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Bio-mimetic Flow Control

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& Bio-Mimetic Engineering Laboratory

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Contents

What is Bio-mimetics?

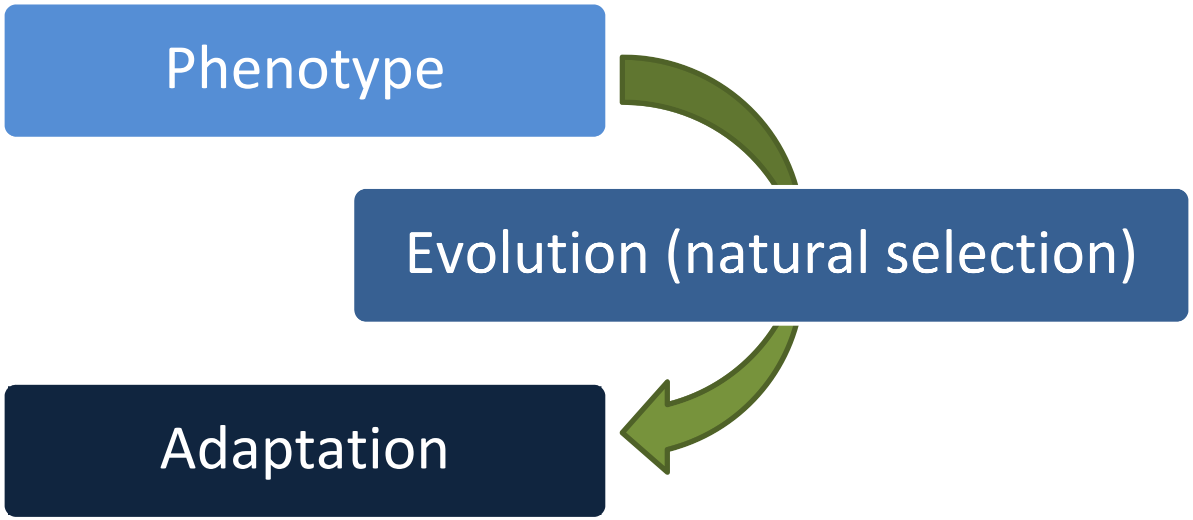
- Application of biological methods and systems found in nature to the study and design of engineering systems and modern technology (from Wikipedia)
- The concept itself is old, but successful developments have been made recently in the field of flow control.

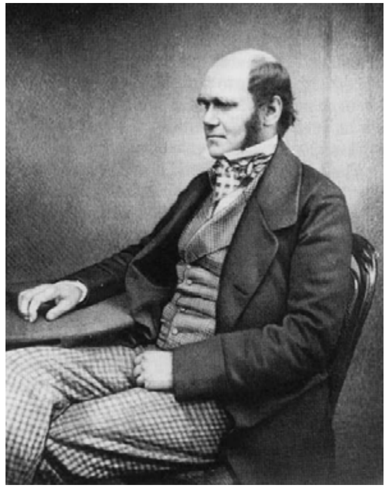
Biological methods

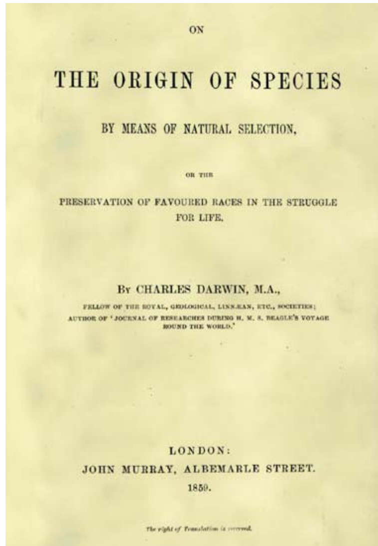
Engineering applications

Why Bio-mimetic?

Through evolution, nature has "experimented" with various solutions to challenges and has improved upon successful solutions (Bar-Cohen 2006).







ON

THE ORIGIN OF SPECIES

BY MEANS OF NATURAL SELECTION,

OR THE

PRESERVATION OF FAVOURED RACES IN THE STRUGGLE FOR LIFE.

BY CHARLES DARWIN, M.A.,

FELLOW OF THE ROYAL, GEOLOGICAL, LINNÆAN, ETC., SOCIETIES;
AUTHOR OF 'JOURNAL OF RESEARCHES DURING H. M. S. BEAGLE'S VOYAGE ROUND THE WORLD.'

LONDON:
JOHN MURRAY, ALBEMARLE STREET.
1859.

The right of Translation is reserved.

Why Bio-mimetic?

Numerous marine creatures, flying insects and birds live in a fluid, i.e. in air and water.







May Provide novel ideas for successful flow control

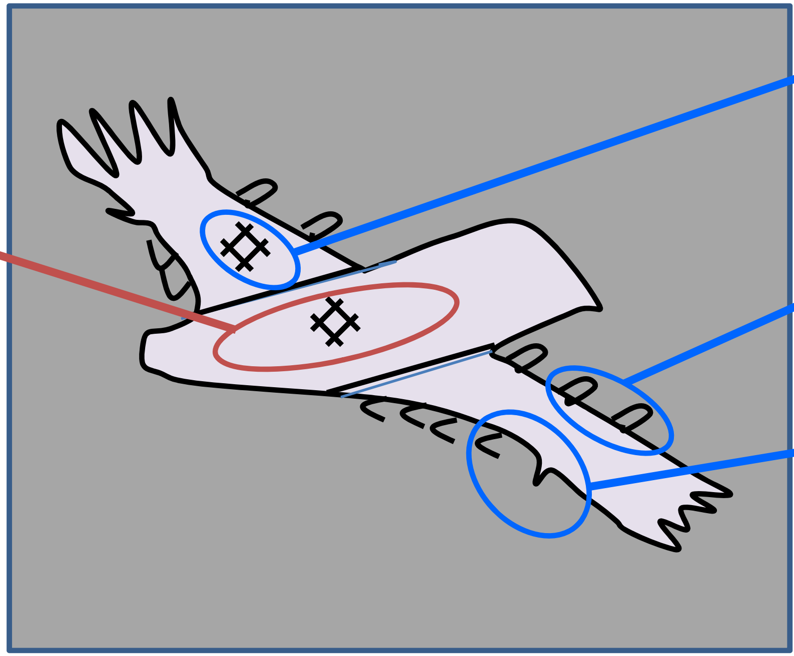
Reviews

Diversity of topics associated with bio-mimetics

- Biomimetic flow control (Anders, AIAA-2000-2543)
- Hydrodynamics of fishlike swimming (Triantafyllou et al., ARFM, 2000)
- Aerodynamics of small vehicles (Mueller & DeLaurier, ARFM, 2003)
- Dissecting insect flight (Wang , ARFM, 2005)
- Passive and active flow control by swimming fishes and mammals (Fish & Lauder, ARFM, 2006)
- Walking on water: biolocomotion at the interface (Bush & Hu, ARFM, 2006)
- And more ……

Bio-mimetic solutions for flow control

Smart surface for low skin friction



Wing-surface device

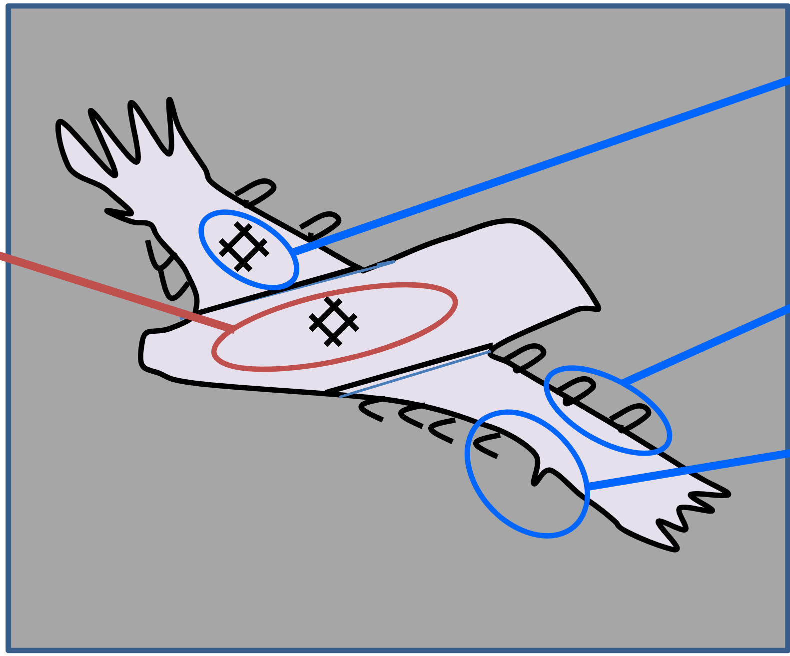
Trailing-edge device

Leading-edge device

for aerodynamic performance enhancement

Bio-mimetic solutions for flow control

Smart surface for low skin friction



Wing-surface device

Trailing-edge device

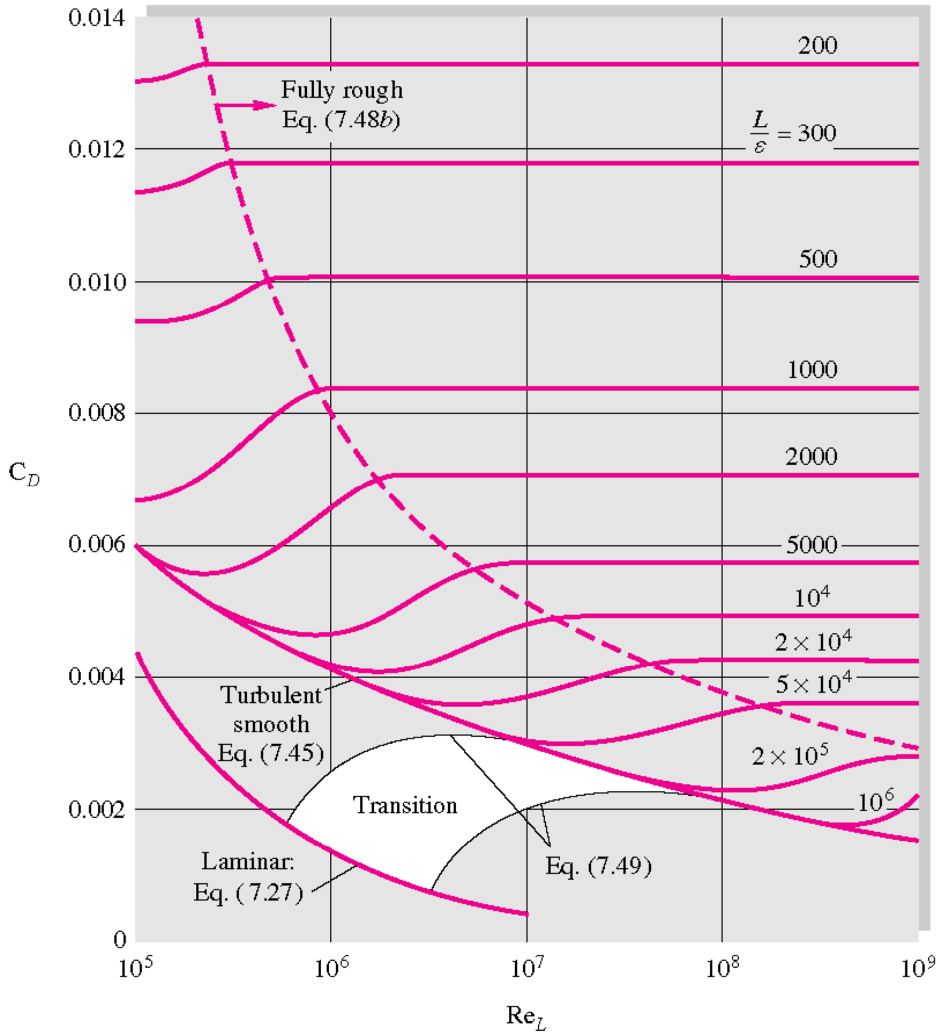
Leading-edge device

for aerodynamic performance enhancement

Smart surface for low skin friction

Drag coefficient vs. Re

(White, Fluid Mechanics)



