Prediction the variation of shark scale’s attack angles in swimming

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ABSTRACT

Shark is the fast swimming animal in the ocean, and it is well-known for sharkskin effect. Sharkskin is covered by the tiny and rigid scales, which can stick out of the viscous sublayer and effectively inhibit the occurrence of turbulence and reduce the wall resistance. The longitudinal sections of the scale surface are not parallel to the flowing direction, but at a particular attack angle, which could be considered as a supplement to the mechanism of sharkskin effect. At present, it is almost impossible to observe the variation of scales’ attack angles during the biological shark’s swimming. Although the real sharkskin surfaces with original sizes have been fabricated by the bio-replicated method, the attack angles cannot be exactly controlled, the result of which is that the drag-reducing efficiency of sharkskin with different attack angles cannot be obtained by the experimental methods. In this paper, the highly accurate three dimensional digital model is exactly built through the high-accurate scanning the biological sharkskin, and the micro flow field is investigated comprehensively and deeply, especially that, the influence of scales’ attack angles on drag-reducing efficiency is analyzed, which has the important significance on exploring the sharkskin effect.

Key words: Attack angle, Biomimetic surface, Drag reduction mechanism, Numerical simulation, Sharkskin.

INTRODUCTION

Through millions of years’ natural selection, the surfaces of some natural creatures have evolved into unique hierarchical micro-structures with superior function to perfectly match their survival environment. For example, lotus leaf has the self-cleaning and super-hydrophobic effect, and there has been the proverb “Lotus coming out of the mud remains undefiled in spite of the general corruption” since ancient times in China (Jiang, 2000; Yuehao, 2014). Penguin, shark and other animals in the ocean have the lower resistance surface in the turbulent stations (Yuying, 2006; Bhushan, 2009; Yuehao, 2015). Therefore, it has developed into an important issue to investigate the biological functional surfaces and put them into application on the practical engineering.

Reif and Dinsklacker (1982) discovered that the morphology on sharkskin scales were different, which had the drag reduction effect in some certain turbulent stations. Since then, lots of researchers have investigated the drag reduction mechanism of sharkskin and explored the manufacturing processes, and now the international research and applications have entered practical engineering stage and obtained the satisfactory results., and lots of profits have been obtained from different fields, including industry, agriculture, nature gas pipelining and so on (Zhang, 2011; Luo 2012). It has become an indisputable fact that biological and biomimetic sharkskin surfaces have the drag-reducing effect. Bechert D. W. (1997; 2000) machined different artificial magnified or idealized sharkskin surfaces by optimization, and the drag-reducing efficiency in test conditions could reach the maximum of about 10%. Luo Yuehao (2013) fabricated the continuous vivid sharkskin with good forming effect by the micro-rolling method for the first time. Zhang and Luo (2011; 2014) put the micro-grooved drag-reducing technology into application on nature gas pipelining, and the field experiments told us that the pressure loss on the same circumstance could be decreased more than 8%. George V. Lauder (2012) explored the self-propelled swimming speed of different surfaces, and he found that sharkskin denticles might enhance thrust, as well as reduce drag. Luo and Zhang (2011; 2013) analyzed the micro flow field over sharkskin surface deeply and explored the drag reduction mechanism from different aspects. Haecheon Choi (1993) studied the direct numerical simulation (DNS) of micro flow field over

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the simplified and direct grooved surface for the first time, and the drag reduction mechanism was investigated and explored deeply. Luo Yuehao (2012) machined the vivid trans-scale enlarged sharkskin scales utilizing the 3-D printing method, which can give the visual impression to us. Li Wen (2014) fabricated the flexible 3D printed sharkskin model, and thousands of rigid synthetic shark denticles were placed on flexible membranes in a controlled, linear-arrayed pattern, the tests in water tunnel showed that the drag-reducing efficiency can reach 5.9%. In a word, the biological and biomimetic sharkskin surface has the tremendous room to be developed for drag reduction in fluid engineering.

The above-mentioned achievements about sharkskin surfaces are mainly focused on the manufacturing processes, experimental testing and numerical simulation. However, the drag reduction mechanism of sharkskin still has not been understood absolutely and thoroughly so far, especially for the influence of scales’ attack angle on drag reduction efficiency, which restricts the practical application. In this paper, the 3-D digital model of sharkskin is exactly built and the numerical simulation of micro flow field over sharkskin surface is carried out by CFD, the relationship between drag reduction efficiency and scales’ attack angles are obtained, which can be considered as the supplement for sharkskin effect.

MATERIALS AND METHODS

Shark and specimen: Fast swimming sharks possess the amazing speed in the seawater, which has become the research hot topic in biomimetic drag-reducing field. The max swimming speed in the ocean can reach more than 10m/s, and the common species of sharks include Sphyrna zygaena, Carcharhinus leucas, Scyliorhinus canicula, Rhincodon typus, Carcharodon carcharias, Isurus oxyrinchus, Carcharhinus brachyurus, mako shark and so on (Springer, 1989; Naresh, 1997), and their shield scales have the sharp ribs and round grooves, which are mainly the typical properties and characteristics of fast-shark scales.

