Determining Drag Forces on 3D Printed Shark Skin and the Conditions in which Drag Forces are Reduced

Kayla M. Bartnicke

University of Arkansas, Fayetteville

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DETERMINING DRAG FORCES ON 3D PRINTED SHARK SKIN AND THE CONDITIONS IN WHICH DRAG FORCES ARE REDUCED
DETERMINING DRAG FORCES ON 3D PRINTED SHARK SKIN AND THE CONDITIONS IN WHICH DRAG FORCES ARE REDUCED

An Undergraduate Honors College Thesis
in the

Department of Mechanical Engineering
College of Engineering
University of Arkansas
Fayetteville, AR

by

Kayla Marie Bartnicke

April 28, 2017
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LIST OF EQUATIONS AND SYMBOLS

Eq. 1: \[ I_{\text{bend}} = \frac{1}{4} \pi ab^3 \] 18

\( I_{\text{bend}} \) = Moment of inertia (in\(^4\))

\( a \) = Horizontal radius of ellipsis (in.)

\( b \) = Vertical radius of ellipsis (in.)

Eq. 2: \[ \delta_{\text{max}} = \frac{p l^3}{3Ei} \] 19

\( \delta_{\text{max}} \) = Maximum deflection (in.)

\( E \) = Young’s modulus (psi)

\( l \) = Length of rod and plate (in.)

Eq. 3: \[ F_d = \frac{\delta_{\text{max}} (3EI)}{l^3} \] 19

\( F_d \) = Drag force (lb)

Eq. 4: \[ C_D = \frac{F_d}{\frac{1}{2} \rho V^2 A} \] 19

\( C_D \) = Drag coefficient

\( \rho \) = Density of fluid (slug/ft\(^3\))

\( V \) = Velocity of fluid (ft/s)

\( A \) = Area (ft\(^2\))

Eq. 5: \[ Re = \frac{\rho VL}{\mu} \] 19

\( Re \) = Reynold’s number

\( L \) = Length of plate (ft)

\( \mu \) = Dynamic viscosity (lb-s/ft\(^2\))
Eq. 6: \[ C_f = \frac{1.328}{\sqrt{Re}} \]

Eq. 7: \[ \frac{\Delta R_1}{R_1} = \left[ \left( \frac{V_b}{V_{in}} + \frac{R_2}{R_1 + (R_2 + R_3)} \right) \right] \frac{1}{1 - \left( \frac{\Delta V_b}{V_{in}} \right) - \left( \frac{R_2}{R_1 + (R_2 + R_3)} \right)} - 1 \]

\( R = \) Resistance (\( \Omega \))

\( V_b = \) Voltage across the bridge circuit (V)

\( V_{in} = \) Input voltage (V)

Eq. 8: \[ \frac{\Delta R_1}{R_1} = \left[ \left( \frac{\Delta V_b}{R_1} \right) + \left( \frac{\Delta V_b}{V_{in}} \right) \right] - 1 \]

Eq. 9: \[ \varepsilon = \frac{1}{GF} \cdot \frac{\Delta R_1}{R_1} \]

\( \varepsilon = \) Strain

\( GF = \) Gage factor

Eq. 10: \[ y = 1/2.01^{*(((0.5)+(((a+0.1)-0.4)/201)/2.5))} / (((0.5)-(((a+0.1)-0.4)/201)/2.5)) - 1) \]
ABSTRACT

This project was conducted at the University of Arkansas with access to 3D printers and a water tunnel. The project examines drag forces over 3D-printed shark skin. Shark skin was chosen to be studied because of its unique three-pronged denticle shape and the assumption that this unique shape has a purpose, such as drag reduction.

A shark denticle was designed using SolidWorks software, multiplied 164 times creating a total skin area of 17.5 in², and printed using both a MakerBot Replicator 2 3D printer and an Ultimaker 2 Go 3D printer. The shark skin was initially printed using NinjaFlex material with the MakerBot, but the final 3D printed shark skin was printed with PLA using the Ultimaker printer. The Ultimaker printer has a higher resolution with an ability to print up to 20 micron, yielding a higher quality print [6].

