Characterization and Analysis of Phoca Vitulina, Zalophus Californianus, and Mirounga Angustirostris Vibrissae

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Abstract

Vibrissae of Phoca Vitulina (harbor seal) and Mirounga Angustirostris (elephant seal) possess undulations along their length. Harbor seal vibrissae have shown potential to reduce vortex induced vibrations and reduce drag compared to cylinders and ellipses. The exact geometry of the whiskers has not been well documented and the parameters that are responsible for the reduction in drag and vortex induced vibrations have not been characterized. Samples of six harbor seal vibrissae, six elephant seal vibrissae and six California sea lion (Zalophus californianus) vibrissae were collected from the Marine Mammal Center in California. The objectives of this study were to (1) Compare measurement techniques for digitizing and extracting parameters of the seal whiskers for the PeTaL (Periodic Table of Life) database. CT scanning, microscopy and 3D scanning techniques were compared. (2) Compare aerodynamic characteristics of a representative harbor seal whisker, elephant seal whisker, California sea lion whisker and ellipse at Re = 12000 and Re = 23000 based on major axis and free stream velocity. The data (in appendices) is available to compare CFD models or for further experimental validation, (3) Show close up images of whiskers and look for surface roughness effects. Variations in the seven parameters of the seal whisker were observed that may either be a feature of the vibration reduction mechanism or a result of natural variation. It is hypothesized that six parameters are sufficient to characterize seal whiskers based on analytic fitting. The drag coefficient of harbor seal whiskers examined in this study were found to be 25 percent lower than that of an ellipse with comparable major and minor axis lengths at Reynolds number of 12000. The dissipation length scale was found to be larger for seal whiskers. Potential applications of seal whisker morphology for aerospace are discussed. Roughness is not thought to play a factor in seal hydrodynamics.

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Introduction

The Biocene is a period of new life: a geological period that will follow the anthropocene. As we enter the Biocene, humans start to look at living systems and systematically learn from natural principles that govern them. This will result in the creation of life-like machines, technology and systems that will demarcate this geological period for future generations. Artificial intelligence (AI) will be a contributing factor but it will also be influenced by the way living systems think and act. There is thus a need for data and the study of living systems to enable the use of AI that will in turn accelerate discovery. This work is a first attempt at gathering such data for the Periodic Table of Life (PeTaL) project (Ref. 1). PeTaL will require measuring techniques and a diversity of datasets that can be interrogated in a broad range of ways for fields like aerospace, structures, guidance and navigation, energy conversion, etc.

For aerospace, more specifically aeronautics, the focus is on reducing drag, noise (vibrations for structure or acoustic emission) and thereby reduce the amount fuel used for propulsion and the overall impact on the environment. In the pursuit of such solutions, a comprehensive literature review was conducted and harbor seal vibrissae were selected for further examination and application (Refs. 2 and 3). Harbor seal whiskers allow the seal to detect slight disturbances in the water upstream of them by pushing the vortices from their whiskers downstream and away from them (Ref. 4). The team, located at the Marine Mammal Center in Rostock, Germany studied the sensory of Harbor seal vibrissae by training one of their seals, blindfolded and ears covered, to follow a submarine. It was noticed that the unsteady forces on the seal vibrissae were reduced by 90 percent while the drag was reduced by 40 percent relative to a cylinder. This is markedly different from other sinusoidal treatments in that most sinusoidal treatments such as the Scruton helix, or sinusoidal leading edges on blades are unable to impact drag in a positive manner while maintaining incidence tolerance or reducing vortex induced vibrations (VIV). Replication and understanding of the drag reduction mechanism is important.

Flow sensing has been found to be used by many different organisms for orientation and maneuvering around obstacles as well as distinguishing between different textures. Bats have micro hairs on their wings to provide aerodynamics in flight by reducing the parasitic drag. These hairs are tapered and can reduce the deflection angle (Refs. 5 and 6). This tapering effect of the hairs is much like the effect of whiskers on other mammals. Rats move their whiskers in a vibrating motion, a behavior called whisking, and touch objects with them to determine different textures. These whiskers can give the rat information, such as, the distance of the object and the direction of the whisker’s deflection (Ref. 7). In previous studies, it has been found that harbor seals use their vibrissae to find prey as well as in avoiding collisions. Thus there is an interest in (1) Characterizing seal whiskers more comprehensively, and (2) Understanding the physics behind their sensing and drag reducing ability.

In this study, three different strategies are compared to determine the geometric characteristics of the vibrissae: 3D scanning, microscopy, and CT scans. Six vibrissae each from young Harbor seals (HS), elephant seals (ES) and California sea lions (CSL) were obtained through the Marine Mammal Center in California. Using these samples, measurements utilizing different strategies were conducted. From the results, an idealized surface model was created and geometrical equations were created and calculated through MATLAB (The Mathworks, Inc., Natick, MA). Microscope images are shown with measurements of whisker parameters presented form a sample of three whiskers for each species. A small sample of measurements from each specimen are compared across gender, weight and species. Scaled-up, 3D printed models of the whiskers were tested in a wind tunnel after matching Reynolds numbers to compare the aerodynamic performance of the whisker geometry at higher than natural Reynolds number (for application to aerodynamics). Suggestions are then made for future exploration of seal whisker morphology and possible applications thereof.
Vibrissae Samples

Vibrissa samples were obtained by the Marine Mammal Center in California for each of the three species, Harbor seal (HS), Elephant seal (ES), and California sea lion (CSL). These species who were stranded and died naturally. Varying numbers of vibrissae from six pinniped of each species were collected (Figure 1). Table 1 lists each individual of whom the whiskers are from along with their cause of death and physical characteristics.

![Image](Figure 1.—Sample of Harbor seal, Elephant seal, and California sea lion vibrissae from The Marine Mammal Center.)

