Turbulence Augmentation over a Bristled Shark Skin Model

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Experiments were conducted to discern the turbulence augmentation achieved over a bristled shark skin model embedded inside a turbulent boundary layer. It is hypothesized that shark scales are passively bristled by the flow in regions where incipient separation is present. The formation of embedded vortices within the model leads to the presence of partial slip velocities adjacent to the main boundary layer flow which range from 5 – 30% of the freestream velocity. The turbulence levels in the boundary layer are increased as measured by the increase in Re stress levels, which also leads to the high partial slip velocities via mixing in and out of the cavities. It is hypothesized that that positive effect of an increase in momentum adjacent to the surface will prevent local flow reversal and global flow separation. Results suggest that the negative aspects of increased overall drag, as evidenced in the boundary layer profiles, would be minimized if only localized bristling were to occur thereby minimizing the surface area of the bristled microgeometry.

Nomenclature

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\begin{align*}
\delta & \quad \text{boundary layer thickness} \\
u & \quad \text{local streamwise velocity} \\
U & \quad \text{freestream velocity} \\
y & \quad \text{vertical height}
\end{align*}
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I. Introduction

Swimming animals have evolved a number of strategies and mechanisms that reduce the drag forces that they experience when moving through the water. The texture of the shark skin is one example. This surface is characterized by denticles, complex 3D placoid scales that aid the shark’s swimming by acting as a drag reduction feature. These denticles contain several details in their geometry that may be beneficial, including a series of ridges (riblets) on the leading surface known to reduce turbulent skin friction drag¹, and a contoured shape. It has been speculated that the denticles if bristled may act as vortex generators³. It is our hypothesis that the denticles additionally function as a passive flow control mechanism for separation control, but using a different mechanism than vortex generators. Biomimetic applications of the shark skin texture for flow control would require little effort to implement if their advantages are fully understood. This work aims at better understanding the beneficial effects of a bristled shark skin microgeometry under turbulent boundary layer conditions for separation control. This will be measured primarily by looking at the increased momentum close to the surface via the partial slip condition

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created by embedded vortices. Additional investigation will focus on the increased mixing of high momentum fluid closer to the surface.

Surface patterning can have several advantages over a smooth surface. One prevalent example of a uniform d-type roughness pattern being used to regulate the boundary layer and prevent flow separation is the golf ball. The dimples present on the sphere create cavity vortices that increase the momentum of the flow close to the wall. The flow creates a partial-slip condition at the wall and induces a transition to turbulence. While laminar flow around the sphere transitions to turbulence and the skin friction drag increases as a result of the surface patterning, the reattached boundary layer is more efficient overall and more so than just tripping the boundary layer to turbulence.

Analyzing the behavior of the boundary layer when it first encounters the roughness feature and comparing with the results of the flow’s prolonged travel over the model will test the hypothesis that the roughness feature is most effective where the flow first encounters it. This would be the condition if indeed the scales are bristled locally only in a region of incipient, global flow separation. In fact, it should be realized that the formation of embedded vortices within the surface really represents confining separation to small, localized regions within the surface. Understanding the function and placement of the bristled shark skin geometry inside a turbulent boundary layer is necessary in order to implement similar features in air and water engineering applications.

Previous studies on the shark skin model as well as simplified cavity models, such as a 2D grooved cavity, a square-sawtoothed model, and a hexagonal mesh, have shown that the presence of these roughness features causes the flow to behave differently than it would over a flat plate control case. One major feature prominent in many different studies and geometries of cavities was the existence of a partial-slip condition at the wall. The fluid has a nonzero velocity, a percentage of the full freestream value, at the surface of the model. In tests of a turbulent boundary layer over square cavities, it was found that the inflows and outflows from the cavities were not uniform and that there were random bursts of fluid moving into and out of the cavities. As a result of the exchange of fluid between the cavities and the boundary layer, the Reynolds shear stress was greater than over a flat plate and peaked over the cavities. Additionally, recent work has shown that these microgeometries (in this specific case an embedded hexagonal cavity) may be most effective immediately after the flow encounters them. Running experiments over a series of cavities will show whether this phenomena occurs over the bristled shark skin geometry as well. Experiments using Digital Particle Image Velocimetry were used to visualize the velocity field of the turbulent boundary layer. These experiments were focused on observing the behavior of the boundary layer itself instead of the activity in the cavities for a turbulent boundary layer encountering a bristled shark skin microgeometry.