The shark skin was placed on a 3D printed ABS plate and tested in a water tunnel against a control plate without shark skin. The plates were set to test at speeds of 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, and at the water tunnel’s maximum speed setting of 5 in/s. The water tunnel, however, only reached a maximum of about 3.52 in/s. Experimental data collected using deflection measurements yielded an average drag reduction value of 32%. This value was greater than expected due to the limited measurement sensitivity of this means of data collection. A strain gage setup was also used to collect data, but due to limited time, the setup was not calibrated as necessary. Preliminary data was taken, however, and is included in this paper.
1. INTRODUCTION

Sharks have unique tooth-like projections, or denticles, that make up their skin. These denticles vary in size depending on the type of shark and their location on the shark’s body [3]. However, they all have the same basic three-pronged shape with riblets. It is thought that this unique shape reduces drag and increases lift and that is why shark skin has evolved in this way [3]. Some tests support this hypothesis but others have found that in some cases it actually increases drag [1]. Data from this project will help answer the question if shark skin really does reduce drag and in what conditions. Results could lead to determining where shark-skin inspired material may be beneficial in real-world applications. The potential drag reduction of shark skin inspired surfaces could lead to fuel savings for boats and airplanes or to improved swimming gear for recreational purposes.

1.1 Research Problem

The purpose of this thesis is to look further into the drag forces that act on shark skin and the possible drag reduction caused by the skin’s surface. The project tasks included designing portions of shark skin and the experimental setup, 3D printing the artificial skin and other testing materials, recording the deflection, testing the strain on the skin, calculating the drag forces, and analyzing the drag data acquired. These experimental drag forces are compared to a flat control plate that does not contain shark skin. The desired outcome is a drag reduction caused by incorporating the 3D printed shark skin onto a flat surface. Optimizing the experimental setup to allow for the most accurate results was a main focus during the project. Optimization efforts included a correct depiction of the unique shape of a shark skin denticle, a high quality 3D print of the skin, a sturdy mount to hold the plates in the water tunnel, and a sensitive way of collecting data with minimal error.


2. BACKGROUND

With water being about 750 times denser than air, it is much harder to move quickly through it [15]. So, what makes some sea animals capable of reaching over 30 mph? This may be due to a lot of different variables such as size of the animal, the size and shape of fins, the muscles, the skin, or the general environment and conditions. One of the fastest animals found in the ocean is the Shortfin Mako shark, or the Isurus Oxyrinchus, reaching recorded speeds of up to 31 mph [16]. A distinct feature on this shark and sharks in general that sets them apart from most other marine animals is their unique skin. The skin is made up of three pronged denticles with riblets which cover the entire shark’s body [3]. Depending on the species, the skin differs slightly in dimensions but the general shape remains the same for most. Similarly, even on a single species, such as the Shortfin Mako, different dimensioned denticles line the shark’s body [2]. The shortest denticles of the Shortfin Mako are found on the caudal keel, the back edge of the caudal, and the lower side of the pectoral fins [3]. The longest denticles are found around the mouth area and the upper and leading side of the pectoral and dorsal fins [3]. The length-width ratios range from about 1.04 to 1.46 [3]. The denticles range in length from about 115.8 to 235.9 µm [3].

2.1 Previous Research

One previous study found, by using a flapping foil robotic device, that a flexible skin membrane had a 12.3% increase in swimming speed [5]. In this particular study, it was found that a rigid body, however, did not increase swimming speed, claiming the shark’s body movement is what causes the drag reduction or thrust that allows a shark to swim quickly [5]. Most studies to date claim shark skin does indeed reduce drag force. However, this conclusion is still up for discussion. A recent computational study done at Stony Brook University and the University of Minnesota suggests that denticles actually increase drag and sometimes by as much as 50% [1].
3. EXPERIMENTAL DESIGN

3.1 Shark Skin

The shark skin was designed using SolidWorks software. The individual denticle was first designed, and then multiple linear patterns were created in SolidWorks to create a sample of shark skin to be 3D printed. The denticle designed for this project had a length of 0.5 in. and a width of 0.36 in., yielding a length to width ratio of 1.4. This denticle shape is most likely to be found near the pectoral fin of a Shortfin Mako shark. The denticle model is shown in the following figure.
As seen in the figure, the denticle was designed with a 3 pronged-end and riblets on the top surface. Due to the complexities that come with 3D printing, the skin did not consist of overlapping denticles which would be found on an actual shark. The artificial skin was designed with denticles in incredibly close proximity, however, to most closely mimic a shark’s skin. The denticle was multiplied 164 times to create a total shark skin area of 17.5 in\(^2\). A model of the shark skin is shown in the figure below.

