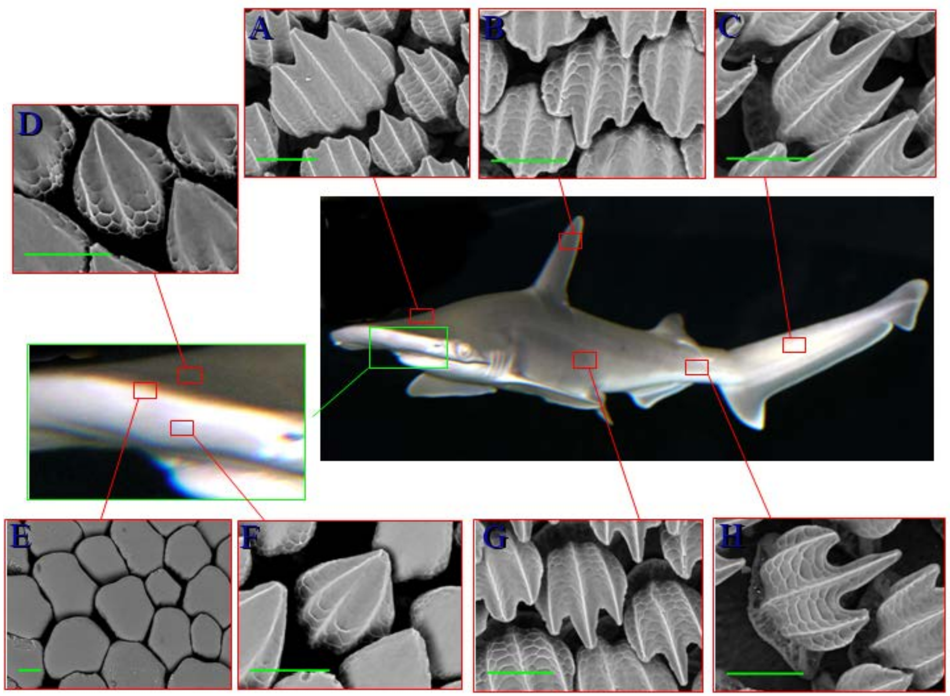
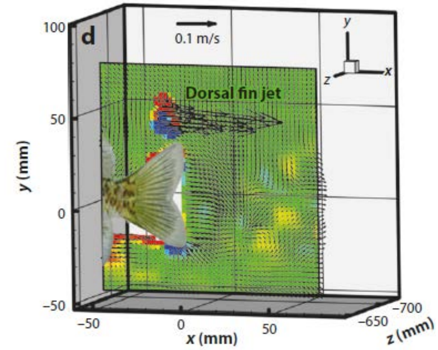
Biomimetics and Fish Hydrodynamics

Johannes Oeffner, Fraunhofer Center for Maritime Logistics and Services CML - Hamburg

Seminar held at INSEAN - Rome, 3rd December 2015





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Biomimetics - Introduction

Biomimetics (Bionics, Biomimicry, Bio-inspiration)

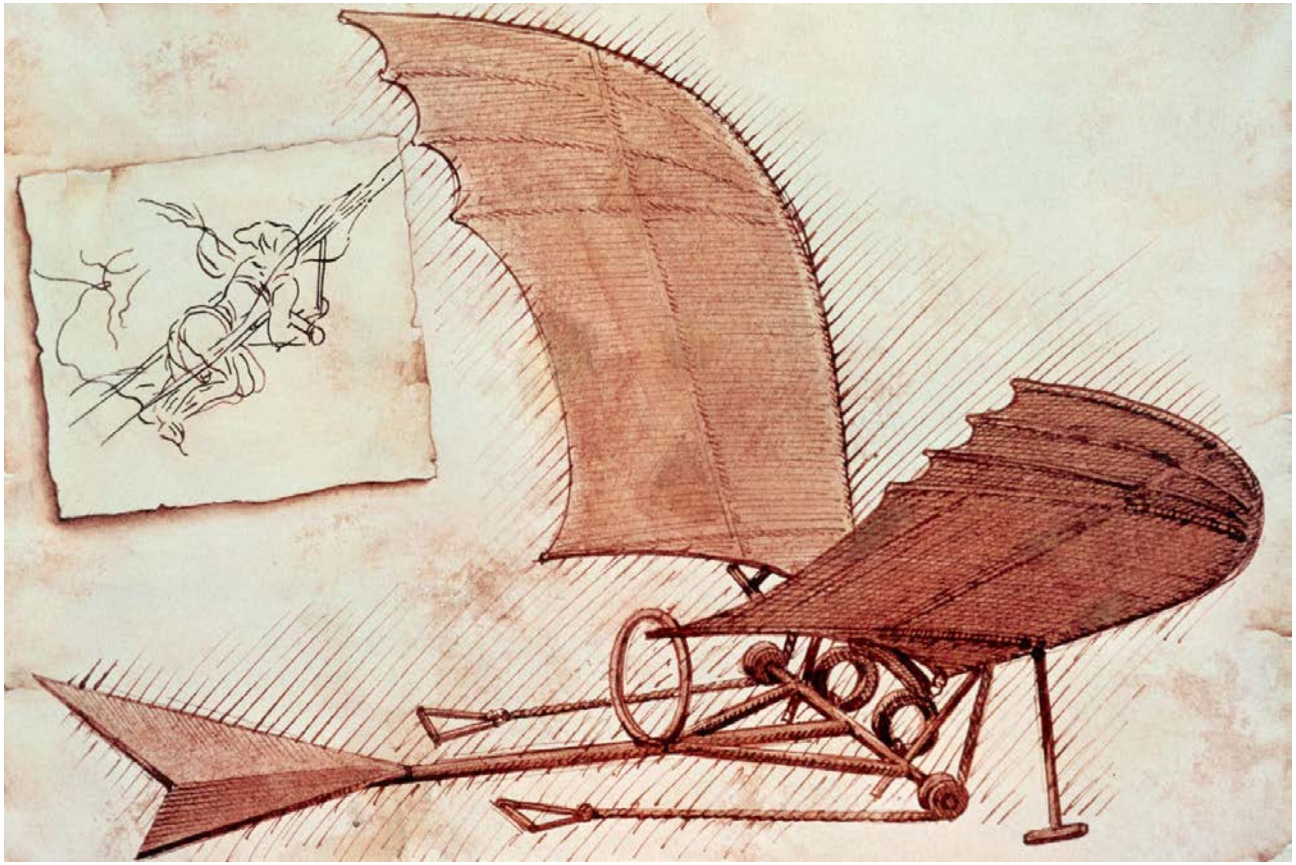
- Systematic investigation of biological models and the transfer to innovative technical applications

- Not just copying nature, but understanding underlying processes!

- Interface of Biology and Engineering

- Application range: Engineering, Material Science, Architecture, Robotics, Artificial Intelligence, Medicine, Mechanical Design, Fluid Dynamics

Biomimetics - Introduction



- **Leonardo Da Vinci, 1452-1519**
- Developed a concept for a flying machine applied from the study of birds and bats flight

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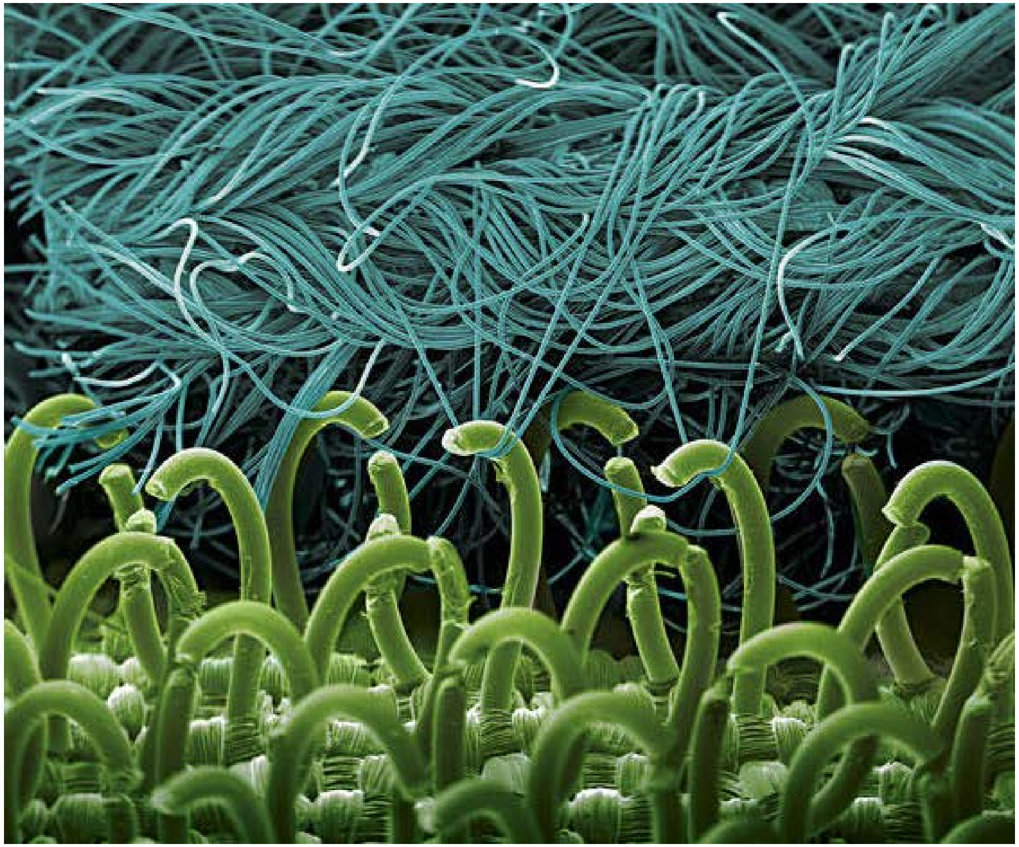
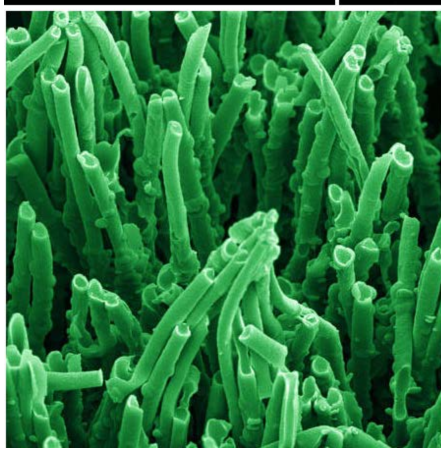
Biomimetics - Examples

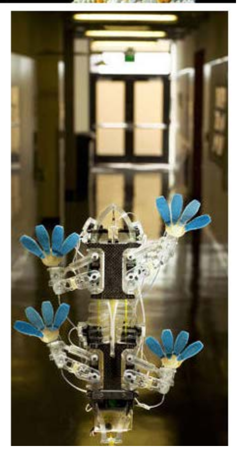
Velcro, George de Mestral, 1948



Biomimetics - Examples

Gecko feet → Adhesion without glue





Principle: 6.5 million setae bind to substrate via van der Waals force → sum of little forces = Adhesion

Lotus effect →Self cleaning

Principle: microstructure and wax layer → non-sticky for water → dirt is washed away

