wake vortex $\alpha = 145°, V_\infty = 8.5$ m/s, $\sigma = 1.95$

Vortex Induced Vibration: Flow Control

Flow Control: Sweeping Jet

Application: Mitigation of vortex induced vibration on a cylinder in EPFL Cavitation tunnel (Master projects E. Boutillon 2017, J. Gildas, 2019)

- *Main Results:*
  - *Sweeping jets at 80° :*
    - *Less cavitation within traveling vortices*
    - *Slight reduction of flow induced vibration*



(A) SWJ OFF (B) SWJ ON

FIGURE 4.11: Cavitating wake vortex $\alpha = 80°, V_\infty = 6.1\ \text{m/s}, \sigma = 2.9$

Main conclusion: No significant benefit of using SJ's in the case of a cylinder

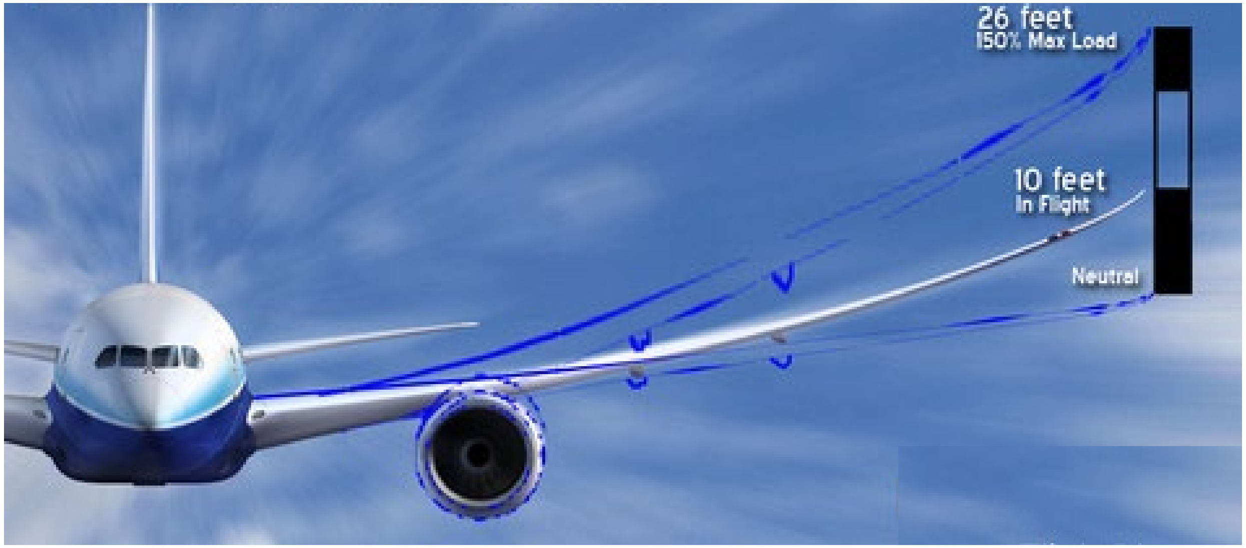
Vortex Induced Vibration: Flow Control

Flow Control: Adaptive Blades

- ***Composite materials:***
  - *Tailored response of a blade by manipulating the fiber orientation within the material matrix*

    → *Offers an additional degree of freedom to designers:*

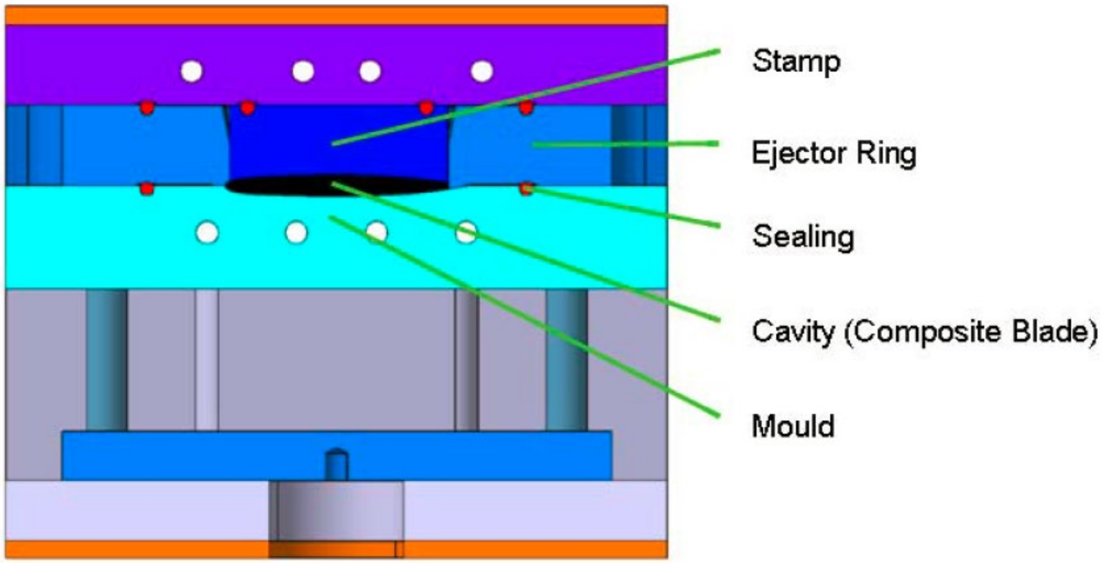
    Use the flexibility of a blade to optimize the performances
  - *Example: Boeing 787 Dreamliner*