![SolidWorks Model of Shark Skin](image)

The drag reduction that may be caused by the shark skin design was predicted to be due to the actual denticle shape and not the overlapping pattern of the denticles. This kind of a design that incorporates denticles but is simpler without the overlapping pattern would be easier to incorporate in real world applications where drag reduction is desired.
3.1.1 3D Printing

Initially, the shark skin was printed using ReplicatorG software to create the GCode, a Makerbot Replicator 2 3D printer, and NinjaFlex material. The printing parameters used are shown in the following figure.

<table>
<thead>
<tr>
<th>MakerBot Replicator 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Object Infill</td>
</tr>
<tr>
<td>Number of Shells</td>
</tr>
<tr>
<td>Feedrate</td>
</tr>
<tr>
<td>Travel Feedrate</td>
</tr>
<tr>
<td>Print Temperature</td>
</tr>
</tbody>
</table>

*Figure 3.3. MakerBot Replicator 2 Printing Parameters*

No support material was used to create the print. The G Code was generated and the file was saved as a x3g file to be compatible with the printer.

NinjaFlex is a type of thermoplastic elastomer, or TPE, and is a very strong yet flexible material [4]. NinjaFlex was initially chosen because of its flexibility which makes it a better option than Acrylonitrile Butadiene Styrene, or ABS, material for achieving a skin-like print. The downside to using such a flexible material, however, was that it was more difficult to print. Oftentimes, the filament’s softness caused extruder jams. Also, the MakerBot printed a gridded pattern to serve as the base of the print. This gridded surface made an uneven bottom surface of the skin, making it difficult to adhere to the flat plate. The end result included spacing between the plate and the skin, allowing for possible undesired water flow through this area which could lead to error. The gridded pattern and the attempt at attaching the skin to the flat plate is shown in the following figure.
Furthermore, the filament as well as the printer itself sometimes caused a stringy final print. A higher resolution was desired to minimize experimental error due to a low resolution print. The final skin that was used to attain the experimental results was printed using an Ultimaker 2 Go printer, Cura software, and Polyactic Acid, or PLA, material. The printing parameters of the Ultimaker 2 Go printer that were set in the Cura program are shown in the figure below.

<table>
<thead>
<tr>
<th>Ultimaker 2 Go</th>
</tr>
</thead>
<tbody>
<tr>
<td>Object Infill</td>
</tr>
<tr>
<td>Print Speed</td>
</tr>
<tr>
<td>Travel Speed</td>
</tr>
<tr>
<td>Print Temperature</td>
</tr>
</tbody>
</table>

Figure 3.5. Ultimaker 2 Go Printing Parameters

Sections of the original NinjaFlex skin and the final PLA print are shown in the following figure.
3.2 Plates

A plate without shark skin was used as a control to compare to the plate onto which shark skin was attached. The shark skin was attached to the plates using silicone rubber. All of the plates were designed in SolidWorks and 3D printed using a CatalystEX program, a uPrint 3D printer, and Acrylonitrile-Butadiene-Styrene, or ABS, material. The ABS material is a strong and durable material, making it a suitable option for the supportive parts, such as the plates and rods [8]. In order to reduce printing time and save material, the plates were initially printed at sparse density. However, after placing these plates in the water tunnel, it was found that they floated, so they were reprinted at the high density setting.

3.2.1 Area

The plates were initially designed and printed to be 2.45 x 1.785 in$^2$. After some preliminary testing, however, it was decided that the plate as well as the skin that was attached to it should be a larger size to allow for larger drag data and, thus, a more distinctive comparison between the control plate and the shark skin plate. The area of the plate was quadrupled with a final area of 4.9 x 3.57 in$^2$. This area was matched to the total size of the 3D printed shark skin.

Figure 3.6. NinjaFlex (Left) and PLA (Right) Shark Skin 3D Prints
A comparison of the initial plate and the final plate are shown in the figure below.

![Figure 1.7. 3D Printed Plates](image)

### 3.2.2 Control vs Shark Skin Plate

The total thickness of the control plate was 0.32 in. The height of the shark skin denticle was measured to be 0.07 in. To account for this additional height, the plate onto which the skin would be attached was designed to have a total thickness of 0.25 in. To ensure the rod was still in the middle of the shark skin plate once the shark skin was attached, it was not centered on the plate design. It was placed 0.09 in. from the edge so that when the shark skin was added with its additional thickness, the rod was in the center of the total thickness of the plate. The models of the control plate and the shark skin plate are shown in the figure below.
The two 3D printed plates are compared in the figure shown below.

