AN INVESTIGATION OF THE FLOW CONTROL MECHANISMS
OF SHORTFIN MAKO SKIN

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ABSTRACT

The skin of fast-swimming sharks is proposed to have mechanisms to reduce drag and delay flow separation. The shortfin mako *Isurus oxyrinchus* is one of the fastest and most agile ocean predators and would benefit from minimizing its pressure drag by controlling flow separation. The skin of shortfin makos is covered in teeth-like denticles with lengths on the order of 0.2 mm. Recent biological studies have shown the bristling angle of these denticles to exceed 50° in locations likely to experience separation first. It is proposed that the reversing flow that occurs near the onset of separation activates denticle bristling. Once activated, the scales would impede the development of a more global separation event over the shark by stopping the reversing flow from travelling further upstream and causing interactions within the boundary layer that allow it to stay attached longer.

Real shark skin samples are exposed to reversing flow and the interactions with the scales are documented with a specialized camera setup. The camera setup provides high magnification while still providing a large enough depth of field to visualize scale movement. It is shown that reversing flow indeed interacts with the scales and causes bristling in flank region specimens.

Because it is not possible to test at the swimming speeds of the real mako in the University of Alabama water tunnel, a biomimetic scale array model is used in the experiment to study the boundary layer, Re stress, and cavity structures over the shark skin. It is shown that the introduction of the scales in the turbulent boundary layer yields a positive benefit in the flow by brings higher momentum fluid toward the surface. An examination of the cavity structures shows cavity vortices in most cases, with the notable exception being the first cavity in the
turbulent boundary layer case which shows no average core vortex and instead shows an outward trend of fluid motion toward the boundary layer above. These results indicate the possibility of shortfin mako scales to control flow separation.
DEDICATION

This dissertation is dedicated to my Dad who always thought I was capable of achieving anything and inspired me to always dream bigger and aim higher. I know he would be incredibly proud as I complete this major milestone in my life and he’d probably smirk and ask when he could expect his corvette. I am forever thankful for the love and support he was so willing to give. Without him, this would never have been possible.
LIST OF ABBREVIATIONS AND SYMBOLS

\( D \)  Jet exit diameter, cm or \( \mu \)m

\( r \)  Radial distance from jet centerline, cm or \( \mu \)m

\( R \)  Jet exit radius, cm or \( \mu \)m

\( Re \)  Reynold's number

\( Re_D \)  Reynold's number based on jet diameter

\( Re_s \)  Reynold's number based on streamwise distance from leading edge

\( s^+ \)  Nondimensional length in spanwise direction

\( TR-DPIV \)  Time Resolved – Digital Image Velocimetry

\( U_{av} \)  Average exit velocity of jet, cm/s or m/s

\( U_{max} \)  Maximum velocity along jet centerline, cm/s or m/s

\( U_\infty \)  Freestream velocity, cm/s or m/s

\( u \)  Component of velocity in \( x \)-direction, cm/s or m/s

\( v \)  Component of velocity in \( y \)-direction, cm/s or m/s

\( x \)  Location in the streamwise direction along the plate, cm

\( \rho \)  Density, kg/m\(^3\)

\( \mu \)  Dynamic viscosity, kg/m·s

\( \nu \)  Kinematic viscosity, m\(^2\)/s

\( \delta_{turb} = \frac{0.16x}{Re_x^{1/7}} \)  Turbulent boundary layer height, mm

\( \delta_{lam} = \frac{5x}{\sqrt{Re_x}} \)  Laminar boundary layer height, mm
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CHAPTER 1

INTRODUCTION

Bioinspiration has been a major focus of engineering research in recent years. Nature’s ability to solve many common problems faced by engineers has inspired collaboration between engineers and biologists to explore and understand the solutions present in nature. Particularly, aquatic animals have been a key area of focus for their drag reduction and flow control abilities [1]. The skin of fast-swimming sharks has been extensively studied in the area of turbulent skin friction drag reduction. More recently, it has been shown that the scales on the skin of shortfin makos may also contribute to flow control and the delay of separation [2]. The key aspect of this new area of research is the high flexibility of the scales along the flank and trailing edge of the pectoral fin [3]. Flow reversal occurs near the start of flow separation and preventing this reversing flow from propagating upstream could have potential benefit by delaying global separation. In order to fully explore this possibility on real shark skin, a specialized system capable of magnifying the 200 μm scales so that they are visible to the human eye while also allowing for a large enough depth of field to capture scale movements was designed. Typical microscope video cameras available could not provide this depth of field required. A combination of macro photography and biological techniques is used to convert an off-the-shelf Nikon D7000 camera body into a video and imaging system capable of documenting scale movements. Chapter two details how this unique system is used to study the shortfin mako scales under reversing flow.
Chapter three examines the effects of bristled scales on the boundary layer. It was not possible to replicate the high speeds of the mako during testing so a biomimetic model of the shortfin mako scales was used and cavity Re was matched. Boundary layer and Re stress profiles are used to note key differences between the flow over the shark scales and the flow over a smooth flat plate.

Chapter four also uses the biomimetic model, but the study focuses on structures formed within the cavity that may interact with the boundary layer that induce mixing. Qualitative and quantitative comparisons of vorticity and velocity within cavities under laminar and turbulent boundary layers are made. These studies combine to yield a more complete picture of the role scales play in flow control over the shortfin mako.
CHAPTER 2

AN EXPERIMENTAL SETUP TO INDUCE AND DOCUMENT BRISTLING OF SHORTFIN MAKO SCALES UNDER REVERSED FLOW CONDITIONS

Abstract

The skin of fast-swimming sharks is proposed to have mechanisms to reduce drag and delay flow separation. The shortfin mako *Isurus oxyrinchus* is one of the fastest and most agile ocean predators and would benefit from minimizing its pressure drag by controlling flow separation. Shortfin mako skin is covered with small teeth-like dermal denticles on the order of 0.2 mm. Biological studies of the shortfin mako skin have shown the bristling angle of their denticles to exceed 50 degrees in areas on the flank corresponding to the locations likely to experience separation first. It is proposed that reversing flow, as occurs at the onset of separation, would activate denticle bristling and impede the reversed flow from leading to global flow separation on the shark. This study shows, for the first time, direct evidence of reversing flow passively bristling denticles on shark skin samples.
2.1 Introduction

The area of bio-inspiration in fluid dynamics has become increasingly popular in recent years, drawing engineers and biologists together to examine and apply nature’s solutions to various flow configurations. A key area of research interest is separation control, and more specifically, passive mechanisms capable of delaying boundary layer separation.

The three types of drag on a body in incompressible flow are form or pressure drag, induced drag, and skin friction drag [1]. Flow separation has an adverse effect on the amount of overall drag and particularly form drag [2]. Therefore, it is desirable to delay boundary layer separation and avoid this significant increase in form drag, particularly for blunt bodies.

Flow separation occurs when the presence of an adverse pressure gradient causes low momentum fluid near the surface to travel upstream and eventually leads to an ejection of boundary layer fluid away from the body [3]. In laminar flow separation, the separation occurs along a spanwise line of flow detachment. However, the point of separation in a turbulent boundary layer is much more difficult to pinpoint due to the fluctuations and unsteady nature of the flow. Due to the transient nature of the turbulent boundary layer, Simpson presents a set of quantitative definitions to describe separation in terms of backflow, or reversed flow [4, 5]. The point where the time-averaged wall shear stress is zero is defined as the point of detachment and has been shown to coincide with the location that experiences backflow 50% of the time. Thus, turbulent boundary layer separation is directly linked to reversed flow.

Sharks are covered with dermal denticles that offer protection from predators and parasites [6]. The surface structures on the scales of fast-swimming sharks, such as the hammerhead Sphyra Zygaena and shortfin mako Isurus oxyrinchus, have also been widely studied for their benefit in reducing turbulent skin friction drag [7, 8]. A riblet configuration
inspired by fast-swimming sharks showed an approximate reduction in skin friction drag compared to a smooth surface of 9% [10]. An inability to efficiently produce a commercial geometry and limited benefit versus required maintenance has delayed its potential use in the aircraft and shipping industries. However, with recent concerns over fuel emissions, advancements in replication and fabrication methods are again being pursued [10, 11].

In 2000, Bechert expanded upon his initial research by studying drag reduction on a shark skin model with compliant scale anchoring [11]. While this research did not lead to significant skin friction reduction results, only about a 3% reduction in shear stress, it did lead to a new hypothesis that reversing flow may cause bristling of shark scales and the scales would then act as vortex generators and delay flow separation by inducing mixing. However, there was no experimental or computational data to accompany this hypothesis. Vortex generators protrude into the flow and are placed upstream of flow separation to be effective [12]. It does not appear feasible that the shark has the ability to control scale actuation, and it is more likely that reversing flow actuates the scales in the region of flow separation and not upstream of the separation. The inability of the shark to bristle specific scales upstream of flow separation would contradict the scales possible role as vortex generators.

Recently, Oeffner and Lauder explored swimming speed of flapping hydrofoils covered in shortfin mako skin and found an increased swimming speed compared to a smooth hydrofoil [13]. This increase was attributed to the variation in the leading edge vortex caused by the presence of the shortfin mako skin. However, the Re for this set of experiments was well below that of the shortfin mako under natural swimming conditions and may not have accurately accounted for the turbulent flow dynamics, including potential reversing flow. In addition, at higher swimming speeds, and higher Re, the caudal fin will not utilize a leading edge vortex like
slower swimming fish do to increase thrust. Rather, attached flow over a lunate tail will provide the necessary pressure forces to cause large thrust [14].

The skin of the shortfin mako is covered in flexible scales on the order of 200 μm [15]. The flexibility of the scales varies by region, with the most flexible scales being located on the flank of the shark’s body and the trailing edge of the pectoral fins. The areas of highest bristling angle along the flank can be seen along the flank in Figure 2.1.