<table>
<thead>
<tr>
<th>TMMC field ID</th>
<th>Name</th>
<th>Sex</th>
<th>Cause of death</th>
<th>Length, cm</th>
<th>Weight, Kg</th>
<th>Age/Class</th>
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<tbody>
<tr>
<td>CSL-10790</td>
<td>Brellie</td>
<td>Male</td>
<td>Anesthesia, Pleuritis, Cardiomyopathy, Trauma</td>
<td>109</td>
<td>27.5</td>
<td>Pup (&lt;1 month)</td>
</tr>
<tr>
<td>CSL-10807</td>
<td>Lyon</td>
<td>Male</td>
<td>Bacterial pneumonia, Aspiration pneumonia</td>
<td>103</td>
<td>26</td>
<td>Yearling (1-2 years)</td>
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<tr>
<td>CSL-10814</td>
<td>Hitchcock</td>
<td>Female</td>
<td>Euthanasia, Neoplasia</td>
<td>161</td>
<td>63</td>
<td>Adult (3+ years)</td>
</tr>
<tr>
<td>CSL-10817</td>
<td>Cobbler</td>
<td>Female</td>
<td>Euthanasia, Obstruction</td>
<td>154</td>
<td>53.5</td>
<td>Adult (3+ years)</td>
</tr>
<tr>
<td>CSL-10922</td>
<td>Carcass</td>
<td>Male</td>
<td>Trauma</td>
<td>128</td>
<td>28.5</td>
<td>Yearling (1-2 years)</td>
</tr>
<tr>
<td>CSL-11002</td>
<td>Knotty</td>
<td>Female</td>
<td>Euthanasia, Domoic acid toxicity (chronic)</td>
<td>164</td>
<td>70</td>
<td>Adult (3+ years)</td>
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<tr>
<td>HS-2343</td>
<td>Rowdy Neal</td>
<td>Male</td>
<td>Pneumonia (aspiration)</td>
<td>71</td>
<td>10.5</td>
<td>Pup (&lt;1 month)</td>
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<td>HS-2347</td>
<td>Myclovio</td>
<td>Female</td>
<td>Prematurity</td>
<td>77</td>
<td>7.8</td>
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<tr>
<td>HS-2355</td>
<td>Maia</td>
<td>Female</td>
<td>Maternal separation</td>
<td>79</td>
<td>11</td>
<td>Pup (&lt;1 month)</td>
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<tr>
<td>HS-2357</td>
<td>Dooby</td>
<td>Male</td>
<td>Prematurity, Maternal separation</td>
<td>81</td>
<td>8.6</td>
<td>Pup (&lt;1 month)</td>
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<td>HS-2372</td>
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<td>Abscess</td>
<td>78</td>
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<td>HS-2373</td>
<td>Golfball</td>
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<td>Unknown</td>
<td>76</td>
<td>11.5</td>
<td>Pup (&lt;1 month)</td>
</tr>
<tr>
<td>ES-3527</td>
<td>Vartha</td>
<td>Female</td>
<td>Trauma</td>
<td>138</td>
<td>102</td>
<td>Weaner (1-12 months)</td>
</tr>
<tr>
<td>ES-3531</td>
<td>Ares</td>
<td>Female</td>
<td>Trauma, Shark bite</td>
<td>138</td>
<td>111</td>
<td>Weaner (1-12 months)</td>
</tr>
<tr>
<td>ES-3546</td>
<td>Endara</td>
<td>Female</td>
<td>Euthanasia, Malnutrition</td>
<td>120</td>
<td>31</td>
<td>Weaner (1-12 months)</td>
</tr>
<tr>
<td>ES-3600</td>
<td>Muir</td>
<td>Male</td>
<td>Unknown</td>
<td>137</td>
<td>42.5</td>
<td>Weaner (1-12 months)</td>
</tr>
<tr>
<td>ES-3636</td>
<td>Ross Co</td>
<td>Male</td>
<td>Otostrongyliasis</td>
<td>135</td>
<td>51</td>
<td>Weaner (1-12 months)</td>
</tr>
<tr>
<td>ES-3645</td>
<td>Neemo</td>
<td>Male</td>
<td>Unknown</td>
<td>120</td>
<td>30.5</td>
<td>Weaner (1-12 months)</td>
</tr>
</tbody>
</table>
Vibrissae Measurement Techniques

3D Scanner

The Romer Absolute Arm (Ref. 7) with integrated scanner was used to capture a 3D image of the vibrissae. The 3D laser scanner can scan 30,000 points per second. During the scanning process the arm of the Romer can be positioned 360° around the object. The scanner is connected to a computer that reconstructs the pieces creating a 3D image. The mount to hold the whiskers was created so as to not allow the specimens to move. Any movement of the whisker would cause poor imaging. The harbor seal vibrissae were translucent, the elephant seals whiskers were all black while the California sea lion whiskers were a mixture of both. The vibrissae were carefully colored with white 3D scanning markers. During the process of scanning the vibrissae the 3D scanner needed to be calibrated to either white or black, depending on the whisker. After scanning, the image was cleaned up and exported as Standard Tessellation Language (STL) file. Drawbacks of the 3D scanner include mounting and quality of image. The vibrissae need complete exposure to allow the scanner to scan all areas. A rudimentary mounting method was initially attempted for proof of concept. One of the mounting methods involved a scanning stand with two clips (one on top and one at the bottom) to hold the vibrissa in place (Figure 2). The final image had a low resolution and was rough around the edges. If the scanner is located in a room with any source of air disturbances, errors may creep into the resulting scan. This means that there must be a method of securing the whisker while allowing for optical access. Any painting or coating of the vibrissae would impact the surface roughness and modify aerodynamic or hydrodynamic qualities. The final STL file of the whiskers were only useful as a prototype (Figure 3). Other 3D scanning methods may bear more fruit as the technology develops and this method should be revisited.

Figure 2.—Mounting stand of vibrissae for 3D scanner.

Figure 3.—STL file of Harbor seal from 3D scanning.
Microscope

Microscopic images of four Harbor seals, two California sea lion, and two Elephant seal whiskers (Figure 4) were created using a Zeiss Axioscop microscope connected to a camera (Figure 5). The program used to acquire the images was Image Pro® 7.0 at a 2.50 magnification. An average of fifteen pictures of vibrissae sections were taken and stitched together to create a panned picture of a full vibrissa (Figure 6). To capture the straight images of the vibrissae, mounting was done carefully. Three to four slides were laid onto the stand and the vibrissae were placed horizontally. Clear, double-sided tape was used to keep the whiskers in place and straight. The vibrissae were not pulled tight as to produce any tension with the assumption that post processing could be used to ‘straighten out’ the digitized model. Two images were captured for each vibrissa, one with the vibrissa lying flat and the second turned 90°. These images were imported into MATLAB where a parameterized model was developed. The result was an equation of the form, \( y = A \sin(\omega x + \phi) + B + Cx + Dx^2 \). This may be a good way to parametrize the seal whisker for application to aerodynamic technology e.g., stacking axis for a wing or turbine blade. The resulting model could then be run through an optimizer to determine the appropriate values of \( A, B, C, D, \omega \) and \( \phi \) that result in low drag or low RMS lift (vibration). Note that there are six parameters here while a previous study proposed seven. Figure 7 shows the seven parameters. There is an elliptic cross section with major and minor axis varying throughout the span of the whisker. We take the cross sections at the maximum major axis and minimum major axis to be two independent measurements although this could be viewed as measuring major axis length and minor axis length along the span. The cross sections have their major axes aligned, when projected onto a plane perpendicular to the span. We take this direction of alignment to be the chord of the vibrissa, defining the leading and trailing edges. Furthermore, the two cross sections are separated by a set span-wise distance, and they have independent yaw angles. This yields t major axes (a1, a2), 2 minor axes (b1, b2), 2 yaw angles, and 1 span-wise distance (pitch), totaling 7 parameters. Arguably, knowing the variation of a, b with span by creating functions \( a = a(x) \) and \( b = b(x) \) reduces the number of independent parameters needed to parametrize the seal whiskers. The space between these two ellipses form the repeating subunit of the vibrissa. The major axis parameters are shown in Figure 7. A similar nomenclature is used for the minor axis (rotating the image in Figure 7 by 90° about the x axis). The interpolation between the two cross sections will be discussed later. The plane of the large cross section is defined by the outermost points on the leading and trailing edges of the vibrissa, while the plane of the small cross section is defined by the innermost points.

![Sample of images of pinniped vibrissae captured using microscope.](image-url)
Figure 5.—Zeiss axioskop microscope with camera.

Figure 6.—Three separate images taken from microscope and stitched together.

Figure 7.—Whisker major axis dimensions.
CT Scanner

A NASA built CT scanner, the Ultra High Resolution World Class Dual Head Micro/Nano Focus CT system (Ref. 8) was used to capture 3D images of the whiskers. The scanner captures digital X-ray pictures at different angles and are then analyzed in a computer to generate virtual slicing and volume rendering. Preparing the whiskers for the CT scanner required mounting them on Styrofoam, which is not picked up by the CT scanner. The scanner is composed of an emitter, an object platform, and a detector. The emitter operated at a voltage of 90 kV and at a current of 60 µA. The object platform is simply a rotating pedestal allowing images to be captured from every angle and then reconstructed. The detector plate is a Dexela 2923; it operated at four frames per second with a pixel pitch of 75×75 µ. The distance from the emitter tube to the detector plate was 760 mm. The vibrissae were kept straight by taping each end and slight tension was applied. The mounting technique used was a Styrofoam dowel that allowed multiple vibrissae to be mounted around it (Figure 8). This allowed the CT scanner to circle the samples more easily (Figure 9). Three separate scans were taken (see Appendix A for settings). One scan consisted of one Harbor seal, one California sea lion, and one Elephant seal vibrissa. This scan was taken at a higher resolution causing a different mounting technique to be used. Since only a small section of each vibrissa was captured, the mounting consisted placing the vibrissae in between two pieces of Styrofoam. The vibrissae were placed in a Styrofoam support (Figure 8 and Figure 9) in groups. The result of each scan gave more than 2,500 slices vertically. These images were cleaned and put together using Avizo Fire Program (see Appendix B for procedure). The program generated a surface image which enabled an STL File to be exported. Finally the STL File was scaled up and 3D printed from a Fortus 250mc 3D printer. From here, the printed whiskers are cooled and printer support material is removed using an alkaline bath.