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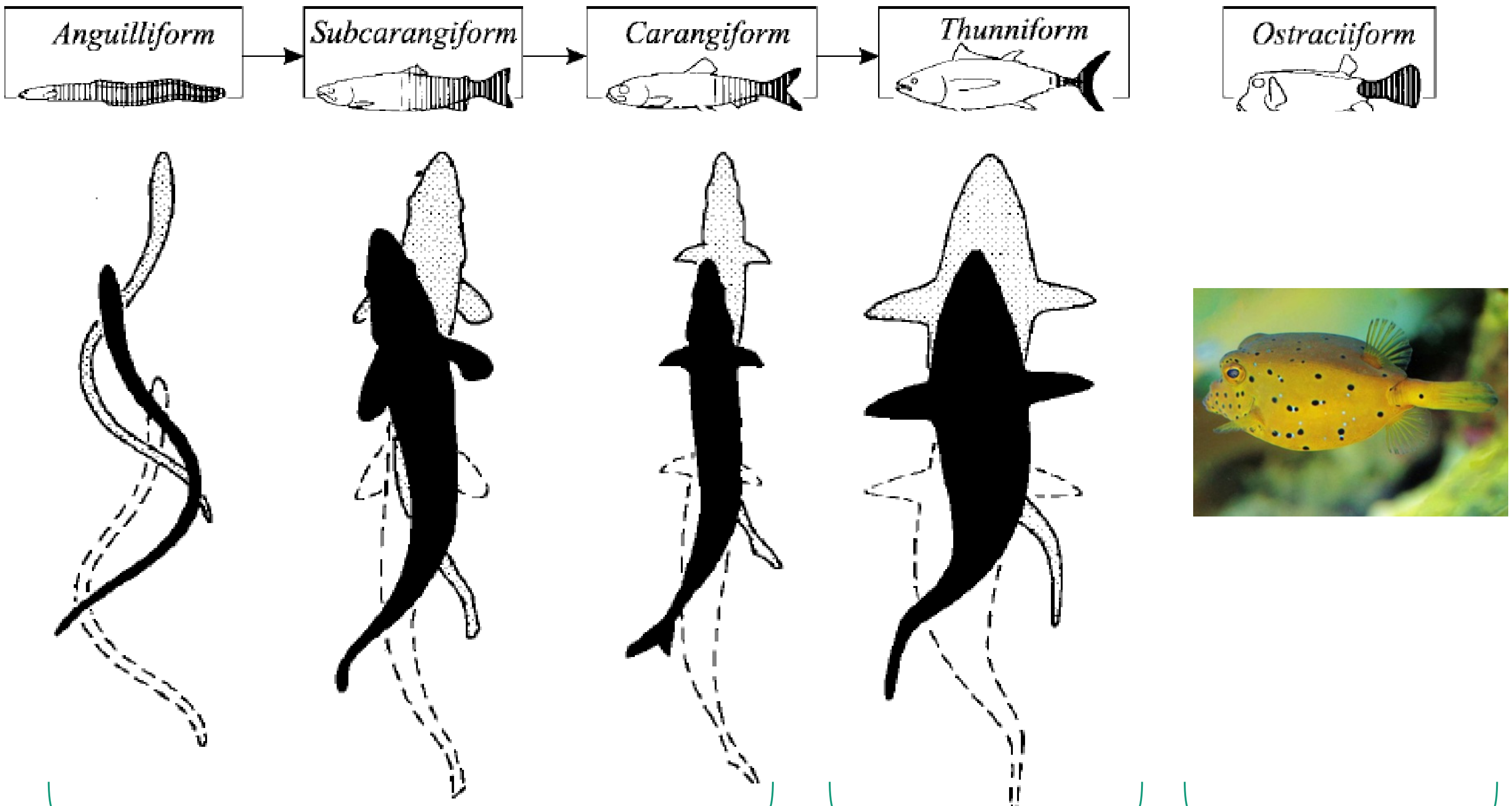
Fish Hydrodynamics – Swimming Modes



Truly undulatory
→thrust contributions of good part of the body

Undulatory with
hydrofoil function
of tailfin

Oscillatory,
thrust from
(tail) fins only

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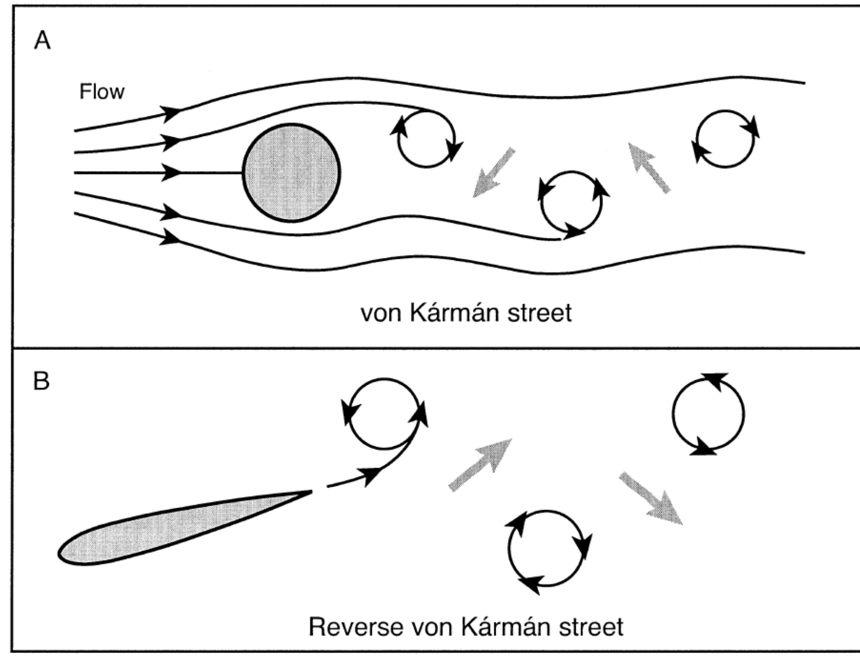
Fish Hydrodynamics – Propulsion by Body and Tail

- Principle



Drucker and Lauder (2002): Experimental hydrodynamics of fish locomotion: functional insights from wake visualization. In *Integrative and Comparative Biology.*

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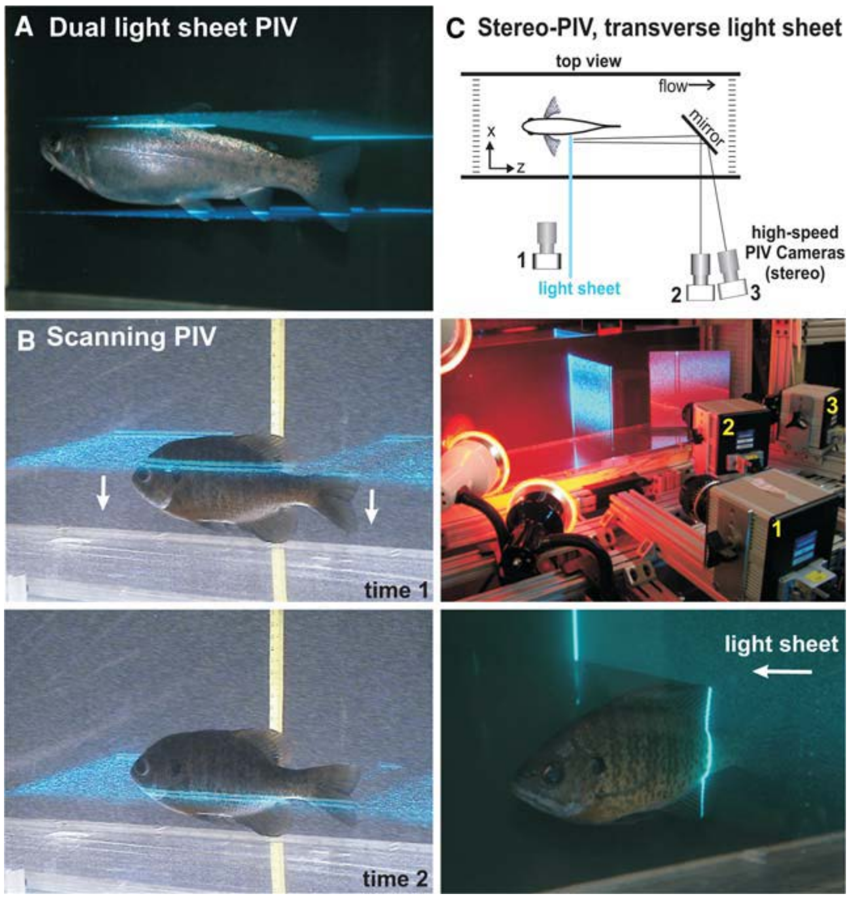
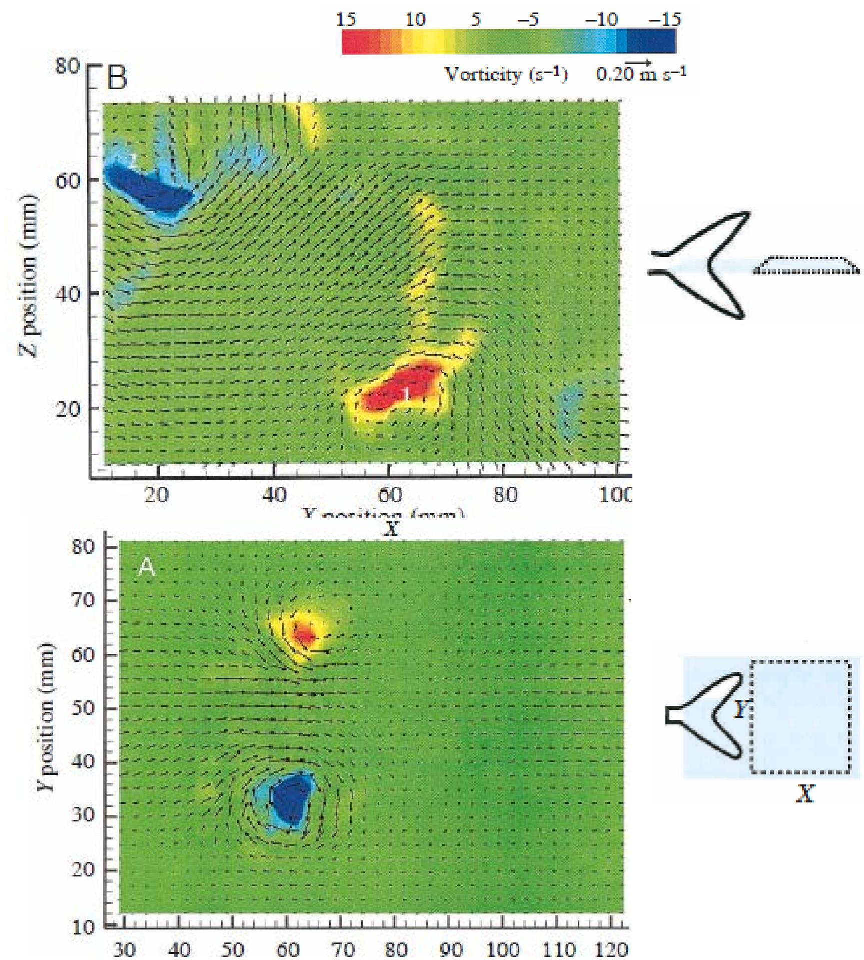
Fish Hydrodynamics – Propulsion by Body and Tail

