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Characterization of seal whisker morphology: implications for whisker-inspired flow control applications

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Abstract

Seals with beaded whiskers—the majority of true seals (Phocids)—are able to trace even minute disturbance caused by prey fish in the ambient flow using only sensory input from their whiskers. The unique three-dimensional undulating morphology of seal whiskers has been associated with their capability of suppressing vortex-induced vibration and reducing drag. The exceptional hydrodynamic traits of seal whiskers are of great interest in renovating the design of aero-propulsion flow components and high-sensitivity flow sensors. It is essential to have well-documented data of seal whisker morphology with statistically meaningful generalization, as the solid foundation for whisker-inspired flow control applications. However, the available whisker morphology data is either incomplete, with measurements of only a few key parameters, or based on a very limited sample size in case studies. This work characterizes the morphology of 27 beaded seal whiskers (harbor seal and elephant seal), using high-resolution computer-tomography scanning at NASA’s Glenn Research Center in Cleveland, OH. Over two thousand cross-sectional slices for every individual whisker sample are reconstructed, to generate three-dimensional morphology. This is followed by detailed statistical analysis of a set of key parameters, under an established framework (Hanke et al 2010 J. Exp. Biol. 213 2665–72). While the length parameters are generally consistent with previous studies, we note that the angle of incidence of elliptical cross-sections varies in a wide range, with a majority falling between −5° and 5°. Angles of incidence at both peaks and troughs appear to roughly follow a Gaussian distribution, but no clear preference of orientation is identified. We discuss the current knowledge of whisker-inspired flow studies, focusing on choices of morphology parameters. The new understanding of whisker morphology can better inform future design of high-sensitivity flow sensors and aero-propulsion flow structures.

1. Introduction

Seals possess one of the most highly-developed arrays of whiskers, which can be grouped into two distinct categories: smooth and undulating (beaded) [2, 13]. The whiskers have been found to enable seals to sense how fast they are swimming in water [26], to effectively navigate to precise locations for breeding over long distances even with human intervention and disorientation [19], and to navigate during low visibility resulting from: the water depth (as deep as 350 m), ice covered water surface, or turbidity [18, 21, 24, 25]. Furthermore, harbor seal whiskers are capable of differentiating sizes of various objects through vibrissae tactile sensitivity, similar to human hands [10]. Studies suggest remarkably enhanced sensing ability of undulating morphology of the harbor seal vibrissae compared to the smooth whiskers of the California sea lions [14]. The difference in performance was observed while subjecting seals to the task of following a toy submarine while blindfolded and wearing earmuffs [9]. The harbor seal tested was able to more accurately track the wake of the toy submarine, which is attributed to its unique undulating whiskers.

The superior sensing capability of harbor seal whiskers is found to be related to suppressing vortex induced vibration (VIV), commonly generated by bluff-bodies in air or water flows. Dependent on the whisker’s orientation to the
incoming flow, VIV is reduced when the major axis is well-aligned with the flow. However, when the major axis exhibits an angle of attack to the inflow VIV can be substantially magnified [6, 15, 22, 23, 31]. Hence the unique undulating morphology of whiskers enable their detection of subtle unsteady velocity fields. The break down of coherent structures is illustrated by a comparison of wake structures behind circular, elliptical, and whisker-like cylinders in a computational fluid dynamics (CFD) study [17]. The whisker-like geometry is able to reduce the recirculation zone and disrupt organized vortical structures. Further decomposition of the undulating features and their relationship to forces acting on the vibrissae indicated that both undulations on the major and minor axis contribute to the disruption of strong von Kármán vortex streets [16]. Inspired by the exceptional hydrodynamic traits of sea whiskers, efforts have been put into designing novel high-sensitivity flow sensors [5], and modifying the geometry of gas-turbine blades for enhanced performance [30]. Other applications utilizing the beaded vibrissa geometry as an effective passive flow control strategy include structures in consistent flow paths, such as wind turbine towers, sensor mounting supports on aircraft frames, and offshore oil drilling rigs. This wide range of potential applications provides a rich environment and motivation for developing a better understanding of the unique geometry of beaded whiskers and its relationship to hydrodynamic behavior.