![Figure 8.—Whiskers placed around Styrofoam core for CT scanning.](image)

![Figure 9.—Ultra-high resolution world class dual head micro/nano Focus CT system with prepared whiskers mounted with Styrofoam.](image)
Setup of Wind Tunnel Experiment

A low speed (Mach number <0.2) wind tunnel facility (Ref. 9), SW-6, at NASA's Glenn Research Center was used to interrogate the complex, highly three-dimensional flow field associated with detached flows and to specifically resolve the shear layers and wake regions. Experiments were carried out in the wind tunnel shown in Figure 10, Figure 11, and Figure 12. This is an open loop tunnel with a temperature controlled coolant loop. The tunnel consists of an aluminum bell mouth, flow conditioning screens, square acrylic sections that are 0.208 m wide and 0.0191 m thick, the test section on the floor of the tunnel and a lid directly above it for either viewing or actuator support. Air was drawn from the room and passed through flow conditioning sections prior to entering the test section.

Figure 10.—CAD model of SW-6 facility.

Figure 11.—Wind tunnel setup, Harbor seal vibrissa placed inside wind tunnel.

Figure 12.—Coordinates and measurement planes for test articles.
Airflow was provided by a 5220W fan at the exhaust of the tunnel. The test section has a square cross section measuring 0.2083 m by 0.2083 m and is 0.8636 m in length. The freestream turbulence intensity measured approximately 1.5 percent without a grid and 8 percent with a square grid based on hotwire surveys. The boundary layer thickness at the center of the tunnel floor is 0.0127 m and is taken to be the vertical distance from the wall at which the velocity is equal to 99 percent of the freestream velocity. To determine the fluid flow rate, a total pressure probe was placed upstream in the tunnel and static pressure taps were placed upstream on the tunnel walls. The test articles are shown in Figure 13 and Figure 14. Figure 12 shows the test section of the wind tunnel and the locations of the measurement planes relative to the test articles. Each test article was placed with its centerline at x = 0 (Figure 12), with the span oriented in the z-direction and major axis aligned with the flow direction (x). Measurements were taken at two locations, L1 = 1.05a from the centerline of the test article with chord, a and L2 = 3.21a from the centerline of the test article with reference length a. A more complete data set should include measurements that are related to the major and minor axis lengths depending on application. For example, for applications to vibrations one might use the minor axis length but for drag reduction one might use the major axis length to calculate Reynolds number (and Strouhal number). Both values are presented here so the reader may compute parameters based on their application. The parameters associated with the test

![Figure 13](image1.png)

Figure 13.—3D printed reference geometry (A)—Cylinder (A1)—used for shedding frequency study, Ellipse for Elephant seal (A2)—not used, and Ellipse for Harbor seal (A3). 3D printed vibrissae (B and C)—California sea lion (B1 and C1), Harbor seal (B3 and C3), and Elephant seal (B2 and C2).

![Figure 14](image2.png)

Figure 14.—Top view of 3D printed reference geometry (A)—Cylinder (A1), Ellipse for Elephant seal (A2)—not used, and Ellipse for Harbor seal (A3). Top view of 3D printed vibrissae (B and C)—California sea lion (B1 and C1), Harbor seal (B3 and C3), and Elephant seal (B2 and C2).
articles are shown in Table 2 with Reynolds number rounded to two significant digits. The hydraulic diameter, $D_h$, of the test articles is also presented. Hydraulic diameter has been used in the literature but is not a reliable way to scale flow features for external aerodynamics especially when the test article is streamlined (viscous drag dominates). Harbor seal whiskers are difficult to classify because their cross section varies from low to high eccentricity along the span. Comparisons with elephant seal whiskers and sea lion whiskers require further analysis because their eccentricities are different from harbor seal whiskers. A more appropriate way to take data would be to first determine the ratio of viscous to form drag and then match Reynolds number based on both reference lengths. In the following sections, HS refers to harbor seal, ES to elephant seal, HSE to harbor seal ellipse and CSL to California sea lion.

To determine the tunnel flow rate, a total pressure probe was placed upstream of the test section and static pressure taps were placed on the sidewalls. Freestream temperature was measured with an open-ball thermocouple located upstream of the holes near the total pressure probe. Hotwire probes were used to obtain the three-dimensional velocity components and turbulent stresses at axial planes downstream of the test articles.

Moving to the left, $y$ values became more negative; to the right, $y$ values became more positive. The floor of the tunnel was referred to as $z = 0$. Each model was tested at two nominal tunnel speeds, $V_1$ and $V_2$. Actual tunnel speed varied for each test case so we decided to show the raw data so that future studies may compare with the data in a manner of their choosing. We suggest normalizing by the maximum velocity for each case (free stream velocity). Measurements were taken at two locations at a distance of $L_1$ and $L_2$ downstream of the test article centerline respectively as shown in Figure 12. This results in four conditions for each test article: $V_1L_1$ (at velocity $V_1$ and location $L_1$), $V_1L_2$ (at velocity $V_1$ and location $L_2$), $V_2L_1$ (at velocity $V_2$ and location $L_1$), and $V_2L_2$ (at velocity $V_2$ and location $L_2$).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>H.S</th>
<th>E.S</th>
<th>S.L</th>
<th>HSE</th>
<th>C1</th>
</tr>
</thead>
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<tr>
<td>Minor axis Length (m): $b_1+b_2)/2$</td>
<td>$b$</td>
<td>0.0091</td>
<td>0.0145</td>
<td>0.0168</td>
<td>0.0091</td>
<td>0.0193</td>
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<tr>
<td>Major axis Length (m): $a_1+a_2)/2$</td>
<td>$a$</td>
<td>0.0193</td>
<td>0.0224</td>
<td>0.0249</td>
<td>0.0193</td>
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<td>1.5439</td>
<td>1.4848</td>
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<td>Hydraulic diameter</td>
<td>$D_h$</td>
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<tr>
<td>1.05a (m)</td>
<td>$L_1$</td>
<td>0.0203</td>
<td>0.0235</td>
<td>0.0261</td>
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</tr>
<tr>
<td>3.21a (m)</td>
<td>$L_2$</td>
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<td>0.0715</td>
<td>0.0797</td>
<td>0.0618</td>
<td>0.0618</td>
</tr>
<tr>
<td>Distance between planes (d2-d1) (m)</td>
<td>$L_{21}$</td>
<td>0.0415</td>
<td>0.0481</td>
<td>0.0535</td>
<td>0.0415</td>
<td>0.0415</td>
</tr>
<tr>
<td>Velocity 1 (m/s)</td>
<td>$V_1$</td>
<td>9.1</td>
<td>7.9</td>
<td>7.0</td>
<td>9.1</td>
<td>9.1</td>
</tr>
<tr>
<td>Velocity 2 (m/s)</td>
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<td>16</td>
<td>14</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>Dynamic Viscosity (m²/s)</td>
<td>$\nu$</td>
<td>1.52E-05</td>
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<tr>
<td>Reynolds number 1, based on $a$, $V_1$</td>
<td>$Re_{1a}$</td>
<td>12000</td>
<td>12000</td>
<td>12000</td>
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</tr>
<tr>
<td>Reynolds number 1, based on $b$, $V_1$</td>
<td>$Re_{1b}$</td>
<td>5500</td>
<td>7600</td>
<td>7800</td>
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<td>12000</td>
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<tr>
<td>Reynolds number 2, based on $a$, $V_2$</td>
<td>$Re_{2a}$</td>
<td>23000</td>
<td>23000</td>
<td>23000</td>
<td>23000</td>
<td>23000</td>
</tr>
<tr>
<td>Reynolds number 2, based on $b$, $V_2$</td>
<td>$Re_{2b}$</td>
<td>11000</td>
<td>15000</td>
<td>16000</td>
<td>11000</td>
<td>23000</td>
</tr>
</tbody>
</table>
Once the images from the CT Scan are cleaned and exported from Avizo Fire, the STL File is imported into Insight 3D printing software by Stratasys where the vibrissae were scaled to fit the wind tunnel test section (span of 8.2 in.) and to match the desired Reynolds number (by adjusting the chord). This results in approximately 3 pitches of sinusoids for the seal whiskers. The Fortus 250mc 3D printer was then used to 3D print the test articles. Test section spacers were also 3D printed through the Fortus 250 (Figure 15). These pieces are of a variety of widths to allow axial variation of mounting location of the test articles.