II. Experimental Method

During these experiments, all trials were conducted in the University of Alabama water tunnel lab using a DPIV system. Tests were run in an Eidetics 1520-EXT low freestream turbulence water tunnel manufactured by Rolling Hills Research Corporation. The tunnel has a test section of 30"x16.25"x108" and can hold roughly 1,500 gallons of water. The water tunnel was run at a velocity, $U$, of 20 cm/s.

Since the tunnel runs at fairly low speed, the boundary layer needed to be tripped to turbulence manually. This was done by placing a small, plastic rod at the front of the flat plate in which the model was embedded (following a long section of leading flat plate). The flow was given sufficient time to transition to full turbulence before encountering the model. The flat plate that the flow passes over before encountering the model allows the boundary layer to grow to more similarly match the boundary layer thickness to roughness height ratio also found for flow over a shark. This flat plate modular section is 18 in long by 24 in wide with an elliptical nose placed at its front. There is a trailing section to the flat plate assembly as well that includes an adjustable back flap to insure smooth flow over the leading edge of the flat plate model.

The model created for the experiment was based on the geometry of the shortfin mako (*Isurus oxyrinchus*) shark, which is estimated to be capable of swimming at speeds around 20 m/s or greater. The bristled shark skin model consisted of an array (26 rows X 16 denticles per row) of 2 cm tall denticles. Alternating rows were each offset by 1 cm and staggered to create a network of peaks and valleys. The model was embedded in a flat plate and placed after a long leading flat plate section, similar to that reported in Lang et al. The origin for the coordinate system was located with $x=0$ at the tip of the denticle and $y=0$ at the effective top of the cavity, not the tip of the model (Fig. 1). The $y=0$ height is level with the flat plate in which the model is embedded.
Time Resolved Digital Particle Image Velocimetry (TR-DPIV) experiments were used to analyze the flow. For these trials, reflective silver-coated glass sphere particles (Conduct-o-Fil ® by Potters Industries Inc.) were seeded into the water tunnel flow. The particles were illuminated by a laser sheet created using a Quantronix Falcon 30 series Nd:YLF laser with a wavelength of 527 nm. Images of the flow with a resolution of 1280 by 1024 pixels were taken using an 8 bit Basler A504k camera at a rate of 400 frames per second (the same as the frequency of the laser) operated using National Instruments LabView software. PixelFlow software processed the images to calculate velocity fields and other turbulent statistics (averaged over 1200 image pairs); data was exported as a text file for use in Microsoft Excel or MATLAB for plotting.

Tests were conducted with a similar cavity flow Reynolds number to a swimming shark; since actual shark scales are ~200 μm in size, 100 times smaller than the model, the freestream velocity in the trials was 20 cm/s instead of 20 m/s, the actual speed of a fast-swimming shark. In the calculation of this Re, the characteristic length was the height of the cavity (2 cm). The Reynolds number for the trials was 2000. As a control for comparison, tests were run with a flat plate at the same velocity under turbulent flow conditions.

The denticles in the model are staggered by the width of half a denticle between rows. Because of the staggering of the denticles in which the tip of one row is aligned with the edge of the next, two views of the model were investigated. The first was run with an offset of 7.5 denticles from the bottom of the model, aligned with the tip (x=0) of the even denticle rows. The second was a quarter of a denticle lower, aligning with the top ridge on one scale and the bottom of the next row over. At these valleys, the tips do not protrude into the flow, allowing for comparison between the points where the denticle obstructs the movement of particles and channels that the flow can pass down without any obstacles. Figure 2 shows a schematic of the peak and valley locations.