The morphology of the undulated whiskers shows identifiable variation depending on species [13]. The morphology of a typical harbor seal whisker can be modeled as an array of ellipsoidal cross-sections with a regularly repeating sequence of peaks and troughs along its length [11–13]. In addition, the elliptical cross-section may be inclined with respect to the whisker axis from bottom to tip. Hanke et al (2010) introduced a framework of seven parameters to describe the undulating three-dimensional morphology of seal whiskers (figure 1). The peak is characterized by a major axis radius \( a \), a minor axis radius \( b \), and an angle of incidence \( \alpha \). Similarly the trough is described by the major axis radius \( k \), the minor axis radius \( l \) and the angle of incidence \( \beta \). The half wavelength \( M \) is the distance between the peak and trough.

However, there is little quantitative data regarding the morphology of Phocid vibrissae, and often these are limited to a few species (Ginter et al 2012). While previous studies on the whisker morphology have mostly focused on length parameters of different seal species, little attention has been given to the angle of incidence \( \alpha \) and \( \beta \). Where the angle of incidence has been reported, the sample size is very limited, and thus not sufficient for meaningful generalization [23]. Furthermore, in several cases of computational and experimental fluid dynamics research on harbor seal whisker–like geometry, the angles of incidence \( \alpha \) and \( \beta \), have mostly been determined as a constant value [17, 32]. Such choices of angles of incidence were often not explicitly explained. Therefore, it is imperative to perform complete measurements of the whisker morphology parameters, both length and angles of incidence, with sufficiently large sample size followed by statistical analysis. The new knowledge will allow us to employ representative whisker-inspired models to better inform the biomimicry design of engineering structures that can improve power production and operating efficiency.

This study aims to better understand the undulating whisker morphology by detailed measurement of 27 beaded seal whiskers using high-resolution computer-tomography (CT) scanning. Robust statistical analysis of the morphology data can serve as the foundation for whisker-inspired design and optimization of engineering systems. Our primary contributions are:

- We determined the measurement method—computer-tomography (CT) scanning, from among three contemporary imaging techniques, laid out procedures of data processing to reconstruct 3D morphology, and analyzed statistics of key morphology parameters (sections 2 and 3);
- We noted that the angle of incidence of the harbor seal and elephant seal whiskers varies in a wide range with a majority between \(-5^\circ\) and \(5^\circ\). The angle of incidence of the tested seal whiskers can be roughly described by a Gaussian distribution, which informs the selection of this parameter (previously not available) in future research, while the length parameters are well aligned with previous studies (section 4);
• We discussed current knowledge of whisker-inspired flow studies in terms of choices of morphology parameters and their effects on wake modification, along with potential exploration for design of high-sensitivity flow sensors and aeropropulsion flow structure (section 4).

2. Whisker samples and experimental technique

2.1. Whisker samples
Whisker samples were provided by the Marine Mammal Center, a nonprofit veterinary research hospital and education center located in Sausalito, California. Whisker samples were collected from deceased seals that were found by the research center or brought to the center for rehabilitation; no seals were harmed in the collection of these whisker samples. Each seal was given a unique identifier, consisting of two letters defining the species (HS for harbor seal and ES for elephant seal), followed by a four-digit number distinguishing the seal from others. This means that each seal has a unique identifier, but the whiskers themselves do not; therefore, if an identifier appears multiple times it should be understood that multiple whiskers from the same seal have been measured. All whiskers were packaged in plastic bags and shipped to the NASA Glenn Research Center (GRC) (figure 2).

It was initially intended to include whisker samples covering the whole demographic of both the harbor and elephant seal populations. We were successful in obtaining both sexes for each species, but were limited to young seals: none of them reaches an age beyond one year. It is possible that further morphological distinctions could be observed in relationship to age and sex of the samples. It was deemed sufficient for this study to characterize the whiskers by species alone, not seeking to extract further distinctions based on gender and age.

