Biomimetic Design Inspired Sharkskin Denticles and Modeling of Diffuser for Fluid Control

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While sharkskin surface roughness has been hypothesized but remains yet controversial to be capable of achieving turbulent flow control and drag reduction, sharkskin-inspired “riblets” have been reported to be an effective biomimetic design (BMD). Here we address an integrated study of biomimetic riblets inspired by sharkskin denticles by 3D digitizing. Diffuser vanes with BMD structures were fabricated using the precision cutting and BMD diffusers were assembled. Diffuser’s fluid control was evaluated to confirm the effect of the BMD on fluid control. Our results indicate that the morphological feature in sharkskin denticles likely play a critical role in passively controlling local turbulent flow and points to the potential of denticle-inspired biomimetic riblets for turbulent-flow control in aquatic vehicles as well as other fluid machinery.

Keywords: Biomimetic riblets, Sharkskin, 3D digitizing, Diffuser, Fluid control

1. Introduction

Biomimetics, that seeks sustainable solutions and solve practical problems by emulating nature’s time-tested patterns, functions and strategies, has developed remarkably in recent years [1]. Flying and swimming animals can attain remarkable performance in terms of propulsion and maneuverability by creating lift and thrust forces while overcoming drag force efficiently. Their surfaces are normally three-dimensional (3D), flexible, and micro-structured with diversity, which are believed to play a crucial role in reducing drag while enhancing fluid dynamic performance [2]. While sharkskin surface roughness and its hydrodynamic functions has been the main subject associated with turbulent flow control and drag reduction for fast aquatic swimmers as well as aquatic and aerial vehicles [3-5], whether and how sharkskin, in particular, its denticles, is capable of improving fluid performance remains controversial

yet.

Sharkskin as illustrated in Fig. 1 is generally covered by numerous small tooth-like elements, termed dermal denticles (simply “denticles” hereafter) [6,7], with complex 3D shapes. The denticles have an inner bone-like layer and an outer enameloid layer, and they protrude above the epidermis and contact fluid directly. The shape of denticles shows distinct feature in different body-part of individual shark and in different species. The hydrodynamic function of sharkskin has been under investigation for more than 30 years with a hypothesis that the microstructure of denticles, i.e., the minute projections is able to passively control turbulent flow and reduce drag [8-15]. As a biomimetic design (BMD) of the denticles, the “riblets,” namely, the regular grooves with triangular or rectangular sections have been studied both experimentally and computationally, and confirmed to be able to reduce drag more or less

[16-23]. Actual denticles however in general demonstrate complicated 3D microstructures with a scale of less than 1 mm. Along with the recent rapid development in high-precision, high-performance 3D structural observation and analysis techniques for material surfaces it has become possible to measure the 3D micro-surface-structures of living organisms such as sharks.

In this study, we proposed a prototype biomimetic riblets design inspired by sharkskin denticles from the result of 3D structural digitizing of the denticles. We selected the centrifugal compressor as the candidate of application and applied the BMD to the diffuser vanes which reducing the efficiency of centrifugal compressor. Diffuser vanes with BMD were fabricated using the precision cutting and BMD diffusers were assembled. We evaluated the diffuser's fluid control and confirmed the effect of the BMD on fluid performance.

Fig. 1. Sharkskin is covered by numerous small tooth-like elements, termed dermal denticles with difference features at different body locations.

2. Experimental

2.1. Measuring and digitizing 3D micro structures of sharkskin denticles with microfocus X-ray CT

The sharkskin surface of Galapagos shark was measured with a high-performance microfocus X-ray CT (inspeXio SMX-100CT, Shimadzu Corporation) as illustrated in Fig. 2, with a size of sample approximately 2×1 cm. A sample that is located between an X-ray generator and an X-ray detector is rotated 360 degrees on a rotation stage while being irradiated with an X-ray beam. X-ray transmission data is collected at each angle, which are used to reconstruct an X-ray tomographic image (CT image) through computer processing. Because the microfocus X-ray CT system is capable of achieving dimension measurements on a focused

small area down to i.e., 2 to 5 μm the microstructures of sharkskin denticles can be measured with sufficiently high resolution for modeling.