Figure 3.8. SolidWorks Models of Control Plate (Left) and Shark Skin Plate (Right)

Figure 3.9. Control Plate vs Shark Skin Plate
3.3 Cantilever Beams

The plates were secured to beams or rods which were suspended from a support and acted as cantilevers. The cantilevers were perpendicular to the water’s surface and allowed for visible deflection which could be measured.

3.3.1 Plexiglass Beam

Originally, the plates were secured to a Plexiglass beam with bolts. The Plexiglass beam was cut to be 0.86 in. wide. After performing experimental trials with the Plexiglass beam, it was decided that a beam or rod with a smaller width was desired to minimize the disruption of the flow.

3.3.2 Circular Rod

To allow for easy adjustments if necessary after experimental trials, a rod was designed in SolidWorks and 3D printed using the CatalystEX program, uPrint 3D printer, and ABS material. The rod had a diameter of 0.09 in. and a length of 10.5 in. This diameter was much smaller than the width of the plexiglass beam but large enough for a strain gage to be attached around the circumference. The end was tapered to be able to fit into the plate. Because the rod was designed in SolidWorks, minor adjustments were able to be made to the bottom portion of the rod when problems were encountered with fitting it into the hole of the plate. The circular rod is shown in the following figure.
After some experimental trials, it was found that the circular rod caused undesired bending in the transverse direction. This bending led to the plates drifting towards the side of the water tunnel, affecting the flow’s direct contact with the front end of the plate. This issue with keeping the deflection in the direction of the flow is shown in the following figure.

![Figure 3.10. SolidWorks Model of Circular Rod](image)

3.3.3. Elliptical Rod

To minimize the transverse bending seen with the circular rod, an elliptical rod with a flatter, wider front was designed and 3D printed. The major and minor axes of the ellipse were 0.2
in. and 0.09 in., respectively. Like the circular rod, the length of the elliptical rod was 10.5 in. However, 0.25 in. at the end of the rod was inserted into the plate and not included as part of the length of the rod during calculations. A circular portion with a diameter of 0.25 in. was extruded from the top of the rod and was secured at this point into the support rod. The elliptical rod is shown in the figure below.

![SolidWorks Model of Elliptical Rod](image)

**Figure 3.12. SolidWorks Model of Elliptical Rod**

The elliptical rod is compared to the circular rod in the figure below.

![Circular Rod (Top) and Elliptical Rod (Bottom)](image)

**Figure 4.13. Circular Rod (Top) and Elliptical Rod (Bottom)**
The elliptical rod corrected the transverse bending issue. It also allowed a flat surface for the strain gage to be attached to rather than the strain gage having to be wrapped around the circular rod. The elliptical rod performed well and was the final design for the cantilever that held the plates in the water tunnel.

3.4 Setup Design

The setup consisted of a stand and 3D printed parts that held the cantilevers perpendicular to the water’s surface. Like the plates and the rods, all parts of the setup that were 3D printed were printed using the CatalystEX program, uPrint 3D printer, and ABS material.

3.4.1 Design 1

The initial setup design consisted of a stand that was made of wood to hold the Plexiglass beam which supported the plate. The beam was attached to a 3D printed support on the wooden stand which was nonadjustable in the vertical direction. The angle of the plate could be adjusted with 3D printed sliders that were part of the support. This design is shown in the figure below.

![Figure 3.14. Wooden Stand and Sliders (Top View)]
3.4.2 Design 2

When the cantilever Plexiglass beam was changed to a circular rod, a new central piece of the 3D printed support was changed to hold a circular rod rather than a rectangular beam. Holes were also added to be able to place the wires of the strain gage through them to attach to the Wheatstone bridge circuit. All other elements of the setup design were kept the same at this point.

3.4.3 Final Design

To allow for a vertical adjustment of the plates in the tunnel, a new stand to support the rods was used. The vertical adjustment ensured the plates could be adjusted to be in the middle of the water tunnel each time. The new stand was an aluminum stand which was heavier and less likely to move. It also only used one vertical bar as a support, allowing for clearer visibility of the plates in the water tunnel. Furthermore, to allow for a direct visual comparison of the shark skin plate and the control plate, the support rod was designed to be able to hold multiple cantilever rods onto which the plates were attached. The final design is shown in the following figure.
Figure 3.15. Final Adjustable Setup Design
4. DATA COLLECTION

4.1 Water Tunnel Speed

The water tunnel could be run theoretically at any speed between 0 to 5 in/s. These speeds were tested by marking the water tunnel with one inch intervals and allowing the water tunnel to reach a constant speed at each speed setting of 1, 2, 3, 4, and 5 in/s. Ink dye was used to visualize how quickly the dye moves to each marked interval. Slow-motion video and a stopwatch were used to assist in the process. The method is shown in the figure below.