➢ Flow Visualization



Lauder and Madden (2007): Fish locomotion: kinematics and hydrodynamics of flexible foil-like fins. In *Experiments in Fluids.*



Nauen and Lauder (2002): Hydrodynamics of caudal fin locomotion by chub mackerel, Scomber japonicus (Scombridae). In *Journal of Experimental Biology*

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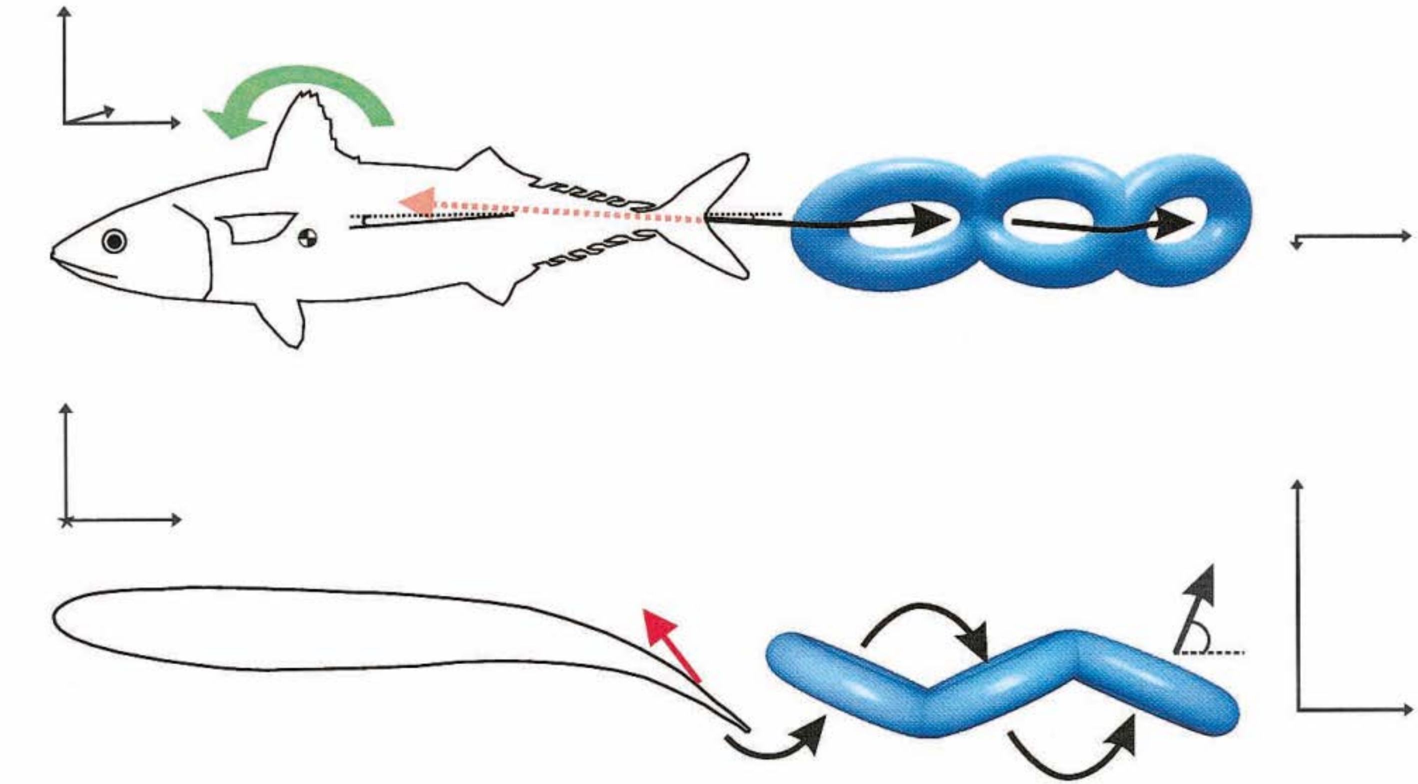
Fish Hydrodynamics – Propulsion by Body and Tail

- Model



Nauen and Lauder (2002): Hydrodynamics of caudal fin locomotion by chub mackerel, Scomber japonicus (Scombridae). In *Journal of Experimental Biology*

- most fish tails function as a distinct propeller
- series of linked elliptical vortex rings, each with central momentum jet flow → thrust !

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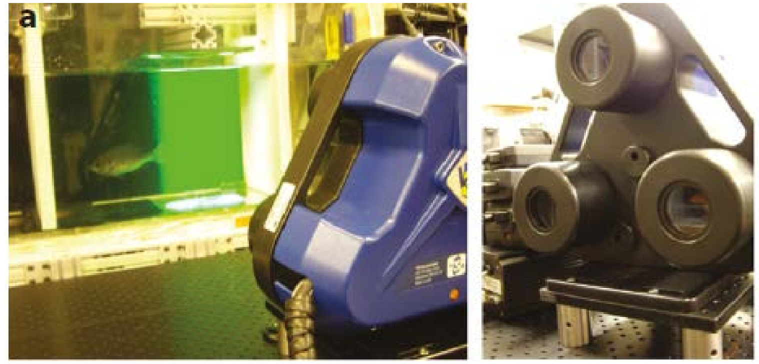
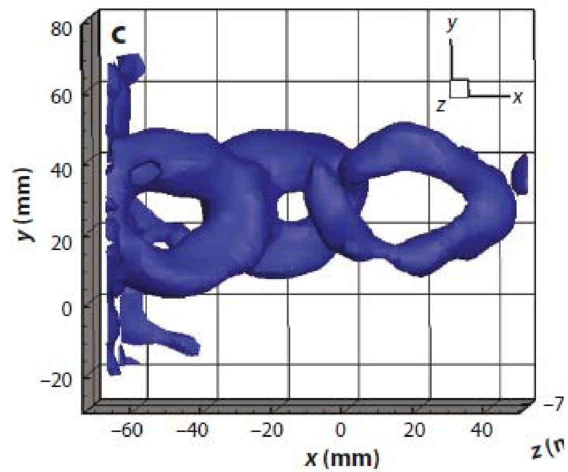
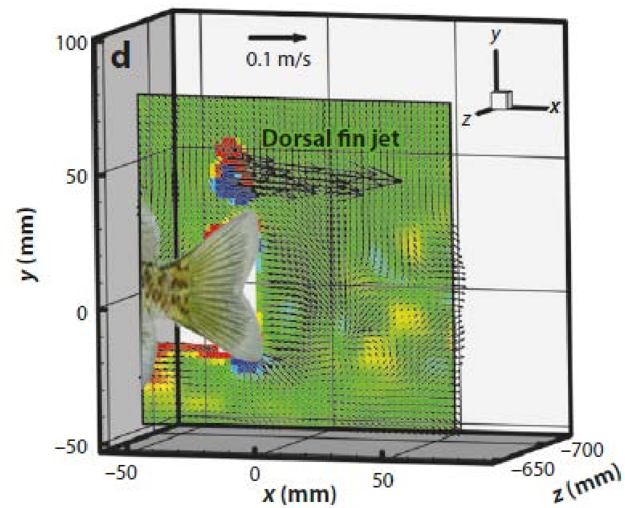
Fish Hydrodynamics – Propulsion by Body and Tail

- Proof of Model
- Volumetric (3D) PIV



Flammang, et al. (2011): Volumetric imaging of fish locomotion. In *Biology letters.*

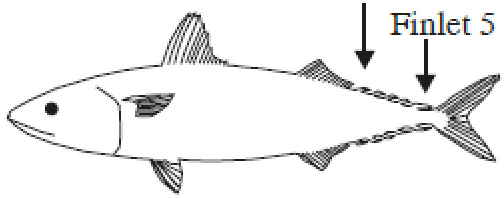


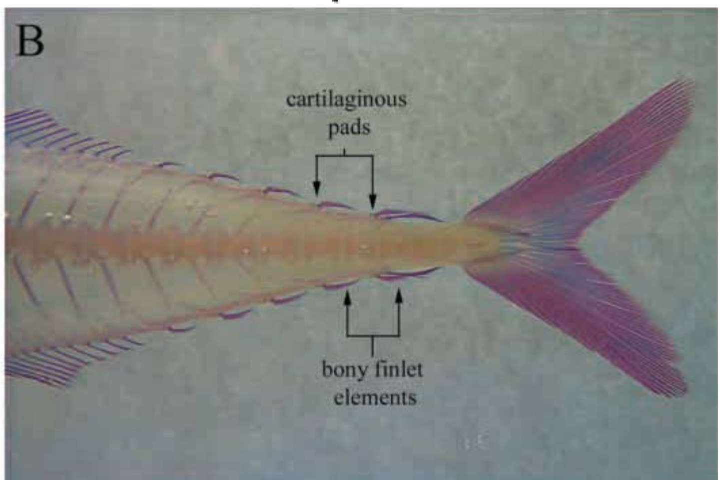


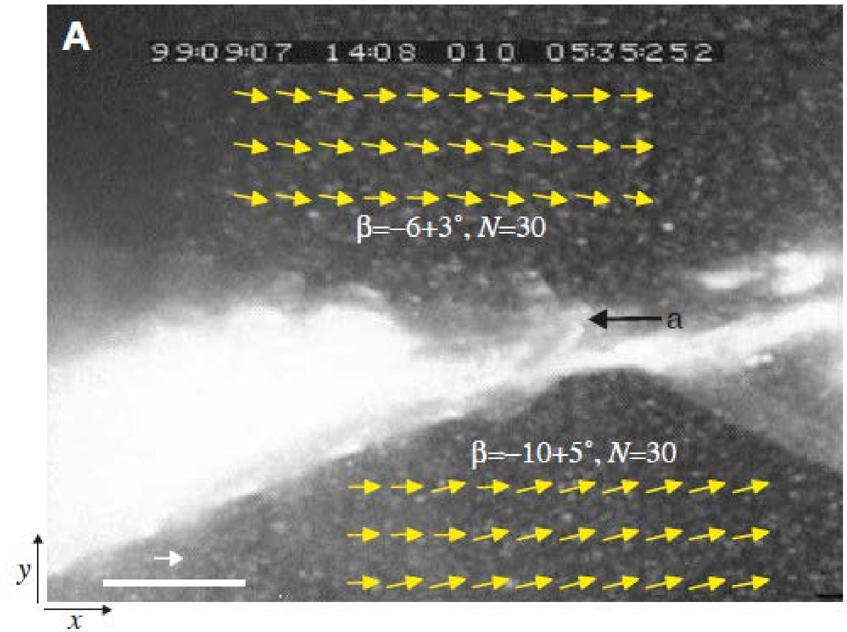
- 3D structure of the linked-chain pattern of vortex rings shed by the tail
- strong wake flows shed by the dorsal and anal fins interact with tail (caudal) fin flows

Fish Hydrodynamics – Propulsion by Body and Tail

- Finlets





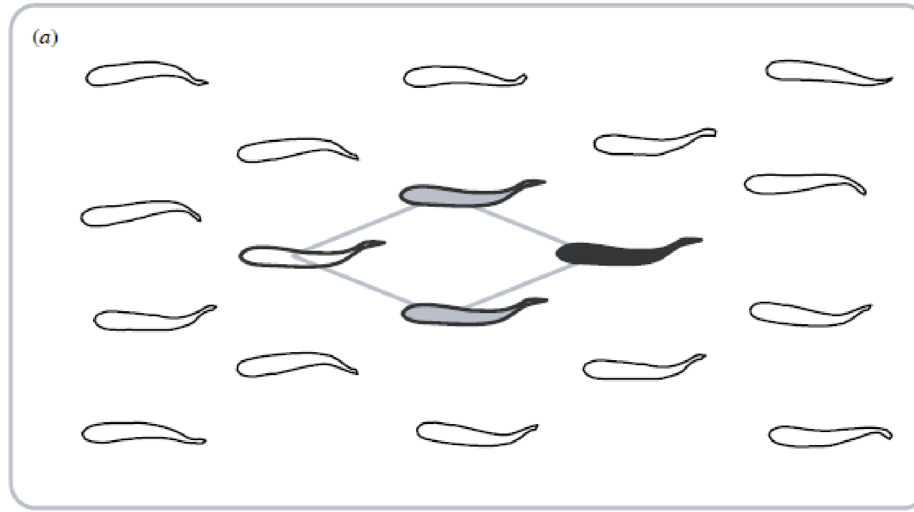


Nauen and Lauder (2001): Locomotion in scombrid fishes: visualization of flow around the caudal peduncle and finlets of the chub mackerel Scomber japonicus. In *Journal of Experimental Biology*.
Nauen and Lauder (2002): Hydrodynamics of caudal fin locomotion by chub mackerel, Scomber japonicus (Scombridae). In *Journal of Experimental Biology*.