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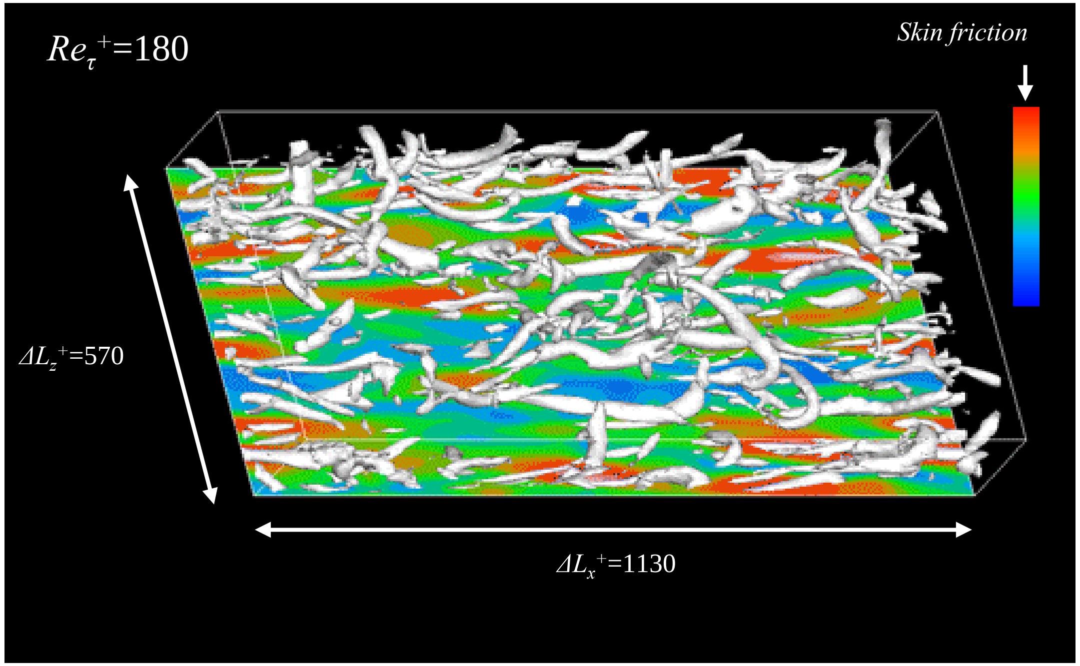
Smart surface for low skin friction



Control of these coherent structures provides drag reduction.

But it is difficult to predict their instantaneous locations.

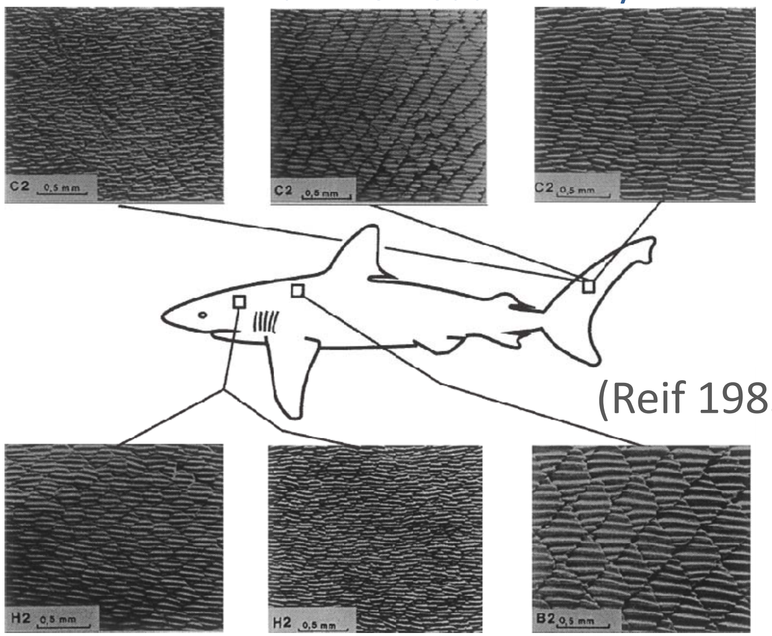
- How to control these? – numerous approaches to reduce the skin friction on the wall including smart blowing/suction, polymer additives, microbubbles, compliant surface, etc.

Smart surface for low skin friction

1. Riblets of shark skin

Scale patterns of fast sharks

Mako | Great hammerhead | Dusky shark

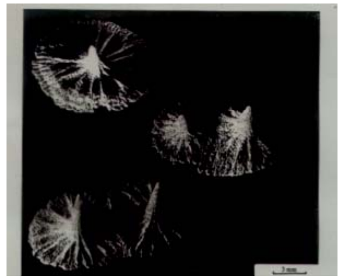


(Reif 1985)

Mako | Smooth hammerhead | Galapagos shark

cf) slow shark

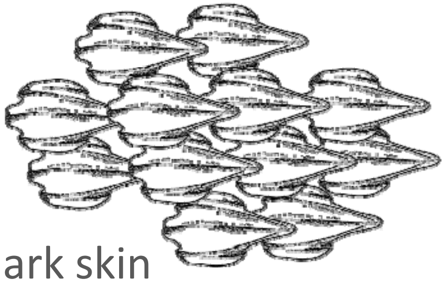
Bramble shark



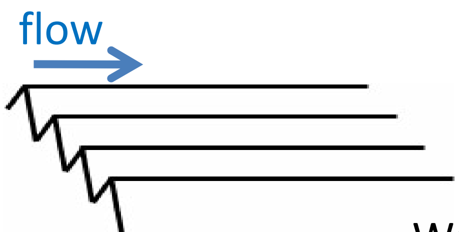
Smart surface for low skin friction

Riblets of shark skin

V- grooved riblets

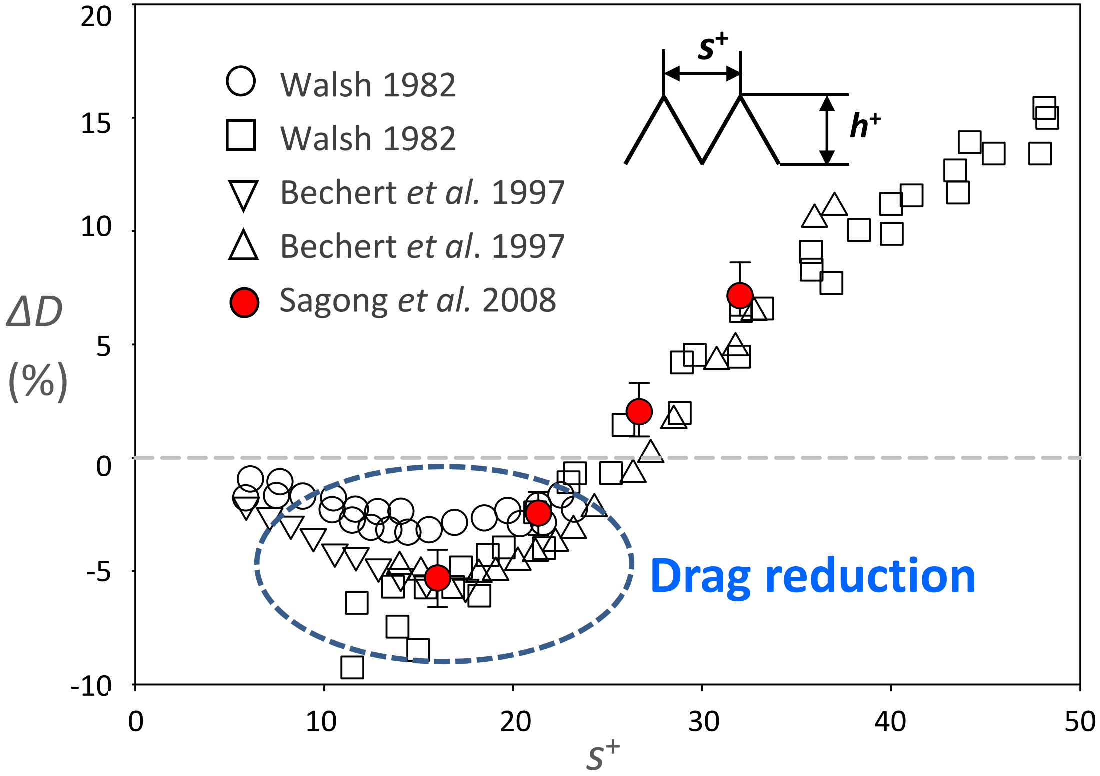


Shark skin



V-grooved riblets

Walsh



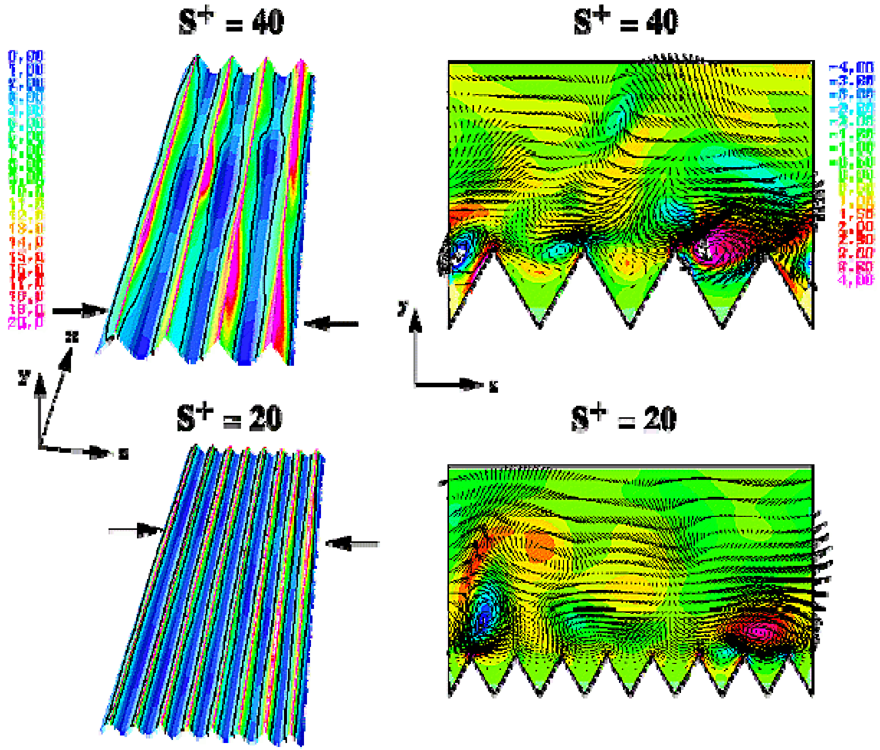
Against our intuition:

