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An Experimental Study of Bio-Inspired Force Generation
by Unsteady Flow Features

Wesley N. Fassmann

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

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Tadd T. Truscott
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Department of Mechanical Engineering
Brigham Young University
May 2014

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ABSTRACT

An Experimental Study of Bio-Inspired Force Generation by Unsteady Flow Features

Wesley N. Fassmann
Department of Mechanical Engineering, BYU
Master of Science

As understanding of the workings of the biological world expands, biomimetic designs increasingly move into the focus of engineering research studies. For this thesis, two studies involving leading edge vortex generation for lift production as observed in nature were explored in their respective flow regimes.

The first study focused on the steady state analysis of streamwise vortices generated by leading edge tubercles of an adult humpback whale flipper. A realistic scaled model of a humpback flipper was fabricated based on the 3D reconstruction from a sequence of 18 images taken while circumscribing an excised flipper of a beached humpback whale. Two complementary models with smooth leading edges were transformed from this original digitized model and fabricated for testing to further understand the effect of the leading edge tubercles. Experimentally-obtained force and qualitative flow measurements were used to study the influence of the leading edge tubercles. The presence of leading edge tubercles are shown to decrease maximum lift coefficient ($C_l$), but increase $C_l$ production in the post-stall region. By evaluating a measure of hydrodynamic efficiency, humpback whale flipper geometry is shown to be more efficient in the pre-stall region and less efficient in the post-stall region as compared to a comparable model with a smooth leading edge. With respect to a humpback whale, if the decrease in efficiency during post-stall angles of attack was only required during short periods of time (turning), then this decrease in efficiency may not have a significant impact on the lift production and energy needs. For the pursuit of biomimetic designs, this decrease in efficiency could have potential significance and should be investigated further. Qualitative flow measurements further demonstrate that these force results are due to a delay of separation resulting from the presence of tubercles.

The second study investigated explored the effects of flapping frequency on the passive flow control of a flapping wing with a sinusoidal leading edge profile. At a flapping frequency of $f = 0.05$ Hz, an alternating streamwise vortical formation was observed for the sinusoidal leading edge, while a single pair of vortices were present for the straight leading edge. A sinusoidal leading edge can be used to minimize spanwise flow by the generation of the observed alternating streamwise vortices. An increase in flapping frequency results in these streamwise vortices becoming stretched in the path of the wing. The streamwise vortices are shown to minimize spanwise flow even after being stretched. Once instabilities are formed at $f \geq 0.1$ Hz due to velocity shearing generated by the increase in cross-radial velocity, the alternating streamwise vortices begin to break down resulting in an increase of spanwise flow.

Keywords: 3D reconstruction, humpback whale flipper, flipper morphology, leading edge tubercles, vortex generator, streamwise vortex, flapping flight, oil flow visualization, sinusoidal edge
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As far as her devotion and patience during the long hours of completing this research, I would personally like to thank my wife, Maren Fassmann.

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<td>$A$</td>
<td>Wing planform area</td>
</tr>
<tr>
<td>$A_p$</td>
<td>Pitch amplitude</td>
</tr>
<tr>
<td>$AR$</td>
<td>Aspect ratio</td>
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<tr>
<td>$a$</td>
<td>Sinusoidal leading edge amplitude</td>
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<td>$\alpha$</td>
<td>Angle of attack</td>
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<tr>
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<tr>
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<td>$Re_v$</td>
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<tr>
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<td>$\rho_a$</td>
<td>Density of air [kg/m$^3$]</td>
</tr>
<tr>
<td>$St$</td>
<td>Strouhal number, $1 / (J \pi), 2 f \phi_{max} b / U_\infty$</td>
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<td>$t$</td>
<td>Thickness</td>
</tr>
<tr>
<td>$U_s$</td>
<td>Mean span velocity [m/s], $2 \phi_{max} b / f$</td>
</tr>
<tr>
<td>$U_\infty$</td>
<td>Mean free-stream velocity [m/s]</td>
</tr>
<tr>
<td>$V$</td>
<td>Max tip velocity [m/s]</td>
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<td>$\Psi$</td>
<td>Volume</td>
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CHAPTER 1. INTRODUCTION

As the general understanding of the biological world expands, biomimetic designs increasingly creep into the focus of engineering research studies [2, 4]. One area of focus in biomimetic design is the augmentation of lift and drag forces as observed in nature, particularly through the use of various unsteady fluid flow features [2, 4, 5]. Unsteady flow features commonly sought after in biomimetic designs to improve force production are vortices along the leading edge of a wing or flipper, such as seen on both humpback whale flippers and other natural swimmers and fliers.