![Figure 2.1. Diagram detailing bristling angles for flank regions of the shortfin mako [15].](image)

Figure 2.2 shows Scanning Electron Microscope (SEM) images of highly flexible shortfin mako scales on the flank region. The scales were manually erected and then allowed to settle naturally before measuring the bristling angle. The scales in the flank region had a settled bristling angle of at least 50°, with maximum bristling angles even higher. The variation in bristling angle over the shark is a direct result of the scale geometry in the various regions. Internal pressurization of the skin did not reveal erection of the scales, reinforcing the idea that the scales are passively activated by flow conditions.
Recent studies have also examined the flow separation control of the shortfin mako skin [16, 17]. These studies on laminar and turbulent flow control detailed cases of reduced backflow over shark skin surfaces versus smooth surfaces where the threshold of reversing flow required to actuate the scales was reached. A reversing velocity magnitude of $10 - 20$ cm/s at 5 mm above the surface was speculated to induce scale bristling, thus inhibiting flow separation. Due to the inability to simultaneously film the scales in the experimental setup in the water tunnel, this conclusion was reached based on the results of the experiments and a lack of flow separation in these particular cases rather than on physically seeing the scales bristle under these test conditions.

This study aims to document shortfin mako denticle behavior under various reversed flow conditions via photographs and video. The hypothesis that denticles can impede flow separation by being actuated by reversed flow is entirely dependent on the velocity magnitude required to bristle the denticles and whether that magnitude is possible at the natural swimming speed of the shortfin mako. This study is the first to document shortfin mako scale behavior under reversing flow conditions.
2.2 Experimental Setup

2.2.1 Shortfin Mako Skin Samples

Three shortfin mako skin samples were used from the flank region of three makos caught off the Atlantic and Gulf Coasts. The scales have nearly the same optical density as water, making them difficult to photograph. To aid in visualizing the scales under reversed flow, Alizarin Red stain was used to dye the samples. This reduced the transparency and allowed for better initial focusing of the samples in the field of view. It should be noted here that Alizarin Red is water soluble and because the samples were placed in water and subjected to water flows, the stain lessened over time. This solubility accounts for the varying shades of color in the results.

2.2.2 Apparatus for Reversed Flow

Two setups were used in order to induce reversing flow over the mako scales. The first was a circular water jet with inner and outer diameters of 103 ± 14 μm and 240 ± 24 μm, respectively. The goal of this particular setup was to produce the ability to actuate a single scale at a time. The second apparatus used was a rectangular water jet with exit height of 0.5 mm and exit width of 5 mm to create a more two-dimensional flow capable of actuating multiple scales at a time. Figure 2.3 diagrams the jet exits used.

![Diagram of jet exits](image)

**Figure 2.3.** Diagram of dimensions at exit plane of the circular jet (left) and rectangular jet (right).
Each jet was connected to an on/off valve that was then connected to a flow meter and attached via hose to the pressurized water source available in the laboratory. The flow meter used with the circular jet was a King 0.1-2.6 GPH flow meter. A Dwyer 4-40 GPH flow meter was used with the rectangular jet. Each jet was connected to a rod with height adjustment that was then connected to a rotating mount affixed to a set of two translating plates (Thor labs tbba0606) that allowed for movement in the three coordinate directions and rotation in one direction. This allowed for precise alignment of the jet parallel to the scales prior to the start of reversed flow.

Each flank skin sample was mounted to a smooth plate with cyanoacrylate. When not in use, each specimen was kept frozen to preserve the integrity of the skin and scales. Prior to testing, the specimens were thawed using cold water. During testing, each plate was submersed in a water tank and positioned approximately 5 cm from the tank wall with metal spacers and held in place with clamps. A fiber-optic light source (Eco-light 150 180 watt light source) was needed to illuminate the skin for image capture. Figure 2.4 shows the typical tank setup during testing. This does not show the adjustable tripod that serves as the camera base.
Figure 2.4. Diagram detailing the tank setup during testing: camera position relative to the sample (top) and jet and specimen position from the point of view of the camera (bottom).
2.2.3 Imaging Setup

To document the results via still image and video, several attachments were used in conjunction with a Nikon D7000 camera body. A Nikon PK-13 27.5 extension ring followed by a Nikon bellows PB-6 and a Nikon PK-12 14 extension ring were used in conjunction with a Nikon br2a reversing ring attached to a Nikon af nikkor 28 mm f 1:2.8 D lens to capture a window approximately 3.7 mm by 2.5 mm. The camera setup was designed to capture images and video with a depth of field capable of viewing bristling. The ISO level was set to 1600, an aperture of f/2.8, and the shutter speed was 1/250. This setup produced a depth of field of approximately 2-4 mm. The video was taken at 24 fps with a resolution of 960 X 720.

2.3 Results and Discussion

2.3.1 Magnification

To give the reader an idea of the level of magnification achieved in the experiments, a shot of a penny in the test frame is shown in Figure 2.5. Figure 2.6 shows the typical view of the mako skin when placed in the experimental setup. Based on the size of the object plane versus the sensor size of the camera (23.5 X 15.6 mm²), the magnification achieved is approximately X6.2.
Figure 2.5. The D stamp on a penny compared to the circular jet using the typical magnification of the experimental setup.
Figure 2.6. A shortfin mako sample using the typical magnification of the experimental setup.

The skin of the shortfin mako is not uniform causing parts of the view to be in the exact focal plane of the camera while other parts may be slightly outside this optimal plane. This produces areas of the image that are extremely clear where each individual scale is easily discernible and other areas that appear slightly out of focus and begin to lose some of the higher contrast detail necessary to discern individual scales.

2.3.2 Single Scale Bristling

The small circular jet was placed parallel to the skin surface such that the exit was in line with the scale tips. Care was taken to avoid pressing the jet into the skin and causing the scales to press into the tissue below. An example of this can be seen in Figure 2.7 and is in stark contrast to the typical test images taken as seen in Figure 2.6. If the jet was accidentally pressed
into the sample too hard, such as in Figure 2.7, another portion of the same sample was used for testing to ensure scale integrity.

Figure 2.7. A shortfin mako sample exposed to too large a pressure from the jet positioning causing the scales to sink into the tissue below.

Scale bristling was seen on each mako sample when exposed to reversed flow from the circular jet. The average flow rate for this setup was measured multiple times during bristling tests and held constant at the flow rate that induced visible bristling, 0.0647 mL/s. The circular jet inner diameter is 103 ± 14 μm. This gives an average exit velocity of approximately 7.7 m/s. Figure 2.8 shows a scale before and after actuation by reversing flow. After the reversing flow is stopped, the scales return to a non-bristled state. Figure 2.9 shows a photo sequence of a scale bristling. Video 1 also documents this bristling sequence.
Figure 2.8. A scale prior to reversing flow (left) and a scale bristled under reversing flow (right). The scale at the jet exit being actuated is circled in white.

Figure 2.9. A sequence of images highlighting scale actuation starting with the scale not bristled prior to reversing flow (top left) and ending with the scale bristled under reversing flow (bottom right).
2.3.3 Multiple Scale Bristling

The flat jet design was used to bristle several scales at once. The total length of the flat jet exit is 5 mm, placing only a portion within the viewing window. Again, the jet was placed parallel to the sample close to the scale tips. Scale bristling was again documented for the flat jet cases. An example of a bristling sequence can be seen in Figure 2.10. Because the flat jet is bristling an entire row, it is a little more difficult to see, but you will notice the jet stays stationary while the scale tips move farther away from the exit as they are actuated and a row not visible initially becomes visible ahead of the jet as they bristle. For this case, it is more difficult to discern scale bristling via images because the row of scales that pushes forward looks the same as the row before it. The included video, Video 2, captures this movement so the reader has a better visual representation of testing and scale bristling.

The flow rate for the flat jet was approximately 21 mL/s resulting in an average exit velocity of approximately 8.5 m/s. The material thickness on the bottom the flat jet is 0.5 mm, or 500 μm, meaning that at the exit, the line of exiting fluid is approximately 500 μm above the
scales at the surface. This leads to fluid of a decreased velocity interacting with the scales. The flat jet was placed parallel to the surface and there was no inclination of the jet relative to the sample surface.

2.3.4 Discussion

This study provides documentation of scale actuation under applied jet flow with no other external forces applied to the system. For the first time, reversing flow and denticle bristling are directly linked via still image and video. The velocities presented previously are the average velocities for the jet. However, it is important to resolve the velocity magnitude interacting with the scales and compare this to possible reversing velocities seen on the mako. The discussion of these velocities will be limited to the circular jet setup.

First, the Re$_D$ of the jet is calculated using Equation 2.1, where $U_{av}$ is the average exit velocity, $D$ is the diameter of the jet, $\rho$ is the density, and $\mu$ is the viscosity [18].

$$Re_D = \frac{\rho U_{av} D}{\mu} \quad (2.1)$$

The Re$_D$ calculated is 793. Because this value falls below the transition Re$_D$ of 2000, the jet flow is laminar [19]. Symons and Labus conducted a study of the velocity profiles of laminar circular jets at various distances after the jet exit [18]. In this study, they showed that at a distance of 3 diameters away from the jet exit, the axial velocity followed a Gaussian distribution. The velocity profiles are presented in the nondimensionalized form $U/U_{max}$, where $U_{max} = 2U_{av}$, versus $r/R$, where $r =$ radial distance from jet centerline and $R =$ radius of the jet. The height between the scales and jet centerline for the current experiment is 51.5-77.25 µm. This yields an $r/R$ value of 1-1.5. The range of $U/U_{max}$ values corresponding to these $r/R$ values are 0.05-0.2 [18]. The corresponding velocities fall between 0.77 m/s and 3.08 m/s.
Now, the reversing flow on the shortfin mako must be resolved to ascertain if the bristling velocities seen in the experiment are plausible over the shark. Fast-swimming species are thought to achieve speeds of at least 10 body lengths per second [20]. Using the total length range of 64 – 340 cm for shortfin mako specimens in a recent study yields swimming velocities of 6.4 – 34 m/s [21]. Studies on reversing flow near regions of separation in a turbulent boundary layer show the reversing flow magnitude to be approximately 10% of the freestream velocity [22, 23]. Based on these results, the reversing flow over the shortfin makos mentioned previously is 0.64 – 3.4 m/s.