![Figure 5.1. Water Tunnel Speed Testing](image)

4.2 Laser

One method that was used to collect data was using a laser on a 3D printed stand with a slider. The slider had marked intervals of 0.05 in. which were used to measure the deflection of the rods in the water tunnel. The laser was lined up to the edge of the front of the plate during testing and at each new speed, the laser was slid, the interval marks were counted, and the total deflection at each new speed was recorded. The laser setup and method of data collection is shown in the figure below.
The deflections experienced by the cantilever rod are demonstrated in the following figure.

\[ I = \pi a b^2 \]  

After the deflections were recorded, the drag forces were found by first finding the moment of inertia \( I \) across the neutral axis of the elliptical rod with the following equation.

\[ I_{bend} = \frac{1}{4} \pi ab^3 \quad (1) \]
where \( a \) and \( b \) are defined as shown in the following figure.

![Figure 4.4. Elliptical Moment of Inertia](image)

Then, the following deflection equation was rearranged to find the drag force as shown in equation (3).

\[
\delta_{\text{max}} = \frac{P l^3}{3 E I} \quad (2)
\]

\[
F_d = \frac{\delta_{\text{max}}(3EI)}{l^3} \quad (3)
\]

where \( \delta_{\text{max}} \) is the maximum deflection of the rod, \( E \) is the Young’s modulus of ABS material, \( F_d \) is the drag force, and \( l \) is the length of the rod and plate. The drag coefficient \( C_D \) was then found using the following equation.

\[
C_D = \frac{F_d}{\frac{1}{2} \rho V^2 A} \quad (4)
\]

where \( \rho \) is the density of the fluid and \( V \) is the speed of the fluid. All constant values used during calculations were taken at a water temperature of 60°F. The Reynold’s numbers were found for the flat plate at each speed and graphed against the drag coefficients. The Reynold’s numbers were found using the following equation.

\[
Re = \frac{\rho V L}{\mu} \quad (5)
\]

where \( L \) is the length of the plate and \( \mu \) is the dynamic viscosity of the water.
Theoretical calculations were done to compare the experimental results. Using the Reynold’s numbers calculated, the skin friction drag coefficient was found. Based on the Reynold’s numbers calculated, the following laminar flow coefficient equation was used.

\[ C_f = \frac{1.328}{\sqrt{Re}} \]  

(6)

4.3 Strain Gage

The second and final method that was used for collecting data was with a strain gage and a Wheatstone Bridge circuit. The strain gage was attached to the 3D printed rod using super glue and sealed with clear silicone rubber. The circuit was used in conjunction with a LabJack and its LJ Tick InAmp. The Labjack was plugged into a computer, and the LogUD program was used to read the strain caused from the deflection of the rod as measured by the strain gage.

The following equation was used to find the equation to input into LogUD to read strain.

\[ \Delta O_A = \left( \frac{R_2}{R_1} \right) \left[ \frac{\Delta V_b}{V_{in}} + \frac{R_2}{(R_2 + R_3)} \right] - 1 \]  

(7)

where strain is measured through the change in its resistance \( R \). Equation (7) can be simplified into the following equation due to all of the resistances being equal.

\[ \frac{\Delta R_1}{R_1} = \left[ \left( \frac{1}{\frac{2}{3}} \right) \frac{\Delta V_b}{V_{in}} \right] - 1 \]  

(8)

where \( V_{in} \) is the input voltage and \( V_b \) is the voltage read across the bridge. Equation (8) was then input into the following equation to find the strain equation that was input into LogUD.

\[ \epsilon = \frac{1}{G F R_1} \frac{\Delta R_1}{R_1} \]  

(9)
where $\epsilon$ is equal to the strain which is the unknown and GF equals the gage factor of the strain gage. After combining Equations (7) and (8), the following equation was input into LogUD.

$$y = 1/2.01*(((0.5)+(((a+0.1)-0.4)/201)/2.5))/((0.5)-(((a+0.1)-0.4)/201)/2.5))-1) \quad (10)$$

As seen in Equation (10), the gage factor of the strain gage used was equal to 2.01 and the voltage input was equal to 2.5 volts. A correction factor of 0.1 was also added to the voltage across the bridge to calibrate the system to be reading a starting output of 0.4V. This correction factor was adjusted if necessary at the start of each trial.