2.2. Selection of measurement method
To yield reliable measurement of the whisker morphology, the measurement method must satisfy several requirements. First, the whiskers are highly three dimensional. Therefore, the measurement tool needs to accommodate the three dimensional variations observed along the length of the whiskers. Second, as the smallest detail of the whisker is much less than the order of 0.1 mm, the measurement tool should have sufficient spatial resolution to resolve fine details of the whiskers. Also, the mounting mechanism should allow whiskers be mounted securely during tests, without distorting the natural geometry (by applying tension or compression). Finally, a sufficiently large sample size is desired for meaningful statistical analysis, and therefore there is a time cost that must also be taken into consideration. These requirements are used to evaluate three contemporary imaging techniques in the laboratory settings at NASA GRC and Cleveland State University (CSU).

The Zeiss Axioskope microscope at the NASA Glenn Research Center [33] and the asyum MFP-3D-IO atomic force microscope [3] at CSU can resolve the fine details of whisker morphology, but proved unable to securely mount a whisker sample. Additionally, the high reliance on the operator’s discernment, during the measurements and image processing, made the repeatability of measurements of seal whiskers questionable in this case. The CT scanner is able to provide high-resolution images through x-ray cross-sectional slices. The re-assembly of thousands of cross-sectional slices using computerized methods instead of the human eye notably minimizes the operator’s influence. However, the CT scanner requires a highly-trained operator to determine appropriate settings to properly resolve surface features. It is also significantly more expensive than the other two options, in terms of the time and cost to operate the CT scanner. More details of comparison can be found in [27].

CT scanning was selected to characterize the whisker morphology, as our priority is to acquire high-resolution whisker morphology data of a sufficiently large sample size under the effect of minimal human factors. Even with the long time required for the CT scanner to scan the long section of the whisker, measurements were obtained much faster with the automation of computer code than those obtained through microscope measurements. The observations on techniques for characterizing seal whisker morphology are similar to those experienced in other efforts to characterize vibrissae. Besides microscopes and CT scanners, SLR cameras and 3D scanners have been investigated for measuring seal whisker morphology [8, 12].

2.3. CT scanning setup
CT scanners have become increasingly common in the application of non-destructive evaluation, including but not limited to: evaluating build quality of new manufacturing techniques, assisting in medical diagnosis, reverse engineering, inspecting fatigue, and general 3D digitization for measurements [7, 28]. A CT scanner comprises three primary components: the emitter, object platform, and detector. The emitter produces and directs x-rays through an object of interest secured on the object platform, and the detector collects the x-rays on the opposite side of the object. The collected x-rays create a grey-scale digital image corresponding to variation of material density. The CT scanner’s rise as a tool for analyzing material is attributed to its ability to capture fine detail from large scale items on the order of 1 m down to the sub-1 \( \mu \text{m} \) level.

This study used a custom designed CT scanner North Star Imaging Inc. machine at the NASA Glenn Research Center [1]. The XRayWorX emitter operated at a voltage of 90 kV and current of 60 \( \mu \text{A} \). The object platform is a simple rotating pedestal allowing images to be captured from every angle. The detector
plate Dexela 2923 operated at four frames per second with a pixel pitch of \(75 \times 75\) µm. Figure 3 depicts the layout of the CT scanning setup in this study. A group of whisker samples were pressed in several thin slits cut radially in the Styrofoam cylinder, ensuring a stable position for the whiskers during the scanning process. Styrofoam is selected from previous CT scanning operation experience and proven track record as an inexpensive and low density material. The significant difference in density allows clear distinction between the two materials being scanned. The cylinder with whiskers was then mounted to the object platform. Figure 4 shows the Styrofoam cylinder holding eight unique seal whiskers and a 3D reconstruction of those whiskers.