Comparing the velocity that induced scale bristling with the reversing flow magnitudes possible over the shortfin mako yields a promising result. The velocity that induced bristling, 0.77 – 3.08 m/s, falls within the possible range of reversing flow over the mako, 0.64 – 3.4 m/s. This result clearly indicates the possibility that reversing flow can actuate scales in the vicinity of flow separation.

Sizing of the scales is also extremely important concerning their role in interacting with a turbulent boundary layer. It has been documented that the riblet spacing on highly flexible scales of the shortfin mako falls in the range of optimal riblet spacing for turbulent skin friction drag reduction. The riblet spacing has been shown to be optimal when $s^+ = 15$ [24]. The riblet spacing on highly flexible flank region scales is approximately 43 μm, with a scale crown width of 150 μm [15]. This would make the $s^+ = 15$ viscous length scales = 43 μm. The crown width would then be approximately 52 viscous length scales. This places the crown width directly into the sizing of low speed streaks, 50 – 75 viscous length scales, observed by Skote and Henningson [23]. This shows the potential for the shark scales to be optimally designed for multiple roles.
In addition to their optimal turbulent skin friction drag design, they may also be optimally designed to be actuated by the reversing flow in low speed streak regions.

2.4 Conclusion

The main focus of this study was to prove that reversing flow could actuate shortfin mako denticles in an experiment that was capable of replicating those results across various samples. This study was successful in documenting scale actuation solely due to reversing flow and the results were replicated across various locations on the unique samples as seen in the results section. It was further shown that the velocities that induced bristling were within the range of reversing velocities along the mako.

Scale riblets have dominated the area of shark scale research in the recent past and have provided valuable insight into mechanisms to reduce turbulent skin friction drag. This study helps add feasibility to the idea that shark scales may have evolved to combat other forms of drag, namely form drag increases that arise from flow separation, in addition to skin friction drag. Flow separation is closely tied to flow reversal at the surface and passively preventing that reversed flow from traveling further upstream would greatly benefit the mako.

In addition, passive mechanisms capable of delaying flow separation would prove valuable in a number of engineering applications. Applications using blades at high speeds, such as helicopters or turbines, face disadvantages due to flow separation. Preventing flow separation would improve efficiency and allow for greater rotation speeds. Using the shortfin mako skin as inspiration may lead to a man-made surface capable of addressing these issues and providing a passive solution based on millions of years of evolution.
The experiments on real shark skin under reversed flow conditions help shed light on how the skin of makos potentially interacts in a turbulent boundary layer at the onset of separation, namely, under reversing flow. This set of experiments showed that reversing flow activated the scales causing them to protrude into the flow and potentially cause cavities that interact with the boundary layer above. The next set of experiments examines a biomimetic scale array modeled after the shortfin mako scales under a boundary layer flow. The next study will examine the variation of boundary layer profiles and Re stress profiles between a flat plate and the mako cavity model.

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References


CHAPTER 3

AN INVESTIGATION OF BOUNDARY LAYER FLOW OVER A SHORTFIN MAKO
3D SCALE ARRAY

Abstract

The skin of fast-swimming sharks is proposed to have mechanisms to reduce drag and delay flow separation. The shortfin mako *Isurus oxyrinchus* is one of the fastest and most agile ocean predators creating the potential need to minimize its pressure drag by controlling flow separation. Biological studies of the shortfin mako skin have shown the passive bristling angle of their denticles to exceed 50 degrees in areas on the flank corresponding to the locations likely to experience separation first. It is proposed that reversing flow, as occurs at the onset of separation, would activate denticle bristling and hinder local flow separation from leading to global separation over the shark. It has been shown that for a bristling angle of 90 degrees, vortices form within these cavities and impose a partial slip condition at the surface of the cavity [1]. These experiments focus on a smaller bristling angle of 45°, closer to the range thought to be achieved on real shark skin. A 3-D bristled shark skin model, embedded below a boundary layer, was used to study boundary layer formation through Digital Particle Image Velocimetry (DPIV).
3.1 Introduction

In recent years, engineers have focused on collaborating with biologists to examine and apply nature’s solutions to various fluid dynamics problems. Fast-swimming sharks, such as the shortfin mako *Isurus oxyrinchus*, and dolphins *Tursiops* have been of particular interest in the area of drag reduction and separation control. The skin of sharks is covered in dermal denticles that serve a variety of purposes, including protection from predators and parasites [2].

The surface of shortfin mako scales, namely the riblets that cover the crown face, have been studied extensively in the area of turbulent skin friction drag reduction [3, 4]. A 9.9% reduction in skin friction drag was seen on a shark-inspired riblet surface compared to a smooth surface [5]. In 2000, Bechert expanded upon his initial experiment and studied scale models with compliant anchoring [6]. While this set of experiments only showed a 3% reduction in turbulent shear stress, it did lead to a new hypothesis that reversing flow could bristle denticles causing them to act as vortex generators. However, this hypothesis was not accompanied by any experimental or computational data. In order to be effective in delaying or preventing flow separation, vortex generators are placed upstream of flow separation [7]. It does not appear feasible that shortfin makos have the ability to actuate individual scales in specific areas making it unlikely that the scales would act as vortex generators.

Oeffner and Lauder explored swimming speed of hydrofoils covered in mako skin and found an increased swimming speed compared to a smooth hydrofoil [8]. This increase was attributed to the variation in the leading edge vortex caused by the presence of the mako skin. However, the Re for this set of experiments was well below that of the shortfin mako under natural swimming conditions and may not have accurately replicated the flow dynamics. In addition, at higher swimming speeds, and higher Re, the caudal fin will not utilize a leading edge
vortex similar to that of slower swimming fish to increase thrust. Rather, attached flow over a lunate tail moving at high speed will provide the necessary pressure forces, due to larger dynamic pressure changes, to cause large thrust [9].

Skin friction drag is not the only type of drag on a blunt body in incompressible flow; instead, blunt bodies are also subjected to form drag and induced drag [10]. If flow separation occurs along the body it significantly increases the form drag, thus having an adverse effect on the overall drag on the body [11]. Therefore, it is desirable to delay boundary layer separation in addition to decreasing skin friction drag. With millions of years of evolution and riblets that are capable of reducing skin friction drag, it is plausible that the shortfin mako has also evolved mechanisms within the scales for delaying flow separation.

It has recently been shown that reversing flow under experimental conditions can erect shortfin mako denticles to form cavities [12]. This particular study also found that under certain flow conditions the shark skin covering a hydrofoil significantly inhibited flow reversal, as compared to a smooth surface, and acted as a passive flow control mechanism.

Cavity rows inspired by shortfin mako skin have also been studied. Initial research on a bristled scale model placed in a boundary layer flow focused on scales at 90° and found that cavity vortices induced a partial slip condition and led to increased momentum adjacent to the surface [1]. However, the geometry of the skin and the bristling angle tested did not align with the geometry of the mako scales or the physical limits of scale bristling.

Howard and Goodman studied circumferential grooves on axisymmetric bluff bodies for their potential benefit in reducing drag [13]. The embedded grooves near the trailing edge of the body produced 35 and 50 % net drag reductions for tripped and laminar boundary layers, respectively. Howard noted that the grooves must be located in an area where the pressure
gradient would be large enough to induce flow separation to be effective. In other words, the grooves were most effective when placed in the location nearest to the onset of separation and not upstream of it.

The denticle geometry of the shortfin mako varies by location, with crown lengths as small as 200 μm on the flank and trailing edge of the pectoral fin, where the denticles are most flexible [14]. The riblet spacing at these locations varies between 35 and 45 μm with a riblet depth as large as 10 μm.

The current study attempts to shed light on how the shortfin mako skin’s ability to form cavities under reversed flow affects the boundary layer as compared to a smooth surface. The experimental model incorporates the recent study of scale geometry and bristling angle referenced above to accurately represent the shortfin mako scales. The lowest test velocities were based on the approximate swimming speeds of 10 body lengths per second thought possible for fast swimming species [15]. Using the specimen total length size of 260 and 340 cm for male and female subjects, respectively, provides velocity estimates of 26 and 34 m/s [16]. An additional higher velocity was tested for comparison and completeness in this study.

3.2 Experimental Methods
3.2.1 Experimental Model

An array of 24 rigid rows of stereolithography (SLA) manufactured shortfin mako denticles embedded in a flat plate beneath a boundary layer flow was used to study the boundary layer growth, Re stress, and mixing versus a smooth flat plate. Because it was not possible to match the freestream speed of the mako, the denticles were scaled to be 100 times larger than on a real mako and the freestream velocities tested were approximately 100 times less in order to
match the cavity Re between the real shark and the model. The rows were aligned to mimic the natural alignment of alternating peaks and valleys of denticles seen on the mako such that a valley in the previous row would be filled by a peak in the following row. Riblet size and spacing was also matched at 100 times the size and spacing on the shortfin mako. Table 3.1 outlines the measurements taken from the shortfin mako and the measurements used for the biomimetic model. Figure 3.1 shows a comparison of the model array to the real denticle array of the mako. The front of one row of scales in the model is spaced 10 mm from the front of the next row of scales and the tips protrude into the flow 2-4 mm. Because the scales are at 45° and the crown faces are curved and covered in riblets, a gap between the leading flat plate portion of the test plate and the first row of scales was formed. Because such a gap would be unnatural on mako skin, the gap was filled such that the first cavity encountered was between two scales. Care was taken to mimic the conditions experienced on the mako as closely as possible at this transition to the scale array.