Although the vortices generated on the leading edge of humpback whale flippers and natural fliers differ in details (e.g., flow regimes and direction across the airfoil), both exhibit similarities. Leading edge vortices were first identified as contributors to lift on delta wings [6]. Recent studies have identified similar structured vortices along the leading edges of humpback whale flippers and bird and insect wings which increase lift [2–16]. In the case of humpback whale flippers, leading edge tubercles (rounded bumps) generate opposite streamwise vortices on either side of a tubercle [3, 6, 12–14, 16–18]. These vortices induce increased lift by supplying momentum to the boundary layer over the tubercles, thereby delaying leading edge separation at high angles of attack [3,6,14,18]. Humpback whales are typically found swimming at large Reynolds numbers (Re \( \geq 10^5 \)) [2]. By comparison, during flapping flight of many natural fliers, such as birds and insects, a spanwise vortex develops along the leading edge and occurs at lower Reynolds numbers (Re \( \leq 10^4 \)). This leading edge vortex augments lift as it remains attached, and once the leading edge vortex separates, it is swept downstream and contributes to the generation of a reverse Von Karman vortex street, resulting in added thrust. Although both of these vortex formations have similarities in terms of structure and force enhancement, they are generated through different mechanisms and exist in different flow regimes.

The two vortex generation mechanisms described above are here classified as being either passive or active. In this context, passive generation of vortices result from a physical design (e.g.,
tubercles) which interacts with the natural environment to redirect the flow. Active generation mechanisms require an input or reaction from the biological system to generate a desired response (e.g., flapping wings). In this study, force production and flow characteristics resulting from vortex generative mechanisms are examined in their respective flow regimes.

1.1 Hydrodynamics of Humpback Whale Flippers with Leading Edge Tubercles

Humpback whales, shown in Fig. 1.1, have been observed to perform various “acrobatic” maneuvers which require the flippers to generate lift at high angles of attack. One that is particularly advantageous occurs during so-called “bubble net feeding” [2, 19, 20]; the act in which humpback whales encircle a school of fish with a curtain of rising bubbles and drive the school to the surface [20,21]. Once the school has reached the surface, the humpback whales turn tightly into the center of the school and lunge with open mouths through the school, toward the surface [2,20].

Figure 1.1: Images of humpback whales. Images courtesy Erik Ruf, used with permission.
Humpback whale flippers have been hypothesized to perform well at high angles of attack. Bubble nets are known to vary in size from 1.5 m to 50 m in diameter [2]. By setting the centripetal force of a turn equal to the generated lift force of flippers, Fish and Battle [2] calculated the minimum turning radius of a 9 m humpback whale. Using an angle of attack of 90°, they calculated a minimal bubble net diameter of 14.8 m. Because humpback whales are known to employ other parts of its body as control surfaces, the minimal turning radius is certainly smaller [2]. Even though other control surfaces are employed in minimizing the turning radius for humpback whales, the conclusion based on these calculations suggests that humpback whale flippers are frequently used at high angles of attack to perform the needed maneuvers.

1.1.1 Humpback Whale Flipper Morphology

By analyzing the flipper design, Fish and Battle found that a humpback whale flipper is designed for hydrodynamic efficiency [2, 20]. With a flipper length varying from $1/4^{th}$ to $1/3^{rd}$ of the total body length, an adult humpback whale has the longest flipper of any cetacean [2,21]. With a half-span of approximately 13 times the maximum chord length and an aspect ratio of around 6, the humpback whale flipper is not only relatively long, but narrow and thin [2]. Examining the cross section of a humpback whale flipper, Fish and Battle determined it to be comparable with a NACA 634-021 airfoil, shown in Fig. 1.2. In order to better identify key morphological characteristics of the flipper, they cut the flipper into 71 segments and analyzed them according to chord length, thickness and position of maximum thickness [2]. The characteristics demonstrated a fairly consistent airfoil cross section along the length, transitioning to a slightly elliptical cross section at the distal end.

Figure 1.2: Humpback whale flipper cross-section from [2] compared to a NACA 634-021 airfoil, used with permission. Shown is cross section number 60 from that study.
Although the humpback whale flipper cross-section is similar to traditional aerodynamic designs, eleven tubercles are uniquely present along the leading edge of the flipper, as seen in Fig. 1.3 [2, 21]. Located respectively with morphological structures, the tubercles are distributed along the span of the flipper, with the largest tubercle being located at about 33% of the half-span [2]. Fish and Battle initially suggested that these tubercles may perform a similar function as leading edge control devices on wings of natural fliers [2]. Previous observations suggest leading edge control devices on natural fliers improve the aerodynamic forces by acting as vortex generators [2, 22]. As described in the rest of this section, follow-up studies have further demonstrated this to be the case with tubercles.