Initially, a MicroMeasurements strain gage was used and wires were soldered onto the gage’s ends. However, there were issues with soldering the wires onto the strain gage which was attached to a plastic rod. The rod melted and the strain gage was damaged. So, new pre-soldered strain gages were ordered and used to collect data. The strain gage used during trials was a 120.4Ω gage with a gage factor of 2.01 and a 3 mm grid.

5. RESULTS/DISCUSSION

5.1 Water Tunnel Speed

The water tunnel was not able to run at its claimed maximum speed of 5 in/s. The speeds were only tested at 1, 2, 3, 4, and 5 in/s. The speeds in between these values were assumed to be halfway between the speeds found for the tested values. The speeds that were set on the water tunnel are shown with their corresponding actual speeds in the following table.
At these speeds, the plates were experiencing a smaller Reynolds number than was predicted and theoretically calculated. As shown from this speed test as well as following data, the water tunnel was not performing to its desired capability. This may have led to some error in the data collected.

### 5.2 Laser

Using the laser method of data collection, the deflections of the rods were found for the shark skin plate and the control plate. The water tunnel was set to speeds of 0, 0.794, 1.322, 1.85, 2.275, 2.7, 2.83, 2.96, 3.24, and 3.52 in/s and was given time to reach a steady flow at these times. The average deflections found for the control plate and the shark skin at each speed are shown in the following figure.
As shown in the graph, the average deflection of the shark skin was less than that of the control plate. A direct comparison of the control plate and the shark skin plate at 3.52 in/s can be found in the figure below.
As seen in the above figure, the shark skin experienced less deflection than the control plate from the flow. Therefore, drag reduction was seen during this method. The drag coefficient values and the percent decrease of the shark skin drag coefficients are shown in the following table.

<table>
<thead>
<tr>
<th>Reynolds Number</th>
<th>Control Plate</th>
<th>Shark Skin</th>
<th>Percent Decrease</th>
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</thead>
<tbody>
<tr>
<td>2163.84</td>
<td>1.93</td>
<td>1.29</td>
<td>33%</td>
</tr>
<tr>
<td>3602.77</td>
<td>1.04</td>
<td>0.70</td>
<td>33%</td>
</tr>
<tr>
<td>5041.70</td>
<td>0.83</td>
<td>0.47</td>
<td>43%</td>
</tr>
<tr>
<td>6199.93</td>
<td>0.74</td>
<td>0.47</td>
<td>37%</td>
</tr>
<tr>
<td>7358.16</td>
<td>0.67</td>
<td>0.45</td>
<td>33%</td>
</tr>
<tr>
<td>7712.44</td>
<td>0.76</td>
<td>0.53</td>
<td>30%</td>
</tr>
<tr>
<td>8066.72</td>
<td>0.83</td>
<td>0.60</td>
<td>28%</td>
</tr>
<tr>
<td>8829.79</td>
<td>0.83</td>
<td>0.62</td>
<td>26%</td>
</tr>
<tr>
<td>9592.86</td>
<td>0.82</td>
<td>0.59</td>
<td>28%</td>
</tr>
</tbody>
</table>

Average 32%

\textit{Table 5.4. Shark Skin Drag Reduction}

The average drag reduction experienced by the shark skin was found to be 32%. The recorded deflection values, however, are larger than what the actual values are believed to be. The laser slider intervals were every 0.05in, and the smallest deflection that could be read was half of an interval at 0.025in. Because deflections smaller than 0.025 were not able to be read, the differences between the shark skin and the control plate may have been larger than the actual deflection differences. The Reynold’s numbers and drag coefficients were found for the plates at each speed. The control plate and shark skin data and their respective error bars are shown in the following figures.
**Figure 5.5. Control Plate with Potential Error**

**Figure 5.6. Shark Skin with Potential Error**
The error ranges were calculated for each speed with a probable error of 0.025 in. deflection reading. As predicted, the lower speeds have a higher probability for error due to the greater effect the deflection has on the overall drag coefficient at these speeds. At the lower speeds, less deflection occurs, so each deflection interval has a greater impact. Thus, the data acquired at the higher speeds contains less probable error in the deflection readings. The experimental and theoretical values of the drag coefficients, their corresponding Reynold’s numbers, and the percent error found for the control plate and shark skin are shown in the table below.