A single denticle of Galapagos shark was extracted from the CT images for 3D reconstruction. The reconstructed 3D denticle of Galapagos shark is depicted in Fig. 3. Obviously the denticle has two unique characteristics: one is a sloping structure against the surface identical with that reported by Luo, et al. [23] (Fig. 3(a)), and the other is a feature of multiple grooves (with distinguished heights or widths) in water flow direction (Fig. 3(b)).

Firstly, the slope angle was investigated as illustrated in Fig. 3(a) in concern with the sloping denticle structure of Galapagos shark. Note that the denticle has its bottom buried beneath the sharkskin surface and thus, the angles of inclination (AOI) was defined as the angle between line "A-B" and line "A-C", where "A" points to the root point of a central projection, "B" the tip point of a central projection, and "C" the intersection point of a vertical line along the surface from point A and a line perpendicular to the surface from point B, respectively. The denticles' AOI of Galapagos shark is measured and observed to 27° .

Figure 4 shows a diagrammatic view of the groove-structured cross-section. The denticle of the Galapagos shark is structured with five-ridges or four grooves, namely, G_n ($n=1, 2, 3, 4$) with G_1 as the leftmost and G_4 as the rightmost groove with different surface areas ($S_{n,L}$ and $S_{n,R}$) at the right and left sides of each groove G_n . Characterized by the distinguished height or spacing in structure, such multiple-groove structure in denticles are herein termed as "non-uniform grooves". The non-uniformity of grooves occurs due to the different height or width between adjacent grooves (e.g. $H_1 \neq H_2$, $W_1 \neq W_2$).

Fig. 2. Set-up of a microfocus X-ray CT measuring system.

Fig. 3. Unique characteristics of the denticle of Galapagos shark: (a) slope structure, (b) multiple grooves.

Fig. 4. Diagrammatic view of a groove-structured cross-section.

2.2. Biomimetic design

It is predicted that the unique structures of the denticle (slope structure and non-uniform grooves) as shown in Fig. 3. are generated complex, three-dimensional local turbulent flows near the denticles, for example a rising flow and multiple longitudinal vortices aligned with water flow direction. It is considered that by generating these flows artificially, it is possible to improve the fluid performance of fluid machinery. Therefore, a surface structure with slope and non-uniform groove structure for generating a similar flows with the denticles is designed as shown in Fig. 5. The slope in Fig. 5(b) are 27 degrees. The grooves in Fig. 5(c) have non-uniformity for heights and width. h_1 and w_1 are 0.1 mm and 0.4 mm respectively. h_2 and w_2 are 0.05 mm and 0.15 mm respectively.

Given a reference speed of 8 m/s, which is a maximum speed when sharks catch prey, a reference length of 0.1 mm, which is a size of a denticle (see Fig. 1), and the dynamic viscosity of water, $1 \times 10^{-6} \text{ m}^2/\text{s}$, Reynolds number (Re) was calculated to be 1000 for the flow of sharkskin. On the other hand, given a reference speed of 100 m/s, which is a velocity in the diffuser, and the dynamic viscosity of gas $1 \times 10^{-5} \text{ m}^2/\text{s}$, a reference length in flow with the same Reynolds number of sharkskin ($Re=1000$), was calculated to be 0.1 mm. From this estimation, fluid control of fluid machinery was possible with a surface fabrication about 0.1 mm to obtain the same

fluid control as sharkskin. In determining the design values shown in Fig. 5, the reference length calculated above (0.1 mm) is set to h_1 . Furthermore, h_1 , h_2 , and w_1 were determined by a fabrication limit of a precision cutting method. The precision cutting method will be described in section 2.3.

Fig. 5. Designed structure based on the sharkskin. Features are slope and non-uniform grooves.