smooth surface should have lowest skin friction

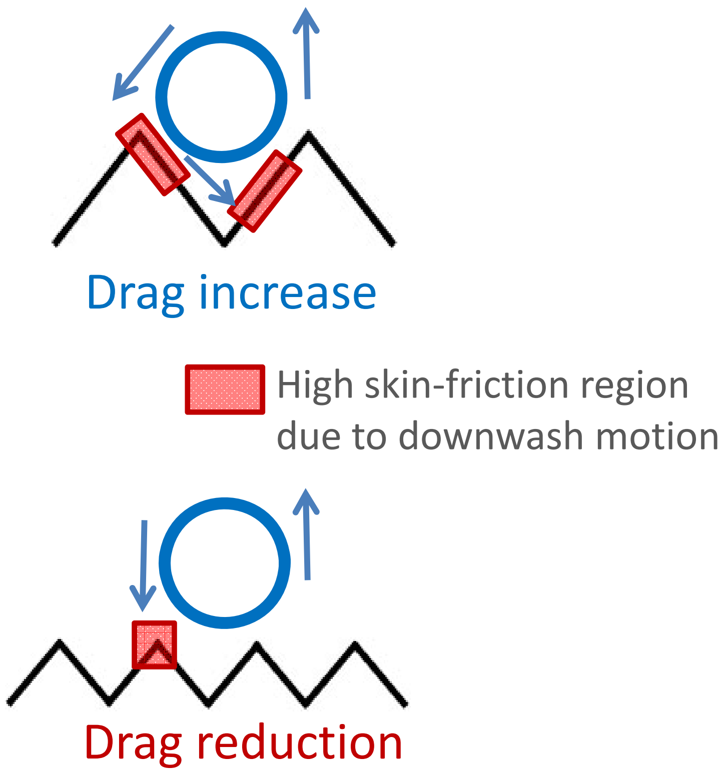
Smart surface for low skin friction

Riblets of shark skin

Mechanism of drag reduction by riblets



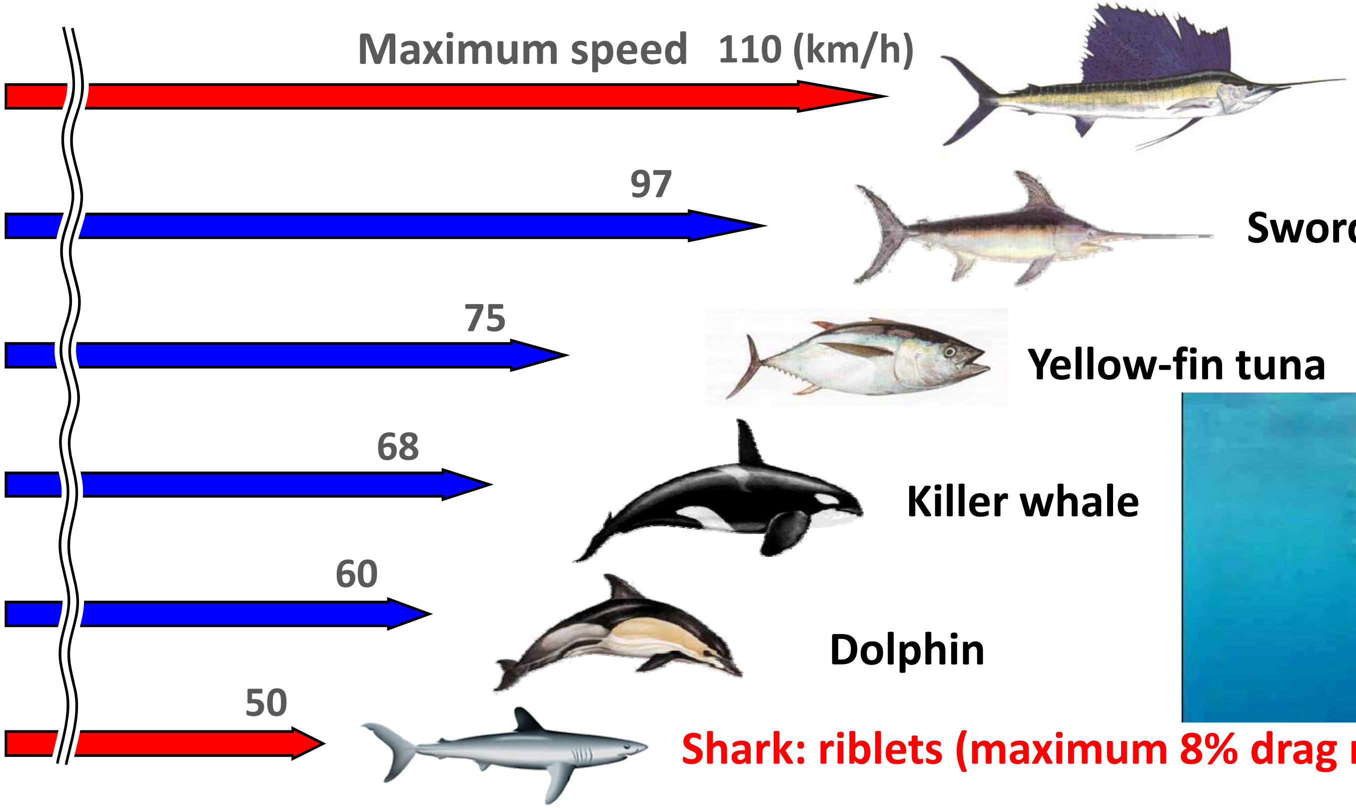
Choi , Moin & Kim (1993)



Smart surface for low skin friction

2. V-shaped protrusions of sailfish skin

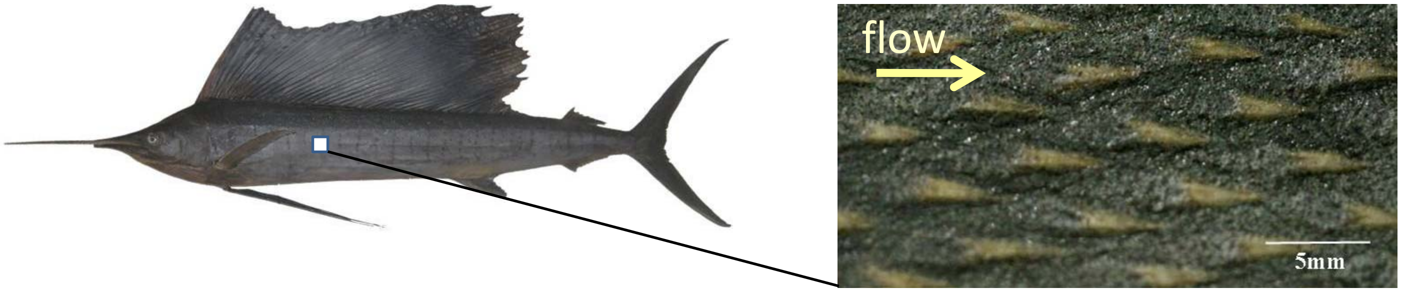
Sailfish: The fastest sea animal



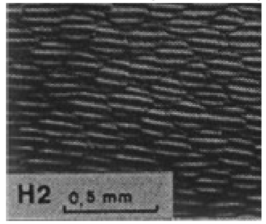
Smart surface for low skin friction

V-shaped protrusions of sailfish skin

Investigate the possibility of skin friction reduction using the skin shape of sailfish



Riblets (Mako)



Large scale structure
(compared to the size of riblets)

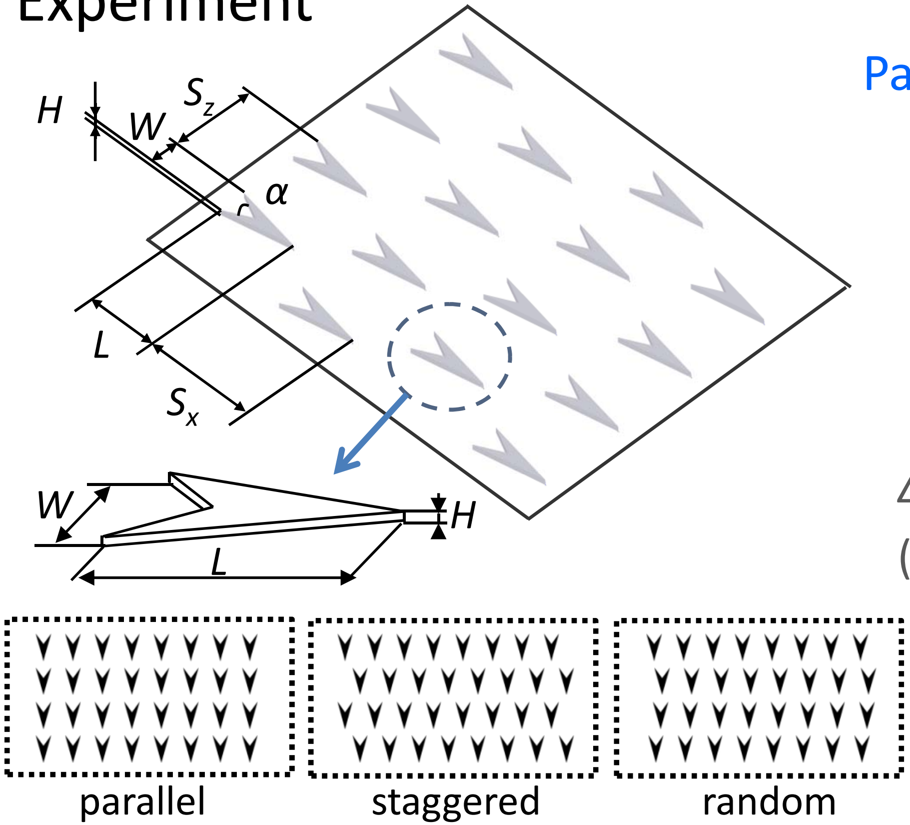
Caught a sailfish from Kuala Rompin, Malaysia (May 2005)

Smart surface for low skin friction

V-shaped protrusions of sailfish skin

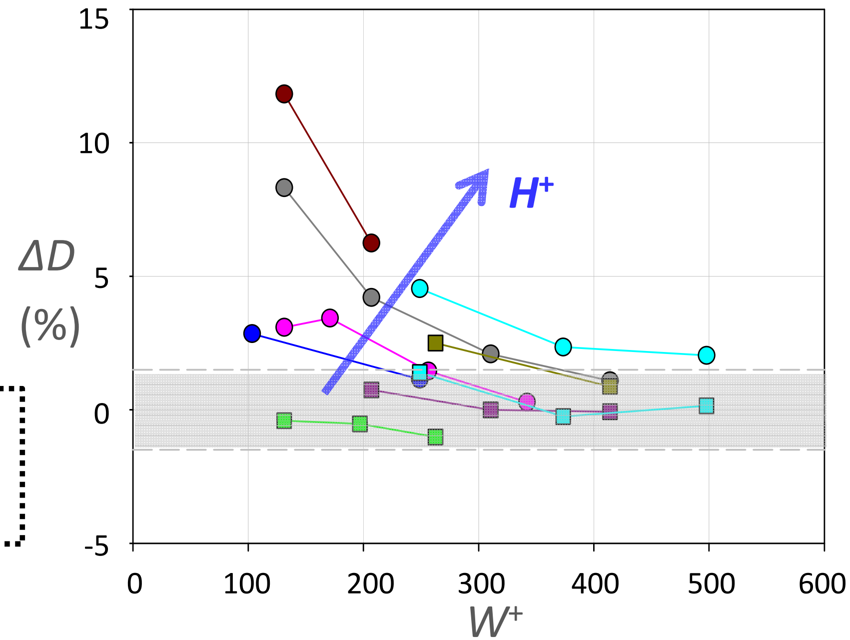
Sagong et al. (2008, PoF)

Experiment



Parametric study ➡ 180 different cases

Drag variation with the width (*W*)



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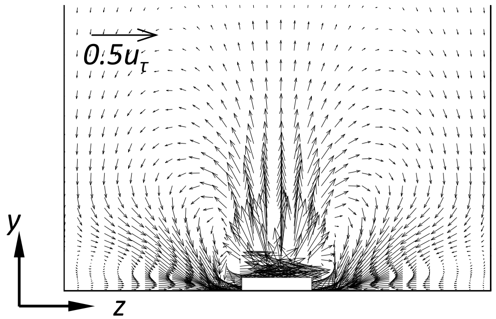
Smart surface for low skin friction

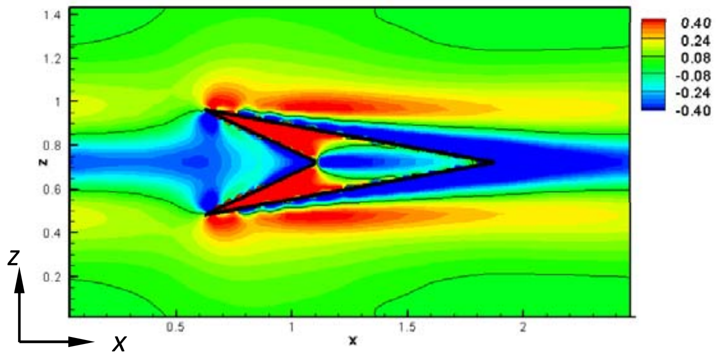
V-shaped protrusions of sailfish skin

Sagong et al. (2008, PoF)

Direct numerical simulation

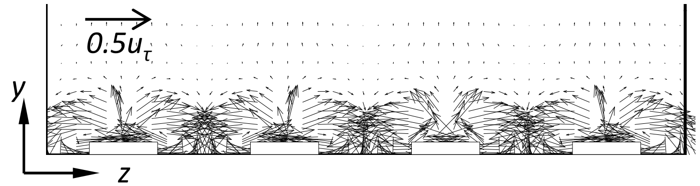


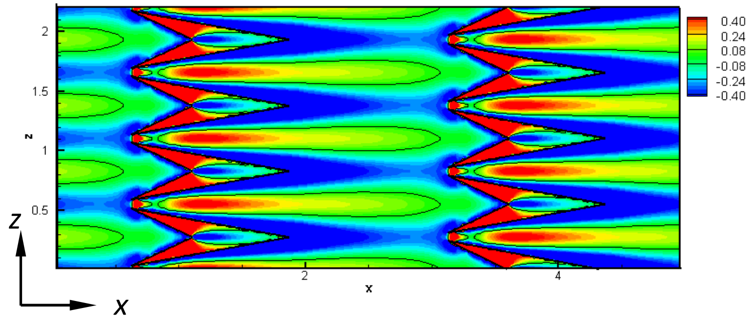
Cross-flow vectors (v, w)



Shear stress contours

(H^+, W^+, S_z/W, S_x/L, pattern) =
(8, 87,1.14, 2, staggered)



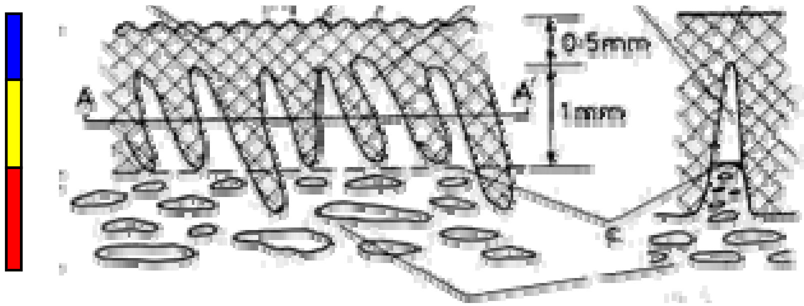


5% Skin-friction reduction

Form drag on the protrusion results in total-drag increase.

