Bio-mimetic Flow Control

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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.
Why Bio-mimetic?

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

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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)
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

flow

V-grooved riblets

Walsh

\[ \Delta D (\%) \]

Drag reduction

Against our intuition:
smooth surface should have lowest skin friction

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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

- Maximum speed 110 (km/h)
- 97
- 75
- 68
- 60
- 50

Sailfish (seen)
Swordfish
Yellow-fin tuna
Killer whale
Dolphin
Shark: riblets (maximum 8% drag reduction)
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

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

Drag variation with the width (W)

Parallel staggered random

Parametric study → 180 different cases

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Smart surface for low skin friction

V-shaped protrusions of sailfish skin

Sagong et al. (2008, PoF)

Direct numerical simulation

\[(H^+, W^+, S_z/W, S_x/L, \text{pattern}) = (8, 87, 1.14, 2, \text{staggered})\]

5% Skin-friction reduction

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

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3. Compliant wall of dolphin skin

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

- 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
$C_M = 1.0, C_d = 0.6, C_K = 1.0$

Anisotropic wall property is being investigated.

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Smart surface for low skin friction

Fast sea animals

- **Sailfish**: 110 (km/h) - **Drag reduction?** No
- **Swordfish**: 97 - **Drag reduction?** No
- **Yellow-fin tuna**: 75 - **Drag reduction?** Maybe Yes
- **Killer whale**: 68 - **Drag reduction?** ??
- **Dolphin**: 60 - **Drag reduction?** ??
- **Shark**: 50 - **Drag reduction?** 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
1. Corrugated wing section of a dragonfly

- 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)

- How about its aerodynamic function during a flapping flight?

Session AV.00010
“Aerodynamic force variation in an inclined hovering motion by ....”
Wing-surface device

Corrugated wing section of a dragonfly

Hovering flight of a dragonfly ($\alpha_d=60^\circ$; $\alpha_u=20^\circ$)

During the downstroke: drag increases
During the upstroke: lift increases and drag decreases

+12% in the vertical force
Wing-surface device

2. Longitudinal grooves on a scallop shell
Wing-surface device

Longitudinal grooves on a scallop shell

![Graph showing the effect of grooves on lift coefficient (C_L) vs. angle of attack (AoA)].

Legend:
- Red circles: With grooves
- Blue circles: Without grooves

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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).

Wind tunnel experiment

- $C_L$ with tails
- $C_L$ without tails
- $C_D$ with tails
- $C_D$ without tails

Numerical simulation

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2. Arrays of small protrusions on a dragonfly wing

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

- 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 ($\alpha_d=60^\circ$; $\alpha_u=20^\circ$)

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

- **Wing-surface device**
- **Trailing-edge device**
- **Leading-edge device** for aerodynamic performance enhancement

**Smart surface for low skin friction**
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

<table>
<thead>
<tr>
<th>Wind Speed</th>
<th>Re Number</th>
<th>CL/CD Graph</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 m/s</td>
<td>Re=26,000</td>
<td><img src="image1" alt="Graph 1" /></td>
</tr>
<tr>
<td>5 m/s</td>
<td>Re=43,333</td>
<td><img src="image2" alt="Graph 2" /></td>
</tr>
<tr>
<td>7 m/s</td>
<td>Re=60,667</td>
<td><img src="image3" alt="Graph 3" /></td>
</tr>
<tr>
<td>9 m/s</td>
<td>Re=78,000</td>
<td><img src="image4" alt="Graph 4" /></td>
</tr>
</tbody>
</table>
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

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

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

Insects also have serrated leading edges.
A few more thoughts on bio-mimetics

Drag reduction from Saguaro cactus

Transverse grooves on a Saguaro cactus

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

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?

- 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.

Raschi & Musick (1986)
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**

Focus on variation (observation)

Tend to measure a lot of samples, instead of repeated measurements

Express variation

= difference among the individuals

What matters is the **fitness**

**The more complex, the better**

Even failure in engineering counts in biology

**Engineering**

Focus on accuracy

Tend to measure small number of representatives repeatedly

Express variability

= measurement error

What matters is the **efficiency**

Applicability is important

**The simpler, the better**

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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