RECENT PROGRESS IN BIOMIMETIC FLOW CONTROL

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1 Introduction

The biomimetic engineering is a scientific discipline of implementing nature-inspired ideas to engineering systems for their performance enhancement (Choi et al., 2012). Based on the premise that the features of living organisms are potentially optimal solutions for their survival and reproduction, the flow-control society has shown much interest in applying plant- and animal-based solutions to the development of novel concepts or techniques for successful flow control. One of the well-known examples of successful biomimetic flow control is the skin-friction reduction by use of smart surfaces, called riblets, inspired by the skin texture of a fast-swimming shark (Walsh, 1982).

The success of biomimetic flow control heavily depends on the collaboration and exchange of information between biologists and engineers, as was suggested by Choi et al. (2012). The pivotal role of biologists in biomimetic studies is to provide the information of living organisms, in the context of their environment, based on the observation. Some biologists explore the features of living organism and make a conjecture which may explain the underlying mechanism that governs the functioning of organisms. The work of engineers links the biological discoveries and conjectures to the analysis of mechanism by testing and screening the hypothesis through the experimental/numerical/theoretical proof. Based on the mechanisms investigated, engineers develop new technological solutions and apply them to related engineering systems to achieve the goal of flow control.

In Choi et al. (2012), we reviewed successful examples of flow controls based on the biomimetic approach, paying a special attention to the surface morphology of living creatures. In that paper, two types of flow control devices were examined: (1) devices attached or added to wing surfaces for high aerodynamic performance; (2) smart surfaces for low skin friction. In the present paper, we present our recent research activities since Choi et al. (2012), mainly focusing on the application of biomimetic concepts to transportation vehicles such as a wing and a ground vehicle. Three types of devices are considered: leading-edge, trailing-edge, and wing surface devices, respectively.

2 Leading-edge devices

Among various marine animals, the humpback whale is one of the biggest animals that shows an acrobatic motion using pectoral flippers characterized by an array of large bumps on their leading edge (Fig. 1). Miklosovic et al. (2004) performed a wind tunnel testing using a three dimensional wing with tubercles.
on the leading edge and showed that the addition of the leading-edge bumps to the airfoil model delays the stall (thus increases the lift and reduces the drag) at $Re_c = 5 \times 10^5$.

We investigate the effect of leading-edge tubercles on the flow around a three dimensional wing in more detail through the force and PIV (particle image velocimetry) velocity measurements. As shown in Fig. 2, the tubercles delay the stall by $5^\circ$ and increase the maximum lift coefficient by 13%. Without tubercles, the cross flow above the wing shows only the wing-tip vortex at high angles of attack (Fig. 3a). With tubercles, however, a strong vortex rotating in counter-clockwise direction is observed in between the wingtip and interior regions in addition to the wing-tip vortex near the wingtip region (Fig. 3b). This single vortex induces high momentum near the surface and delays the main separation. This result is very different from those found in a two-dimensional wing with tubercles with which a pair of strong counter-rotating streamwise vortices were observed (Zhang et al., 2013).

Another example of the biomimetic leading-edge device is the alula. The alula is a group of two to six feathers attached to a bird’s first finger at the bend of its wing (Chaplin and Faaborg, 1988). When a bird flies at a low speed or during landing, the alula moves slightly up- and forward creating a small slot on the wing’s leading edge (Fig. 4), whereas it is folded beneath the wing otherwise. The alula increases the stall angle and increases the maximum lift coefficient. The effect of alula on a bird wing may be similar to that of the two-dimensional slat on the wing of an aircraft in that both delay the stall (Lee et al., 2009), but the underlying mechanism may be different because the alula is three-dimensional in shape and its operating Reynolds number is much lower ($10^4$-$10^5$) than that of SD7003.

Figure 4: Alula: a magpie in landing approach (left) and the detailed view of an alula on a magpie wing (right).

Figure 5: SD7003 airfoil with alula-shaped device.
We devise a new leading-edge device that mimics the alula and applied this device to a low-Reynolds-number airfoil (SD7003) at $Re_\alpha = 10^5$ which is within the operating range of the alula (Fig. 5). At high angles of attack after stall, the alula-shaped leading-edge device increases the lift coefficient by 5% (Fig. 6) and decreases the drag coefficient by 20%, resulting in the increase of the lift-to-drag ratio by 26%. The velocity field measured using a PIV indicates that the enhancement of aerodynamic performance results from the delay of flow separation on the suction surface of the airfoil, and the wake behind the airfoil becomes narrow (Fig. 7).