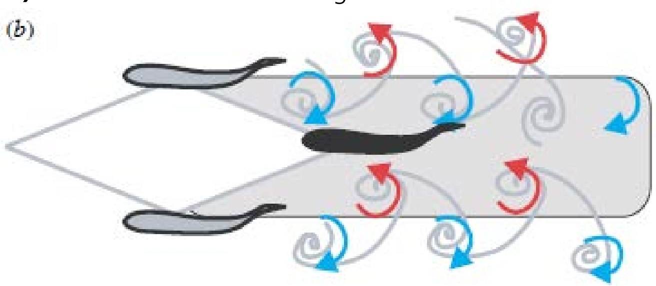
- hydrodynamic effect on local flow during steady swimming
- Vortex generators: to delay boundary layer separation → drag reduction!

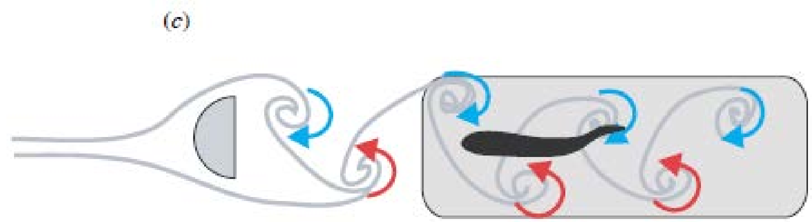
Fish Hydrodynamics – Propulsion by Body and Tail

- Fish Swarms



Liao (2007): A review of fish swimming mechanics and behaviour in altered flows. In *Philosophical Transactions of the Royal Society B: Biological Sciences.*





- Diamond shape swarm formation benefits individual hydrodynamics
  - swimming in reduced relative flow
  - harnessing the energy of vortices

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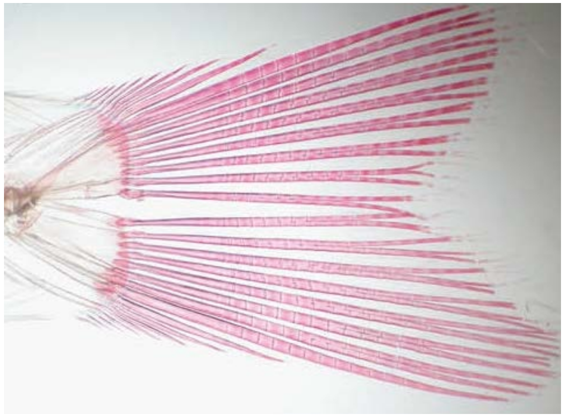
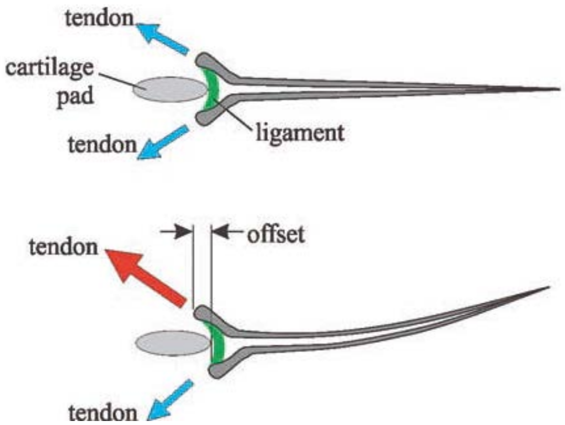
Fish Hydrodynamics – Propulsion by Fish Fins

➢ Morphology





Alben, et al. (2007): The mechanics of active fin-shape control in ray-finned fishes. In *Journal of The Royal Society Interface.*

→ Base Muscles allows sliding motion actively bend each fin ray and control the surface shape

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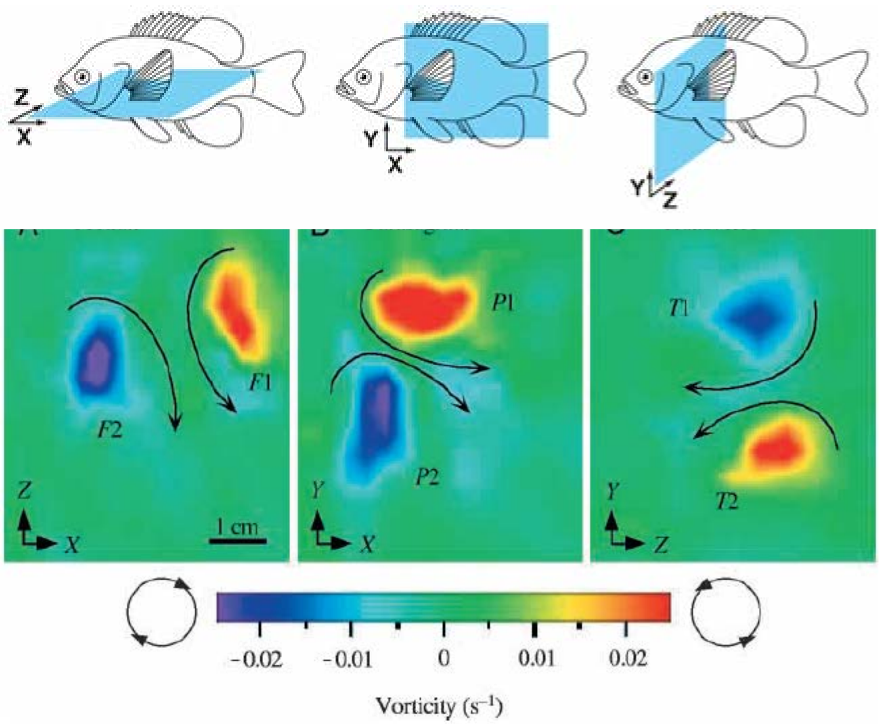
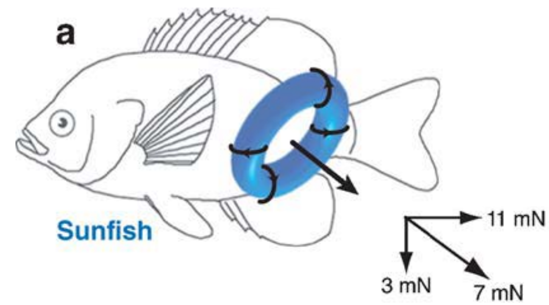
Fish Hydrodynamics – Propulsion by Fish Fins

➢ Model





Drucker and Lauder (1999): Locomotor forces on a swimming fish: three-dimensional vortex wake dynamics quantified using digital particle image velocimetry. In *Journal of Experimental Biology.*

- ➢ each fin-beat cycle → formation of a single vortex
- ➢ at low speeds only pectoral fin
- ➢ at higher speeds added tail, dorsal & anal fin and linked vortex chain

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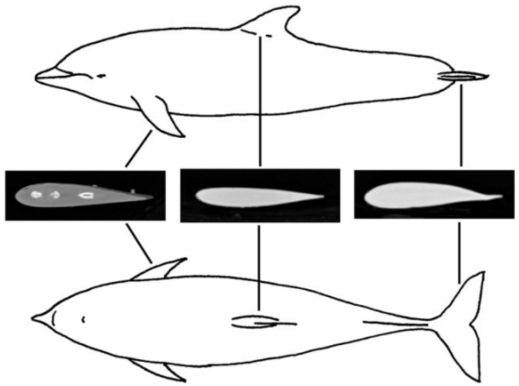
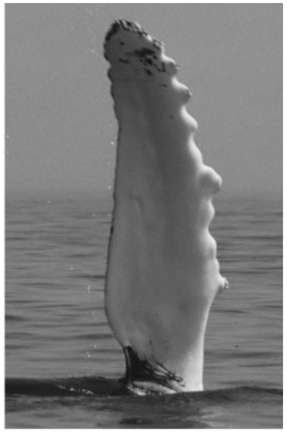
Flow Control – Introduction

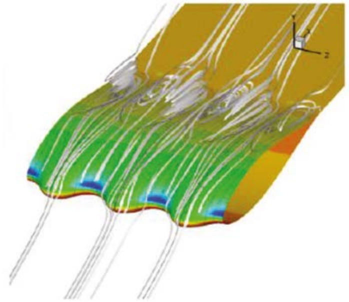
➢ Streamlining



Fish, et al. (2008): Hydrodynamic flow control in marine mammals. In *Integrative and Comparative Biology.*

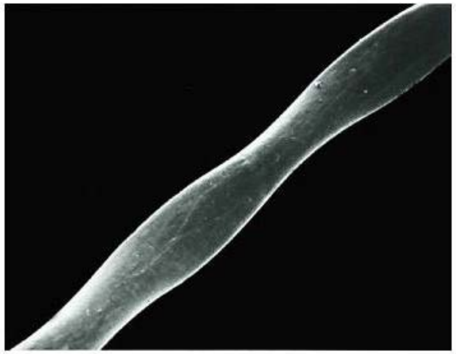
➢ Humback Whale Tubercles



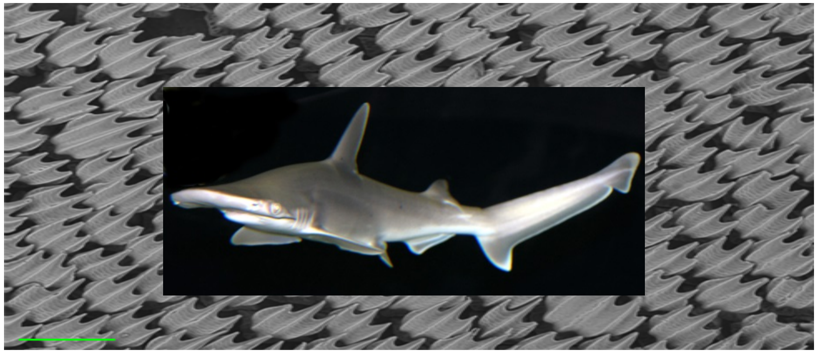


Fish, et al. (2008): Hydrodynamic flow control in marine mammals. In *Integrative and Comparative Biology.*

➢ Seal Whiskers



➢ Shark Skin



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Flow Control – Flow Sensing With Seal Whiskers

Hanke, Oeffner, et al. (2010): Harbor seal vibrissa morphology suppresses vortex-induced vibrations. In *Journal of Experimental Biology.*
Miersch, Oeffner, et al. (2011): Flow sensing by pinniped whiskers. In *Philosophical Transactions of the Royal Society B: Biological Sciences.*

- Detect hydrodynamic wake with isolated vibrissae?
- Difference between sea lion and seal? Why has seal special shape?