The ability to suppress vortex-induced vibrations is an adaptation that allows seals to sense disturbances in the flow. In order to use this geometry in engineering applications, it is useful to analyze the sensitivity of the vibration-suppressing effect to exact geometric parameters, and ultimately to understand the mechanism by which this shape produces the desired effects. To this end, we created a parameterized model of the vibrissae suitable for CFD simulation and optimization. Before creating this model, we obtained physical measurements from vibrissa samples, providing a baseline for sensitivity analysis.

We obtained 3D images of the vibrissae via CT scans, and established an automated routine for extracting measurements. Using this method, we confirmed the validity of the above model and determined ranges of values for the seven parameters. Our CT scans take the form of a series of intensity images in two-dimensional slices along the span-wise direction of the vibrissa. We determine the boundary points of the vibrissa within each slice using a Canny edge filter algorithm. This yields a three-dimensional point cloud for the outline of the vibrissa shown in Figure 16.

Figure 15.—Spacers for wind tunnel, 3D printed whisker attached to a spacer.

Figure 16.—Point cloud of harbor seal whisker.
We next determine the direction along which the chord of the vibrissa lies. Within each slice, we determine the two points with the greatest separation, and form the unit vector between these points. Then the unit vectors from each slice are averaged, giving the chord of the vibrissa.

As mentioned before, the large and small cross sections are defined by the extremal points on the leading and trailing edges of the vibrissa. To find these extrema, we fit a sine wave to the leading and trailing edges and identify the minima and maxima (Figure 17). In fact, due to the natural curvature of the whiskers, the 3D profiles are somewhat bent, so that a simple sine wave fit fails. A small parabolic correction was found to sufficiently account for this curvature and allow the periodic function to be fit. The outline of the vibrissa is closely approximated by a sinusoid. The full equation used to fit the leading and trailing edges is: \( y = A \sin(\omega x + \phi) + B + Cx + Dx^2 \), showing that six parameters are sufficient. However, the remainder of the article uses seven parameters to maintain consistency with other studies.

Call the vector from the leading edge maximum (minimum) to the trailing edge maximum (minimum) \( \vec{V} \). Then the plane of the cross section is determined by the vectors \( \vec{V} \) and \( \vec{V} \times \hat{z} \) (see coordinates in Figure 7), where \( \hat{z} \) is the unit normal in the z direction. To test whether the cross section is elliptical and to determine parameters, all points in the point cloud are collected that intersect this plane (up to some small difference due to finite resolution). We then perform a least-squares fit and find that both cross sections are indeed well approximated by ellipses (Figure 18).

Figure 17.—Straightening out the whisker using MATLAB.

Figure 18.—Verifying elliptical cross section of whisker.
We have verified that the seal vibrissae has sinusoidal leading and trailing edge profiles, and that the cross sections at the widest and narrowest points are elliptical. We use SolidWorks’ Loft feature to interpolate a full 3D model, using the mathematical form of the cross sections and edges as constraints. Qualitative examination showed satisfactory correspondence between the 3D model and the CT scans.

It is important to note that we have, so far, assumed that the geometry that is being fitted is repeatable or periodic and this assumption is likely not valid in general. For this reason, several measurements of the elliptical section yaw angles were made using a microscope. Variations in geometry are to be expected and a statistical approach should be taken to characterizing the whisker morphology. Variation in parameters may also be a feature of vibration reduction or drag reduction. This may occur because length scales in the flow are broken into a range of length scales thus distributing energy across the spectrum of length scales.

**Variations of Whisker Geometry**

In this section of the report, the macro-scale images of the seal whiskers are presented. It is from these images that the dimensions in Table 3 are obtained. Figure 19 shows the dimensions that are tabulated in Table 3. They include the maximum and minimum values of the major axis (a1 and a2 respectively), the pitch at the major axis and the major axis lean angle. Similar dimensions are obtained for the minor axis of each whisker.

<table>
<thead>
<tr>
<th>TABLE 3.—MEASURED VALUES OF WHISKER PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>HS-2373</td>
</tr>
<tr>
<td>HS-2347</td>
</tr>
<tr>
<td>HS-2343</td>
</tr>
<tr>
<td>ES-3527</td>
</tr>
<tr>
<td>ES-3628</td>
</tr>
<tr>
<td>ES-3600</td>
</tr>
<tr>
<td>CSL-10807</td>
</tr>
<tr>
<td>CSL-10814</td>
</tr>
<tr>
<td>CSL-10817</td>
</tr>
</tbody>
</table>
Looking at the whisker geometry reveals some variation along the length of the whisker. At the root of the whisker, the structure is thicker in cross section with defined elliptical cross sections. Toward the tip, the whisker tapers to a point. Figure 19 shows the whisker dimensions in mm plotted for HS, ES and CSL and arranged in order of increasing age from left to right. This was done to determine if there is any variation in parameters based on age. Figure 20 shows a similar distribution based on weight (Table 1). There is little variation in the HS data partly because all specimen were from pups. HS data also does not vary with weight given the narrow range of weights and sizes of the sample. CSL data shows a variation with age and size as is expected. Figure 21 shows the dependencies of the parameters on each other. It appears that the ratio of major to minor axis for seal whiskers is constant at the two cross sectional locations, a and b. It also appears that pitch is related to major and minor axis length and the ratio of pitch to these lengths is constant across the range of seals characterized here. Thus, a transference to aerodynamic shape should mimic these parameters, justifying the hypothesis used for turbine blade application in Shyam et al. (Refs. 2 and 3). Note that ES shows a smaller b1/b2 than HS while a1/a2 are approximately the same.

The following section includes images of the major and minor axis for each whisker that was viewed under the microscope. Under the microscope, the whiskers for any one seal specimen showed significant variation in length and thickness making it difficult to come up with a single set of dimensions that represents vibrissae of all species of pinniped. For this study the middle third region of the whisker is used to investigate whisker morphology.

![Figure 19.—Summary of microscope measurements for HS, ES, CSL arranged in increasing order of age from left to right.](image_url)
Figure 20.—Summary of microscope measurements for HS, ES, CSL arranged in increasing order of weight from left to right.

Figure 21.—Ratios of various parameters to notice dependencies.
Harbor Seal

A harbor seal whisker from three different harbor seals were viewed under a microscope at a magnification of 15X; for each whisker, an image is taken of the major axis and another of the minor axis. The images are shown in Figure 22, Figure 23, Figure 24, Figure 25, Figure 26, and Figure 27 with even numbered figures showing major axis planforms and odd numbered figures showing minor axis planforms. The horizontal axis is taken as the x direction and the vertical axis as y direction consistent with Figure 12.