<table>
<thead>
<tr>
<th>Region</th>
<th>Measured (μm)</th>
<th>Model (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B2</td>
<td>B5</td>
</tr>
<tr>
<td>Crown Length</td>
<td>221 ± 7</td>
<td>202 ± 4</td>
</tr>
<tr>
<td>Crown Width</td>
<td>167 ± 3</td>
<td>149 ± 3</td>
</tr>
<tr>
<td>Riblet Depth</td>
<td>8 ± 0</td>
<td>7 ± 0</td>
</tr>
<tr>
<td>Riblet Spacing</td>
<td>43 ± 1</td>
<td>43 ± 1</td>
</tr>
</tbody>
</table>

Table 3.1. Measurements from the shortfin mako flank (B2, B5, and A2) and trailing edge of pectoral fin (P3) taken from Motta et al and the measurements of the biomimetic model used in this study [14]. *Riblet depth was modeled slightly smaller than the real shortfin mako scale due to 3D printing gradient restrictions.
Because the bristling angle of denticles along the shortfin mako varies greatly by location, the bristling angle was chosen to match an area on the flank likely to experience separation first. This area also exhibited the largest bristling angles. Denticles on the flank can be erected to greater than 50°, so a slightly more conservative angle of 45° was chosen for testing. It should be noted that the denticles on the mako in the flank region are compliantly anchored and lie flat, with riblets parallel to the flow, until bristled. This experiment only focuses on the case of denticle bristling and does not examine the compliant anchoring. It should also be noted here that it is unlikely that all the scales would bristle simultaneously and at the same angle, but this model was chosen for simplicity. This setup decouples the difficulty of
determining the damping coefficient of the scales and exactly replicating a compliant surface from the tests and allows for a focused examination of flow structures under bristled conditions.

3.2.2 Water Tunnel Testing

This set of tests was conducted in a modified version of the Rolling Hills Research Corporation’s Eidetics Model 1520 water tunnel. The test section of this 1520-EXT is 2.74 meters long by 0.76 meters high and is capable of freestream speeds of approximately 0.5 m/s.

The model was tested at three different speeds under both laminar and turbulent conditions. The flat plate case was run at freestream velocities of 26.2, 35.5, and 47.7 cm/s. While the tunnel operated at the same test frequencies for both the flat plate and shark skin model tests, the velocity was slightly higher in the shark skin model case due to a slight decrease in water level between testing runs. The resulting freestream velocities were 27.7, 38.0, and 48.1 cm/s, with a largest percent difference in freestream velocity between the flat plate and scale model cases of approximately 7%. Results for each test were nondimensionalized by their respective freestream velocities. Table 3.2 details the cavity Reynolds number for each case.

<table>
<thead>
<tr>
<th>Case</th>
<th>Freestream Velocity (cm/s)</th>
<th>Cavity Re</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>27.7</td>
<td>5584</td>
</tr>
<tr>
<td>2</td>
<td>38.0</td>
<td>7660</td>
</tr>
<tr>
<td>3</td>
<td>48.1</td>
<td>9696</td>
</tr>
</tbody>
</table>

Table 3.2. Freestream velocities and cavity Re for the shark skin model tests. Cavity Re based on crown length.

The scale array was placed in an interchangeable section of flat plate in the center of a three section test setup mounted vertically in the tunnel. The entire test model is 228.6 cm in
length. The test model begins with a 91.44 cm elliptical leading edge section, followed by the 45.72 cm interchangeable plate, and ends with the 91.44 cm trailing edge. The last 45.72 cm of the trailing edge is a flap with an adjustable angle in order to properly align the flow and prevent flow detachment along the length of the test model. The scale array begins 102.84 cm downstream from the start of the leading edge. This position is defined as the $x = 0$ position for all data comparisons. Figure 3.2 details the plate setup.

![Figure 3.2](image)

**Figure 3.2.** View of the plate setup from the position of the camera underneath the water tunnel. $X = 0$ marks the location of the start of the shark skin model and the reference point for both the flat plate and the shark skin measurements.

A base data set was acquired for the smooth surface by placing a flat plate without the embedded scale array in the center section of the test setup. The $x = 0$ position coincides with the same location for both the scale array and smooth plate tests. Measurements were acquired over the first eight cavities of the model.

Time Resolved Digital Particle Image Velocimetry (TR-DPIV) was used to study the velocity fields and Reynolds stresses. The Basler A504K 8-bit high-speed digital camera with a Nikon AF Micro Nikkor 105 mm lens attached captured the images for use in processing. The standard setup allows for a capture frame rate of up to 500 frames per second with a resolution of 1280x1024 pixels, with 1000 frames per second possible by reducing the resolution. The data for this study was acquired at 400 – 500 frames per second. The flow was seeded with neutrally buoyant hollow glass spheres with a diameter of 13μm manufactured by Potters Industries. To
illuminate the silver-coated particles in the field of view, the Darwin 527-30-M laser manufactured by Quantronix was used. A diagram detailing plate, laser sheet, and camera setup can be seen in Figure 3.3.

![Figure 3.3](image)

**Figure 3.3.** View of the experimental setup from above with the camera positioned beneath the setup underneath the water tunnel.

A LabVIEW program was used for image acquisition and conversion for processing. Processing was performed with Insight 4G (Appendix). Prior to processing, all images were run through background image subtraction to eliminate the background noise. While the interrogation window size varied across the tests based on tunnel speed, a Recursive NyQuist Grid, FFT Correlation Engine, and Gaussian Peak Engine were consistently used for all test
cases. Post-processing filtering and validation eliminated any bad vectors due to localized spots of insufficient seeding.

3.3 Results and Discussion

The main area of interest in this study is the boundary layer profiles, and more importantly, the differences that arise in the profiles for the shark skin model compared to the flat plate. All profiles are time averaged over 12 seconds and 24 seconds, for laminar and turbulent cases respectively, taken in 2.4 second bursts. The Re stress profiles are also compared for each case. The $x = 0$ location corresponds to the start of the mako model 102.84 cm from the leading edge, and all figures use this zero point as reference. Baseline flat plate data was compared to theoretical boundary layer profiles, and the results for $U_\infty = 26.2$ cm/s are shown in Figures 3.4 and 3.5. The other velocity baselines follow similar trends and are not shown here.
Figure 3.4. Laminar experimental boundary layer profile compared to theoretical boundary layer fit for $U_\infty = 26.2$ cm/s for location $x = 0$. 
The laminar experimental results agree well with the theoretical calculations for a favorable pressure gradient with $\beta = 0.5$. Values for the Falkner-Skan fit were calculated using the numerical results published by Katagiri [17]. The power law fit for a turbulent boundary layer does not account for a favorable pressure gradient and the shift away from the $1/5$ curve fit seen in Figure 3.5 is reasonable under a favorable pressure gradient. The experimental flat plate data at each x-location is used for comparison in each respective scale model case.
While data was recorded for both the laminar and turbulent cases, the turbulent cases are the main area of focus because the majority of the shark, especially where scale flexibility is highest along the flank of the shark, would experience a turbulent boundary layer. Figure 3.6 shows the global velocity contours for the turbulent case.
Figure 3.6. Turbulent boundary layer velocity contours spanning the initial 80 mm of cavity arrays for $U_0 = 27.7$ cm/s
Boundary layer profiles were extracted at various locations along the model and are shown in the following figures. Figure 3.7 details turbulent boundary layer profiles for the lowest test velocity at initial spanwise locations, $x = -12$ to $x = 0$ mm.

![Graphs showing boundary layer profiles](image)

**Figure 3.7.** Turbulent boundary layer profiles for $U_\infty = 26.2$ cm/s (27.7 cm/s for scale model) at streamwise locations $x = -12$ mm (left), $x = -3.5$ mm (middle), and $x = 0$ mm (right).

The initial shift in the scale model boundary layer is expected due to the scale tips protruding into the flow approximately 2-4 mm along the test plate. This study could not replicate the high speed of the mako and used larger scales to match cavity Re. The larger scales protrude into the boundary layer more than the scales on the actual mako. This larger protrusion
height caused a slight blockage and a negative effect in the lower boundary layer that would not be as prominent in the flow over real shark skin. It is important to note here that the scale protrusion into the boundary layer is approximately 5-10% of the boundary layer height for the turbulent set of experiments. Using the turbulent boundary layer height calculated using Equation 3.1 as an estimate for a shortfin mako traveling at 10 m/s (Re$_x$ = 1 $\times$ 10$^7$) yields a $\delta$ of approximately 1.5 cm at a distance 1 m from the nose of the mako. Using a scale of crown length 220 μm along the flank erected at 45° gives a protrusion height of approximately 156 μm [14]. Therefore, the scale protrusion into the boundary layer along the flank of the shortfin mako is approximately 1%.

$$\delta_{turb} = \frac{0.16\chi}{Re_x^{1/7}} \quad (3.1)$$

It can be seen from these initial graphs, that the upper portion of the boundary layer is the same prior to the start of the scales. Figures 3.8 and 3.9 detail the remaining turbulent boundary layer plots for this velocity.
Figure 3.8. Turbulent boundary layer profiles for $U_{\infty} = 26.2$ cm/s (27.7 cm/s for scale model) at streamwise locations (top row) $x = 5$ mm (left) and $x = 10$ mm (right), (middle row) $x = 15$ mm (left) and $x = 20$ mm (right), (bottom row) $x = 25$ mm (left) and $x = 30$ mm (right).
Figure 3.9. Turbulent boundary layer profiles for $U_\infty = 26.2$ cm/s (27.7 cm/s for scale model) at streamwise locations (top row) $x = 35$ mm (left) and $x = 40$ mm (right), (middle row) $x = 45$ mm (left) and $x = 50$ mm (right), (bottom row) $x = 55$ mm (left), and $x = 80$ mm (right).
From these graphs, it is evident that the introduction of the scales begins to bring higher velocity fluid closer to the surface and shift the boundary layer profiles to the right. It is also apparent that this positive effect does not continue indefinitely. By the last three locations, any positive effect the scales have made has dissipated. Locations 4-9 (corresponding to $x = 5$ mm to $x = 30$ mm) experience the greatest benefit in velocity profiles. Similar trends were seen in the two higher velocities tested and a subset of locations for these cases is detailed in Figures 3.10 and 3.11.
Figure 3.10. Turbulent boundary layer profiles for $U_\infty = 35.5 \text{ cm/s}$ (38.0 cm/s for scale model) at streamwise locations (top row) $x = 0 \text{ mm}$ (left) and $x = 5 \text{ mm}$ (right), (middle row) $x = 15 \text{ mm}$ (left) and $x = 25 \text{ mm}$ (right), (bottom row) $x = 30 \text{ mm}$ (left) and $x = 80 \text{ mm}$ (right).
Figure 3.11. Turbulent boundary layer profiles for $U_\infty = 47.7$ cm/s (48.1 cm/s for scale model) at streamwise locations (top row) $x = 0$ mm (left) and $x = 5$ mm (right), (middle row) $x = 15$ mm (left) and $x = 25$ mm (right), (bottom row) $x = 30$ mm (left) and $x = 80$ mm (right).
Based on the results of the three velocities tested, the introduction of the scale array causes similar events across the range of velocities tested at approximately the same downstream distances.