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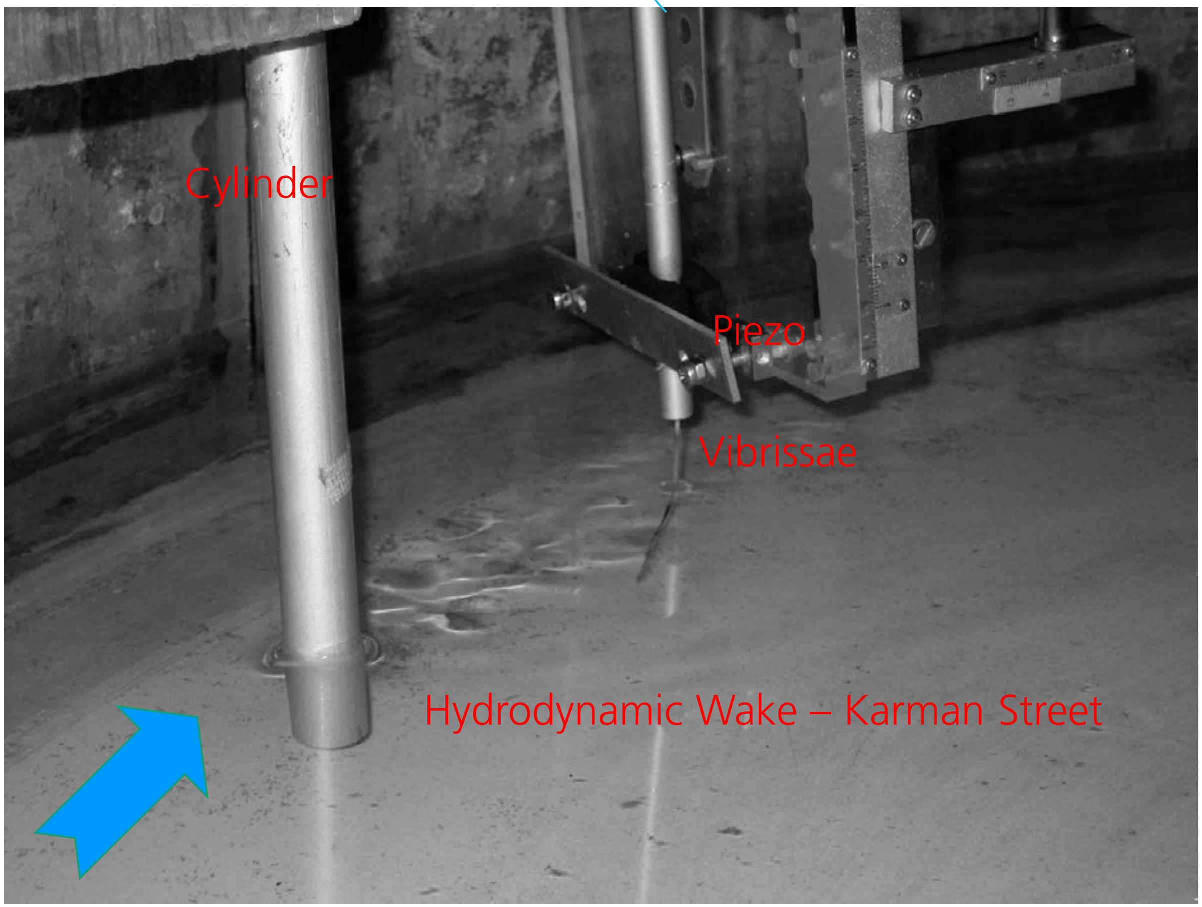
Flow Control – Flow Sensing With Seal Whiskers

- Setup



- Measure frequency of Karman Street
- Compare to calculated Frequency
- Determine SNR
- Compare seals and sea lions vibrissae

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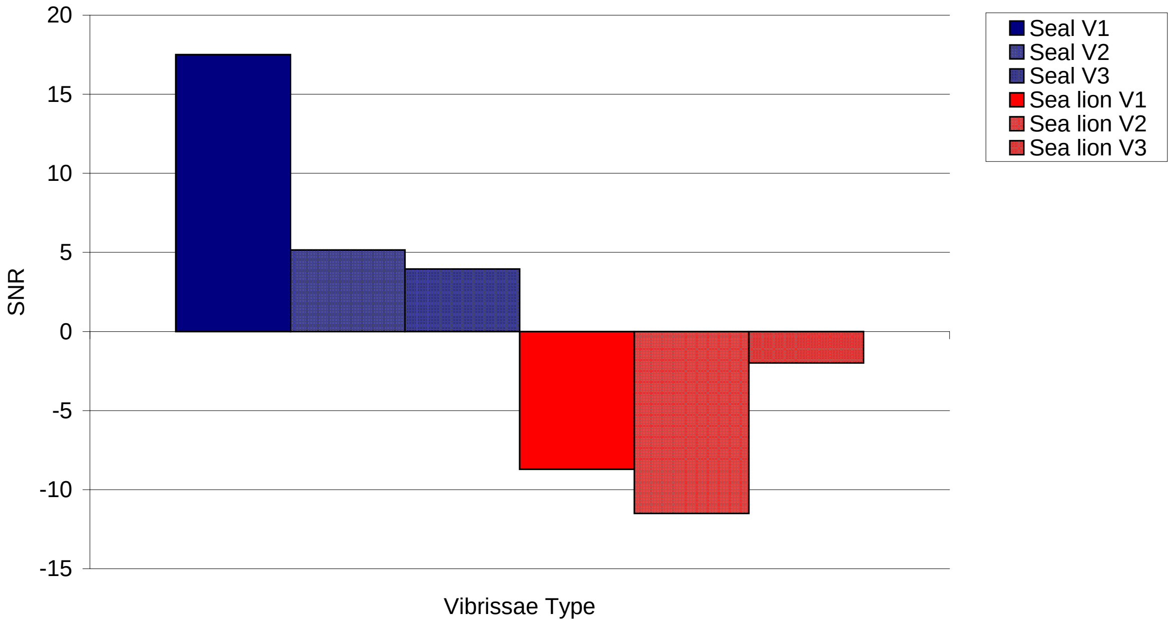
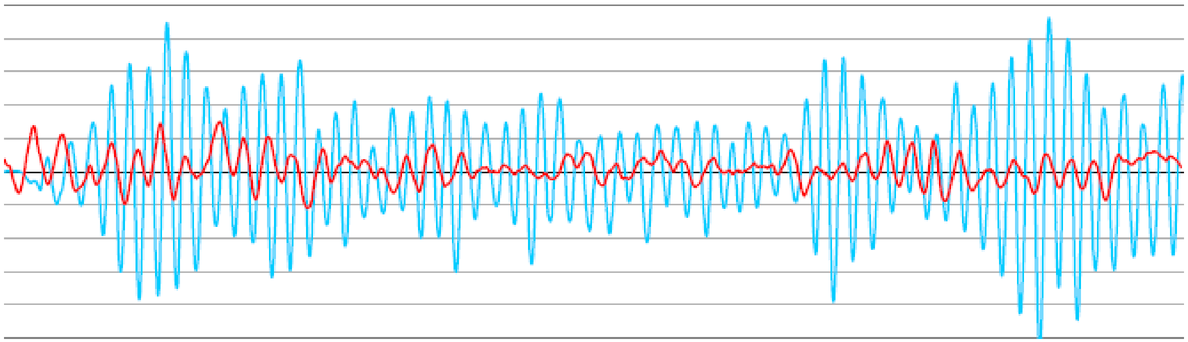
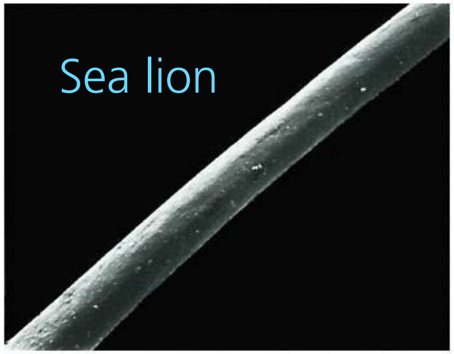
Flow Control – Flow Sensing With Seal Whiskers

- Results







- High noise (self-oscillation)

- Low noise (self-oscillation)
- Reduces vibration
- Also reduces drag?

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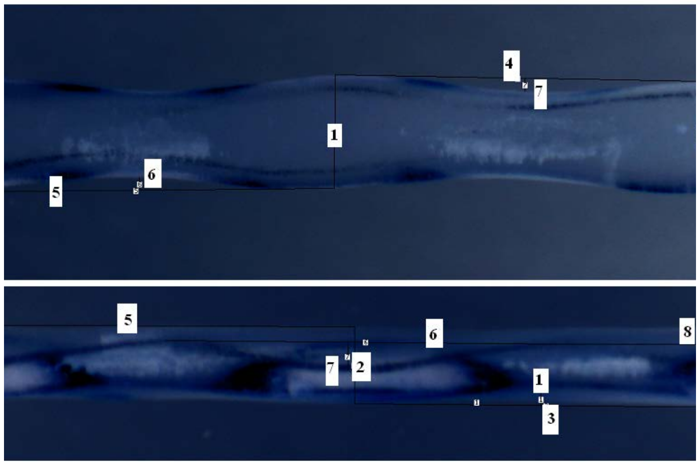
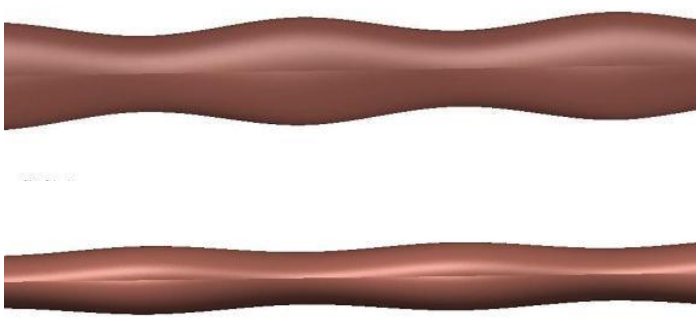
Flow Control – Flow Sensing With Seal Whiskers