Figure 22.—Harbor seal HS-2343 major axis, 0.254 mm/div.

Figure 23.—Harbor seal HS-2343 minor axis, 0.254 mm/div.

Figure 24.—Harbor seal HS-2347 major axis, 0.254 mm/div.
Looking at the images in Figure 22, Figure 23, Figure 24, Figure 25, Figure 26, and Figure 27 it is clear that there are significant variations in pitch and angle that should be investigated and characterized further. Figure 28 is another image of harbor seal HS-2373 whisker major axis at higher magnification with the dimensions annotated directly on the figure in mils (1/1000 in. = 0.0254 mm); the first undulation has \(a_1 = 1.02\) mm and \(a_2 = 0.25\) mm; the peaks of the first undulation are aligned and so the angle of the major axis is 0°. The distance between the first and second undulation is 3.53 mm. The second undulation has a peak diameter of 1.02 mm and the peaks are not at the same x location; there is an angle of 22° between the peaks. Figure 29 shows the details of how the angle for one of the harbor seal whisker undulations is calculated as an example. While precision is 0.01 mil, manually marking the images translates to uncertainty of ±0.1 mils or ±0.03 mm.
Figure 28.—Harbor seal HS-2373 major axis at higher magnification annotated.

Figure 29.—Harbor seal whisker major axis angle measurement.
Elephant Seal

Similarly, an elephant seal whisker from three different elephant seals were imaged using a microscope and camera. The images are shown in Figure 30, Figure 31, Figure 32, Figure 33, Figure 34 and Figure 35 with even numbered figures showing major axis planforms and odd numbered figures showing minor axis planforms.

Figure 30.—Elephant seal ES-3527 major axis, 0.254 mm/div.

Figure 31.—Elephant seal ES-3527 minor axis.

Figure 32.—Elephant seal ES-3600 major axis, 0.254 mm/div.
Figure 33.—Elephant seal ES-3600 minor axis, 0.254 mm/div.

Figure 34.—Elephant seal ES-2628 major axis, 0.254 mm/div.

Figure 35.—Elephant seal ES-3628 minor axis, 0.254 mm/div.
Figure 36.—Elephant seal ES-3527 major axis at higher magnification annotated.

Like the harbor seal, the elephant seal whisker also showed variation in geometric parameters along its length. Figure 36 is an image of higher magnification annotated to show the variability in one of the elephant seal whisker specimens (ES-3527). The figure shows three undulations; the distance between the first and second is 4.55 mm and that between the second and third is 4.24 mm. The first peak shows a zero-degree angle (i.e., the top and bottom are aligned); the second shows a 27° angle and the third a 30° angle. The maximum thickness, a1, of the three peaks are 1.37, 1.22, and 1.22 mm (from left to right). The minimum thickness, a2, is 0.97 mm for both sections. This shows the level of variability in just one section of one whisker of one elephant seal.

**California Sea Lion**

Images of three California sea lion whiskers were taken with an optical light microscope. The sea lion whiskers did not appear to have any undulations. They did appear to be flattened so one could identify a major and minor axis for the elliptical cross section of the whisker shaft. Figure 37, Figure 38, Figure 39, Figure 40, Figure 41 and Figure 42 show images of the major and minor axes of three California sea lion whisker specimens.

As alluded to previously in this report, the dimensions of the whiskers are highly variable, even within the same whisker. The values in Table 2 were obtained using a measuring tool in the microscope imaging software and were based on a single region (preferably in the middle third of the whisker) or where the whisker showed the least curvature so that it was possible to measure a pitch without straining the whisker to straighten it. In the case of the California sea lion, the whisker was fairly straight but it was tapered (i.e., there was a sharp decrease in cross sectional area from root to tip) so the value in the table is at a region in the middle third and could be treated as an average. With whiskers being as varied as they are, there is no universal whisker shaft thickness or perhaps it may be best to carry out an extensive statistical analysis of many more specimens to reach some dimensionless parameters that would best describe the geometry in a more universal way (if one exists) such as a1/pitch, a2/pitch, b1/pitch, b2/pitch, where lengths are nondimensionalized by pitch. An alternative might be to use the span of the whisker as a reference. The exact method of nondimensionalizing would depend on the application the whiskers are being tested for. For drag, a major axis average might be used. For comparison to circular cylinder, a hydraulic diameter may be used. For structural analysis, some measure of cross sectional area variation would be identified.
Figure 37.—California sea lion CSL-10807 major axis, 0.254 mm/div.

Figure 38.—California sea lion CSL-10807 minor axis, 0.254 mm/div.

Figure 39.—California sea lion CSL-10814 major axis, 0.254 mm/div.

Figure 40.—California sea lion CSL-10814 minor axis, 0.254 mm/div.
Pinniped Vibrissae Surface Roughness

This section presents images obtained using extended depth of focus imaging at high magnification for three whiskers. For each whisker a composite image is generated as described in the methodology section and from that composite image, a line of Z-profile (surface height) data is obtained which will be the basis of a roughness estimate. Figure 43 shows the image of a harbor seal whisker (HS-2373) with Figure 44 showing the height variation across the surface. Figure 45 and Figure 46 show the surface roughness for an elephant seal whisker (ES-3628). Figure 47 and Figure 48 show the same image/surface height plots for a California sea lion whisker (CSL-10817).

The mean roughness, $R_a$, varies from 8 to 10.6 $\mu m$ with an $R_{RMS}$ range of 10.7 to 14.04 $\mu m$. The variation arises from sampling different areas of the whisker and may be due to wear and tear in addition to natural roughness. These numbers are not particularly striking in that they are similar to the surface finish of an operating turbine blade in a jet engine with ranges of approximately 1 to 15 $\mu m$ (Ref. 10). The whiskers operate at low speed (~2 m/s) (Ref. 11) and are therefore considered hydrodynamically smooth. For the elephant seal, mean roughness, $R_a$, varies from 0.97 to 1.21 $\mu m$ with an $R_{RMS}$ range of 1.3 to 1.65 $\mu m$. These whiskers are again hydrodynamically smooth. The mean roughness of the California sea lion whisker (CSL-10817), $R_a$, is 3.3 $\mu m$ with an $R_{RMS}$ of 4.2 $\mu m$. There is nothing extraordinary based on the preliminary observations of roughness of the pinniped vibrissae that suggests that roughness plays a major role in the hydrodynamics of pinniped whisker sensing, vibration reduction or drag.
Figure 43.—Harbor seal composite surface image.

Figure 44.—Harbor seal surface height along span in microns.
Figure 45.—Elephant seal composite surface image.

Figure 46.—Elephant seal surface height along span in microns
Figure 47.—California sea lion composite surface image.

Figure 48.—California sea lion surface height along span in microns.
Results and Discussion

Data from hotwire surveys was saved as ‘.data’ files, and the set of data points for each axial plane scan was saved as a text file. Tecplot Focus 2013R1 was used to create contour plots. The macro adjusted axial planes to allow viewing of the y-z plane (the cross section of the tunnel perpendicular to airflow). Additionally, the data was normalized within the macro using free stream conditions. The hotwire recorded velocity, turbulence, Reynolds stress, and length scale, for each test piece. Once each contour plot was constructed, the plots of the twenty trials (five test pieces × two distances × two wind velocities) were compared and modified in order for the plots of the different models to have the same data range for the same characteristic. To further compare the contour plots, the y (horizontal) and z (vertical) axes were nondimensionalized and each was adjusted so every plot showed the same region of the y-z axial plane. The raw data was imported into MATLAB to compute drag coefficient, \( C_D = \frac{D}{S} \frac{V^2}{\rho a} \).