In this paper, the short fin mako shark is set as the research object, as shown in Fig.1, its weight is 25Kg and its total length is about 1.2m, and it is one kind of the large-medium sized animals living in the tropical and temperate waters, and it belongs to the fastest swimming sharks. The main body features of short fin mako shark are as following (Springer, 1989; Naresh, 1997): (1) the basic color is cyan, the side and abdomen is white; (2) its trunk is hypertrophic and fusiform, its head and tail are changing tapered gradually; (3) it is obvious by the keel on the caudal peduncle, the pointed snout, the homocercal tail, the coloration on the pelvic fin, and the relatively small anal fin. The templates used in this paper were sampled from dead shark, and its skin is covered by many diamond-arranged small scales, the SEM image of sharkskin is shown in Fig.2, the extension direction of scale is proximately parallel to its swimming direction, and the groove tips of scale can stick out of the viscous sublayer, which can effectively inhibit the occurrence of turbulence and has the function of reducing wall resistance.

Structure of sharkskin scale: Sharkskin scales differ from those of bony fishes both in structure and material, they do not increase in size as the fish grows, so it can be regarded that the scales from the same part of a skin have the same groove structure. Furthermore, sharkskin scales are made of enamel, and they consist of sharp spines and a rectangular base plate which is deeply embedded in the skin, so the spines and the base plate build a firm cantilever beam, as shown in Fig.3. There are a lot of secretion mucus on sharkskin, the four kinds of sharkskin functions applying the scales and slime can be concluded: protection, drag reduction, anti-fouling
The three dimensional image of sharkskin scale can be obtained by the highly precise scanning method, as shown in Fig. 4, the width of scale groove is about 50um, the depth of scale groove is different at different positions and varying from 5um-40um. The scale is made of enamel, although it is very rigid and un-deformable, its root basis is embedded in the muscle and dermal tissues, which can produce the flexible deformation under the adjustments of nervous system, therefore, the attack angles of sharkskin scales are possible to be changing at different swimming conditions.

**Method of analyzing attack angles’ variation:** The variation of attack angles during swimming can be regarded as the supplement of sharkskin effect, and however, it is impossible to observe it on the live and locomotive shark at the present research levels, and the direct numerical simulation is a good attempt.

In this paper, Fig. 5 shows the process flow sheet of analyzing variation of sharkskin scales’ attack angles during swimming. The main steps are as following: (1) pretreat the sampled sharkskin and get the clean surface of biological templates for scanning, in which for purpose of obtaining the clean and neat surface of biological sharkskin, it should include cleaning, chemical fixation, re-cleaning, dehydration and desiccation; (2) sputter the surface of biological sharkskin for good optical reflection and electric conduction, the subtle particles of Au should be uniformly distributed on the scale surface; (3) scan the morphology on sharkskin scale with highly accurate equipment and obtain the sufficient and precise data; (4) build the three dimensional and accurate digital model of sharkskin scale; (5) carry out the numerical simulation of micro flow field with CFD and explore the drag reduction mechanism.

**NUMERIAL SIMULATON ANALYSIS**

**Model building of biological sharkskin:** For investigating the variation of scales’ attack angles during swimming by the CFD method, the accurate digital model should be built at first, and the main steps are as following: 1) super highly accurate scanning the single biological scale; 2) data analyzing and processing; 3) building three dimensional digital models of single scale and sharkskin in a large area. 4) building the computational domain; 5) building CFD model and numerical simulation. Because all the relevant information of the computational domain derives from the real biological sharkskin samples, the results of numerical simulation have the more convincing effect.

In the process of building digital model, the highly precise instruments are adopted to obtain the sufficient and precise data, which mainly include Phase Shift MicroXAM-3D (produced by AEP Technology Co. in the USA), with
RMS repeatability of 1 nm, the minimum of vertical scanning resolution of 0.1nm and the calibration accuracy less than 0.1%. The scanning experiments were carried out in the State Key Laboratory of Tribology, TsingHua University, and the light was exposed to the sharkskin surface vertically in scanning process, the three/two dimensional image of single scale surface can be obtained, and the more detailed and precise data could be received by marking the line, as shown in Fig.6.

Sharkskin scale has many sharp edges on its surface and the results received from SPIP software are relatively closed, so the information of all points cannot be obtained directly. In this paper, the data of the cross-section curve is fitted firstly, and then imported into the Solidworks software, and the 3-D digital model of sharkskin scale can be built by the lofting forming method. Additionally, the longitudinal sections of the scales are not parallel to the flowing direction, but at a particular attack angle, the attack angle ($\alpha$) is usually ranging in 10°-35° by observation and inspection, and the digital model of sharkskin scale is built at last, as shown in Fig.7.