- CFD

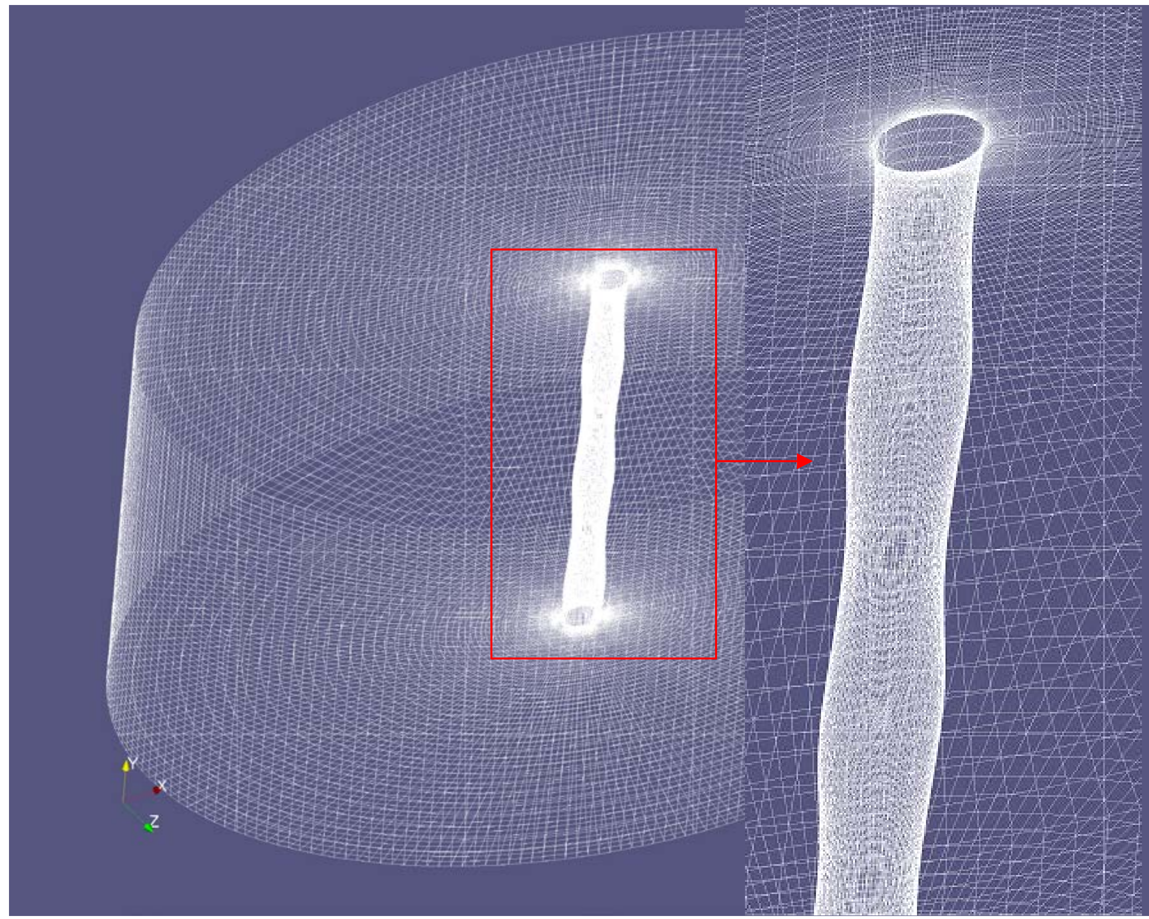
1) Microscopy Images



2) Transfer to CAD Model



3) CFD Mesh



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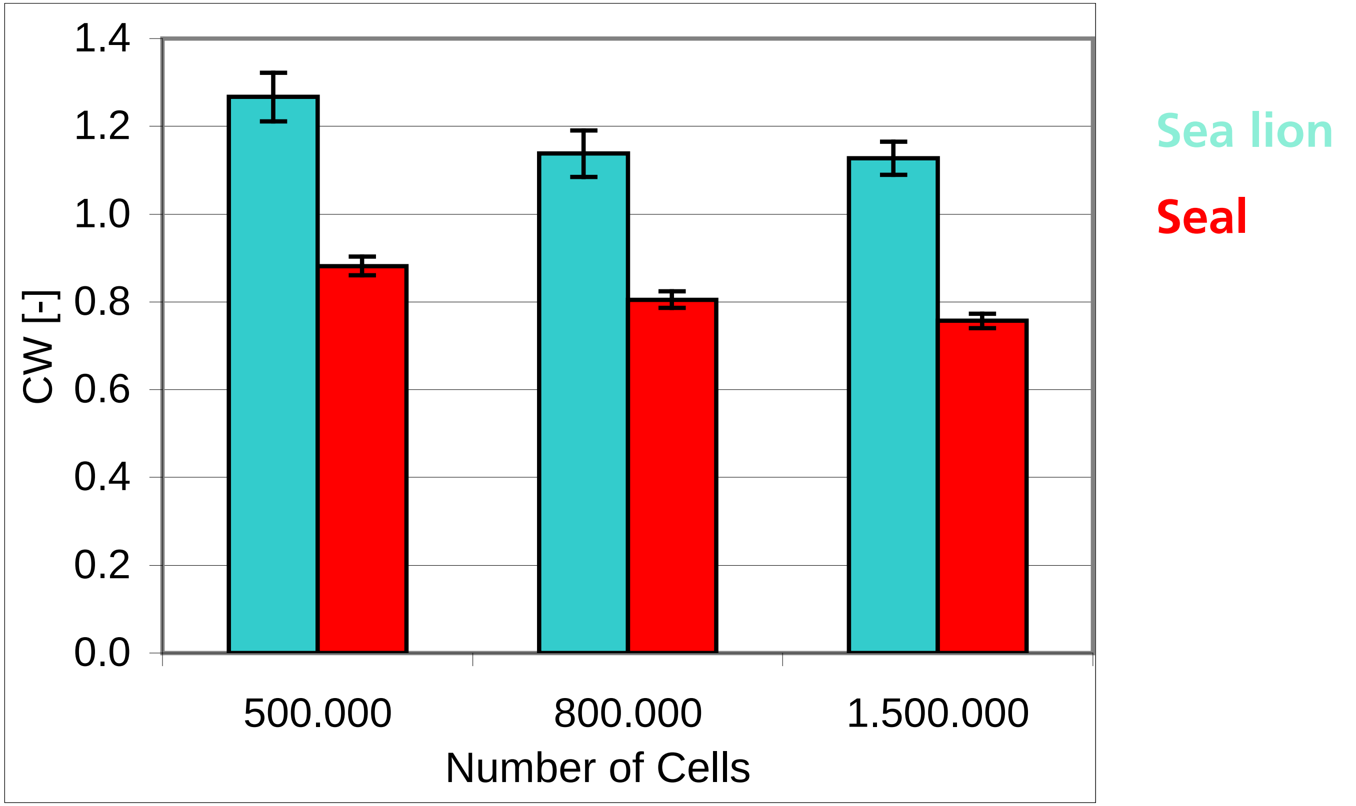
Flow Control – Flow Sensing With Seal Whiskers

- Results – Drag Coefficient



- C_D Seal about 30% reduced
- Undulated Structure minimizes drag!

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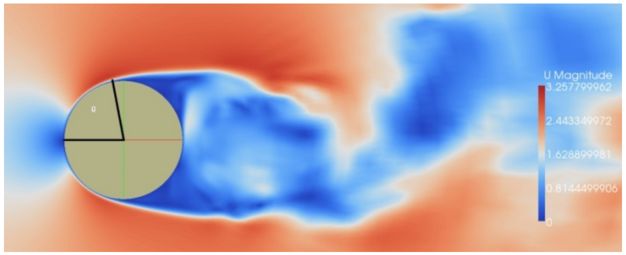
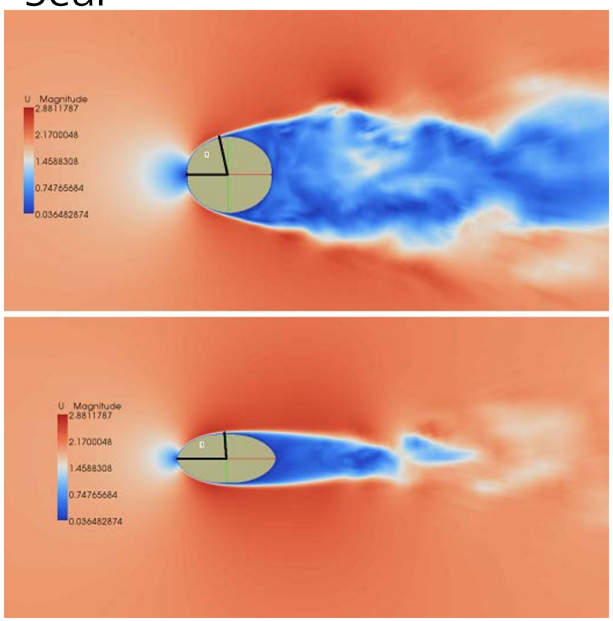
Flow Control – Flow Sensing With Seal Whiskers

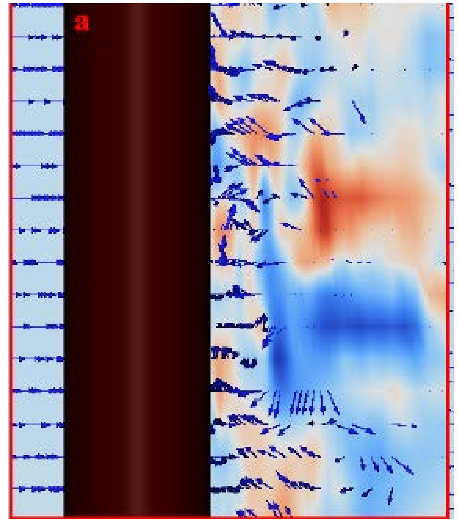
- **Results – Flow Visualizations**

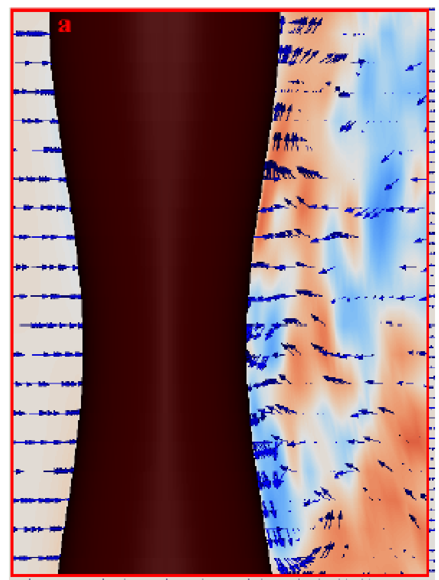
Sea lion



Seal







- trailing wake in average smaller, no periodical shedding
- reduced vortex-induced vibration (self-oscillation)
- reduced drag