Here \( S \) is the seal whisker span (length) and \( a \) is the average major axis length or chord. Drag per unit length, \( D/h \), was computed at each span-wise measurement location as \( D = \rho \int V(1 - V) \, dy \). Drag coefficient was computed at L1 in this manner to see variation of drag along the span of the vibrissae. At L2 the wake was too diffused (free stream velocity uncertainty is high) to perform a reliable integration. To put into context the results presented here, drag coefficients for cylinders of varying aspect ratio are shown in Figure 49. The plots of drag coefficient, \( C_D \), for the vertical and horizontal flat plates, cylinder and ellipse with major to minor axis diameter (a/b) equal to 2.0 are well known (Ref. 13).

![Figure 49.—Drag coefficient as function of Reynolds number for various cylinders.](image-url)
Superimposed on Figure 49 are yellow triangles showing the drag coefficients \( (C_D = 0.21 \text{ at } Re = 12000, C_D = 0.192 \text{ at } Re = 23000) \) calculated from hotwire data in the SW-6 wind tunnel for harbor seal ellipse (HSE). The black triangles are the expected values of the data. There is clearly a small discrepancy that may be attributable to surface roughness and deviations of tunnel flow velocity from nominal. For a circular cylinder, surface roughness does not play a role in aerodynamic drag at Reynolds numbers below 50,000. However, for an elliptic cylinder that is more streamlined, it may be that increased roughness in the laminar regime would delay separation and result in a reduction of drag coefficient. The under-prediction at both Reynolds numbers and the low surface roughness of the samples, however, would indicate otherwise. Due to the low surface roughness of the whiskers (see section on whisker surface roughness), the wind tunnel models were smoothed and the dimensions were checked after smoothing. It is thus logical to assume that the experimental conditions (uncertainty in tunnel velocity due to low speed, density and humidity during testing, angle of incidence, measurement location relative to test article) are responsible for the error. Regardless, the reference ellipse (HSE) provides reference values to compare the harbor seal whisker’s drag coefficient in a consistent manner. The green points provide an estimate for drag coefficient of an ellipse with \( a/b = 1.5 \). Data was interpolated using drag coefficient at Reynolds number of 66,000 as a reference (Ref. 14). Variation in drag with \( a/b \) was then assumed to be linear with Reynolds number. Elephant seals and California sea lions appear to possess elliptic cross sections with \( a/b \) approximately equal to 1.5, with ES showing span-wise undulation similar to HS. In fact, the average dimensions of ES and CSL are so similar that they provide a second set of experiments to compare effect of undulations on aerodynamics albeit for a different \( a/b \) than HSE and HS. One would expect that as \( a/b \) decreases (skin friction becomes less dominant) the average diameter/length would become the dominant driver of drag and both whiskers would show similar drag coefficients.

Figure 50 shows the range of drag coefficients (at different span-wise locations) for the vibrissae at two Reynolds numbers per vibrissa type. The HS shows a much wider spread and lower drag coefficient overall relative to the ES and CSL. The minimum drag location is downstream of \( b_2 \) (minimum \( b \)) and maximum drag is behind \( b_1 \) (maximum \( b \)). This says nothing about the sensing ability of the whiskers that is reliant on the vibrations (unsteady lift) of the vibrissae. It is possible that there is a tradeoff between sensing accuracy and strength of the whisker attachment. As predicted, ES and CSL show similar drag coefficients at both Reynolds numbers. The harbor seal vibrissae (HS) show a 25 and 12 percent reduction in drag coefficient relative to the reference ellipse (HSE) at Reynolds numbers of 12000 and 23000 respectively (Figure 51). Appendix C provides Tecplot contours of the flow downstream of the test articles at L1 and L2 for tunnel speeds V1 and V2.

The shedding frequencies of HS and C1 were analyzed using an in-house National Instruments LabVIEW program. The integral length scale is an average of the macro-turbulence eddies for the selected point. The dissipation length scale is the scale of eddies that transfer energy from the integral scales to the Kolmogorov scales for dissipation. The rate of dissipation is proportional to the dissipation length scale. A larger length scale would thus be indicative of a smaller rate of dissipation and thus reduced drag. Figure 52 shows that HS has a larger dissipation length than C1 with significant variation along the whisker length. Figure 53 shows the frequency in the wakes of C1 and HS. For a given reference length, \( a \), velocity \( V_2 \), and frequency, \( f \), the Strouhal number, \( St = \frac{fa}{V_2} \), is calculated for HS and C1. The cylinder, C1 exhibits \( St \approx 0.18 \) while the harbor seal whisker, HS exhibits a range of frequencies from 0 to 700 Hz corresponding to \( 0 < St < 0.68 \). Figure 54 shows the integral length scale for HS and C1. The integral length scale of C1 is approximately 0.7 in. that corresponds to the diameter of the cylinder (0.019 m). The HS shows a range of length scales from 0.1 to 0.6 in. Plots of frequency spectrum in the wake for various locations in the wake at L1 and L2 for HSE, HS, ES, CSL and C1 are shown in Figure 119 and Figure 120 in Appendix D. It is clear that for both ES and HS, behind the location of minimum major axis length, \( a_2 \), the amplitude is lowest and behind the location of \( a_1 \), amplitude is highest. This corresponds with regions of maximum and minimum frequencies, respectively. There is a broadband reduction in amplitude for HS and ES behind \( a_2 \), while the flow behind \( a_1 \), is still comparable to that of the cylinder and ellipse.
Figure 50.—Range of local drag coefficients for various span-wise locations on the vibrissae of HS, ES, and CSL.

Figure 51.—Overall drag coefficients for all test articles compared to reference values.
Figure 52.—Dissipation length scale at L1, V2 for HS and cylinder, C1.

Figure 53.—Frequency in the wake of HS and C1 at L1, V2. Strouhal number based on V2, a, and frequency for cylinder is between 0.174 and 0.18. Strouhal number for HS varies from 0 to 0.68.
Figure 54.—Integral length scale at L1, V2 for HS and cylinder, C1.

TABLE 4.—CHARACTERISTIC AND ADAPTIVE DIFFERENCES OF HARBOR SEAL AND NORTHERN ELEPHANT SEAL

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Harbor seal</th>
<th>Northern elephant seal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean swim speed</td>
<td>2 m/s (Ref. 15)</td>
<td>1.6 m/s (3 m/s maximum) (Ref. 16)</td>
</tr>
<tr>
<td>Mean dive time (Ref. 17)</td>
<td>3 to 7 min, maximum 40 min</td>
<td>2 hr</td>
</tr>
<tr>
<td>Maximum length (Ref. 17)</td>
<td>1.7 to 1.9 m</td>
<td>Males: 4 m Females: 3 m</td>
</tr>
<tr>
<td>Maximum weight (Ref. 17)</td>
<td>300 lbs</td>
<td>Males: 4500 lbs Females: 1500 lbs</td>
</tr>
<tr>
<td>Food (Ref. 17)</td>
<td>Sole, flounder, sculpin, hake, cod, herring, octopus, squid</td>
<td>Deep-water, bottom dwelling animals, ratfish, swell shark, spiny dogfish, eels, rockfish, squid</td>
</tr>
<tr>
<td>Habitat location (Ref. 17)</td>
<td>North of equator in Atlantic and Pacific oceans, can range from Alaska to Baja California</td>
<td>North Pacific, Baja California, Mexico to the Gulf of Alaska and Aleutian Islands</td>
</tr>
</tbody>
</table>

Further investigation is required to determine the significance of these trends and these are beyond the scope of this study. The harbor seal and Northern elephant seal have different a/b values for their elliptic cross sections. The harbor seal whiskers undulate more than the northern elephant seal (b1/b2 larger for HS while a1/a2 constant). Harbor seal whiskers seem to have a lower drag coefficient than the elephant seal due to their higher eccentricity. The northern elephant seal swims at greater depths and this may mean withstanding larger pressures and stresses on their whiskers. They also swim at slower speeds to conserve energy. Their whiskers therefore may have not suffered from reduced drag. Their average swim speed is less than half of the harbor seal. A comparison of the harbor seal and northern elephant seal are shown in Table 4.
Conclusions and Future Work

Capturing images of small objects can introduce large uncertainties in the results. The purpose of this study was to compare ways to capture the features of whiskers belonging to a harbor seal, an Elephant seal, and a California sea lion and to produce a scaled-up 3D printed model. The most useful strategy to produce a model of the vibrissae is the CT scanner. This is however quite time consuming and CT scanners are not easily accessible to the general population. Table 5 shows a comparison of the measurement techniques based on the experience of the authors.