**Building of CFD model:** The surface of sharkskin scale is so complicated, and it is very difficult to paste different surfaces without any gap, so the continuity of computational domain cannot be ensured. In this paper, the real sharkskin surface is simplified in a reasonable way, as shown in Fig.8. Similar to the most turbulent flow simulations, CFD can be classified in three groups: Reynolds-Averaged Equation (RANS), Large Eddy Simulation (LES) and Direct Numerical Simulation (DNS), and the DNS method is adopted in this paper. For ensuring the high accuracy of computation and reducing the total number of grids, the distribution and the course of simulation should comply with the following principles: 1) In order to capture the features of flow filed near the wall, the grid near the upper wall and lower wall location in the turbulent boundary layer should be close as soon as possible. 2) Limited by the capacity of computer, the total number of grid of the computational domain should be constrained in 1,600,000, so the grids should be sparse in the region far from the wall. 3) The RNG $k$-$\varepsilon$ turbulence model is selected, and the Enhanced Wall Treatment is put into application near the wall, others can be set as default, which can exactly simulate the flow filed situation near the tiny grooves. 4) Because of the fully developed turbulent, the flow inlet and flow outlet of the computational flow field should be set as periodical boundary condition. 5) Among the span wise of the flow field, the flow is not constrained. In order to ensure the flow field without other interference, the boundary condition along the span wise of the computational flow field.
is set as symmetry condition. 6) The upper smooth wall and the lower real sharkskin surface wall are set as no-slip and impenetrable boundary condition.

The distribution of grids on sharkskin scales is very important to numerical simulation, and the distribution is shown in Fig. 9, the total number of grids in the whole computational fluid zone is about $1.5\times 10^6$, and the maximum and minimum of grid volume are $4.5 \times 10^{-16}$ m$^3$ and $3.6 \times 10^{-20}$ m$^3$ respectively.

**Analysis of micro flow field:** When the attack angle of scale is set as $15^\circ$ and the average velocity in the flow field is 6 m/s, the Reynolds number exceeds the critical value and the flow comes into a fully developed turbulent station. In the process of numerical simulation, the number of iterations is set as 200, the contours of shear stress in the flow direction over real shark skin surface and smooth surface can be obtained, at the same time, in order to further analyze the shear stress, the contours of shear stress on a single scale are also received, as shown in Fig. 10.

According to the results of numerical simulation, the shear stress on the smooth surface is almost uniform, about 408 Pa - 738 Pa, but on the single real sharkskin scale it takes a value of about -580 Pa - 4700 Pa on the flow direction, and the maximum is on the tip, which is larger than that on the smooth wall, the minimum is on the valley, which is so much less than that on the smooth surface or even opposite to the flow direction. Therefore, the integral of the shear stress over the real sharkskin is also less than that on the smooth surface, so the real sharkskin shows a drag reduction effect.

Several key points (A, B, C and D) at different positions of the cross-section are chosen to investigate the velocity distribution, as shown in Fig. 11 and Fig. 12. It can be seen that the velocity gradient on A is the largest and the velocity gradient on C and D is much less than that on B, in which, point A is on the tip of scale, point B is on the smooth surface, and points C and D are on other places of scale except the tip. Therefore, the average velocity gradient on surface is less than that on smooth surface.

**RESULTS AND DISCUSSION**

When the attack angle of sharkskin scale is set as $10^\circ$, $15^\circ$, $20^\circ$, $25^\circ$, $30^\circ$, $35^\circ$ respectively, the drag reduction efficiency of sharkskin surface in different velocities can be obtained and the relationship can also be received, as shown in Fig. 13, it can be seen that the maximum of drag reduction efficiency can exceed 12%.
FIG 13: Relationship between drag reduction efficiency and attack angles

which is larger than that of simplified and straight grooved surface. Moreover, with the increasing velocities, the drag-reducing efficiency corresponding to different attack angles are all first ascending, and then to the maximum, and then descending. And the preliminary finding by numerical simulation can be obtained: in shark’s swimming, the attack angles are changing with its swimming states and conditions.

OUTLOOK: Based on the above-mentioned analysis, the relationship between drag reduction efficiency and attack angles can be regarded as the effective supplement of sharkskin effect. Although the numerical simulation of micro flow field on sharkskin surface is carried out in detail and the important stand-points are obtained, the all scales in the computational fluid zone is set as uniform, additionally, the real sharkskin surface is not exactly plat but some certain

FIG 14: Scanning the whole shark and point-cloud model of shark
curved. Therefore, there are inevitably some deviations in the conclusions.

In this paper, the whole shark is precisely scanned and the point-cloud model is built, as shown in Fig. 14. In order to investigate the variation of scales’ attack angles during swimming and explore the drag reduction mechanism further, the more comprehensive analysis on the whole shark should be carried out.

CONCLUSIONS

The precise digital model of sharkskin scale is built and the numerical simulation of micro flow field is carried out in this paper, especially, the influence of scale’s attack angle on drag reduction effect is investigated. The main conclusions are as follows:

1) The attack angle of sharkskin scales is one important factor to produce the high drag reduction efficiency, which can decrease the turbulence intensity on the basis of grooves, which can also lead to the occurrence of tiny back flow on the valley of the scale.
2) By comparing the influence of attack angles, the preliminary conclusion can be obtained by numerical simulation: the scales’ attack angles are changing with its swimming stations.
3) For purpose of exploring the drag reduction mechanism further, the more comprehensive analysis on the whole surface of shark should be carried out, and now the point-cloud model of shark has been preliminarily built, which has important significance.

REFERENCES