Next, the Re stress is analyzed for each velocity at the six key locations identified previously, namely, x = 0, 5, 15, 25, 30, and 80 mm. Turbulent, or Reynolds, stresses occur in a turbulent boundary layer due to the fluctuating nature of the velocity within the boundary layer [18]. The positive Reynolds shear stress, Re stress, in a 2-D boundary layer can be defined as \(-u'v'\), where \(u'\) and \(v'\) are the velocity fluctuations from the time-averaged mean velocity in the x-direction and y-direction, respectively. The Re stress is a measure of mixing within the boundary layer and can be used with velocity profiles to examine momentum exchange between embedded cavities and the boundary layer above. A global view of the nondimensionalized Re stress can be seen in Figure 3.12. The Re stress profiles at the six locations highlighted previously are detailed for each velocity in Figures 3.13-3.15.
Figure 3.12. Turbulent Re stress contours for the initial flat plate location (top) and the shark skin model spanning the initial 80 mm of cavity arrays (bottom) for $U_\infty = 27.7$ cm/s.
Figure 3.13. Turbulent Re stress profiles for $U_{\infty} = 26.2$ cm/s (27.7 cm/s for scale model) at streamwise locations (top row) $x = 0$ mm (left) and $x = 5$ mm (right), (middle row) $x = 15$ mm (left) and $x = 25$ mm (right), (bottom row) $x = 30$ mm (left) and $x = 80$ mm (right).
Figure 3.14. Turbulent Re stress profiles for $U_\infty = 35.5$ cm/s (38.0 cm/s for scale model) at streamwise locations (top row) $x = 0$ mm (left) and $x = 5$ mm (right), (middle row) $x = 15$ mm (left) and $x = 25$ mm (right), (bottom row) $x = 30$ mm (left) and $x = 80$ mm (right).
Figure 3.15. Turbulent Re stress profiles for $U_\infty = 47.7$ cm/s (48.1 cm/s for scale model) at streamwise locations (top row) $x = 0$ mm (left) and $x = 5$ mm (right), (middle row) $x = 15$ mm (left) and $x = 25$ mm (right), (bottom row) $x = 30$ mm (left) and $x = 80$ mm (right).
The Re stress profiles show that the main difference in early locations is the sign of the Re stress. While the Re stress for the flat plate stays consistently positive (based on the conventional \(-u'v'\) definition), this is not true for the scale model. To affirm that the scales were causing this change in sign for the Re stress, a profile 12 mm prior to the introduction of the scale array was taken for each velocity. As can be seen in Figure 3.16, the expected sign for Re stress is seen in each case.

**Figure 3.16.** Turbulent Re stress profiles at \(x = -12\) mm for \(U_\infty = 26.2\) cm/s (27.7 cm/s for scale model) (left), \(U_\infty = 35.5\) cm/s (38.0 cm/s for scale model) (center), \(U_\infty = 47.7\) cm/s (48.1 cm/s for scale model) (right).
Laminar boundary layer profiles for the initial spanwise locations, x = -12 to x = 0 mm, for $U_\infty = 26.2$ cm/s can be seen in Figure 3.17.

**Figure 3.17.** Laminar boundary layer profiles for $U_\infty = 26.2$ cm/s (27.7 cm/s for scale model) at streamwise locations x = -12 mm (left), x = -3.5 mm (right), and x = 0 mm (bottom).

In the laminar case, the protrusion height is a much larger percentage of the experimental boundary layer height, as much as 25-50%, because the scale array was not altered between laminar and turbulent cases. This is evident when examining the initial graphs and the location of scale introduction when compared to the turbulent cases. Again, consider a mako swimming at 10 m/s and take a location near the center of the pectoral fin of 5 cm ($Re_x = 5 \times 10^5$).
Assuming the flow to be laminar and using Equation 3.2 yields a δ of approximately 0.353 mm. Using a scale crown length from this region of 205 μm and a bristling angle of 23° gives a protrusion height of approximately 80 μm [14]. Therefore, the scale protrusion into the laminar boundary layer at this location on the shortfin mako would be approximately 23%. However, this is only true if scales are activated at this location and the percentage of protrusion decreases as you move aft along the fin, making 23% the maximum, but not typical, case.

\[ \delta_{lam} = \frac{5x}{\sqrt{Re_x}} \]  

(3.1)

Figure 3.18 details the next six locations for this velocity.
Figure 3.18. Laminar boundary layer profiles for $U_\infty = 26.2$ cm/s (27.7 cm/s for scale model) at streamwise locations (top row) $x = 5$ mm (left) and $x = 10$ mm (right), (middle row) $x = 15$ mm (left) and $x = 20$ mm (right), (bottom row) $x = 25$ mm (left), and $x = 30$ mm (right).
The laminar cases lack the mixing benefit seen in the turbulent cases previously. The laminar boundary layer profiles for the two higher velocities show similar trends and are not presented here.

The main focus of this set of experiments was to examine the effect bristled scales have on turbulent and laminar boundary layers. The results clearly show enhanced mixing in the turbulent boundary layer cases as compared to a flat plate and show immediate benefit upon scale introduction by bringing higher momentum fluid closer to the surface. The results also show that scale bristling in a laminar boundary layer does not produce this same boundary layer enhancement upon scale introduction. However, this is not to say that scale bristling does not provide another type of benefit in laminar boundary layers, namely the case of preventing laminar boundary layer separation possible at the trailing edge of the shortfin mako pectoral fin. The majority of the mako’s body experiences a turbulent boundary layer, but its pectoral fins may remain under laminar flow and, much like an airfoil, could lose flow control capability if the flow were to detach from the edge of the fins. While the boundary results are obviously more favorable in the turbulent conditions of this test, the results are somewhat expected because the test more closely mimicked the protrusion height of the scales during turbulent flow.

3.4 Conclusion

These studies shed further light on the possible function of the dermal denticles of the shortfin mako shark. While the riblets on the scale surface have been the main focus of turbulent skin friction drag reduction research in the past, the recent studies of flow separation and scale flexibility give validity to the idea that the scales serve a purpose in flow control that would enhance the shark’s ability to achieve high speeds and execute tight maneuvers [12, 14, 19].
The turbulent tests conclude that, once bristled, the scales would interact with the boundary layer and bring higher momentum fluid toward the surface. The laminar test results do not yield this same result. However, Lang et al demonstrated laminar separation control due to shortfin mako shark scales [12]. One key variation from the real shark skin in this experiment is the protrusion height into the boundary layer. The model scale array protrudes farther into the boundary layer than the actual mako shark scales would. While this study matched cavity Re, it could not replicate all variables of the shortfin mako during testing. The model has a much higher percentage of protrusion height into the boundary layer than the real mako scales, particularly in the laminar case. The mako scales would extend into the boundary layer roughly 1-3% versus 25-50% for the laminar model during testing. Therefore, the mechanisms utilized in a laminar boundary layer may not have been accurately captured in this experiment due to this key difference.

The turbulent results in this study are important because they show a benefit in the boundary layer profiles at initial locations and enhanced mixing caused by the scales. Enhanced mixing is a mechanism used to delay flow separation. While these tests did not look directly at cases of separating flow, they still confirm the effects on a turbulent boundary layer produced by scales protruding significantly into that boundary layer. The ability to delay flow separation would be extremely useful to the shortfin mako, allowing for a reduction in form drag.

Another important result of the turbulent tests is the lack of a continually increasing benefit in the downstream direction after the bristled scales are introduced. The greatest benefit is seen immediately after scale introduction and declines after x = 30mm, the end of the third cavity. This implies that having all the scales in a large area bristled would not yield an overall benefit, and it is more likely that a few scales are bristled to hinder local reversing flow from
translating to flow separation. This gives stronger support to the hypothesis that reversing flow along the shark can passively actuate the denticles as a means of separation control.

Understanding how the scales of shortfin makos interact with the boundary layer, and at what scale, will lead to the potential for biomimetic man-made surfaces that could be used in engineering applications where flow separation hinders performance. Specific examples for application include wind turbine blades and helicopter rotor blades, where flow separation inhibits higher speed and performance possibilities.

This study examined the boundary layer and Re stress profiles at various locations along a biomimetic array modeled after the shortfin mako scales. This study showed that the introduction of the scales caused increased mixing and higher momentum fluid to be pulled toward the surface of the model. This increase in mixing highlights the potential of the shortfin mako scales to contribute to flow control over the mako and delay flow separation. The next study expands on the previous set of experiments by examining the cavity structures that form within the scale array. The next study also examines the vorticity, injection, and ejection within the critical first cavities of the model.