The results of this study show that there is potentially a large variation in seal whisker ellipse lean angle. Assuming a constant lean angle for the wind tunnel studies may not be appropriate. However, based on results shown here and on results from translation of this concept to airfoils, it is possible that the major aerodynamic/vibration benefit derives from the variation of length scales along the whisker that serves to distribute energy across a range of scales and the eccentricity of the elliptic cross sections. Elephant seals should be studied in more detail to understand why their whiskers possess a lower eccentricity. It may be a tradeoff between sensing ability and strength of whisker or there may be no evolutionary advantage to a more hydrodynamic whisker due to the low swim speed of the elephant seal. Interestingly, the higher the eccentricity of the elliptical cross section being undulated, the lower the drag appears to be. Thus the undulations seem to reduce viscous drag rather than form drag. Airfoils, having high chord to thickness ratios, would seemingly benefit from such undulations.

Due to the potential drag reduction and noise reduction benefits of the seal whisker, they may be used on off-shore oil rigs, off shore wind turbine mounts, airfoils that are subject to incidence variation and need to maintain low drag or heat exchangers that need to maintain a low pressure drop with enhanced mixing. It is hypothesized that introducing a variety of length scales into the geometry may lead to a mixing out of dominant length scales in the flow. This strategy may be used for wind tunnel probe holders to reduce vibration and thus uncertainty in data acquisition. 3D relief combined with span-wise pressure gradients may allow for delay of separation for airfoils. Thus, even the elephant seal whiskers may show drag reduction benefits at non-zero incidence angles.

<table>
<thead>
<tr>
<th>Measurements strategies</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D scanner</td>
<td>Many undulations captured</td>
<td>Low resolution Difficult to mount and scan rough edged images May require coating Intensive post-processing required</td>
</tr>
<tr>
<td></td>
<td>STL file obtained</td>
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</tr>
<tr>
<td>Microscope</td>
<td>Close up examination of vibrissae</td>
<td>Difficult to straighten vibrissa on mount</td>
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<tr>
<td></td>
<td>Captured image may be processed</td>
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<tr>
<td></td>
<td>using analysis tools such as python</td>
<td></td>
</tr>
<tr>
<td></td>
<td>or MATLAB</td>
<td></td>
</tr>
<tr>
<td>CT scanner</td>
<td>Higher resolution than 3D scanner</td>
<td>Few undulations</td>
</tr>
<tr>
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<td>Clean images</td>
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<td></td>
<td>Easily scanned and straightened</td>
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</tr>
<tr>
<td></td>
<td>using analysis tools</td>
<td></td>
</tr>
<tr>
<td></td>
<td>STL file</td>
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</table>
Appendix A.—Calibration and Scan Technique for CT Scans

1. Calibration data

North Star Imaging, Inc. CT Calibration summary

Computation date: 7/18/2014 11:23:22 AM

Tracking: 9 points used, over 60 views

Calibration tool: Spacing [0.762]mm ([0.03] inches)

Detector pixel pitch: 0.075x0.075 mm (0.00295x0.00295 inches)

Image modification: H-flip | Rotate(90 degree) | Crop #pixels left=5 top=5 right=5 bottom=5

X-ray-source / Detector distance: 727.044 mm (28.624 inches)
Rotation axis / Detector distance: 687.832 mm (27.08 inches)
Rotation axis / X-ray-source distance: 39.212 mm (1.544 inches)

Magnification: x18.54
Optimum voxel size: 4 microns (0.0001593 inches)
Geometric unsharpness: x17.5
5 micron focal spot will be 87.71 micron wide (1.2 pixels)

Rotation: Found Counter-Clockwise (CCW) rotation direction
Rotation axis: 0.00227070925709821 -0.999997421936412 0
Rotation axis angle: -179.87 degree

Image center: (149.621, 142.611) mm / (5.891, 5.615) inches

Calibration images folder: Calibration
Starting image used: calib*.tif
60 images, 6 degree step

radiographs "Calibration\calib*.tif"
6 degree angle step (assuming a full 360 degree acquisition)
2. CT Scan technique data sheet “Technique-140718 seal Whiskers 8 #1”

North Star Imaging, Inc. CT Acquisition Technique Sheet

Xray source: XRayWorX
- voltage: 160 kV
- current: 150 µA
- focal spot size: 0 microns
- focal spot mode: Nanofocus

Detector: Dexela 2923 [2216]
- pixel pitch: [75 x 75] microns
- mode: Sequence (High gain)
- gain:
- binning: 1x1
- framerate: 5 fps (200.004 ms integration time)

flip: horizontal
rotation: 90 degree
crop: (l,t,r,b)=(5,5,5,5) pixels

defect map: 6980 defective pixels (0.0584056577510458%) (saved)

offset map: 0.0775, dev 0.0078, 120 fravg, 5 fps (acquired 7/18/2014 8:50:53 AM)
gain map 0: 0.294, dev 0.0178, 120 fravg, 5 fps (acquired 7/18/2014 8:52:16 AM)
gain map 1: 0.211, dev 0.0129, 120 fravg, 5 fps (acquired 7/18/2014 8:53:04 AM)

Distances:
- tube to detector: 720 [mm] (FDD)
- tube to part: 50 [mm] (FOD)
calculated Ug: n/a
zoom factor: x14.4

Fixturing: sample on the rotational stage
Filter: none

CT Scan:
- project name: D:\140718 seal Whiskers 8 ultimate mag\140718 seal Whiskers 8 ultimate mag.nsipro
- type: step
- # projections: 1800
- # frames averaged: 5
- delay: 0 ms
- monitor xray down: max allowed image variation 9%
- start: 7/18/2014 10:20:59 AM
- end: 7/18/2014 11:14:21 AM
- duration: 53m22s

Notes:
Appendix B.—Image Processing Using Avizio Fire

1. Before opening any data, select Preference in the toolbar, go to Units and make sure the Display and Working Units are consistent to the units wanted.

2. To start, press Open Data and select image(s) wanted.
   a. To create 3D image from CT scan, all slices are selected and opened. An Image Read Parameters box gives information the image will be opened as (size, voxels, etc.) 0.0017 mm was given for each voxel size as the width of each slice. Another box appears with the unit desired. In this case, millimeters are used.
   b. Right click the green icon on the right. Select Ortho Slice and data image will appear.

3. Right click on the new green icon (data.tif) and create a Non Local Means filter. This will help clean out the noise in the images. The Local Neighbor was changed to a value of 2. The lower the value, the more noise will be cleaned.
4. Right click on the new data created (data_filtered). Create an Edge Preserve Smoothing. This is given a better contrast to preserve the edging of the image. The contrast value was changed to 1.0. The lower the value the sharper the image will be.

5. From the newly created data right click and create Curvature Driven Filter. This gives the image a sharper appearance. The higher the Sharpness Factor the sharper the image. In this case a value of 7.5 was used.
6. Once filters wanted have been applied, create Interactive Thresholding. Using Colormap, adjust the levels to the amount wanted. Press Apply.

7. To clean up possible islands and holes, click on the Segmentation Editor in the properties section of the data.threshold. Four sections will be created in the image area. Select Segmentation at the top of the menu and click Remove Islands.
Make sure 3D is selected and enter the voxel size desired. Press Highlight all Islands for a preview and then press Apply.