<table>
<thead>
<tr>
<th>Reynold’s Number</th>
<th>Control Plate</th>
<th>Shark Skin</th>
<th>Theoretical</th>
<th>Control Plate</th>
<th>Shark Skin</th>
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<td>0.03</td>
<td>6661%</td>
<td>4407%</td>
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<td>3602.77</td>
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<td>5041.70</td>
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<td>0.47</td>
<td>0.02</td>
<td>4335%</td>
<td>2435%</td>
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<tr>
<td>6199.93</td>
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<td>0.47</td>
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<tr>
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<tr>
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<td><strong>3473%</strong></td>
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*Table 5.7. Experimental and Theoretical Drag Coefficients and Error*

As shown in the above table, the experimental drag coefficients were significantly greater than the theoretical values. The error is at its maximum at the smallest Reynold’s number, reaches its minimum in the mid-range of the Reynold’s number values, and starts to increase again at the largest Reynold’s numbers tested. The general trend of the experimental drag coefficients is shown in the following figure.
Figure 5.8. *Experimental and Theoretical Drag Coefficients*

The error is at a maximum at the smallest Reynold’s number tested because, as stated before, any slight error in the reading of the deflection greatly affected the final result. Also, at this low Reynold’s number, the plate experienced oscillation within the water tunnel, leading to probable error in the reading of the deflection. The control plate and shark skin drag coefficients are inversely proportional to the Reynold’s numbers, as expected, at the lower to mid-range values of Reynold’s numbers. At the larger Reynold’s numbers, error may have been due to the orientation of the plates at these greater deflections. The theoretical calculations were based on a plate parallel to the flow. At the higher speed settings, the plates experienced larger deflections, causing the plate to no longer be completely parallel to the flow.

A large percentage of the error is thought to be due to the Young’s modulus value given for ABS material. It is possible that the 3D printing and the orientation in which the rods were sliced affected the properties of the rod. Calibration tests need to be performed to assess the Young’s modulus of the material and its possible variation from the given value.
Furthermore, some error may be due to human error in not perfectly lining up the laser to the end of the plate every time it was moved and equipment error with the water tunnel. The water tunnel demonstrated issues with reaching a steady state flow as is discussed in section “5.3.2 Dynamic Trials at Varied Speeds.” Finally, the adjustable rod allowed the setup to be tested in the future for varying angles of orientation, but may have caused some error if the plate was not exactly parallel with the flow each trial.

5.3 Strain Gage

5.3.1 Dynamic Maximum Speed Trial

The strain was measured for the control plate and the shark skin plate as the water tunnel was turned on and set to its maximum velocity of 3.52 in/s. The data collection was a dynamic study. The strain was recorded every 0.5 seconds for 142 seconds as the water tunnel’s speed gradually increased until reaching its maximum speed. The recorded strains, after a correction factor was added to each to zero out the starting value, are shown in the following figure.

![Figure 5.9. Strain of Shark Skin vs Control Plate from 0 to 3.52 in/s](image)
The shark skin appears to have consistently less strain than the control plate. However, it peaks at around \( t = 115s \) and has approximately the same strain values as the control plate until \( t = 142s \). This sudden spike could have been due to a disturbance of the water tunnel from a bump that caused the plate to move.

### 5.3.2 Dynamic Trial at Varied Speeds

Another trial was run where a portion of strain data was collected at each speed as well as during the time it took for the water tunnel to reach each speed. The data is shown in the following figure.

![Control Plate vs Shark Skin with Increasing Speed](image)

**Figure 5.10.** Control Plate vs Shark Skin with Increasing Speed

It was discovered from this data that the water tunnel experienced some difficulty with reaching a constant speed. The speed did not gradually increase. It peaked each time the tunnel speed was
increased and then slowed down again to try to reach the appropriate speed, yielding a fluctuating trend of data.

More data collection using the strain gage can be found in section 7.2 of “Future Research.” Due to the limited time, the system was not calibrated as necessary and more work can be done to collect more valuable data using the strain gage method.