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References


CHAPTER 4
AN INVESTIGATION OF FLOW STRUCTURES WITHIN SHORTFIN MAKO INSPIRED CAVITIES EMBEDDED IN A BOUNDARY LAYER FLOW

Abstract

The shortfin mako *Isurus oxyrinchus* is one of the fastest and most agile ocean predators creating the potential need to minimize its pressure drag by controlling flow separation. The skin of fast-swimming sharks, such as the shortfin mako, is proposed to have mechanisms to reduce drag and delay flow separation. The skin of the shortfin mako is covered in dermal denticles that can be erected to angles greater than 50º along flank regions likely to experience separation first. It is thought that the onset of flow separation, namely localized areas of reversing flow, activates the scales to interact with the boundary layer and prolong flow attachment. Previous studies on a bioinspired scale model with denticles at 90º showed that vortices form within the cavities and impose a partial slip condition at the surface of the cavity. This new study uses a more geometrically accurate denticle model of the shortfin mako based on recent biological studies and incorporates a new bristling angle of 45º, shown to be closer to the range achieved on a real shark. A 3-D bristled shark skin model is embedded beneath a boundary layer flow and cavity structures are studied using flow visualization and Digital Particle Image Velocimetry (DPIV).
4.1 Introduction

The area of bioinspiration has been of particular interest in recent years mainly because nature has many examples of solutions to various fluid dynamics and other engineering problems. Engineers and biologists have begun to collaborate to examine and apply these solutions in the area of drag reduction and flow control. Aquatic animals have been of particular interest in the area of flow control [1]. Dolphin *Tursiops* skin has long been the center of study due largely to Gray’s paradox: the seeming inability to reconcile power needed to overcome the drag on the dolphin’s body with the power available from the dolphin’s muscles [2]. Large protuberances called tubercles line the leading edge of humpback whale flippers and have been shown to aid in the delay of stall angle while increasing lift, much like vortex generators near the leading edge of aircraft wings [3].

Fast-swimming sharks, such as the shortfin mako *Isurus oxyrinchus*, have also been of particular interest in the area of drag reduction and separation control. Small dermal denticles cover the skin of sharks and serve a variety of purposes, including protection from parasites [4]. Riblets cover the crown surface of the scales and have been the main focus of turbulent skin friction drag reduction tests [5, 6]. A significant reduction in skin friction drag, around 10%, was seen on a shark-inspired riblet surface compared to a smooth surface [7]. In 2000, Bechert expanded upon his initial experiment and studied scale models with compliant anchoring [8]. While this set of experiments only showed a 3% reduction in turbulent shear stress, it more importantly led to a new hypothesis that reversing flow could bristle denticles causing them to act as vortex generators. However, this hypothesis was not accompanied by any experimental or computational data. In the case of vortex generators, they must be placed upstream of flow separation to be effective [9]. Because it does not appear feasible that the shortfin mako has the
ability to actuate individual scales in specific areas, the scales role as vortex generators is unlikely. However, the bristling may contribute to flow control in some other way as discussed in later sections.

Oeffner and Lauder explored swimming speed of hydrofoils covered in mako skin and found an increased swimming speed compared to a smooth hydrofoil [10]. This increase was attributed to the variation in the leading edge vortex caused by the presence of the mako skin. However, the Re for this set of experiments was well below that of the shortfin mako under natural swimming conditions and may not have accurately replicated the flow dynamics, specifically the potential for a turbulent boundary layer. Azuma also notes that at higher swimming speeds, and higher Re, the caudal fin would not utilize a leading edge vortex like slower swimming fish do to increase thrust. Instead, attached flow over a lunate tail moving at high speed would provide the necessary pressure forces, due to larger dynamic pressure changes, to cause large thrust [11].

Skin friction drag is not the only type of drag on a blunt body in incompressible flow, instead, they are also subjected to form drag and induced drag [12]. If flow separation occurs along the body it significantly increases the form drag, thus having an adverse effect on the overall drag on the body [13]. At the higher Re of fast-swimming species, it is desirable to delay boundary layer separation in addition to decreasing skin friction drag. With millions of years of evolution and scales that offer numerous other benefits, such as riblets capable of reducing skin friction drag, it is plausible that the shortfin mako has also evolved mechanisms within the scales for delaying flow separation.

Flow separation occurs when the presence of an adverse pressure gradient causes low momentum fluid near the surface to travel upstream and eventually leads to an ejection of
boundary layer fluid away from the body [14]. For laminar flow separation, the point of separation occurs along a spanwise line of flow detachment and is easily discernible. However, the point of separation in a turbulent boundary layer is much more difficult to pinpoint due to fluctuations and the unsteady nature of the flow. To account for the unsteady and transient nature of turbulent boundary layer separation, Simpson presents a set of quantitative definitions to describe separation in terms of backflow, or reversed flow [15, 16]. The point where the time-averaged wall shear stress is zero is defined as the point of detachment and has been shown to coincide with the location that experiences backflow 50% of the time. This shows that turbulent boundary layer separation is directly linked to reversed flow near the surface.

Djenidi’s study of square transverse cavities beneath a turbulent boundary layer found strong interaction between the cavities and outer layer of fluid [17]. Inflow and outflow between the cavities and boundary layer above the cavities was seen and seemed to coincide with the passage of quasi-streamwise vortices above the cavity. The study found three types of events using flow visualization, intervals of injection of flow into the cavity, intervals of flow ejection from the cavity, and intervals without any interaction between the cavity and outer boundary layer flow. These events were observed to be random in time and space. An area of recirculation, i.e. vortex, was also clearly seen within the cavities. It is thought that the ejections from the cavity play an important role in the self-preservation of the boundary layer.

It has recently been shown that reversing flow can erect shortfin mako denticles to form cavities [18]. In this study, flow control was observed in conjunction with significantly inhibited reversed flow over a real shark skin specimen covering a hydrofoil when compared to a smooth surface.
Cavity flow inspired by shortfin mako skin has also been studied. Initial research on a bristled scale model placed in a boundary layer flow focused on scales at 90° and found that cavity vortices induced a partial slip condition and led to increased momentum adjacent to the surface [19]. However, the geometry of the skin and the bristling angle tested did not align with the exact geometry of the mako scales or the physical limits of scale bristling [20].

For the present study, a biomimetic scale array was designed using a recent set of measurements acquired from the shortfin mako scales as reference [20]. The denticle geometry of the shortfin mako varies by location, with crown lengths as small as 200 μm on the flank and trailing edge of the pectoral fin, where the denticles are most flexible. The riblet spacing at these locations varies between 35 and 45 μm with a riblet depth as large as 10 μm.

The current study attempts to quantify the structures present in the shortfin mako skin’s cavities and determine the interaction the flow has with the boundary layer above. The test velocities were based on the rough estimate of 10 body lengths per second thought possible for fast swimming fishes such as the shortfin mako shark [21]. Using 260 and 340 cm total length for male and female specimens respectively, provides velocity estimates of 26 and 34 m/s [22]. Speculations based on video taken of accelerating shortfin makos yield even higher burst speeds, but they have not yet been verified.

4.2 Experimental Methods

4.2.1 Experimental Model

An array of 24 rigid rows of stereolithography (SLA) manufactured shortfin mako denticles embedded in a flat plate beneath a boundary layer flow was used to study the cavity structures present and interactions between cavity and boundary layer fluid. It was not possible
to match the freestream speed of the mako, the denticles were scaled to be 100 times larger than on a real mako and the freestream velocities tested were approximately 100 times less to match the cavity Re between the real shark and the model. The rows were aligned to mimic the natural alignment of alternating peaks and valleys of denticles seen on the mako such that a valley in the previous row would be filled by a peak in the following row. Table 4.1 outlines the measurements acquired from the study referenced earlier and the measurements of the biomimetic model. Figure 4.1 shows a comparison of the model array to the real denticle array of the mako. The spacing between rows is approximately 10 mm and the scale tips protrude into the flow 2-4 mm. Because the scales are at 45° and the crown faces are curved and covered in riblets, there was a gap, of varying width, between the leading flat plate portion of the test plate and the first row of scales. Because this would not happen on the actual mako, the gap was filled such that the first cavity encountered was between two scales.

<table>
<thead>
<tr>
<th>Region</th>
<th>B2</th>
<th>B5</th>
<th>A2</th>
<th>P3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crown Length</td>
<td>221 ± 7</td>
<td>202 ± 4</td>
<td>221 ± 6</td>
<td>191 ± 5</td>
</tr>
<tr>
<td>Crown Width</td>
<td>167 ± 3</td>
<td>149 ± 3</td>
<td>175 ± 10</td>
<td>139 ± 4</td>
</tr>
<tr>
<td>Riblet Depth</td>
<td>8 ± 0</td>
<td>7 ± 0</td>
<td>10 ± 0</td>
<td>6 ± 0</td>
</tr>
<tr>
<td>Riblet Spacing</td>
<td>43 ± 1</td>
<td>43 ± 1</td>
<td>45 ± 1</td>
<td>35 ± 1</td>
</tr>
</tbody>
</table>

Table 4.1. Measurements from the shortfin mako flank (B2, B5, and A2) and trailing edge of pectoral fin (P3) taken from Motta et al [20] and the measurements of the biomimetic model used in this study. *Riblet depth was modeled slightly smaller than the real shortfin mako scale due to 3D printing gradient restrictions.
Because the bristling angle of denticles along the shortfin mako varies greatly by location, the bristling angle was chosen to match an area on the flank likely to experience separation first. This area also exhibited the largest bristling angles. Denticles on the flank can be erected to greater than 50°, so a slightly more conservative angle of 45° was chosen for testing [20]. It should be noted that the denticles on the mako in the flank region are compliantly anchored and lie flat, with riblets parallel to the flow, until bristled. This experiment only focuses on the case of denticle bristling and does not examine the compliant anchoring. It should also be noted here that it is unlikely that all the scales would bristle simultaneously and at the same angle, but this model was chosen for simplicity. This setup decouples the difficulty of
determining the damping coefficient of the scales and exactly replicating a compliant surface from the tests and allows for a focused examination of flow structures under bristled conditions.