### 3 Trailing-edge devices

The secondary feathers on the upper surface of bird wings tend to pop up during landing (Fig. 8) and prevent further proliferation of separation (Liebe, 1979). This concept was applied to an airfoil for lift increase at high angles of attack (Schatz et al., 2004). In our study, we apply the concept of this pop-up feather to a road vehicle, GM model (Han et al. 1996), for drag reduction. The GM model is a simplified, three-dimensional model vehicle (Fig. 9a). We modify this model such that it contains a slant upper surface at its rear part. The passive device mimicking the secondary pop-up feather, called an AMD (automatic moving deflector), is attached to the top rear edge of this model vehicle (Fig. 9b). Note that this device does not require any external power for flow control. When applied, the AMD automatically pops up owing to the flow near the trailing edge of the vehicle model, and reduces the drag on the GM model by up to 7.5% (Fig. 10). By measuring the velocity field around the GM model.
Figure 10: Variation of the drag coefficients ($C_D$) of the GM model for different streamwise lengths ($h$) of AMD ($H$ is the height of the GM model).

Figure 11: Contours of the mean streamwise velocity at $Re = 1.3 \times 10^5$ (a) no control; (b) AMD control ($h/H = 0.03$).

model, we show that, without the AMD, the flow separation occurs at the leading edge of the slant part (Fig. 11a) and low-pressure regions are formed on the slant surface as well as the base surface (Fig. 12a).

However, with the AMD, the flow separates at the trailing edge of the AMD (Fig. 11b), and the slant and base pressures are significantly recovered (Fig. 12b), resulting in drag reduction.

4 Wing-surface devices

Some scallops have grooves located radially on their upper and lower surfaces (Fig. 13). Bushnell and Moore (1991) conjectured that large grooves on a scallop shell control flow separation through vortex generation, and Choi et al. (2012) showed that the longitudinal grooves increase the lift-to-drag ratio by 5-25% at $\alpha \geq 5^\circ$, where $\alpha$ is the angle of attack. The range of the Reynolds numbers based on the mean chord length of the scallops is about $10^4$-10$^5$ (Hayami, 1991), and is within the operating regime of UAVs (unmanned aerial vehicle) (Mueller and DeLaurier, 2003). Thus, we apply the longitudinal grooves or strips to both the pressure and suction surfaces of a low-Reynolds-number airfoil (SD7003) for improving its aerodynamic performance (Fig. 14). As shown in

Figure 12: Contours of the pressure coefficient ($C_P$) on the rear slant and base surfaces at $Re = 1.3 \times 10^5$: (a) no control; (b) AMD control ($h/H = 0.03$).

Figure 13: Grooves on a sea scallop (*Patinopecten yessoensis*)
Fig. 15, the longitudinal strips delay the stall angle by about 2.4° and increase the maximum lift coefficient by 8% and lift-to-drag ratio by 8–108% at α ≥ 8° at Re = 6×10⁴, implying that the longitudinal strips on the surface of the airfoil enhance the aerodynamic performance of the airfoil at high angles of attack. We also conduct velocity measurements using a hot wire anemometry and a PIV, and showed that a counter-rotating streamwise vortex pair is formed above the valley between strips (Fig. 16), which enhances the vertical transport of high momentum fluid to the suction surface and delays laminar separation farther downstream. Transition to turbulence then occurs along the separated shear layer, which is followed by the flow reattachment, forming a secondary separation bubble above the suction surface. Owing to high momentum near the surface, main separation is delayed, and maximum lift coefficient and stall angle are increased.

5 Conclusions

In the present paper, we presented recent research activities of biomimetic flow control for the aerodynamic performance enhancement and drag reduction. Depending on the original locations of the features of living creatures, we classified the devices as the leading-edge, trailing-edge, and wing-surface devices, and they successfully enhanced the aerodynamic performance and/or reduced the drag force.

Since the animal locomotion is accomplished in air or water, its dynamics or mechanism is likely to be explained by the fluid mechanics principle. Therefore, as was pointed out by Vincent (2005), there are great opportunities in the field of biomimetic flow control to find nature-inspired simple and efficient solutions.

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References