2.3. Fabrication of BMD and prototype of diffuser

The centrifugal compressor shown in Fig. 6 is an important mechanical component in industrial processes such as petroleum and chemical processing and iron manufacturing and energy infrastructure such as gas-turbines and natural-gas pipe-lines [22]. The suction power is generated by the impeller and diffuser. The impeller is rotated with a rotor at several-ten-thousands revolutions per minute (rpm). The rotating impeller makes the swirl flow. The swirl flow is connected to the diffuser, and the kinetic energy of swirl gas flow is partially converted to the gas pressure. The diffuser configuration is shown in Fig. 7. This diffuser has vanes, so it is called a vaned diffuser. The gas velocity reaches Mach 0.6-0.8 at the front of the diffuser vanes. Therefore, instability of gas flow is often caused at the tips of vanes. Thus, BMD is used for vanes, and the diffuser characteristics are

evaluated.

BMDs were fabricated on the tips of aluminum vanes by a precision cutting method (“BMD area” shown in Fig. 7). High performance five-axis cutting machine (V33, Makino, Inc.) was used for precision cutting. Figure 8 shows the SEM images of BMD. As shown in Fig. 9, the width of grooves ($W1$, $W2$), the length of slope ($L1$, $L2$, $L3$), the height of grooves ($H1$, $H2$), and the slope angle ($\alpha1$, $\alpha2$) are measured to reveal a fabrication accuracy.

Figure 10 shows the comparison of design and measured values of BMD. Figure 11 shows the error values of BMD. The errors between CAD and fabricated patterns in plane and depth were less than 10% except the height of grooves $H2$. The error of $H2$ may be improve by correcting the setting value of the cutting height of the end mill at the time of the second cutting at the time of forming the non-uniform structure.

Fig. 6. Outlook of vaned diffuser.

Fig. 7. Outlook of vaned diffuser.

Fig. 8. SEM image of the front-edge of vane fabricated BMD structure.

Fig. 9. Measurement parameter of BMD.

Fig. 10. Comparison of design and measured values of BMD.

Fig. 11. Error values of BMD.

3. Results of evaluation of fluid control

The fluid characteristics of the assembled diffusers were evaluated by using compressor evaluation equipment. The evaluation equipment can generate high-speed gas flow by rotating the impeller. The gas is introduced to the assembled diffuser. The flow volume is controlled by the flow control valve located at the gas inlet side.

Figure 12 shows the schematic diagram of diffuser. Pressure at inlet and measure point are measured and evaluate of fluid performance from the difference of pressure between measure point and inlet, δP , given as

$$\delta P = P_{\text{measurepoint}} - P_{\text{inlet}} \quad (1)$$

Figure 13 shows the pressure recovery characteristics of the BMD diffuser and conventional diffuser. The conventional diffuser which has plane vanes stalled at a low flow rate, i.e., in the high gas velocity region. However, the diffuser with BMD has a wider stable range, i.e., a large surge margin. This seems the effect of turbulent control by BMD. This feature is attractive for improving compressor ability because it enables the compressor to be controlled in a wider range of plant operation conditions.

Fig. 12. Schematic diagram of diffuser.

Fig. 13. Pressure recovery characteristics of diffuser.

4. Conclusion

In this study, we conducted an integrated study on the biomimetic design by measuring and digitizing “fresh” denticles with a micro-focus X-ray CT. Realistic 3D structures of Galapagos shark are digitized based on the measurements of a micro-focus X-ray CT, which reveals a featured denticle morphology: a sloping shape with large angles of inclination (AOI) 27° and a structure of the non-uniform grooves with five sharp ridges and a large height-to-spacing ratio. Biomimetic designed structures to generate a similar flow with sharkskin were fabricated on the tips of aluminum vanes accurately by a precision cutting method, and the diffuser with biomimetic designed structures was assembled. Our results revealed that the diffuser with sharkskin denticle-inspired biomimetic riblets have effect for turbulent-flow control and improving compressor ability.

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