III. Results

The influence of the shark skin model was visible in the velocity field of the boundary layer as soon as the geometry was encountered. First, partial slip velocities were measured at the y = 0 plane and peak values were found for each cavity in both the peak and valley planes. These are shown in Figure 3.
Figure 3. The peak values for the partial slip velocities over the span of the model. The difference between the tips and the denticle edge behaviors is prominent. The valleys had slightly more consistent values.

In the peak orientation, the partial slip velocities were always lower in the cavities directly before encountering the denticle tip. Since the tips force the fluid to move around them, this could lead to the higher partial slip velocities in the following cavity as fluid moves back through while encountering an obstruction in the next row. In the valleys, the partial slip location increased at some locations while the tip velocity decreased. As a result of the tips, fluid moved into these regions of the model, and higher velocities would develop to compensate for the obstructions elsewhere.

The partial slip velocities along the span of the model also demonstrated the impact of prolonged exposure to the denticle geometry. The velocities increased over the first cavities and reached their peak near the middle of the model. The decrease in partial slip velocity near the end of the model suggests that embedded cavities may have limited ranges of effectiveness. The location of the peak partial slip velocities varied as a result of the position relative to a tip as well (Fig. 4). For the odd cavities, the location of the highest momentum fluid was at roughly 60-70% of the cavity width for the tips and started falling slightly earlier in the cavity after exposure to several rows of denticles. In contrast, the position in the even cavities was earlier in the cavity and fell between 30-50% of the cavity width. These values also tended to reach the maximum velocity earlier in the model in the later cavities. As was the case with the valley velocities themselves, the location of the peak velocities in the valleys was less dependent on odd or even row than with the tips. Since the velocities peaked sooner in rows after encountering the tips, the higher partial slip velocity and the earlier location in the cavity are both likely a result of fluid entering the cavity.

Figure 4. The location of the maximum partial slip velocity for each cavity. The rows immediately following the tips peaked much sooner than those at the gap between denticles. The valley orientation demonstrated less of a clear trend since the fluid is moving through that location without encountering obstructions.
Averaging the turbulent boundary layer over time allowed for analysis of the boundary layer velocity profiles. From the partial slip condition present at $y = 0$ over the roughness feature, the influence of the cavities on the flow above them was analyzed. All boundary layer profiles were taken at the center of the cavity being investigated. Figure 5 shows the profile at the center of the second cavity. In the early cavities, other than the imposed partial slip velocity, the boundary layer profiles are very similar to that of the flat plate. The flat plate does maintain slightly higher momentum in upper regions in the earliest segments though. However, the prolonged flow over the cavities shows that while there is still a partial slip velocity acting at $y = 0$, the fluid is moving much slower than in the flat plate case in the rest of the boundary layer (Fig. 6). The uppermost regions ($y/\delta = .6$ and above) of the boundary layer fluctuate with regard to which has the highest momentum though, suggesting that averaging over a greater time interval may be needed for more accurate results.

The lower momentum fluid in the upper regions of the boundary layer suggests that the intrusion of the denticle tips may have impeded the flow and caused the fluid to slow. With the bristling mechanism of separating flow pushing back up on the denticles to create the cavities, it is likely that the angle of attack on a swimming shark is not $90^\circ$ as it is in this model. This could be a reason why the tips are impeding the flow as well as having beneficial effects. Recent observations on shortfin mako skin suggest angles of 60 to 70 degrees for bristling.

Figure 5. The boundary layer profile over the center of the second cavity is similar for all 3 trials. This is after the first exposure to the full denticle tips in the plane.