Smart surface for low skin friction

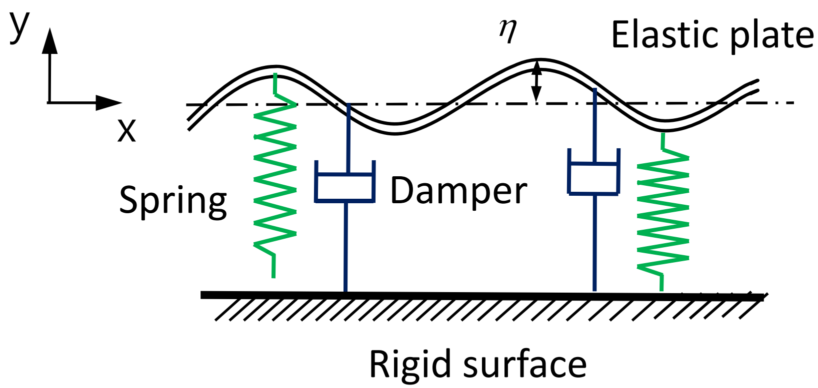
3. Compliant wall of dolphin skin



Stiff inner skin
Damping layer
Outer membrane
} Soft outer skin

Kramer (1960)

Compliant wall model



$$C_M \frac{\partial^2 \eta}{\partial t^2} + C_d \frac{\partial \eta}{\partial t} + C_B \left(\frac{\partial^4 \eta}{\partial x^4} + 2 \frac{\partial^4 \eta}{\partial x^2 \partial z^2} + \frac{\partial^4 \eta}{\partial z^4} \right) + C_K \eta - C_{T_x} \frac{\partial^2 \eta}{\partial x^2} - C_{T_z} \frac{\partial^2 \eta}{\partial z^2} = -p_w$$

Carpenter & Garrad (1985)

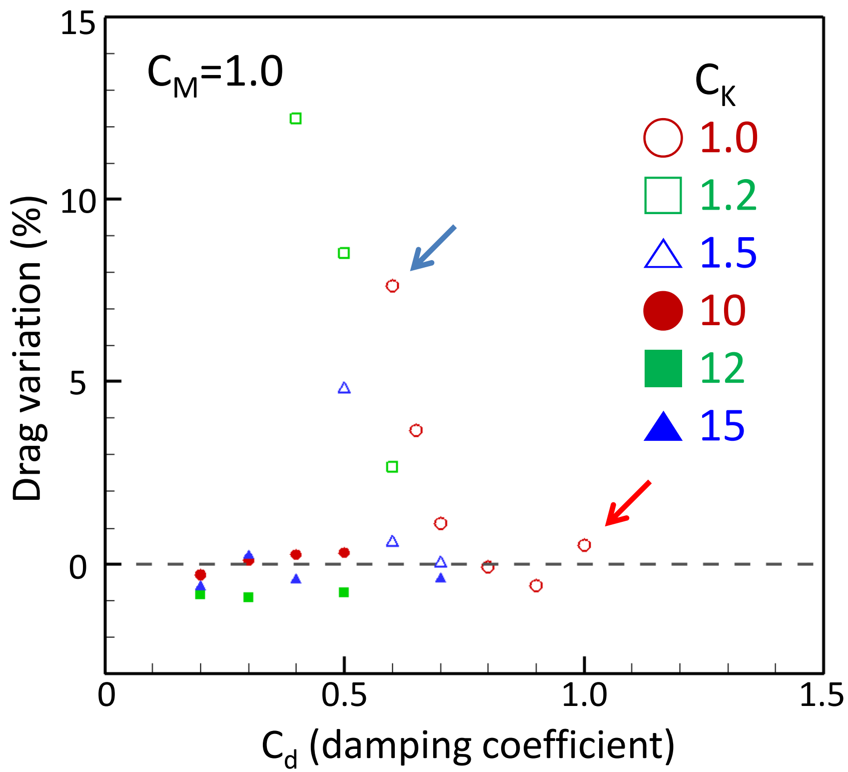
- Drag reductions, no change in drag, and drag increase have been reported.
- Recent DNS studies reported no drag reduction.

Smart surface for low skin friction

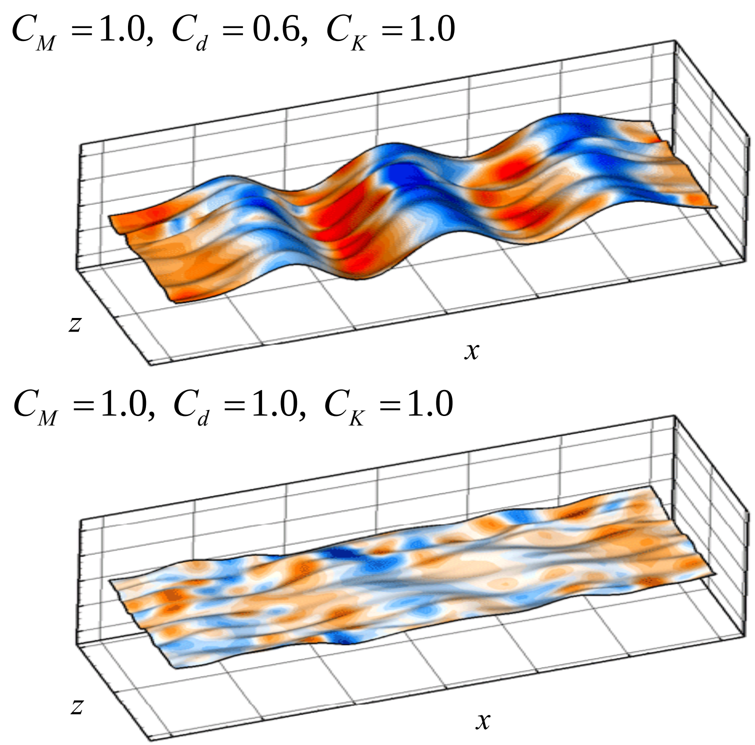
Compliant wall of dolphin skin

Direct numerical simulation

(about 200 cases)



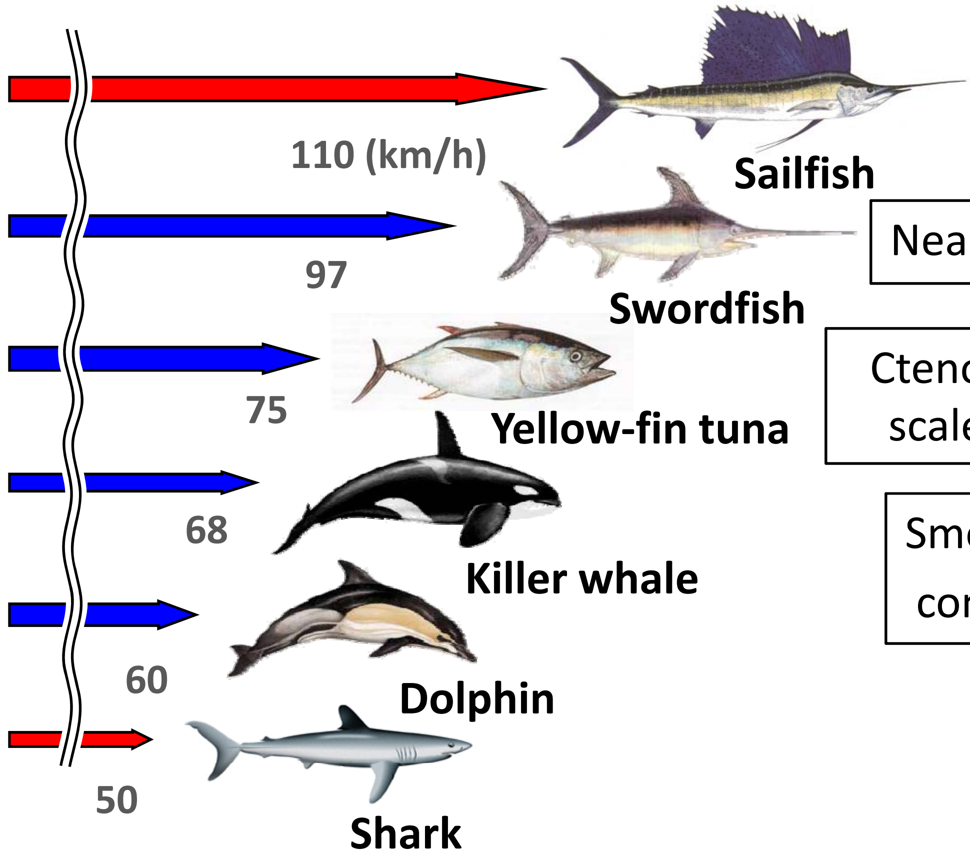
Wall motion



Anisotropic wall property is being investigated.

Smart surface for low skin friction

Fast sea animals



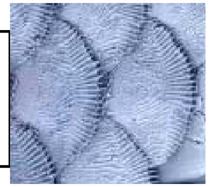
Drag reduction?

No

Nearly no protrusion

No

Ctenoid scales

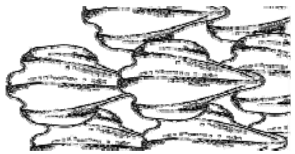


Maybe Yes

Smooth surface & compliant surface

??

??