The spatial resolution of the CT scanning, measured by the voxel size, is inversely proportional to the size of the window of interest. A summary of the different scanning cases used to characterize the geometry of the seal whisker is in table 1. The 4 µm voxels is achieved when only two–three peak and trough features per whisker are in frame. The 10.5 or 10.7 µm voxel sizes are achieved with much longer length sections of the whisker samples, containing up to 10 peak and trough features per whisker. The different cases were conducted to provide a range of species, seals, and when possible multiple whiskers from the same seal. Case 1 contained a single sample from each seal species (in total three samples) with a higher resolution, Case 2 and Case 3 contain multiple samples from each seal species at the same resolution (capturing 2-3 undulations per whisker), Case 4 and Case 5 contained four samples from harbor seals and four samples from elephant seals, with a larger viewing window (thus a lower resolution) to maximize the number of undulations observed. The total number of whiskers measured with the CT scanner is 37; this includes ten samples of smooth California sea lion whiskers and 27 beaded or undulating whiskers—the focus in this study.
3. Data processing

3.1. 3D reconstruction of whisker morphology

The CT scanning images were processed in three steps: (a) establish a threshold to distinguish the density of the whiskers from Styrofoam; (b) determine the outlines of cross-sections for each whisker among the group; and (c) store the x–y coordinates defining the whisker cross-sections.

The first step was accomplished by using the ImageJ feature ‘Analyze Particles’ [4], identifying a threshold value of the grey-scale image that accurately categorizes the Styrofoam and whisker as two separate objects. Next, a script was written to automate the process for thousands of images representing each cross-sectional slice of the whiskers. The thresholds were manually identified for each CT scan case, as the intensities varied and needed to be fine tuned to produce the best results for each batch of CT scanned images. Individual raw images in each CT scan case were randomly selected to be visually inspected and a 3D rendering was completed for each case, to ensure all cross-sectional scans were valid. Lastly, the x and y coordinates for each whisker outline were stored enabling 3D reconstruction. Figure 5 demonstrates the image processing procedure.

The cross-section slices are overlaid to reconstruct the 3D whisker morphology. This was accomplished with a custom MATLAB code that identified the four end points defining the ellipsoid major and minor axis at each cross sectional slice of each whisker. The end points were identified by calculating the distance of each outline point to the centroid of the outline. The major axis was identified with the largest distance; the minor axis was identified as perpendicular to the major axis. The data of major axis was further broken into leading and trailing edge data sets.

The distances were smoothed using the combination of an outlier removal followed by a moving window average and a Savitzky–Golay filter function [29]. The Savitzky–Golay filter applies a polynomial fit to the data set, with the advantage of maintaining the integrity of the peaks and troughs within the smoothing process. This is of critical importance in identifying the correct location of the peaks and troughs along the whisker length.

The following equations define the Savitzky–Golay filter function.

\[
S_j = \sum_{i=(m-1)/2}^{(m-1)/2} C_i \delta_{j-i} \\
\frac{m+1}{2} \leq j \leq n - \frac{m-1}{2}
\]  

where \( \delta_{j+1} \) is the observed data and \( C_i \) is the coefficient of the polynomial fit, \( m \) is the number of convolution coefficients and \( n \) is the data sample size. Finally \( S_j \) is the smoothed data representing the distance from the centroid to the edge of the whisker. Equation (2)
determines the range over which the Savitzky–Golay filter is allowed to operate, defined by one wavelength. Figure 6(a) is the reconstruction of a whisker, displaying the centroid in green, leading edge in red, and trailing edge in blue along the length of the whisker. The seal whiskers exhibit an overall curvature along the length of the whisker, from the nose of the seal towards the tail of the seal. The major axis can be thought of possessing a leading edge, identified as the convex edge of the whisker, and a trailing edge, identified as the concave edge of the whisker. No smoothing has been applied to the coordinates of the whisker outline at this stage of the processing. The figure 6(b) shows the same whisker after calculating the distance from the centroid for the trailing edge, and identifying the peaks and troughs of the trailing edge. The displacement is shown in the blue line, where the peaks are identified by red squares and the troughs are identified by green squares. The peak and trough locations are stored, after which the seven basic geometry properties that define the whisker are calculated.