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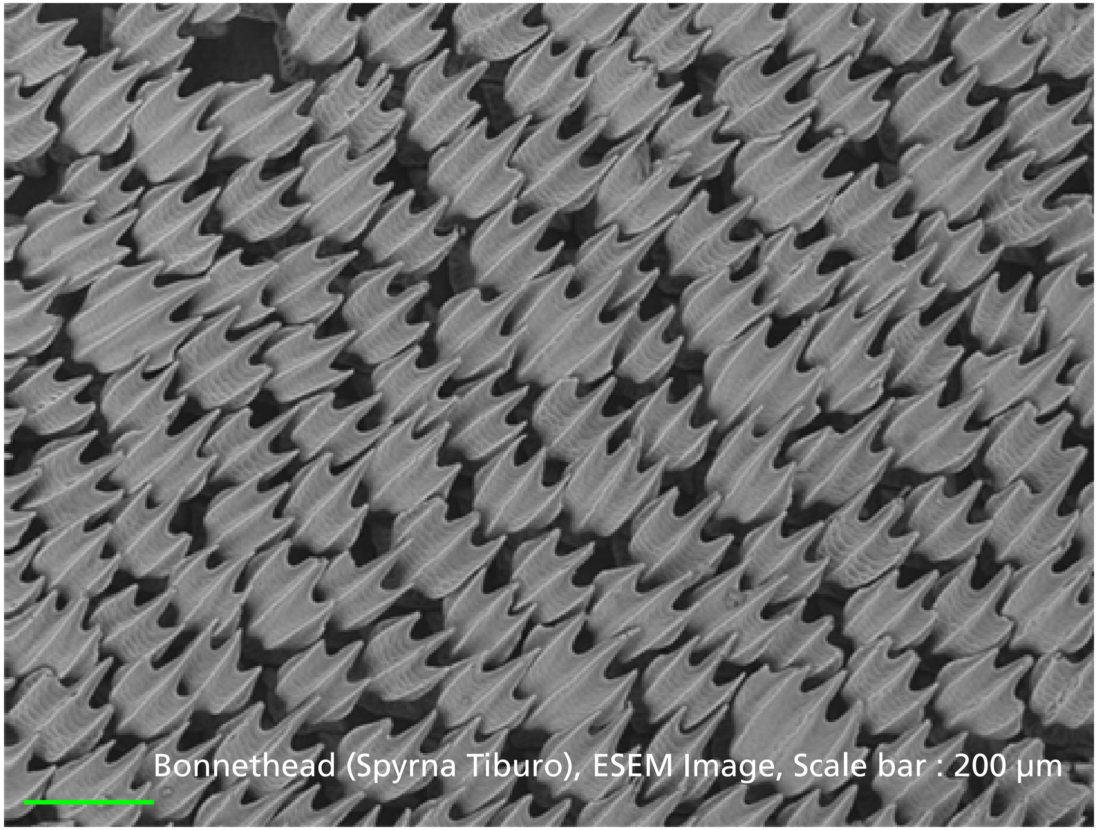
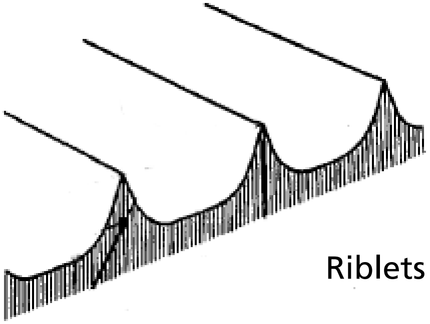
Flow Control – Hydrodynamic Function of Shark Skin

Oeffner and Lauder (2012): The hydrodynamic function of shark skin and two biomimetic applications. In *The Journal of Experimental Biology*.

Shark Skin


Bonnethead (Spyrna Tiburo), ESEM Image, Scale bar : 200 µm

Biomimetic products


Riblets

Speedo Swimsuit FS II

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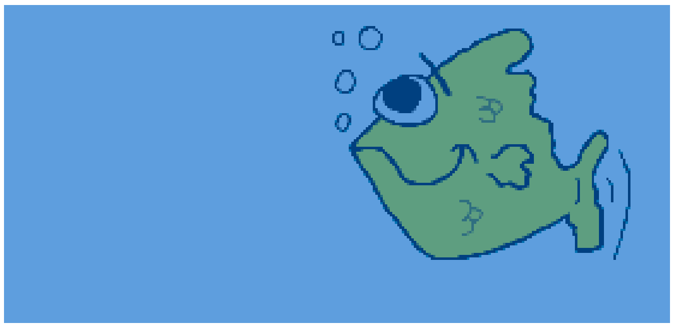
Flow Control – Hydrodynamic Function of Shark Skin

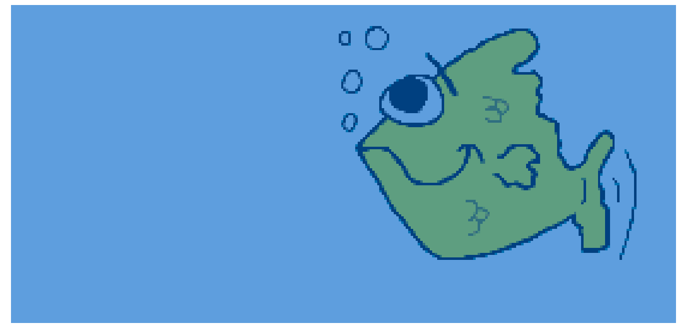
- **Two types of drag**

Rigid object



- glides through water without changing shape and speed
  - e.g. gliding shark
  - e.g. aircraft/ship with riblets
- **Static Drag**

Moving object



- moves through water and is constantly changing shape and speed
  - e.g. swimming shark
  - e.g. swimming human (wearing swimsuit)
- **Dynamic Drag**

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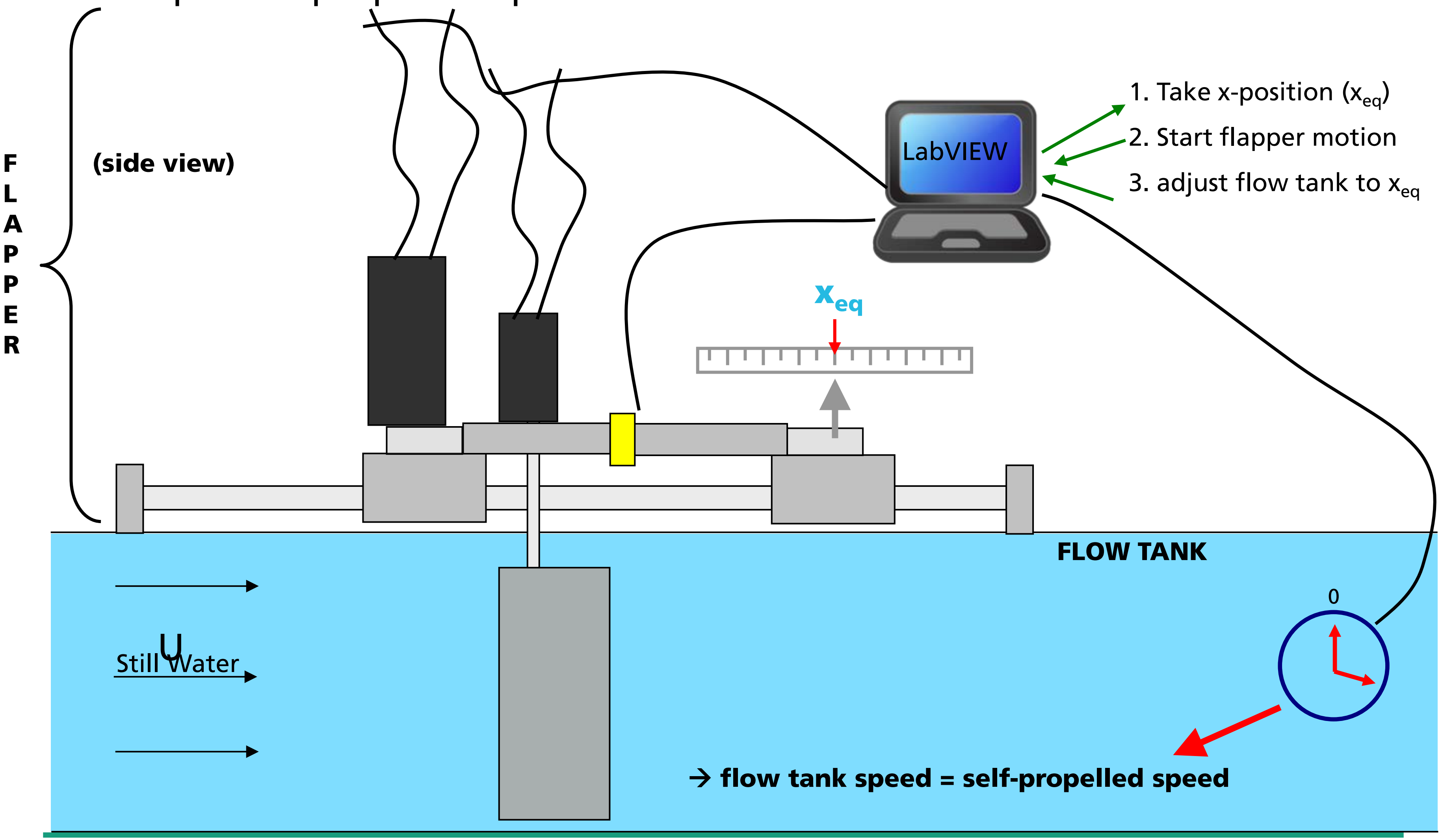
Flow Control – Hydrodynamic Function of Shark Skin

- Setup – Self propelled Speed



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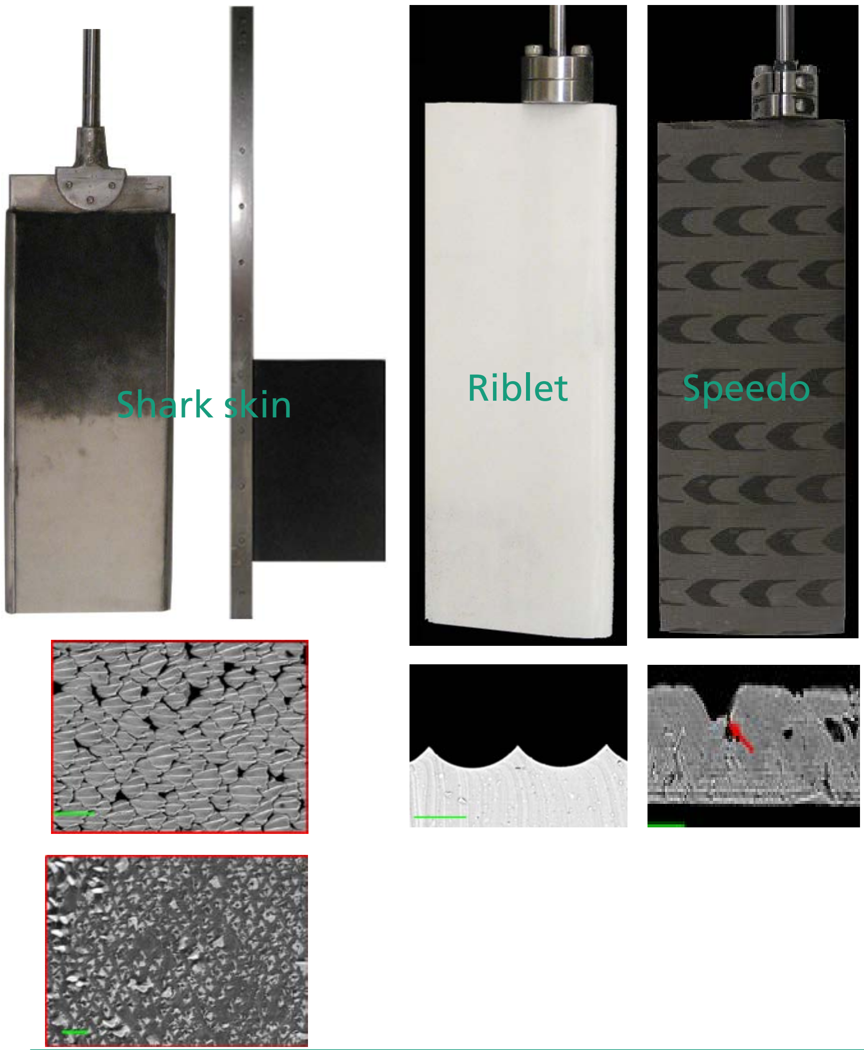
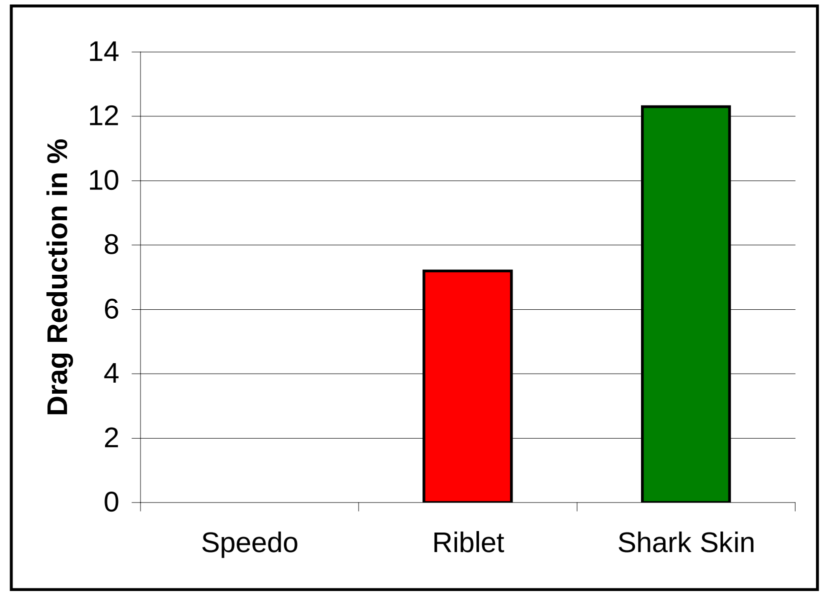
Flow Control – Hydrodynamic Function of Shark Skin