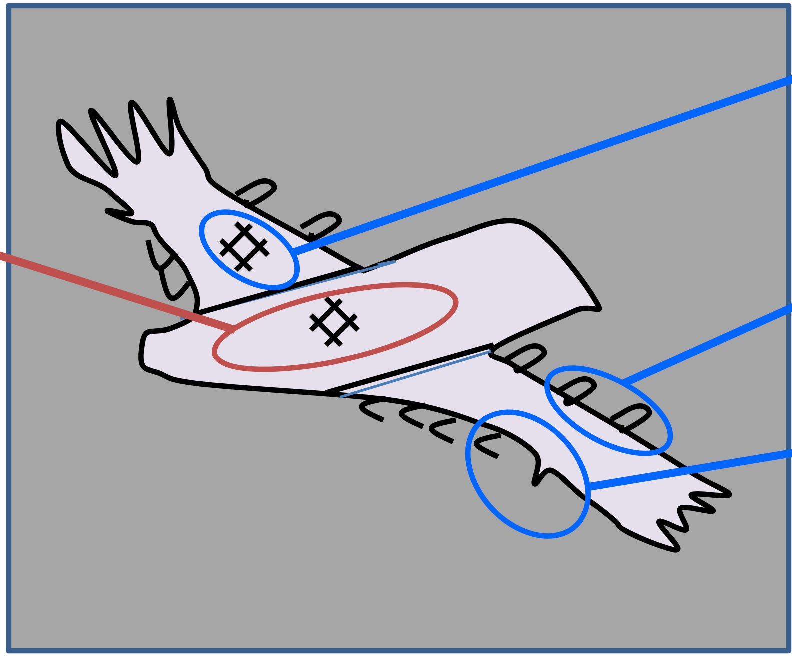


8%

*Slime secretion: too expensive, maybe only in emergency (Vogel 1994)

Bio-mimetic solutions for flow control

Smart surface for low skin friction



Wing-surface device

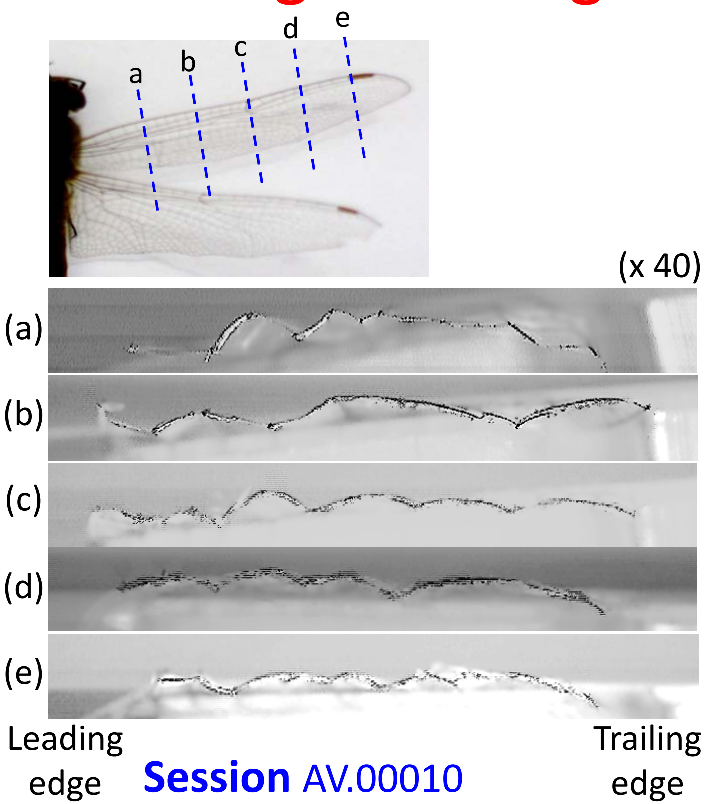
Trailing-edge device

Leading-edge device

for aerodynamic performance enhancement

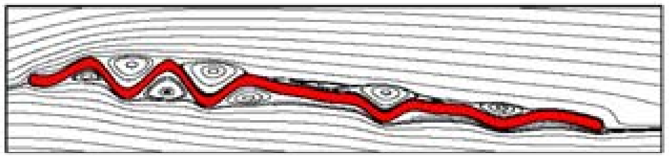
Wing-surface device

1. Corrugated wing section of a dragonfly



Session AV.00010
"Aerodynamic force variation in an inclined hovering motion by …."

- In "structural sense", surface corrugations provide resistance against bending and twisting.
- In a gliding flight condition, lift enhancement (Okamoto et al. 1996; Kesel 2000; Vargas et al. 2008; Kim et al. 2009) or drag reduction (Vargas et al. 2008; Levy & Seifert 2009)



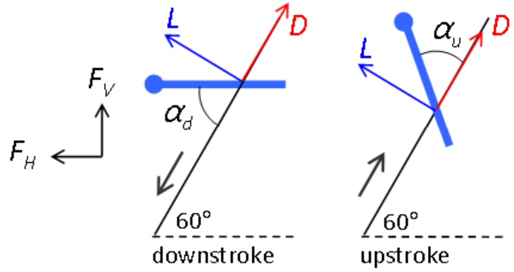
(Vargas et al. 2008)

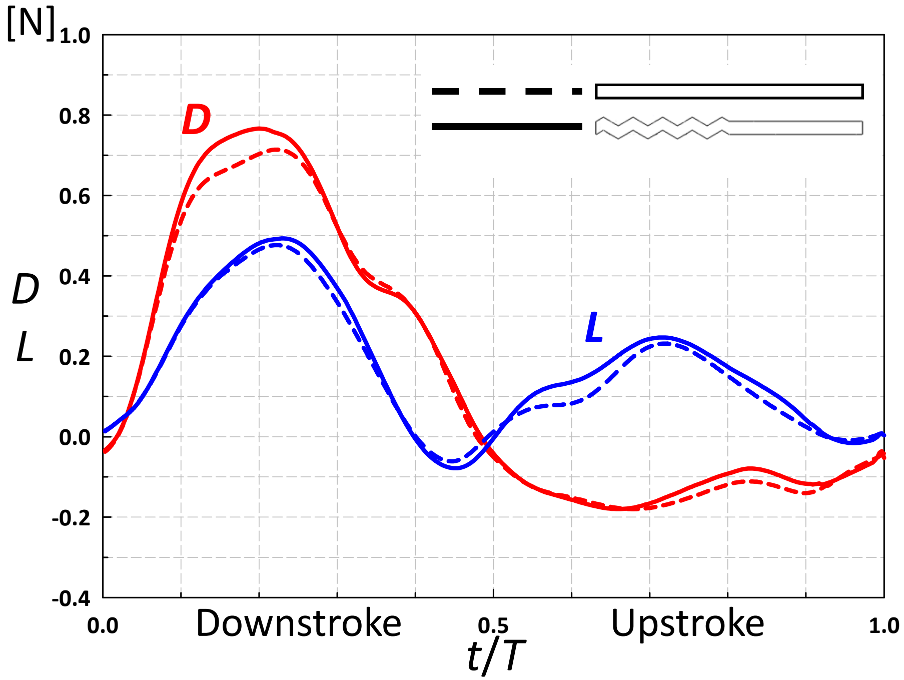
- How about its aerodynamic function during a flapping flight?

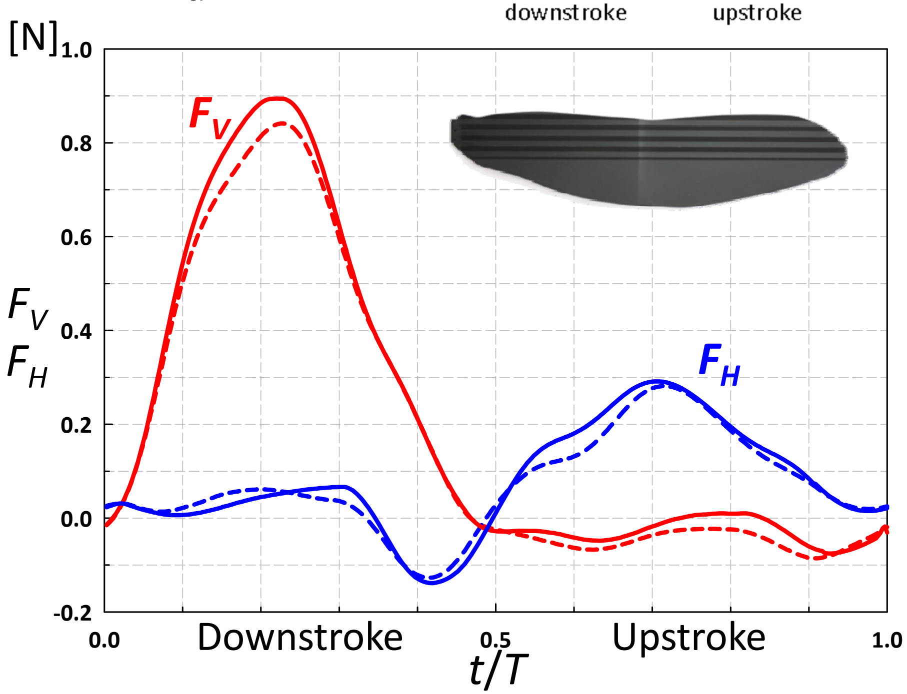
Wing-surface device

Corrugated wing section of a dragonfly

Hovering flight of a dragonfly (α_d=60˚; α_u=20˚)







During the downstroke: drag increases

During the upstroke: lift increases and drag decreases

→ +12% in the vertical force

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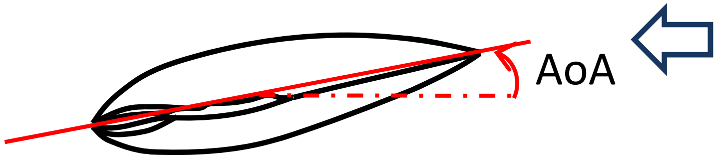
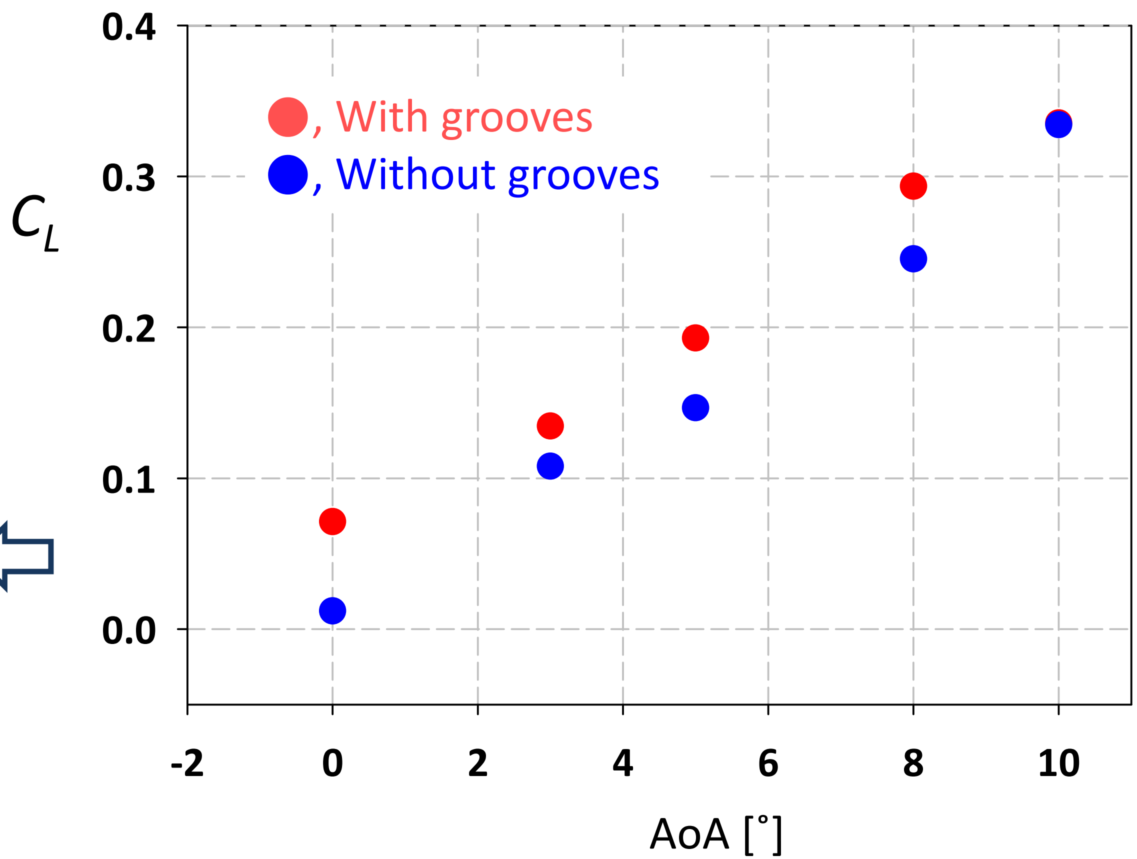
Wing-surface device