3.2. Parameter extraction

Once all of the whisker data sets were processed, a statistical analysis was performed on the extracted properties to identify trends and patterns in the whisker morphology.

In addition to the seven basic parameters, $D_m$ is the average of the four diameters defining the ellipse cross section at the peak and trough location defined by equation (3):

$$D_m = \frac{a + b + k + l}{2}.$$  

(3)

The average distance between peaks or troughs is defined by $\lambda$. Due to the complex geometry, there are two wavelengths per feature: a distance between peaks on the leading edge of the whisker, and the trailing edge. This is also true of the trough wavelengths, as such—and, due to their similar spacing, the four values can be combined as a single parameter to define the spacing between features defined in equation (4):

$$\lambda = \frac{\lambda_{\text{peakLE}} + \lambda_{\text{peakTE}} + \lambda_{\text{troughLE}} + \lambda_{\text{troughTE}}}{4}.$$  

(4)

Hanke et al defined $M$ as the distance between adjacent peak and trough locations [17]. This measurement is equivalent to half of the average $\lambda$ as defined in equation (5):

$$M = \frac{\lambda}{2}.$$  

(5)

For this study, the eccentricity, $e$, will be the measure used to quantify the difference in cross sectional shape defined by equation (7); here values of 1 signify a perfect parabolic shape and values of 0 signify a perfect circle:

$$e_{\text{peak}} = \sqrt{\frac{a^2 - b^2}{a^2}},$$  

(6)

$$e_{\text{trough}} = \sqrt{\frac{k^2 - l^2}{k^2}}.$$  

(7)

The angles of incidence, $\alpha$ and $\beta$, define the rotation of the elliptical plane with respect to the whisker axis at the peak and trough locations. These angles are calculated by expressing the relationship between the leading and trailing edge of the whisker as follows: the hypotenuse is defined as the distance along the elliptical plane between the leading and trailing edge peak and trough locations; the opposite side of the triangle is defined by the distance along the z-axis between the leading and trailing edge of the whisker. Figure 1 shows the hypotenuse and opposite sides of
the triangle defining the angle $\beta$ highlighted in yellow. The angle of incidence can be calculated using the inverse sinus function described in the following equations:

$$\text{hyp} = \sqrt{(x_{\text{LE}} - x_{\text{TE}})^2 + (y_{\text{LE}} - y_{\text{TE}})^2},$$  \hspace{1cm} (8)
$$\text{opp} = z_{\text{LE}} - z_{\text{TE}},$$  \hspace{1cm} (9)
$$\alpha = \arcsin\frac{\text{opp}_{\text{peak}}}{\text{hyp}_{\text{peak}}},$$  \hspace{1cm} (10)
$$\beta = \arcsin\frac{\text{opp}_{\text{trough}}}{\text{hyp}_{\text{trough}}}. $$  \hspace{1cm} (11)

Equations (8) and (9) use the subscripts LE, referring to the leading edge; and TE, referring to the trailing edge of the whisker. Equations (10) and (11) use the subscripts peak and trough to indicate hypotenuse and opposite measurements taken at the peak and trough locations.

It should be noted that the overall whisker experiences varying degrees of curvature along the length of the whisker, as well as from sample to sample. The approach taken in this measurement method was to focus on scanning the mid-sections of the whisker, where curvature is limited. In addition, it was assumed, due to the measurements being conducted in a piece-wise fashion, (length calculations are only performed between two adjacent peak or trough points), that the curvature would have a minimal effect on the measurement and could be ignored. This assumption was shown to be acceptable, as the wavelength measurements obtained in this study show strong agreement with literature—as explained in greater detail in the next section.

4. Results and discussion

4.1. Statistics of length parameters

Table 2 summarizes the mean and standard deviation of all the quantities (defined in section 3.C) of 27 beaded whisker samples consisting of 133 peak and
130 trough locations. The length parameters $a$, $b$, and $l$ tend to be consistent, and well-represented by the mean values. The elephant seal whiskers show slightly larger lengths compared to those of the harbor seal whiskers. The leading and trailing edge wavelength are similar; thus, only an averaged wavelength is provided (defined by equation (4)).