Vortex Induced Vibration: Flow Control

Flow Control: Adaptive Blades

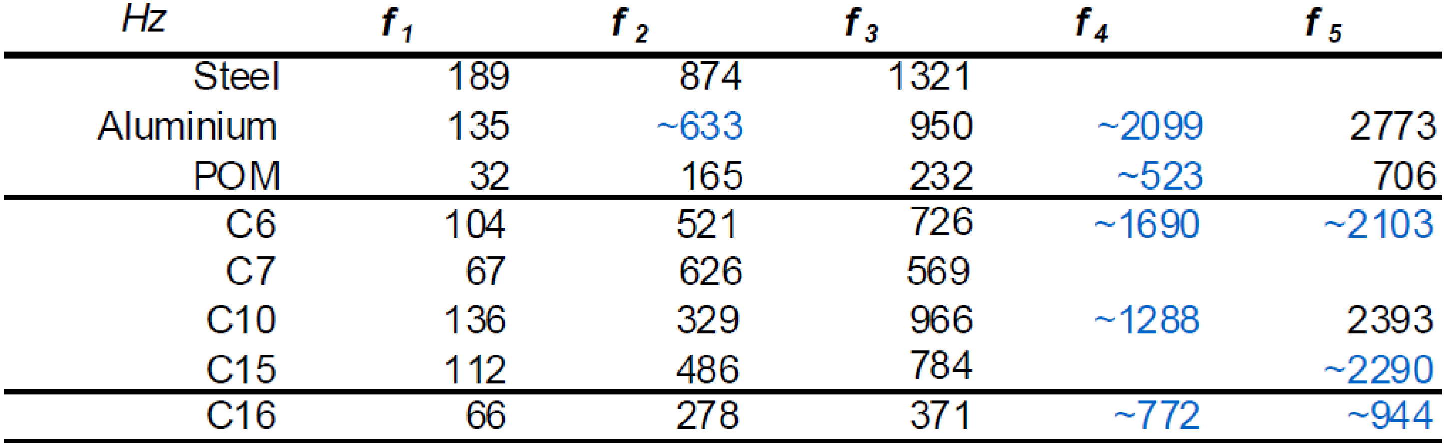
- ***Tailored response of composite materials:***
  - *Possibility to tune the resonance frequencies for a given blade shape*
  - *Example : Naca 0009 hydrofoil*



Flow Control: Adaptive Blades

- ***Tailored response of composite materials:***
    - *Possibility to tune the resonance frequencies for a given blade shape*
    - *Example : Naca 0009 hydrofoil*

Table 5 - Measured natural frequencies in water (blue values were identified in flowing water)



Hz	***f*** $_1$	***f*** $_2$	***f*** $_3$	***f*** $_4$	***f*** $_5$
Steel	189	874	1321		
Aluminium	135	~633	950	~2099	2773
POM	32	165	232	~523	706
C6	104	521	726	~1690	~2103
C7	67	626	569		
C10	136	329	966	~1288	2393
C15	112	486	784		~2290
C16	66	278	371	~772	~944

Vortex Induced Vibration: Flow Control

Flow Control: Adaptive Blades

- ***Tailored response of composite materials:***
    - *Generated a lot of hope ~20 years ago*
        - *A large amount of research was produced*
        - *Still not yet broadly adopted*
            - *A famous example: Flexible wings of Boeing Dreamliner*
            - *Attempts in marine propulsion, still limited*

Vortex Induced Vibration: Flow Control

ANNUAL REVIEWS

Annual Review of Fluid Mechanics

Aeroacoustics of Silent Owl Flight

Justin W. Jaworski[1] and N. Peake[2]

[1]Department of Mechanical Engineering and Mechanics, Lehigh University, Bethlehem, Pennsylvania 18015, USA; email: jaworski@lehigh.edu

[2]Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge CB3 0WA, United Kingdom; email: n.peake@damtp.cam.ac.uk

Annu. Rev. Fluid Mech. 2020. 52:395–420

First published as a Review in Advance on August 28, 2019

The *Annual Review of Fluid Mechanics* is online at fluid.annualreviews.org

https://doi.org/10.1146/annurev-fluid-010518-040436

Keywords

aeroacoustics, silent flight, noise generation, owl morphology

Abstract

The ability of some species of owl to fly in effective silence is unique among birds and provides a distinct hunting advantage, but it remains a mystery as to exactly what aspects of the owl and its flight are responsible for this dramatic noise reduction. Crucially, this mystery extends to how the flow physics may be leveraged to generate noise-reduction strategies for wider technological application. We review current knowledge of aerodynamic noise from owls, ranging from live owl noise measurements to mathematical modeling and experiments focused on how owls may disrupt the standard routes of noise generation. Specialized adaptations and foraging strategies are not uniform across all owl species: Some species may not have need for silent flight, or their evolutionary adaptations may not be effective for useful noise reduction for certain species. This hypothesis is examined using mathematical models and borne out where possible by noise measurements and morphological observations of owl feathers and wings.