4.2.2 Water Tunnel Testing

This set of tests was conducted in a modified version of the Rolling Hills Research Corporation’s Eidetics Model 1520 water tunnel. The test section of this 1520-EXT is 2.74 meters long by 0.76 meters high and is capable of freestream speeds of approximately 0.5 m/s.

The scale array was placed in an interchangeable section of flat plate in the center of a three section test setup mounted vertically in the tunnel. The entire test model is 228.6 cm in length. The test model begins with a 91.44 cm elliptical leading edge section, followed by the 45.72 cm interchangeable plate, and ends with the 91.44 cm trailing edge. The last 45.72 cm of the trailing edge is a flap with an adjustable angle in order to properly align the flow and prevent flow detachment along the length of the test model. The scale array begins 102.84 cm downstream from the start of the leading edge. This position is defined as the \( x = 0 \) position for all data comparisons. Figure 4.2 details the plate setup.

![Figure 4.2](image)

**Figure 4.2.** View of the plate setup from the position of the camera underneath the water tunnel. \( X = 0 \) marks the location of the start of the shark skin model and the reference point for both the flat plate and the shark skin measurements.
Time Resolved - Digital Particle Image Velocimetry (TR-DPIV) was used to study the cavity flows for two cases, laminar and turbulent boundary layer with $U_\infty = 0.38$ m/s (cavity Re of 7660). The Basler A504K 8-bit high-speed digital camera with a Nikon AF Micro Nikkor 105 mm lens attached captured the images for use in processing. The standard setup allows for a capture frame rate of up to 500 frames per second with a resolution of 1280x1024 pixels, with 1000 frames per second possible by reducing the resolution. The data for use in PIV for this study was taken at 500 frames per second. The flow was seeded with neutrally buoyant hollow glass spheres with a diameter of 13µm manufactured by Potters Industries. To illuminate the silver-coated particles in the field of view, the Darwin 527-30-M laser manufactured by Quantronix was used. A diagram detailing plate, laser sheet, and camera setup can be seen in Figure 4.3.
Figure 4.3. View of the experimental setup from above with the camera positioned beneath the setup underneath the water tunnel.

A LabVIEW program was used for image acquisition and conversion for processing. Processing was performed with Insight 4G. Prior to processing, all images were run through background image subtraction to eliminate the background noise. While the interrogation window size varied across the tests based on tunnel speed, a Recursive NyQuist Grid, FFT Correlation Engine, and Gaussian Peak Engine were consistently used for all test cases. Post-processing filtering and validation eliminated any bad vectors due to localized spots of insufficient seeding.

Flow visualization was also used to qualitatively identify cavity flow structures and determine the presence, or lack thereof, of fluid injection and ejection from the cavities. Flow visualization was performed at the same testing conditions used for the DPIV. The flow was
seeded with the same particles used for DPIV. Streak images were created by pulsing the laser 10 times faster than the camera frame rate allowing 10 locations of a single particle to be traced in one image. Sets of 400 images were taken at frame rates of 50 and 100 fps, with laser frequency set to 500 and 1000 Hz, respectively.

4.3 Results and Discussion

Baseline boundary layer profiles over a flat plate were taken and compared to theoretical boundary layer fits prior to inserting the shark skin array. The graphs in Figure 4.4 show the data versus fit for the $U_\infty = 0.38$ m/s for location $x = 0$.

![Figure 4.4. Laminar (left) and turbulent (right) experimental boundary layer profiles compared to theoretical boundary layer fits for $U_\infty = 0.355$ m/s for location $x = 0$.](image)

The laminar experimental results agree well with the theoretical calculations for a favorable pressure gradient with $\beta = 0.5$. Values for the Falkner-Skan fit were calculated using the numerical results published by Katagiri [17]. The power law fit for a turbulent boundary layer does not account for a favorable pressure gradient and the shift away from the 1/5 curve fit seen in Figure 4.4 is reasonable under a favorable pressure gradient. The experimental flat plate data at each x-location is used for comparison in each respective scale model case.
There was a slight increase in freestream velocity to $U_\infty = 0.38 \text{ m/s}$ over the shark skin from $U_\infty = 0.355 \text{ m/s}$ over the flat plate. This was most likely due to the slight decrease in water level between testing runs and the plate shifting toward the front tunnel wall while switching out the center test plate. The difference is slight and not enough to significantly affect the boundary layer profiles obtained. The profiles are also nondimensionalized by their respective freestream velocities. First, the results for the laminar case will be presented, followed by the results of the turbulent case in order to start a discussion on the noticeable differences between them. The cavity structures are not entirely constant in the cavity for either case, but the structures do adhere to typical patterns consistent across the tests.

4.3.1 Qualitative Laminar Boundary Layer Results for Cavity 1

The flow visualization of the first cavity for $U_\infty = 0.38 \text{ m/s}$ is examined first. Figure 4.5 shows a series of streak images that captures a core cavity vortex with clockwise rotation in three consecutive images.

![Figure 4.5. A core cavity vortex rotating clockwise visualized at 1000 Hz laser pulse for $U_\infty = 0.38 \text{ m/s}$. $\Delta t$ between images is 0.001 seconds.](image)

Even though the flow is laminar, it observed that the cavity structures change with time. Figure 4.6 details a sequence of images showing the core vortex seen in Figure 4.5 being imposed upon and altered by a secondary vortex, of opposite vorticity, within the cavity.
Figure 4.6. A sequence of streak images depicting a counterclockwise vortex gaining strength and encroaching on the core cavity clockwise vortex before becoming a pair of counter-rotating vortices visualized at 1000 Hz laser pulse for $U_\infty = 0.38$ m/s. $\Delta t$ between images is 0.001 seconds.

The diminishment of this second vortex can also be seen at later times and such an instance is observed in Figure 4.7.

Figure 4.7. A sequence of streak images depicting the second counter-rotating vortex diminishing and the core vortex dominating the cavity flow again visualized at 1000 Hz laser pulse for $U_\infty = 0.38$ m/s. $\Delta t$ between images is 0.001 seconds.

The previous figures are just a sampling of images taken exhibiting the same flow characteristics. One noticeable characteristic missing from this laminar cavity flow is burst
flows injecting or ejecting from the cavity. While the boundary layer is indeed fueling the vorticity seen in the cavities, the flow at the cavity exit is dominated by streamwise flow. Flow fluxes in the direction perpendicular to this streamwise flow were not observed in the laminar case. Figure 4.8 details this typical lack of fluid exchange seen in the laminar cases. It should be noted here that the geometry changes in the spanwise direction as the scales are symmetric, but not constant shape. This lack of fluid exchange may not be typical at a different spanwise location along the model.

![Figure 4.8](image)

**Figure 4.8.** A set of streak images taken at random test times over a range of cavity structures depicting a lack of fluid exchange between the cavity and fluid layer above visualized at 500 Hz laser pulse for $U_\infty = 0.38$ m/s. $\Delta t$ between images is 0.002 seconds.

4.3.2 Qualitative Turbulent Boundary Layer Results for Cavity 1

Next, the flow visualization of the first cavity for $U_\infty = 0.38$ m/s under a turbulent boundary layer is discussed. Figure 4.9 shows a series of streak images that captures a core cavity vortex.
Figure 4.9. A core cavity vortex rotating clockwise visualized at 1000 Hz laser pulse for $U_\infty = 0.38$ m/s. $\Delta t$ between images is 0.001 seconds.

This set of images, typical of the turbulent case, shows a significant difference in core vortex size from the laminar case. The core vortex in the laminar case filled nearly the entire space between the two scale rows, when not being impeded by the secondary vortex as seen in Figures 4.5 and 4.6. While a cavity vortex is present in the turbulent case, it is far less discernible over the time span. In addition, the second counter-rotating vortex depicted in Figure 4.6 was not seen in the turbulent case. While it does appear that flow within the cavity is influenced by vortices, it does not appear to be dominated by them as seen in the laminar case. Near the bottom of the first cavity is a clockwise rotating vortex that appears much more consistently than the core vortex, which is more of a rare occurrence in this turbulent case. Figure 4.10 shows examples of this vortex in the lower region of the cavity.

Figure 4.10. A cavity vortex in the lower right section of the first cavity and the absence of a core cavity vortex typically seen in the laminar case visualized at 1000 Hz laser pulse for $U_\infty = 0.38$ m/s. $\Delta t$ between images is 0.001 seconds.

The most important difference in the turbulent case is the bursts of fluid present into and out of the cavity. In cavity one, only ejections of fluid were seen. Figure 4.11 shows two instances of fluid ejection from the cavity into the boundary layer.
4.3.3 Qualitative Laminar and Turbulent Boundary Layer Results for Cavity 2

The structures in the second cavity are somewhat similar between laminar and turbulent cases, thus the results of cavity 2 have been combined in this section. Cavity 2 sustains a vortex, in both laminar and turbulent cases, similar to the core vortex seen in Figure 4.5 for the first cavity under laminar conditions. If the second counter-rotating vortex that exists in cavity 1 is present in cavity 2, it was not seen due to the scales blocking that area of the flow to a greater degree in the second cavity. Figure 4.12 shows a typical vortex structure seen in cavity 2 for both laminar and turbulent conditions.
As in the laminar case for the first cavity, the second cavity does not appear to exhibit fluid injection or ejection between the cavity and boundary layer. The second cavity in the turbulent case, however, does exhibit strong fluid movement into and out of the boundary layer above the cavity. Examples of this ejection and injection of fluid from the cavity can be seen in Figure 4.13.
4.3.4 Quantitative Laminar and Turbulent Boundary Layer Results for Cavities 1 and 2

The main focus of the DPIV experiments was to produce time-averaged results to examine the average flow structures. Figure 4.14 shows the vorticity contours for cavities 1 and 2 for the laminar case.
Figure 4.14. Average vorticity contours of cavity 1 (left) and cavity 2 (right) for the laminar case for $U_\infty = 0.38 \text{ m/s}$. Positive values indicate counter-clockwise rotation. The black lines represent the scale faces of scale 2 (left) and scale 3 (right).
The vorticity in cavity 2 is slightly stronger than in cavity 1 and does not have a discernible secondary counter-clockwise rotation. Once averaged over time, the secondary vortex present in cavity 1 does not have as great a magnitude as the primary core vortex. Figure 4.15 shows the vorticity contours for cavities 1 and 2 for the turbulent case.
Figure 4.15. Average vorticity contours of cavity 1 (left) and cavity 2 (right) for the turbulent case for $U_\infty = 0.38$ m/s. The black lines represent the scale faces of scale 2 (left) and scale 3 (right).
The difference in vorticity between the laminar and turbulent cases is apparent in these time-averaged contours. It was noted in the previous section that the qualitative results indicated the lack of a consistent core vortex in the first cavity for the turbulent case. The time-averaged results confirm this indication. The small clockwise vortex noticed more consistently for this case indeed shows up in the time-averaged results, lending quantitative validity to its more consistent presence.