Figure 6. The evolution of the boundary layer profiles shows the partial slip velocity, but that the velocities are lower in the rest of the boundary layer.
Since tests were conducted for turbulent flow conditions, the unsteady portion of the fluid velocity was another major area of investigation. Time-averaged comparisons of the Reynolds stresses for the model demonstrated the exchange of fluid between the cavities and flow mixing near the surface \( (y = 0) \). The Reynolds stresses above each cavity did not reach their peak magnitude until the middle of the model, suggesting that it takes some time for the greatest exchange of fluid between the cavities and the boundary layer to develop and that the cavity effectiveness at promoting this mixing may not peak at initial encounter, but after some exposure (Fig. 7). In the peaks, lower Reynolds stress magnitudes were observed in the odd cavities, when fluid is exiting the cavity prior to encountering the tip of a denticle. When the cavities do not have imminent obstructions, as they do in the even numbered sections, there is more of an exchange between the high momentum fluid of the boundary layer and the low momentum fluid of the cavities instead of fluid simply exiting the cavity as it does in the odd arrangement. The magnitude of the Re stress was higher in the peak orientation than in the valleys. This could be caused by the more consistent geometry of the valley’s prohibiting the larger fluctuations in velocity caused by the intrusion of the tips in the peaks. Unlike the partial slip values, the location of the peak Re stress was not uniform across the trials and sections.

![Maximum Reynolds Stress](image)

**Figure 7. Maximum magnitude Reynolds stress measured over each cavity.**

The Reynolds stress contours for the cavities showed the exchange of fluid between the cavities and the boundary layer and disturbances to the flow created by the microgeometry itself (Fig. 8 shows for example the distribution over the peaks). While the maximum value for the Re stress varies based on whether it is over an odd or even cavity, the shape of the contours depends more on the location in the span of the model. The mixing extends further out into the boundary layer growth as the fluid is exposed to the denticles for longer. Cells of high positive Re stresses could be found on odd denticles. Since the flow is not physically encountering a denticle at this point, both the fluid in the cavities and in the boundary layer have high momentum, as opposed to the mixing of high momentum boundary layer and low momentum cavity fluid. In general, the Reynolds stress values were higher in the peak view than the valleys, and this is shown by studying Re stress profiles which are shown also compared to the flat plate case in Figure 9. The profiles show high Reynolds stresses extending further from the model in the later cavities, similar to what is shown in the contours. The mixing extending further above \( y = 0 \) is also prominent in the profiles; there is a taller region of high Re stress values in the higher cavities. The valleys tended to peak at a lesser distance above the cavity than the tips. This is likely the result of the denticles themselves not extending as far into the flow at this location, effectively making the cavity section lower in the \( y \) plane.

**IV. Conclusions**

The shark skin geometry has a significant impact on the behavior of the boundary layer. By creating higher momentum fluid near the wall, a partial slip condition is generated throughout the span of the model. The decrease in partial slip velocities at the end of the geometry suggests that in any implementation of the embedded cavities, careful attention to the length of the roughness needed for maximum effectiveness should be an issue. The need for the flow to pass several cavities before reaching peak Reynolds stress values suggests that some of the beneficial effects of the cavities on the flow to deter separation need to develop over initial exposure to the geometry and do not occur immediately upon first encounter.

The boundary layer profiles show that a major concern in future studies should be the angle of attack of the denticles. In their current orientation, the tips may be obstructing the flow too much for a realistic simulation of the shark skin. A lower angle of attack, as suggested recently to be 60 – 70 degrees by biological studies, should provide a more accurate model of the shark and a more beneficial cavity shape.
Figure 8. Reynolds stress ($\text{cm}^2/\text{s}^2$) contours over the beginning and ending cavities. The stresses created by the cavities extend further into the boundary layer at the end of the model.

Figure 9. Reynolds stress profile above the model at 3 locations along the span of the cavities. The peaks flatten towards the end of the model, creating larger regions of high Re stress.

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