2. Longitudinal grooves on a scallop shell

Wing-surface device

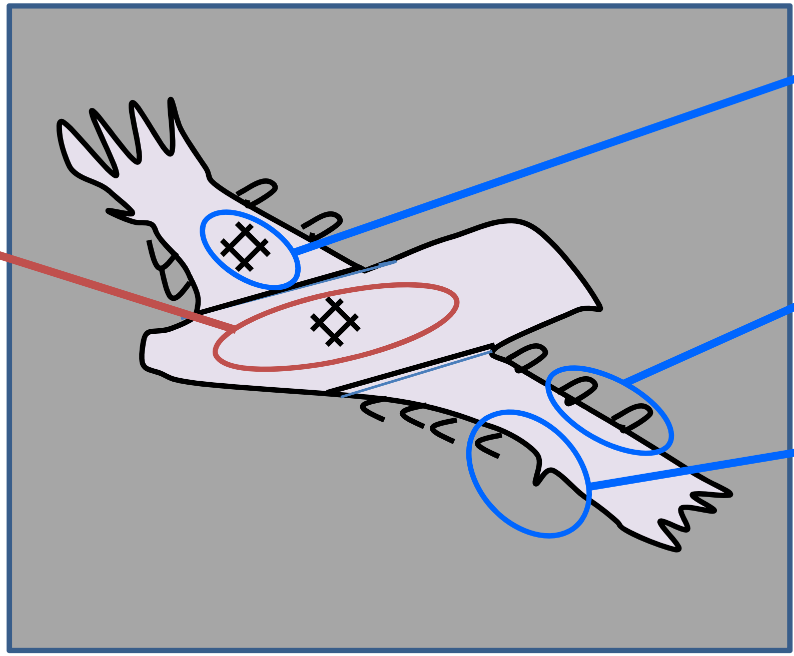
Longitudinal grooves on a scallop shell





Bio-mimetic solutions for flow control

Smart surface for low skin friction



Wing-surface device

Trailing-edge device

Leading-edge device

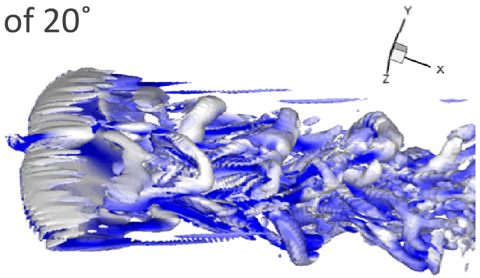
for aerodynamic performance enhancement

Trailing-edge device

1. Hind-wing tails of a gliding swallowtail butterfly

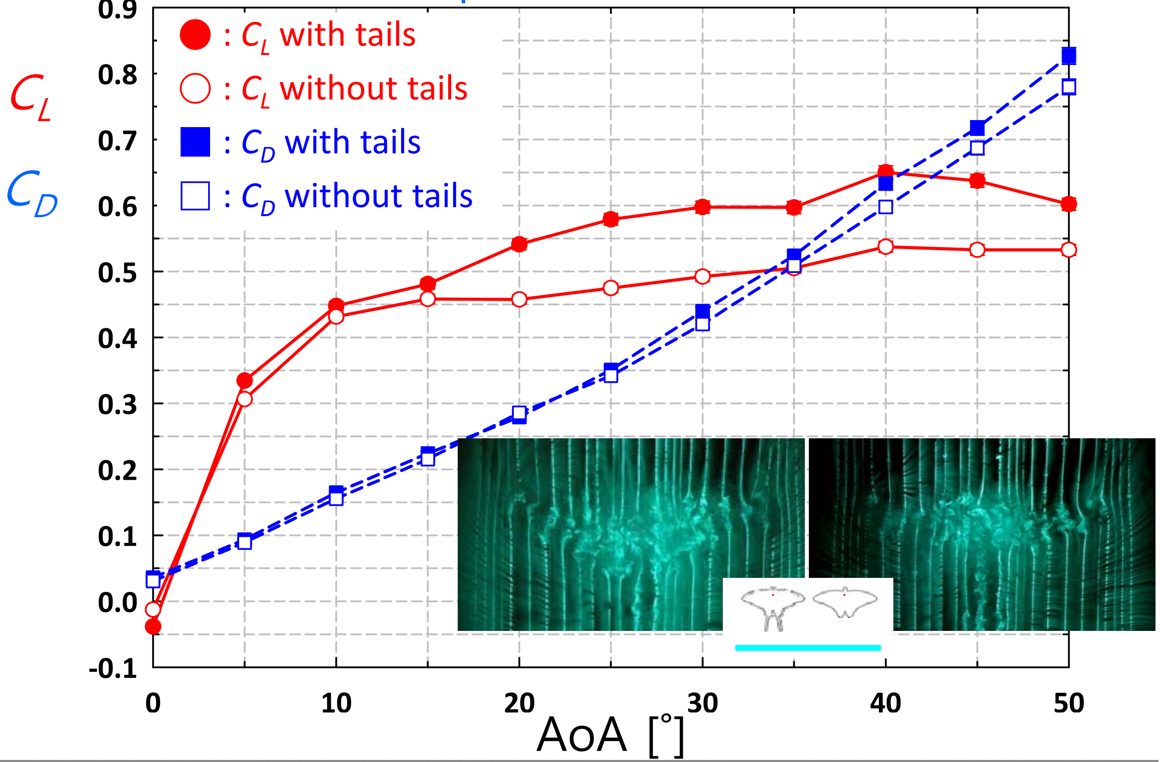
It was conjectured that the hind-wing tails reduce the drag force on a wing (Martin & Carpenter, 1977).

Attack angle of 20˚



Numerical simulation

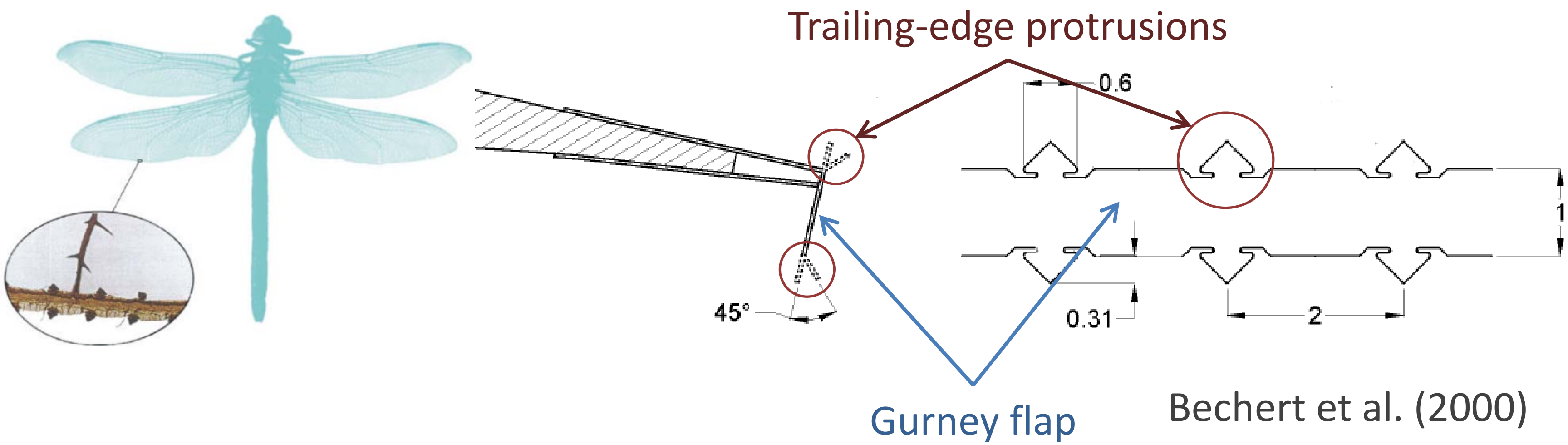
Wind-tunnel experiment



Trailing-edge device

2. Arrays of small protrusions on a dragonfly wing

Spade-like protrusions on the trailing-edge of a dragonfly wing



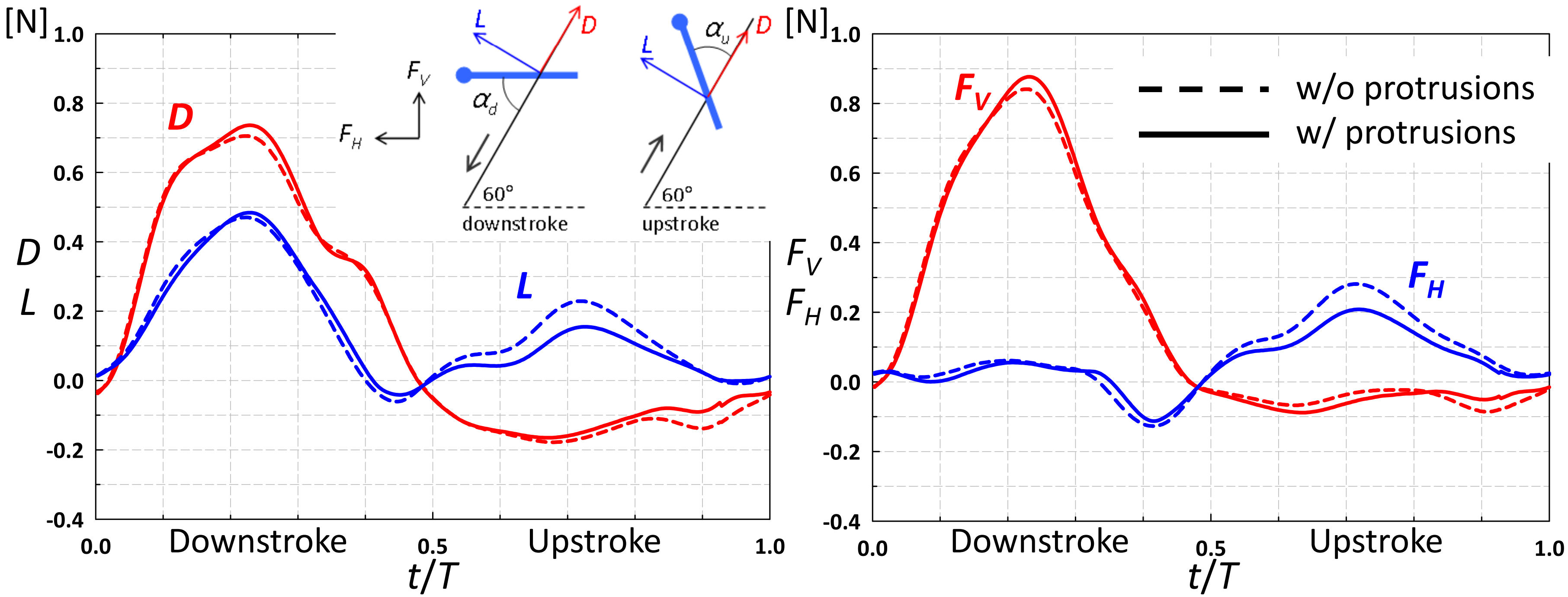
Bechert et al. (2000)

- At gliding flight condition, Bechert et al. (2000) obtained 10% reduction of drag on an airfoil having a gurney flap by introducing protrusions.
- How about the flapping flight?

Trailing-edge device

Arrays of small protrusions on a dragonfly wing

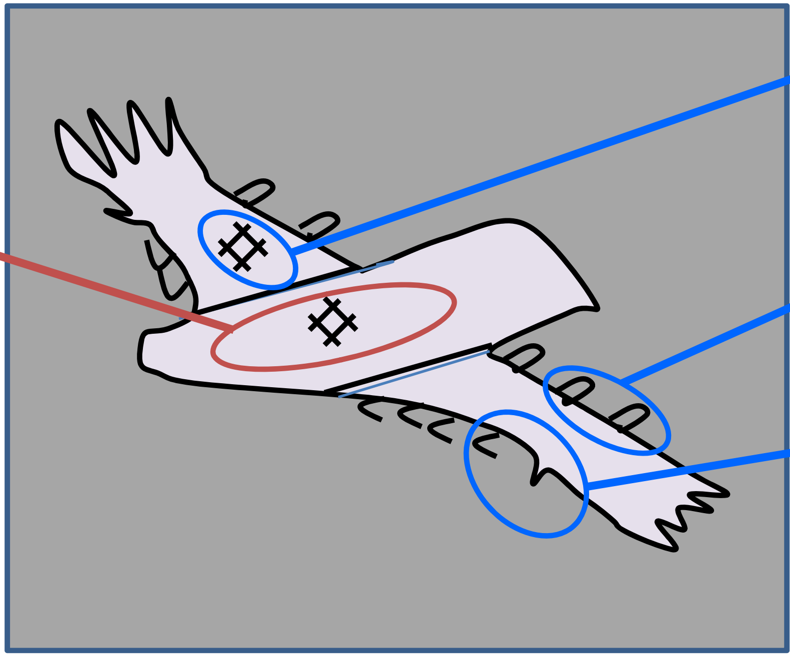
Hovering flight of a dragonfly (α_d=60˚; α_u=20˚)



During the upstroke, lift and drag decrease, but the vertical force in a period is almost unaffected → Less power required to produce same vertical force