The u and v velocity components within the cavity are now presented. Figure 4.16 highlights the u component of velocity for the laminar and turbulent cases. Figure 4.17 highlights the v component of velocity for the laminar and turbulent cases.
Figure 4.16. Average $u$ component velocity contours of cavity 1 (left) and cavity 2 (right) for the laminar (top row) and turbulent case (bottom row) for $U_w = 0.38$ m/s. The black lines represent the scale faces of scale 2 (left) and scale 3 (right).
Figure 4.17. Average v component velocity contours of cavity 1 (left) and cavity 2 (right) for the laminar (top row) and turbulent case (bottom row) for \( U_0 = 0.38 \) m/s. The black lines represent the scale faces of scale 2 (left) and scale 3 (right).
These contours again show the lack of a consistent core vortex in the first cavity for the turbulent case. The \( v \) component averages also show a slight trend of the flow to travel upward out of the first cavity in the turbulent case, coinciding with the numerous flow ejections seen in the qualitative studies. The \( u \) and \( v \) components for the other cavities reinforce the idea that a primary core vortex is present in these cases.

The time history of the \( v \)-component of velocity was also examined near the surface of the first cavity for the turbulent case. Figure 4.18 details the two locations examined for the following discussion. Figure 4.19 shows the instantaneous \( v \) component of velocity at 12000 points in time for a single point near the tip of scale 1. The points are recorded in 10 different sets of 1200 images, where the time step between each of the 1200 images is 0.002 seconds. The sets were recorded at random times, so the delta \( t \) between sets is not constant and is generally several seconds. Figure 4.20 shows the instantaneous \( v \)-component of velocity at a second point near the end of the first cavity.

![Figure 4.18](image.png)

Figure 4.18. The locations of the two instantaneous time-history velocity profiles detailed in Figures 4.19 and 4.20.
Figure 4.19. The instantaneous time-history of the \( v \)-component of velocity at a height of 3.65 mm at a downstream location of 6.2 mm for the turbulent case for \( U_\infty = 0.38 \) m/s.
Figure 4.20. The instantaneous time-history of the v-component of velocity at a height of 3.65 mm at a downstream location of 10 mm for the turbulent case for $U_\infty = 0.38$ m/s.

An interesting, though not entirely unexpected, result arises when analyzing the v component of velocity. The introduction of the first scale causes an upward flow away from the surface, as seen in Figure 4.18 by the fluctuations having a mean greater than zero. The scale is bristled at 45° and protrudes into the boundary layer, so it is expected that the incoming flow will be affected directly by this angle.
4.4 Conclusion

When comparing the turbulent results of this study with those of Djenidi, the overall characteristics are similar, despite this study dealing with cavities that protrude into the flow slightly instead of lying completely beneath the boundary layer. The most notable difference appears in the first cavity under the turbulent boundary layer. For the shark skin model, there is not a consistent vortex present in this cavity at the spanwise depth chosen for study. Because the model is three-dimensional, other slices may reveal varying characteristics. It should be noted here that the lack of a discernible cavity vortex found in this study does not necessarily exclude the existence of a core vortex at all in this cavity because the vortex could possibly occur at some other depth. However, the lack of a cavity vortex at this particular location does lend itself to fluid mixing rather than a partial slip condition, which aligns with the idea that localized reversing flow activates the scales to avoid flow separation. Once activated, it would be advantageous for the shark if those scales then initiate a mixing of fluid bringing higher momentum flow closer to the surface and allowing the flow to stay attached longer. While the results only show consistent ejection from the first cavity, they offer further promise from the injection and ejection of flow seen in the second cavity.

The areas of the shark with greatest scale flexibility are found along the flank and trailing edge of pectoral fins where flow is most likely to be turbulent. The results also confirm added benefit for the turbulent boundary layer case versus the laminar case, in terms of fluid mixing. While the laminar case shows consistent vortex formation, the increased mixing between the cavities and the external flow is not seen for this case. However, Lang et al showed laminar separation control due to shark skin, so it is possible that other factors also play a role in separation control [18]. One key variation from the real shark skin in this experiment is the
protrusion height into the boundary layer. The model scale array protrudes farther into the boundary layer than erected mako shark scales would. While this study matched cavity Re, it could not replicate all variables of the mako swimming exactly. The mako scales have a much lower percentage of intrusion into the boundary layer versus the scale model, 1% for the mako versus 5-10% for the turbulent model versus 25-50% for the laminar model. Therefore, the mechanisms utilized in a laminar boundary layer may not have been accurately captured in this experiment.

Based on the boundary layer protrusion height calculated, the scales of the shortfin mako may be long enough, once erected, to just protrude into the buffer layer. The buffer layer is thought to contain the most interesting dynamic processes within the turbulent boundary layer regions [24]. Interaction and alterations within this near wall layer may enhance mixing in this region. The near wall region of turbulent boundary layers is well known to contain low speed streaks and bursts, but these events occur randomly within the turbulent boundary layer [25]. Smith et al. expanded on the series of events needed to regenerate the hairpin vortices within a turbulent boundary layer, especially the burst phenomena thought to be the primary means for regeneration within the boundary layer and the production of new turbulence within the layer [26]. Perhaps the mako scales bristle to initiate an ejection into the boundary layer from near the surface to postpone flow reversal by forcing a series of turbulent events to occur that enhance the turbulent boundary layer as seen in the natural evolution of the turbulent boundary layer. The instantaneous time history of the \( v \) component of velocity may offer insight into this possibility. As seen in Figures 4.18 and 4.19, the introduction of the first scales causes the trend of fluid motion to be away from the surface and toward the outer layers.
It is important to note that the scale bristling on the shark is most likely happening at small time scales and the denticles do not stay bristled at the same angle indefinitely as studied in this case. The scales could potentially act to redirect the flow away from the surface into the boundary layer above, much like a burst ejection seen in typical turbulent boundary layers, before going back to a zero bristling angle. If reversing flow activates the denticles in regions close to flow separation, it is possible the scale uses this upward ejection of fluid to manually, though passively, mimic burst ejection and generate new turbulence allowing the boundary layer to stay attached longer. These events could be happening at several locations simultaneously, while other scale regions utilize the riblets to reduce the turbulent skin friction drag.

While this study did not examine scale actuation by reversing flow, the goal was to better quantify structures that exist within the cavities once the scales are bristled and this set of experiments has delivered an initial insight into those structures. The case of scale bristling and the shortfin mako’s potential ability to control flow separation is a very complicated process fueled by millions of years of evolution. Examining specific pieces of this phenomenon individually will help unlock key aspects needed to understand and adapt the mako’s solution for flow control to modern engineering problems.

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References


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CHAPTER 5

CONCLUSIONS

This series of experiments aimed to provide further insight into the possible flow control mechanisms of shortfin mako skin. The initial goal was to develop a system capable of inducing reversing flow over mako scales while simultaneously being able to view the interaction with the scales. Two jet setups, one with a goal of bristling a single or small group of scales and the second with the goal of bristling a row of scales, were designed and induced reversed flow over several samples from the mako flank region. The camera system assembled allowed for magnified viewing while still providing the depth of field necessary to see the scales actuate. This experiment provided a direct link between reversing flow and scale bristling. This experiment also showed that the velocity magnitudes capable of bristling the scales of the shortfin mako are within the range of reversing flow velocities along the shark under natural swimming speeds.

The second goal of this study was to quantify changes in the boundary layer and Re stress caused by the introduction of bristled scales from the mako. This was done by using a biomimetic model embedded beneath a boundary layer flow in a water tunnel. This study showed an initial positive impact of mixing and bringing higher momentum fluid closer to the surface over the first few scales compared to a flat plate for the turbulent boundary layer case. This benefit did not continue indefinitely and the flow over the later cavities was hindered. While the laminar case did not show any benefit in this study, it was potentially due to the lack of protrusion height similarity in this case. Future work should focus on identifying the key
number of scales that need to be bristled for maximum benefit. Future laminar testing should also aim to match the protrusion height more closely.

The third area of focus was placed on cavity structures within the shortfin mako model. Again, the model was embedded beneath a boundary layer flow, but this particular experiment focused strictly on the cavities created by the scales. It was shown that cavity vortices were dominant structures in the first two cavities under laminar and turbulent conditions with the exception of the first cavity under turbulent conditions. The first cavity under turbulent conditions instead showed no consistent vortex, but rather a trend of flow out of the cavity. The v component of velocity near the first scale tip also showed this upward trend, much like an ejection, into the boundary layer. This experiment concluded that bristled shark scales may act as burst ejection triggers that initiate a series of turbulent flow events seen naturally within a turbulent boundary layer that would help the flow stay attached longer. While these are promising results, future work at various streamwise distances should be conducted to gather a more global picture of events occurring over the scales.

References


APPENDIX - LABVIEW IMAGE ACQUISITION PROGRAM