6. CONCLUSIONS

This research successfully established accurate models of a shark denticle and high resolution prints of shark skin. It was concluded that an Ultimaker 2 Go printer with PLA material yielded a higher resolution print than a Makerbot Replicator 2 printer with NinjaFlex material. Furthermore, experimentation of multiple setups yielded a reliable and adjustable setup that allowed for an accurate data collection. The final setup allowed for adjustment in the vertical direction and allowed for multiple plates to be compared at once. The vertical adjustment proved necessary for ensuring the plate was in the middle of the water tunnel. This allowed the option of printing different sized plates without having to reprint rods with a new length each time. The ability to run multiple plates at once could allow data to be collected on multiple plates during the same trial given the resources for two strain gages, two Wheatstone bridge circuits, two LabJacks, two LJ TickInAmps, and two computers running the LogUD program. During this research, the multiple plate option allowed for a clear visual of the drag reduction experienced by the shark skin. Furthermore, it was concluded that an elliptical rod was the most successful cantilever for attaching a strain gage as well as preventing bending of the rod in the transverse direction.

Based on the data collected, it was concluded that shark skin does indeed reduce drag. The experimental values resulted in an average drag reduction of 32%. More methods can be done to achieve data with less probable error. Further steps should be taken to properly calibrate the
experimental setup. This can be done by applying known forces to the plate, recording the corresponding strains, and finding a curve fit of the trend line to use for future data collection.

7. FUTURE RESEARCH

The results found during this research allow for many additional research opportunities.

7.1 Denticle Shape

Although, most denticles have the same basic 3-pronged shape, there are differing length and width ratios depending on the part of the body where the shark is found. The denticle used in this research with a length to width ratio of about 1.4 was most likely to be found near the pectoral fin of a Shortfin Mako. Variations of the basic denticle shape that may be found on another part of the shark’s body can be designed and tested. These different versions of shark skin can be compared to the control plate as well as each other to determine the part of the body where the most drag reduction may be experienced.

7.2 Numerical Simulation

Numerical simulation using COMSOL or within SolidWorks can assist in better calibrating the system in addition to experimental calibration tests. A point force can be applied to the end of the rod where the plate would be and a corresponding strain can be recorded and used to calibrate the strain gage setup. More strain gage data was collected during this research but due to limited time, all of the necessary steps were not completed in calibrating the system. The strain gage raw data that was collected during static trials is shown in the following figure.
Based on trials to see the amount of time it took for the water to reach steady state, the water tunnel was given three minutes to settle at each new speed setting before the data was collected. Additional research is necessary to properly calibrate the strain gage setup being used.

**Figure 7.1. Static Trials 1 (Top) and 2 (Bottom) of Control Plate vs Shark Skin**
After the system is properly calibrated, the strain gage method can provide accurate and meaningful data regarding the drag force experienced by each plate.

**7.3 Plates**

The plates used in this particular project were rectangular plates. An airfoil shape or another shape that would cause less stagnation pressure could be considered. A larger deflection may have been seen in this project due to the stagnation pressure experienced by the flat plate. Furthermore, trials could be run with the shark skin attached to the entire surface area rather than one side of the plate.

**7.4 Motion Effect**

During this research, the trials involved a static plate whose only movement was the deflection caused by the fluid flow. The effect of a self-propelled plate or robotic-like fish covered in the 3D printed shark skin may yield valuable data as to the effect a shark’s movement patterns may have on the drag reduction of its skin. Similarly, different angles of orientation of the plate can be tested.

**8. REFERENCES**


9. APPENDICES

9.1 Appendix A – Equipment

Figure A.1. MakerBot Replicator 2 3D Printer

Figure A.2. Ultimaker 2 Go 3D Printer
Figure A.3. uPrint 3D Printer

Figure A.4. Water Tunnel
Figure A.5. Wheatstone Bridge Circuit with LabJack and LJ Tick InAmp

Figure A.6. 3 mm Grid Strain Gage on Elliptical Rod
9.2 Appendix B – Data Calculations

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<td></td>
<td></td>
</tr>
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Figure A.7. Properties of Elliptical Rod and Flat Plate

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<th>Drag Coefficient</th>
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Figure A.8. Control Plate Laser Deflection Calculations
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<th>Speed (m/s)</th>
<th>Marks Traversed</th>
<th>δ (m)</th>
<th>Drag Force (N)</th>
<th>Drag Coefficient</th>
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*Figure A.9. Shark Skin Laser Deflection Calculations*
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*Figure A.10. Tolerances of Control Plate and Shark Skin*