Bio-mimetic solutions for flow control

Smart surface for low skin friction



Wing-surface device

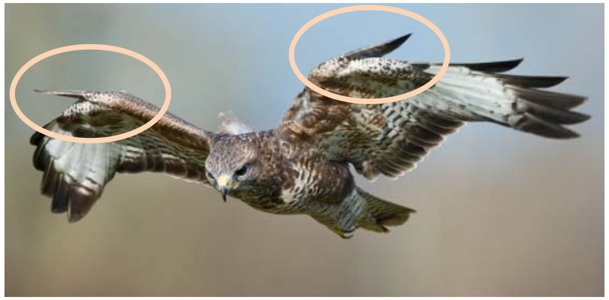
Trailing-edge device

Leading-edge device

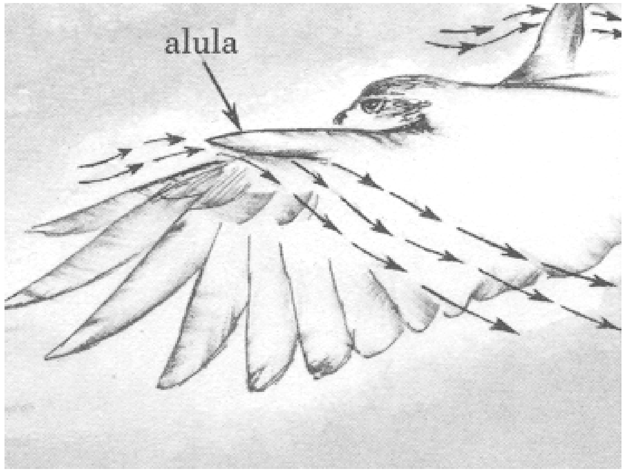
for aerodynamic performance enhancement

Leading-edge device

1. Alula of a landing bird



"A group of two to six feathers projecting from the phalanx of the bird's first finger (its thumb) at the bend of the wing. It reduces turbulence by allowing fine control of airflow over the wing." (Handbook of Ornithology)

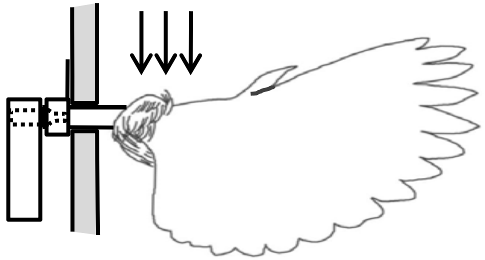


Hypothesis: alula helps in flight at high attack angles by preventing or delaying stall (Kaufmann, 1970)

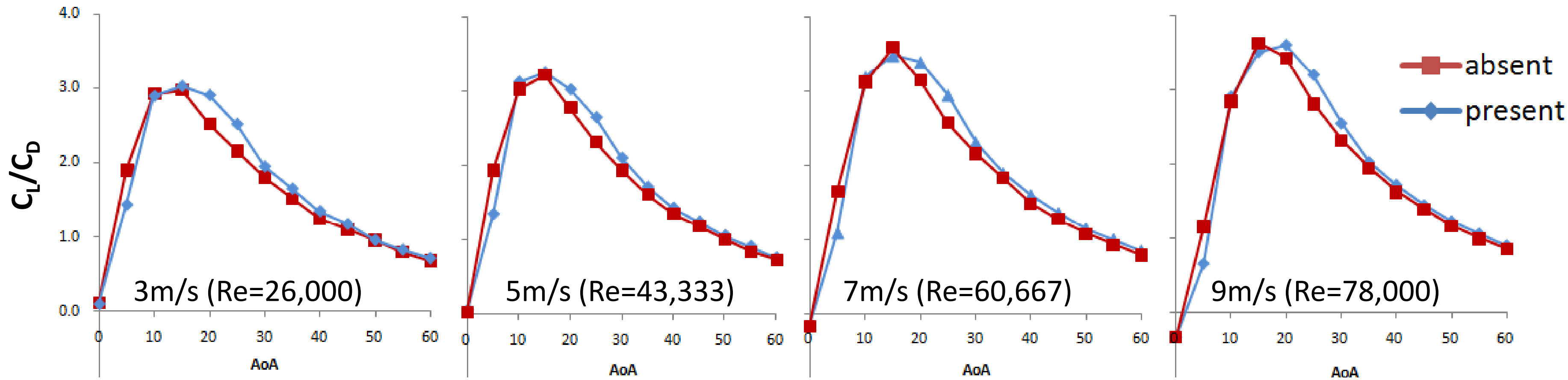
Leading-edge device

Alula of a landing bird

In our experiments, birds performed steeper and slower flight with alula.



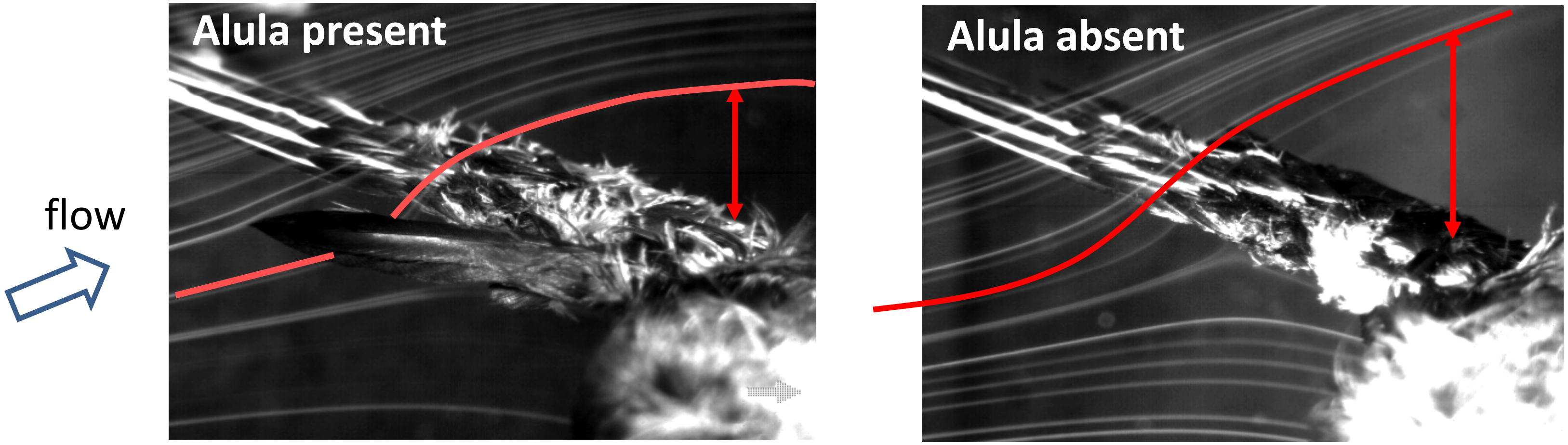
Wind-tunnel experiment with the wing of a magpie



Leading-edge device

Alula of a landing bird

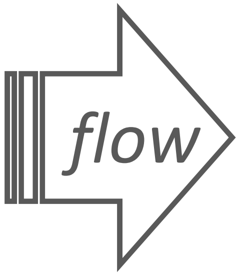
AOA = 25°

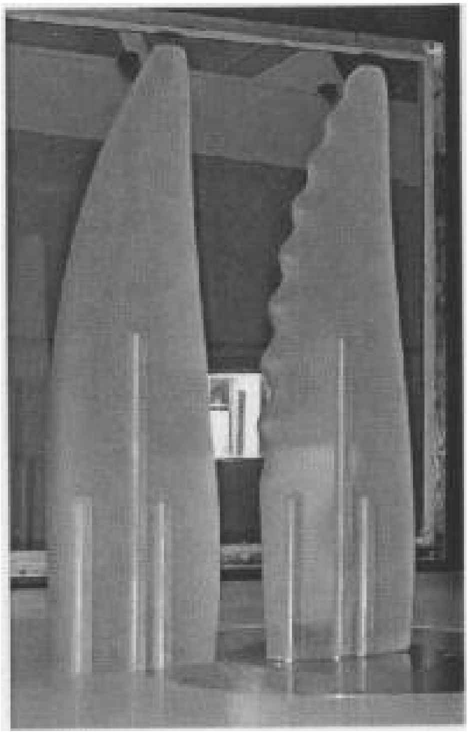


Alula delays stall by keeping the boundary layer attached to the wing surface at high attack angles.

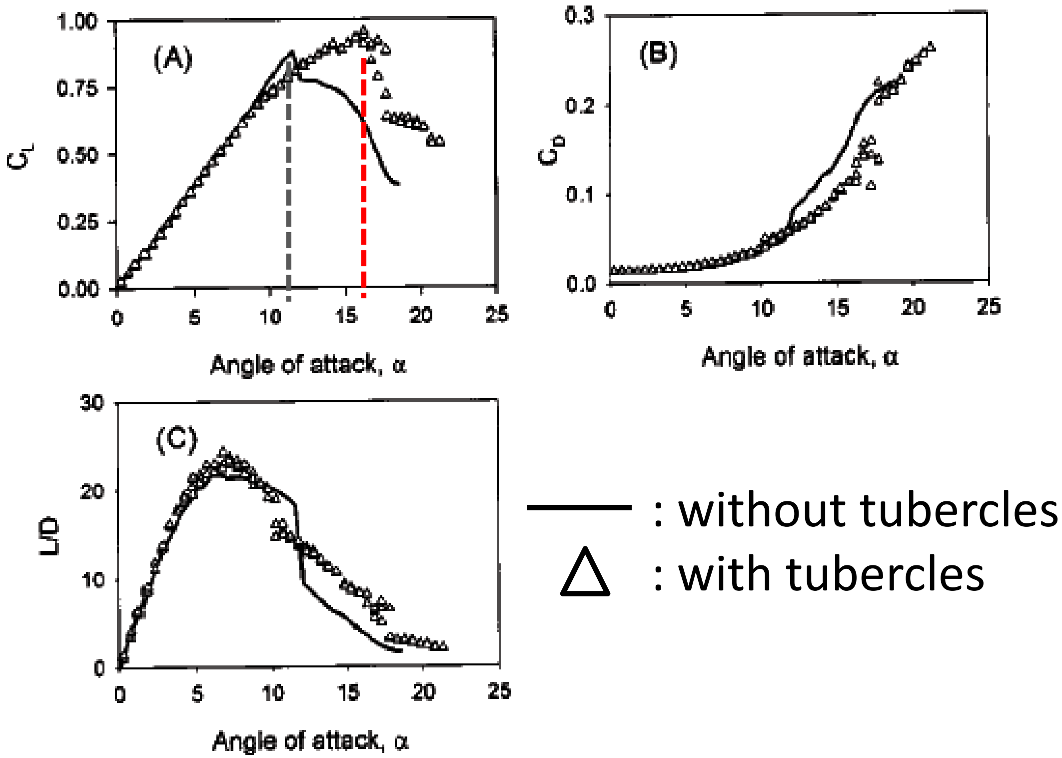
Leading-edge device

2. Leading-edge bumps of a humpback whale flipper





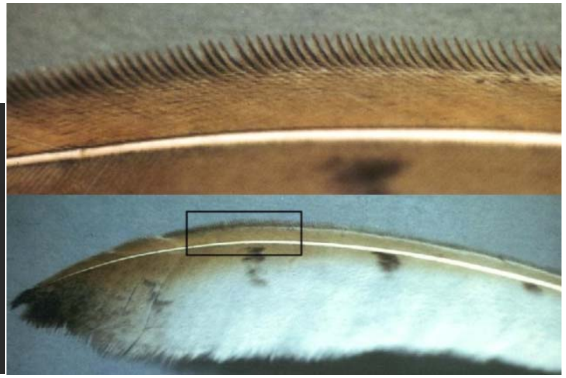
Miklosovic et al.
(2004, PoF)

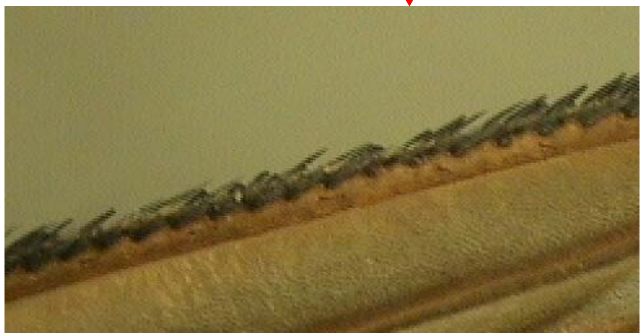


Leading-edge device

3. Leading-edge serration of an owl

Silent flight of the owl

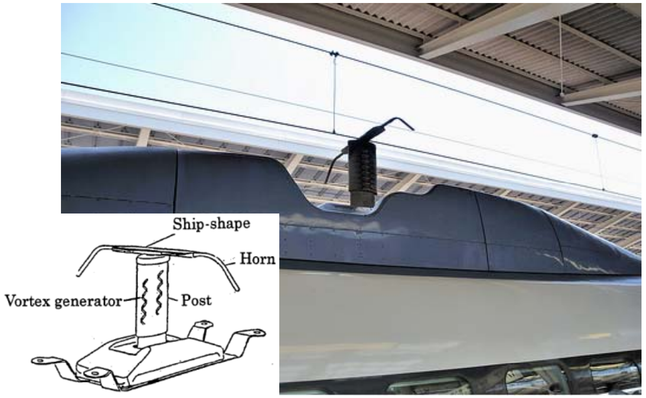




Combed leading edge of the owl reduces the noise and also acts as a separation control device (Lilley 1998; Anders 2000; Ito 2009).