The major axis radii, $a$ and $k$ as well as the wavelengths measured at the leading/trailing edges of the peak locations in table 2, are compared to previously reported data. The data include 15 harbor seal whiskers in [13], three harbor seal whiskers from [23], 13 whiskers from [17], and the current study, as shown in table 3. The present measurement agrees with data from [13, 23] quite well, with differences within one standard deviation. The ratio of major axis radius, $a/k$, is consistent across all studies. The wavelength, however, is significantly smaller in [17]—nearly half of those reported in other works. This has been commented on in Beem et al [6], where the wavelength-to-diameter ratio is observed to be different in [13] and [17]. It is not clear why the wavelength in [17] is significantly shorter, but it must be considered untypical, as the other studies agree strongly.

While the whiskers of elephant and harbor seal species display variations in their cross-section profiles, the cross-sections at peaks exhibited more elliptical shapes in comparison with those at the troughs. The range of the eccentricity at both peaks and troughs is 0.751–0.924, clearly indicates that the cross-sections tend to have pronounced elliptical shape.

### 4.2. Statistics of angle of incidence

The angles of incidence $\alpha$ and $\beta$ vary in a wide range across whisker samples, as indicated by the extremely large value of standard deviation in table 2. This suggests that both angles of incidence cannot be characterized simply by a mean value. Instead, it is essential to examine the histogram of the angle of incidence, or how often different angles of incidence occur within the sample set.

Figure 7 shows frequency of the occurrence of $\alpha$ and $\beta$ in 2.5° increments, covering the range from $-17.5^\circ$ to $20^\circ$. The dominant trend is that the majority of angle of incidence magnitudes fall between $-5^\circ$ and $5^\circ$, containing 68.5% of the harbor seal whisker measurements. The distribution of both angles roughly resembles a Gaussian distribution, defined as equation (12):

$$N = \frac{W}{\sigma \sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

where $N$ is the normal distribution function, $W$ is the product of bin size and sample size, $\sigma$ is the standard deviation of the data set, $\mu$ is the mean of the data set, and $x$ is the range over which the data is distributed. Comparing figures 7(a) to (b) $\beta$ has a slightly larger span $\sigma = 5.933$ to $\sigma = 5.302$. Both figures 7(a) and (b) are shifted slightly right of zero with $\mu = 0.303$ for $\alpha$ and $\mu = 1.079$ for $\beta$.

Figure 8 shows the angle of incidence distribution of both $\alpha$ and $\beta$ in 5° increments for the elephant seal whisker samples. There is a wider range of angles pre-
sent in the elephant seal, ranging from \(-35^\circ\) to \(25^\circ\). The distribution is more widely spread for the elephant seal whiskers, with 40.2\% of the angles falling between \(-5^\circ\) and \(5^\circ\). The elephant seal distribution also follows a Gaussian distribution. Figures 8(a) and (b) both have larger standard deviation than those observed in the harbor seal, where \(\alpha = \sigma = 7.975\) and \(\beta = 10.947\). Both of the elephant seal distributions are shifted slightly left of zero, with \(\mu = -0.494\) for \(\alpha\) and \(\mu = -2.57\) for \(\beta\).

Collectively, the angle of incidence for harbor and elephant seal whiskers has about 56\% of the data falling between \(-5^\circ\) and \(5^\circ\). This is of particular interest, because previous studies often use whisker-like models of angle of incidence around positive 15° [17, 32]. Specifically, Hanke et al. (2010), Wang and Liu (2016) and Beem et al. (2015) selected \(\alpha = 15.27^\circ\) and \(\beta = 17.60^\circ\). Hans et al. included the additional case of \(\alpha = \beta = 0^\circ\). Shaym et al. (2015) used \(\alpha = \beta = 5^\circ\). Our results show that even though the angles used in other studies fall in the range of observed tendencies, \(\alpha = 15.27^\circ\) and \(\beta = 17.60^\circ\) are on the extreme edges of this sample set. This further suggests that findings from previous work may be affected by the large values of angle of incidence. This may not be representative characterization of the wake features produced by seal whiskers. Since research has not been conducted with various magnitudes and orientations of angle of incidence studied, it is not certain whether having an angle of incidence on the larger end of the spectrum enhances or detracts from the effect on the wake structure.