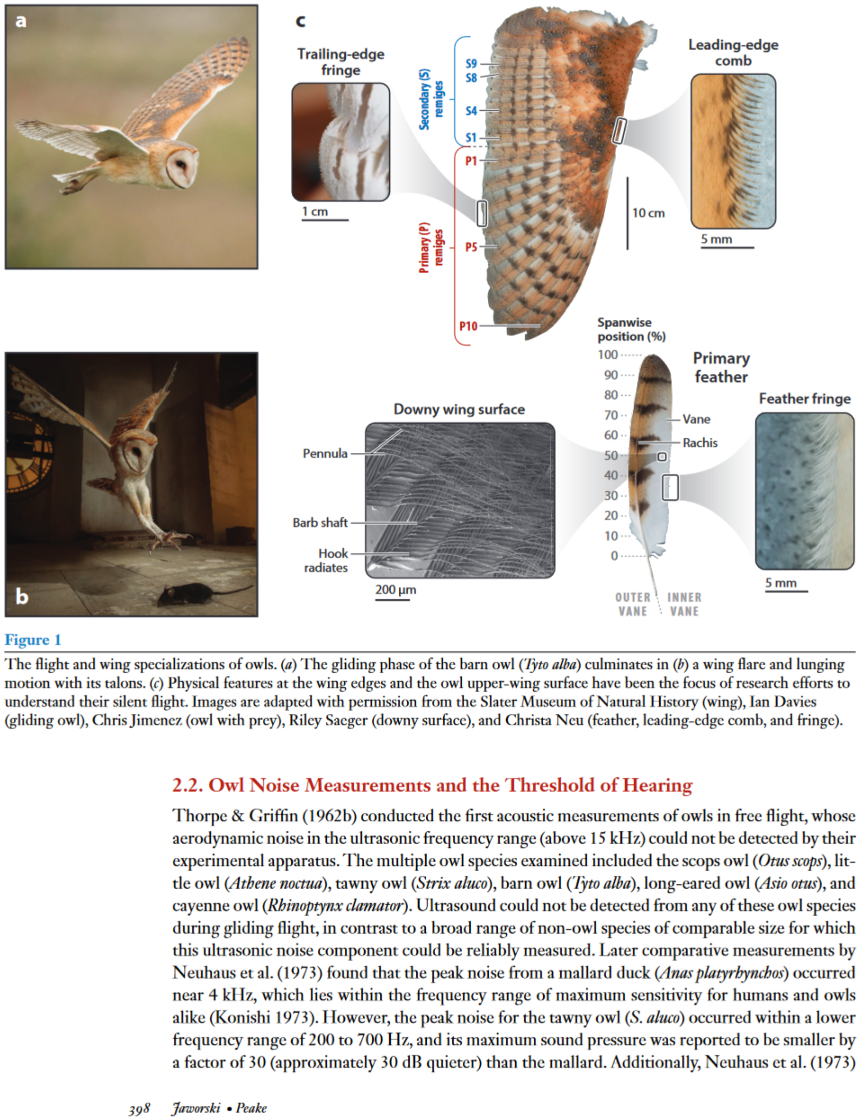


Figure 1

The flight and wing specializations of owls. (*a*) The gliding phase of the barn owl (*Tyto alba*) culminates in (*b*) a wing flare and lunging motion with its talons. (*c*) Physical features at the wing edges and the owl upper-wing surface have been the focus of research efforts to understand their silent flight. Images are adapted with permission from the Slater Museum of Natural History (wing), Ian Davies (gliding owl), Chris Jimenez (owl with prey), Riley Saeger (downy surface), and Christa Neu (feather, leading-edge comb, and fringe).

2.2. Owl Noise Measurements and the Threshold of Hearing

Thorpe & Griffin (1962b) conducted the first acoustic measurements of owls in free flight, whose aerodynamic noise in the ultrasonic frequency range (above 15 kHz) could not be detected by their experimental apparatus. The multiple owl species examined included the scops owl (*Otus scops*), little owl (*Athene noctua*), tawny owl (*Strix aluco*), barn owl (*Tyto alba*), long-eared owl (*Asio otus*), and cayenne owl (*Rhinoptynx clamator*). Ultrasound could not be detected from any of these owl species during gliding flight, in contrast to a broad range of non-owl species of comparable size for which this ultrasonic noise component could be reliably measured. Later comparative measurements by Neuhaus et al. (1973) found that the peak noise from a mallard duck (*Anas platyrhynchos*) occurred near 4 kHz, which lies within the frequency range of maximum sensitivity for humans and owls alike (Konishi 1973). However, the peak noise for the tawny owl (*S. aluco*) occurred within a lower frequency range of 200 to 700 Hz, and its maximum sound pressure was reported to be smaller by a factor of 30 (approximately 30 dB quieter) than the mallard. Additionally, Neuhaus et al. (1973)