Insects also have serrated leading edges.

Noise reduction on a pantograph of Japanese high speed train (Iwamoto & Ueda, 1997)



A few more thoughts on bio-mimetics

Drag reduction from Saguaro cactus

Transverse grooves on a Saguaro cactus

(b)

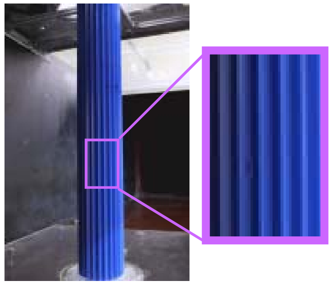
Talley et al. (2001, 2002) suggested the possibility of drag reduction by grooved cylinder mimicked Saguaro cactus.

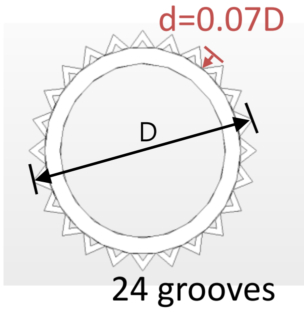
Typical diameter: 0.5m

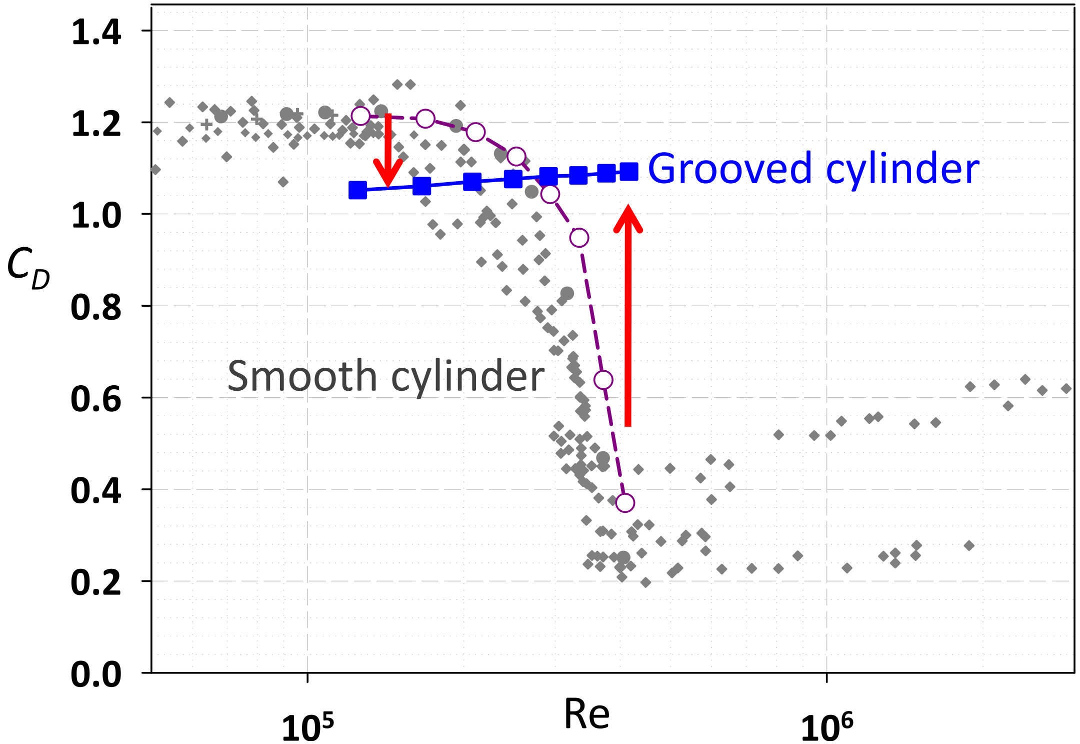
Re number can be as large as 10^6 at the highest wind speed.

A few more thoughts on bio-mimetics

Drag reduction from Saguaro cactus







For Saguaro cactus, the drag force actually increases.

So, grooves exist for some other purposes such as heat transfer enhancement/reduction, etc.

However, the geometry can be used for engineering purposes at appropriate Re numbers.

A few more thoughts on bio-mimetics

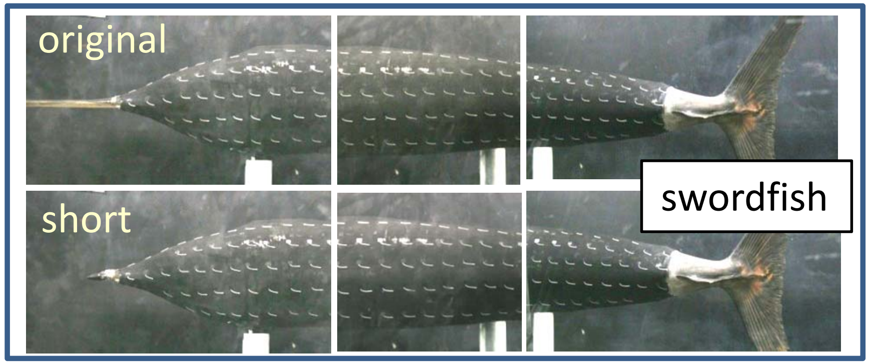
Bill of a swordfish

Session EV. 00007
"Hydrodynamic characteristics of sailfish and swordfish"

Role of bill:

- Conjecture 1 (Ovchinnikov 1966; Webb 1975; Videler 1995):
  Bill generates turbulence → Separation delay → form drag reduction

- Conjecture 2 (Kozlov 1973; Aleyev 1977; Bushnell & Moore 1991):
  Bill generates turbulence → boundary layer growth → skin-friction reduction



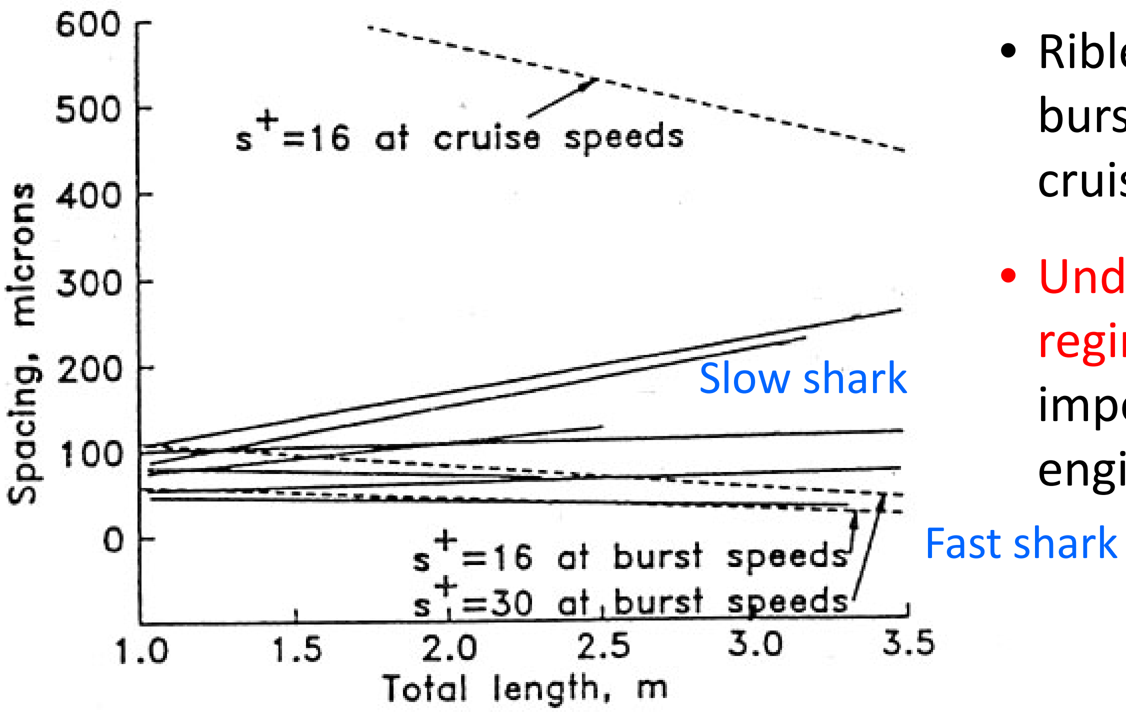
No change in drag!
Then what is the role of bill?

Feeding? Defense? Mating?
Or just passed on from its ancestors?

A few more thoughts on bio-mimetics

Riblets on shark skin

When do the riblets reduce the drag on the shark?



Raschi & Musick (1986)

- Riblets reduce the drag at the bursting speed, not at the cruising speed.
- Understanding of dynamic regimes in a biological system is important for the application to engineering systems.

A few more thoughts on bio-mimetics

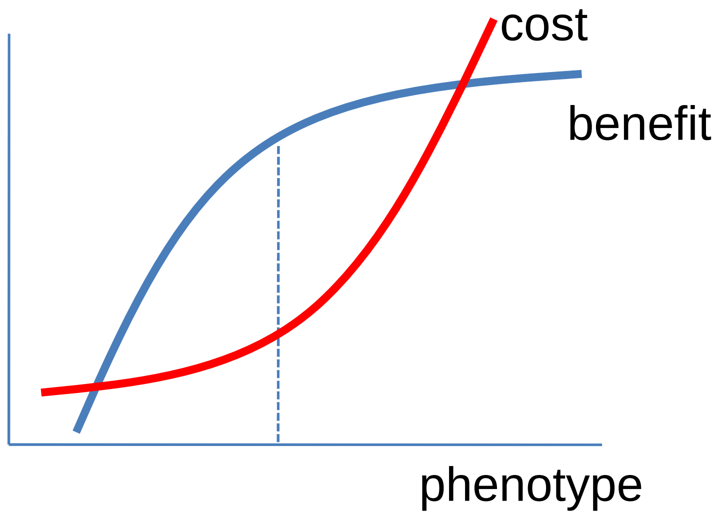
The biological features that you test for engineering applications might be

- imperfect adaptation
- the traits that are used for courtship or mating
- or just “passed on” from ancestors.

→ Failure of bio-mimetic approaches

A few more thoughts on bio-mimetics

- Biological systems have been optimized for multiple purposes (for survival and/or reproduction) and are mostly complex.
- There is a trade-off between the cost and the benefit of resource allocation.



- Even if a certain form is the best for benefit, it would not be observed in nature if the cost of producing it is bigger than the benefit.
- Thus, some biological systems may not be the optimal solution from the viewpoint of engineering.

→ Understanding of biological systems or methods is a key element for successful bio-mimetic flow control.

A few more thoughts on bio-mimetics

Biology	Engineering
Focus on variation (observation)	Focus on accuracy
Tend to measure a lot of samples, instead of repeated measurements	Tend to measure small number of representatives repeatedly
Express variation = difference among the individuals	Express variability = measurement error
What matters is the **fitness**	What matters is the **efficiency** Applicability is important
The more complex, the better	**The simpler, the better**
Even failure in engineering counts in biology	If fails, move on to find another subject

Concluding remarks

- Combining two different principles (biology & engineering) opens new area of research.

- "At present, there is only a 10% overlap between biology and technology in terms of the mechanisms used" (J. Vincent – Univ. of Bath): great opportunities.

- Knowing the biological systems or methods provides a proper path as well as a shortcut to engineering applications.

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