4.3. Root-to-tip variation of parameters
This section will focus on depicting how key parameters vary along the length of the sample whiskers. The data mainly captured from the mid-section of whiskers are presented along the whisker length, from root to tip. Because each whisker has a different length, the CT scans vary in their exact location on each whisker. Therefore, the zero location does not indicate the
same absolute distance from the root of the individual whisker.

Figure 9 shows how the major axis radii \( (a \text{ and } k) \) and the minor axis radii \( (b \text{ and } l) \) vary along the length of the whisker, using two representative whiskers (one harbor and one elephant seal whisker). Generally, the radii of both major and minor axes decreases with increased distance from the root, indicating an overall tapering of the whisker from root to tip. Clear distinction is visible between the major and minor axis at peak and trough locations. The undulations observed in the minor axis are less dramatic than that observed in the major axis. Variation in the minor axis radii—\( b \text{ and } l \)—is roughly 0.05 mm, and variation in the major axis radii—\( a \text{ and } k \)—is roughly 0.1 mm. Finally, it should be noted that variation of radii along the length can skew the average values depending on which section of the whisker is sampled. For this study all data resides in the mid section of the whiskers providing reasonable overall averages.

Figure 10 shows how eccentricity of the whisker varies along the length from the root to the tip. The same two sample whiskers are used here. Both harbor and elephant seal whiskers show greater tendency towards elliptical cross sections (where eccentricity is larger than 0.5) as the distance from the root increases toward the tip. The peak locations tend to be more parabolic (0.73–0.88) and the trough locations are more circular (0.52–0.75). The harbor seal whiskers show slightly more elliptical cross sections as compared to the elephant seal whiskers at peaks and troughs.

Figure 11 shows the angle of incidence of harbor seal whiskers—\( \alpha \) at the peak and \( \beta \) at the trough—as a function of whisker length (twelve samples). The only strongly observable feature is that both \( \alpha \) and \( \beta \) remain within \( \pm 20^\circ \), centering on 0°. None of the harbor seal whiskers show angles of incidence that are all positive or all negative. There does not appear to be any pattern in the angle of incidence direction along the length either: some whiskers (es3546 and hs2353_2) flip back
and forth between positive and negative direction, while others (es3628 and hs2373_4) change direction only once. No clear distinction can be observed between \( \alpha \) and \( \beta \), nor does there appear to be a pattern of alternation between angle of incidence at peaks and troughs. Additionally, multiple whiskers from seals hs2373, hs2347, hs2357, and hs2372 are presented in the data set. Comparing samples from the same seal yields no clear trend in angle of incidence distribution.

The angle of incidence of elephant seal whiskers (thirteen samples) in figure 12 exhibit similar characteristics to the harbor seal whiskers. A larger maximum angle of incidence, 30° is observed in the elephant seal, which may be due to the overall larger features of the elephant seal whisker. Similarly to the harbor seal whiskers, no strong relationships between angle of incidence and distance from the root are evident for the elephant seal whiskers. This observation agrees with harbor and elephant seal whisker data in [22, 23].

4.4. Discussion: implication for whisker-inspired design

This work analyzed statistics of length and angle of incidence of morphology of the harbor and elephant seal whiskers using CT scanning data. The length parameters, including the major and minor axis radii and the wavelength, are well represented by the mean values. The results compare well with literature (in
It is noted that the peaks are generally more towards elliptical shapes than the troughs for both harbor seal and elephant seal whiskers. However, the angles of incidence of the elliptical cross-sections vary across a wide range; their mean value is insufficient to be a good representative of the nature. The random variation along the whisker length and magnitude ranges was consistent with the data of three whisker samples in [23].