Materials and Results





Drag Reduction:

- Speedo: 0%
- Riblet: 7.2%
- <u>Flexible</u> Shark Skin: 12.3%

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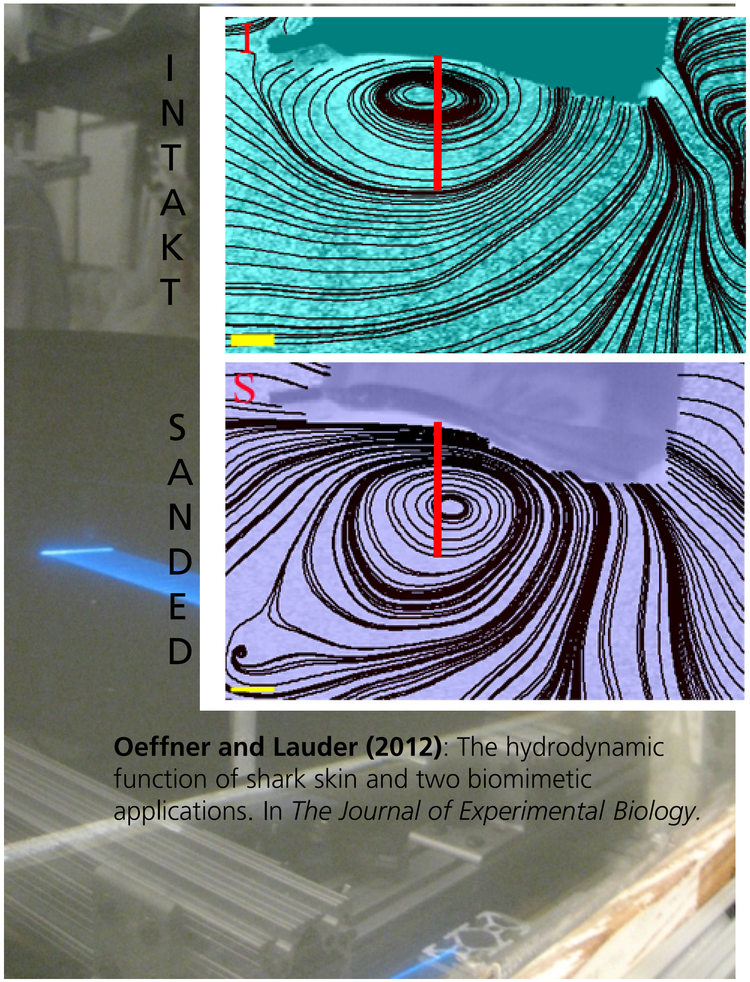
Flow Control – Hydrodynamic Function of Shark Skin

➢ PIV Experiments



Oeffner and Lauder (2012): The hydrodynamic function of shark skin and two biomimetic applications. In *The Journal of Experimental Biology*.

- Vortices generate suction forces
- Shark skin makes vortex to stay closer to surface
- suction forces are fully utilized
- optimal thrust production / drag reduction!

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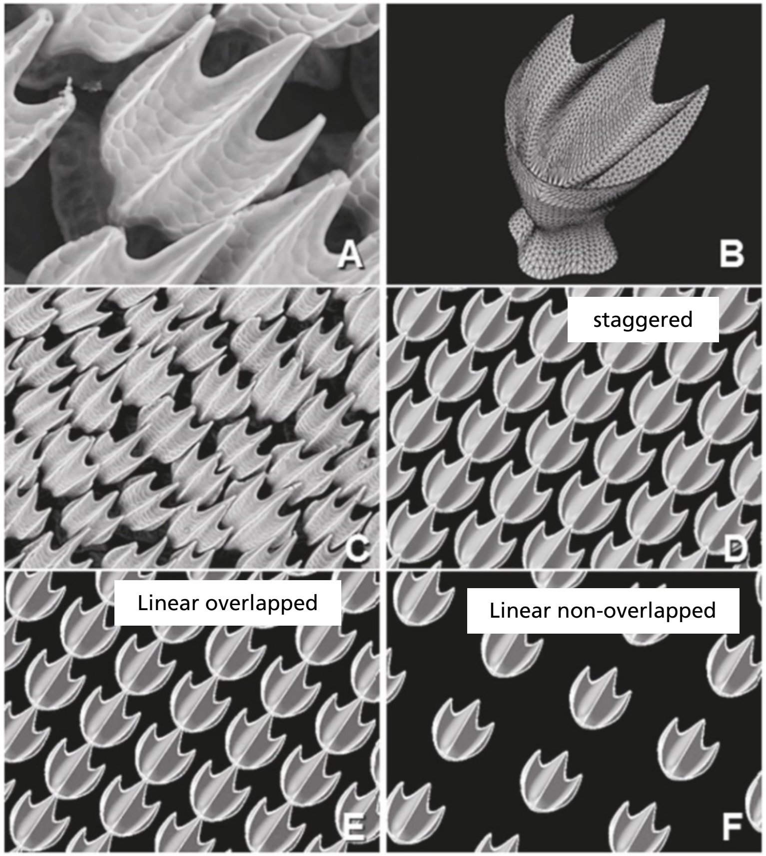
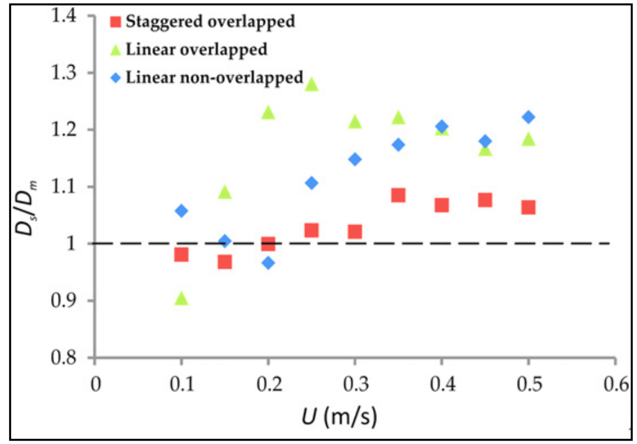
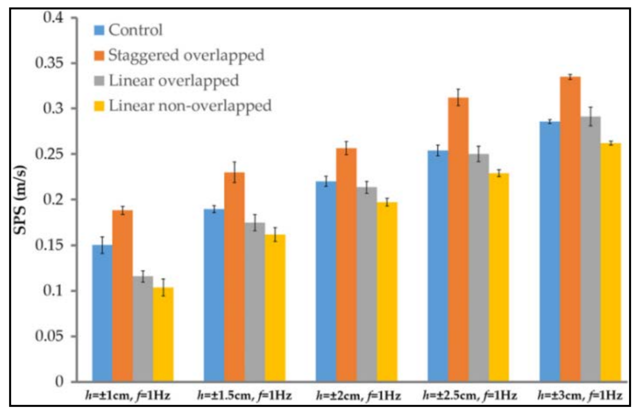
Flow Control – Hydrodynamic Function of Shark Skin

➢ Biomimetic Shark Skin





Static Drag Reduction ($D_{Control}/D_{biomimetic}$)

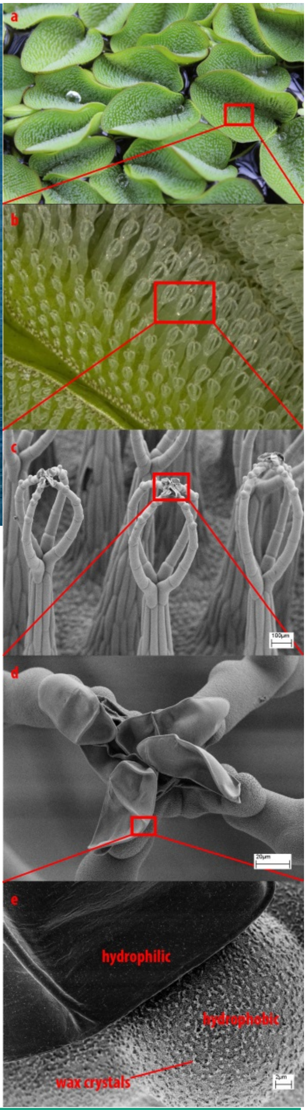


Dynamic Thrust (Drag)

Wen, et al. (2014): Biomimetic shark skin: design, fabrication and hydrodynamic function. In *The Journal of experimental biology.*
Wen, et al. (2015): Hydrodynamic function of biomimetic shark skin: effect of denticle pattern and spacing. In *Bioinspiration & Biomimetics.*

- Nature optimized fish for biological / dynamic motion
- Not as effective to stiff human-made technology (robots, ships, planes..)

Biomimetics - Salvinia Effect



Koch and Barthlott (2009): Superhydrophobic and superhydrophilic plant surfaces: an inspiration for biomimetic materials. In *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences.*

- Principle: hydrophobic surfaces + complex nano- and microstructure traps air when submerged in water for up to several weeks
- Biological Function: floating plant mats maintain function within air-layer
- Biomimetic Application: Applied to ship hull → ship would float on air-layer → Drag reduction of up to 30 %.

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Questions

???

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