8. If unwanted identities are attached to the object stay in the segmentation view. On the right of the four blocks are editing tools. To select the unwanted parts, click the paint brush and ‘paint’ over it. Once every unwanted part is selected, click the minus sign (-) on the right. Be careful and make sure the unwanted identity is erased from all three angles. If one angle is deleted too close to the object, line indents will be present in the final project.

*After deleting the unwanted objects, continue through Generate Surface. The Threshold will still show the parts deleted. After creating a data.surf, click on surface view to see the cleaned up object.
9. Right Click on the new data.thresholded and create Generate Surface. And press Apply. Once the green data.surf icon is created, go to the Properties box and fix the amount of faces needed. Check the intersection tests strategies. In this case, 20,000 faces were used as a maximum in order to import a solid into Solidworks.
10. Export the data.surf by right clicking the icon and going to Save Data As. The surf file can be exported in a number of different file types.
To Connect/Disconnect Data

To change the route for data or simply disconnecting data, click on the data icons that it is connected to. To disconnect the data.tif, click on the red Non Local Means Filter icon and go to Data in the Properties Box. Click No Source. Now the original data.tif is disconnected from other filters and new actions can be applied to it.

The lines are the designated route paths the data takes through manipulation. To change the lines or rearrange the order, click the points at the end of the lines and dragging them to the wanted data icon. Do one change at a time and click apply or auto-refresh in the Properties Box.
Export in Slices

1. Once going through all of the filters needed to clean up the images, continue with the Interactive Threshold. First make sure the Generate Surface is disconnected from the data.thresholded. Click on the green icon data.thresholded to view the Properties box. Click on the Transform Editor and a box will appear.

2. In the Relative Local tab make sure the Rotate degree is 0. Select around local z-axis in the scroll down bar next to degrees. This determines the origin of slices. Click Apply then Close.
3. Right click on the data.thresholded and create a Resample Transformed Image and click Apply in the Properties box. A new green icon will appear as data.transformed. Connect an Ortho Slice to the new data and orient it to where the slices need to occur. In this case, XY was required.

4. To save the data, right click the data.transformed and go to Save Data As. In Save as Type, choose 2d.tiff and save.
Appendix C.—Wake Contour Plots Downstream of HS, HSE, ES, AND CSL

The data presented here may be digitized for further analysis (Figure 55 to Figure 118). It is suggested that velocity be normalized by free stream velocity, $z$ be normalized by test section height (8") and $y$ normalized by average minor axis length, $b$.

Measurements at L1, V1

![Figure 55.—Velocity in wake of HSE, L1, V1.](image1)

![Figure 56.—Reynolds stress in the wake of HSE, L1, V1 (z component).](image2)
Figure 57.—Reynolds stress in the wake of HSE, L1, V1 (y component).

Figure 58.—Length scale in the wake of HSE, L1, V1.
Figure 59.—Velocity in wake of HS, L1, V1.

Figure 60.—Reynolds stress in the wake of HS, L1, V1 (z component).
Figure 61.—Reynolds stress in the wake of HS, L1, V1 (y component).

Figure 62.—Length scale in the wake of HS, L1, V1.
Figure 63.—Velocity in wake of ES, L1, V1.

Figure 64.—Reynolds stress in the wake of ES, L1, V1 (z component).
Figure 65.—Reynolds stress in the wake of ES, L1, V1 (y component).

Figure 66.—Length scale in the wake of ES, L1, V1.
Figure 67.—Velocity in wake of CSL, L1, V1.

Figure 68.—Reynolds stress in the wake of CSL, L1, V1 (z component).
Figure 69.—Reynolds stress in the wake of CSL, L1, V1 (y component).

Figure 70. Length scale in the wake of CSL, L1, V1 (y component).
Measurements at L2, V1

Figure 71.—Velocity in wake of HSE, L2, V1.

Figure 72.—Reynolds stress in the wake of HSE, L2, V1 (z component).
Figure 73.—Reynolds stress in the wake of HSE, L2, V1 (y component).

Figure 74.—Length scale in the wake of HSE, L2, V1.
Figure 75.—Velocity in wake of HS, L2, V1.

Figure 76.—Reynolds stress in the wake of HS, L2, V1 (z component).
Figure 77.—Reynolds stress in the wake of HS, L2, V1 (y component).

Figure 78.—Length scale in the wake of HS, L2, V1.
Figure 79.—Velocity in wake of ES, L2, V1.

Figure 80.—Reynolds stress in the wake of ES, L2, V1 (z component).
Figure 81.—Reynolds stress in the wake of ES, L2, V1 (y component).

Figure 82.—Length scale in the wake of ES, L2, V1.
Figure 83.—Velocity in wake of CSL, L2, V1.

Figure 84.—Reynolds stress in the wake of CSL, L2, V1 (z component).
Figure 85.—Reynolds stress in the wake of CSL, L2, V1 (y component).

Figure 86.—Length scale in the wake of CSL, L1, V1.
Measurements at L1, V2

Figure 87.—Velocity in wake of HSE, L1, V2.

Figure 88.—Reynolds stress in the wake of HSE, L1, V2 (z component).
Figure 89.—Reynolds stress in the wake of HSE, L1, V2 (y component).

Figure 90.—Length scale in the wake of HSE, L1, V1 (y component).
Figure 91.—Velocity in wake of HS, L1, V2.

Figure 92.—Reynolds stress in the wake of HS, L1, V2 (z component).
Figure 93.—Reynolds stress in the wake of HS, L1, V2 (y component).

Figure 94.—Length scale in the wake of HS, L1, V2 (y component).
Figure 95.—Velocity in wake of ES, L1, V2.

Figure 96.—Reynolds stress in the wake of ES, L1, V2 (z component).
Figure 97.—Reynolds stress in the wake of ES, L1, V2 (y component).

Figure 98.—Length scale in the wake of ES, L1, V2 (y component).
Figure 99.—Velocity in wake of CSL, L1, V2.

Figure 100.—Reynolds stress in the wake of CSL, L1, V2 (z component).
Figure 101.—Reynolds stress in the wake of CSL, L1, V2 (y component).

Figure 102.—Length scale in the wake of CSL, L1, V2.
Measurements at L2, V2

Figure 103.—Velocity in wake of HSE, L2, V2.

Figure 104.—Reynolds stress in the wake of HSE, L2, V2 (z component).
Figure 105.—Reynolds stress in the wake of HSE, L2, V2 (y component).

Figure 106.—Length scale in the wake of HSE, L2, V2.
Figure 107.—Velocity in wake of HS, L2, V2.

Figure 108.—Reynolds stress in the wake of HS, L2, V2 (z component).
Figure 109.—Reynolds stress in the wake of HS, L2, V2 (y component).

Figure 110.—Length scale in the wake of HS, L2, V2.
Figure 111.—Velocity in wake of ES, L2, V2.

Figure 112.—Reynolds stress in the wake of ES, L2, V2 (z component).
Figure 113.—Reynolds stress in the wake of ES, L2, V2 (y component).

Figure 114.—Length scale in the wake of ES, L2, V2.
Figure 115.—Velocity in wake of CSL, L2, V2.

Figure 116.—Reynolds stress in the wake of CSL, L2, V2 (z component).
Figure 117.—Reynolds stress in the wake of CSL, L2, V2 (y component).

Figure 118.—Length scale in the wake of CSL, L2, V2.
Appendix D.—Shedding Frequency Data

Figure 119.—Amplitude vs. frequency in the wake of test articles downstream of a1.
<table>
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<th>Edge (mm) width</th>
<th>VI, L1</th>
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<tr>
<td></td>
<td>Cylinder</td>
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<tr>
<td>Edge (mm) width</td>
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Figure 119.—Concluded.
References