The values of length and angles of incidence reported in [17] set the baseline for subsequent studies of flow induced by the unique seal whisker-like geometry. These studies have provided insights into the undulating whisker-like geometry’s ability to disrupt vortex shedding events, and hinder the establishment of a von Kármán vortex street. It must be noted here that the angles of incidence informed by [17], $\alpha = -15^\circ$ and $\beta = -17^\circ$, are within the range identified in this study. But these values are of very large magnitude—obviously off the majority of the histogram. In addition, a constant value of $\alpha$ and $\beta$ along the entire length of the whisker-like geometry is not representative of nature. No studies have captured both positive and negative angles of incidence so far. It would be prudent, therefore, to investigate how a variety of angles of incidence along the length of the whisker would influence the wake structure. As the capability of the undulating whisker-like geometry to reduce VIV is associated with disrupting the coherent vortex structures in the wake, a variation in the orientation of the angle of incidence could further aid in breaking down coherent vortex structures than reported in [16].

For both harbor and elephant seal whiskers, the cross-sections at peaks exhibit more elliptical shapes...
in comparison with those at the troughs. It is reason-
able to model the cross-section as an elliptical shape. Murphy et al (2013) examined the vibration of three
whisker samples along their shaft at angle of attack
(AOA) of 0°, 45° and 90°. They found that the AOA
significantly changed the vibration frequency and
amplitude of whiskers. However, it is unclear how the
angle of attack would affect the ambient flow behavior
-especially the vortex shedding-which is the source of
the vibration. This is especially relevant when applying
the whisker morphology to turbine blades [30].

The wavelength—the distance between peaks/
troughs—is another critical parameter in whisker-
inspired design. The finding from our study yields the
wavelength-to-diameter ratio \( \lambda / D \) of 4.66 and 5.26
for the elephant and harbor seal whiskers. Lin et al
(2016) reported an optimal \( \lambda / D \) of 6.06 and 1.89 for
reduction of lift and drag forces acting on the sinusoi-
dal wavy cylinder [20]. The two ratios reflect different
fluid dynamics mechanisms. Additionally, \( \lambda / D = 5 \)
and 2 are adopted in a flow sensor design ([5, 6]).
These studies have investigated the effects of \( \lambda / D \)
and the role this parameter plays in the reduction of
force produced from vortex shedding events found
on undulating cylinder structures. The coincidence
of \( \lambda / D \) values may suggest that the whisker undula-
tion sizing has been optimized by 3.8 billion years of
natural evolution, which is one of the cornerstones of
biomimicry.

5. Conclusions

To achieve a better understanding of the seal whisker
morphology, we measured 27 beaded whiskers
using high-resolution CT scanning and analyzed
the statistics of the length parameters and angles of
incidence according to the established framework by

The results clearly show that of the seven basic
morphology parameters, five length parameters—a, b,
I, k, and M—can be well represented by their mean val-
es measured from the sample whiskers. These values
remain pretty consistent along the middle section of
a specific whisker, as well as across multiple whiskers of
the same seal species. The angle of incidence at peak
(\( \alpha \)) and trough (\( \beta \)) locations, however, cannot be well
represented by their mean values, in that the magnitude
covers a wide range, and the orientation varies ran-
domly along the length of each whisker. Our data sug-
gest that the angles of incidence roughly follow a Gauss-
ian distribution, with the majority falling between —5°
and 5°. The orientation of the angle of incidence does
not show clear preference. This information has not
been available for the majority of previous studies.

Interest in applying the unique undulating morphol-
y of beaded seal whiskers to various engineering
design scenarios has long been sustained, to enhance
hydrodynamic performance, energy production, and
operational efficiency. The mean values for the length
parameters can be confidently used to design whisker-
inspired models, while various angles of incidence
can be taken into account to understand the effect
on the wake structure. In short, the statistical gener-
alization of whisker morphology can better inform
future research, and serve as a reliable foundation for
whisker-inspired flow control applications.

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