### 1.1.2 Previous Research on Leading Edge Tubercles

Force data and flow visualization techniques have demonstrated that sinusoidal leading edge tubercles placed along an airfoil function similar to vortex generators forming streamwise vortices on sides of the tubercles [3, 6, 14, 17, 23, 24]. These streamwise vortices result in a delay of separation behind the tubercles [3, 6, 14, 17, 23, 24]. Miklosovic et al. [3] measured a delay in stall due to the presence of leading edge tubercles, in addition to an increase in lift coefficient after stall has occurred, using an idealized humpback flipper model (Fig. 1.4). Subsequent investigations demonstrated similar results, such as an increase in lift coefficient \( (C_l) \) during post-stall angles of attack \( (\alpha) \) for different Reynolds numbers \( (Re) \), airfoil shapes, and 2D airfoils. They
have shown, for example, that the tubercle size amplitude and location/width wavelength influences the resultant force generation. As described below, flow visualization and computational studies have verified that the leading edge tubercles function as vortex generators by developing three dimensional vortices between the tubercles which contribute energy back to the boundary layer, preventing separation on the tubercles, the consequence of which is force augmentation at post-stall angles of attack.

Miklosovic et al. [3] initially investigated the addition of idealized tubercles placed on an idealized humpback whale flipper and observed an increase in lift in addition to a delay of the stall angle. Two flipper models, one smooth and one scalloped as shown in Fig. 1.4, were developed with a cross sectional profile similar to a NACA 0020 foil section. The steady state lift and drag at varying angles were compared for $Re = 5 \times 10^5$. The smooth model performed as expected for an idealized airfoil, i.e., a linear change of lift was observed with respect to angle of attack, $\alpha$, until a point of stall or separation ($\alpha = 12^\circ$), beyond which the lift dramatically decreased. With the addi-

Figure 1.4: (Left) Smoothed and scalloped idealized humpback whale flipper with a NACA 0020 cross-section. (Right) A) $C_l$ vs. angle of attack ($\alpha$), B) $C_d$ vs. $\alpha$, C) $C_l/C_d$ vs. $\alpha$, and D) Flipper model design [3]. Reprinted with permission from Miklosovic, D. S., et al. “Leading-edge tubercles delay stall on humpback whale (Megaptera novaeangliae) flippers.” Physics of Fluids (1994-present) 16.5 (2004): L39-L42. Copyright 2004, AIP Publishing LLC.
tion of idealized tubercles on the leading edge, similar coefficients were observed for $\alpha \leq 10^\circ$. At higher angles of attack, the addition of tubercles delayed stall from $\alpha = 12^\circ$ to $\alpha = 17.5^\circ$, beyond which a similar drop in $C_l$ after stall was exhibited. Although the $C_l$ demonstrated changes due to the addition of tubercles, the drag coefficient ($C_d$) showed almost no difference with the addition of tubercles. This initial study demonstrated that the addition of idealized leading edge tubercles, stall could be delayed. From these results, they concluded that the leading edge tubercles do act analogous to vortex generators, adding momentum to the boundary layer to prevent separation.

A follow up study by Murray and Miklosovic [24] investigated the effect of varying sweep angles on the force production of idealized tubercles. By varying the sweep angle of the idealized tubercle model, they found that with respect to the angles investigated, sweep improved force generation performance. They concluded that the $19^\circ$ sweep-back observed by Fish and Battle [2] further improves the flipper hydrodynamic efficiency.

Contrary to the comparison of 3D flipper models with idealized tubercles previously discussed, 2D hydrofoils with the addition of tubercles decrease the $C_l$ for pre-stall conditions, although force augmentation is still observed during post-stall angles of attack. Stein and Murray [23] investigated the effect of tubercles on a 2D airfoil with amplitude and wavelength equal to the mean of those found on humpback whales for prestall conditions ($0^\circ \leq \alpha \leq 12^\circ$) and $\text{Re} = 2.5 \times 10^5$. Throughout these angles of attack, the tubercle model demonstrated a decrease in $C_l$ production compared to an unmodified airfoil. Using $\text{Re} = 2.75 \times 10^5$ for the 2D airfoil section and a $\text{Re} = 5.5 \times 10^5$ for the idealized model, Miklosovic and Murray compared the influence of tubercles added to a 2D airfoil and idealized humpback flipper model [24]. During pre-stall $C_l$ production, the idealized model improved on the unmodified model as previously reported and the 2D airfoil section showed a decrease in lift production, while post-stall $C_l$ production was improved for both the idealized tubercle model and tubercle 2D airfoil section. These results suggest that the addition of tubercles has a greater $C_l$ benefit for a finite wing by preventing separation, but tubercles cause early separation for the 2D airfoil, resulting in a decrease in $C_l$.

Research studies have determined that variations in tubercle parameters such as wavelength ($\lambda$) and amplitude ($a$) effect the resultant force generation. Using a 2D NACA 634-021 airfoil section, Johari et al. [17] explored the variation of tubercle wavelengths, $\lambda = 25\%$ and $50\%$ of chord ($c$), and amplitude, $a = 2.5\%, 5\%$, and $12.5\%$ of chord ($c$). As with previous 2D airfoil investi-
gations, they observed a decrease in pre-stall $C_l$ and an increase in pre-stall $C_d$ with the addition of any tubercles on a 2D airfoil section. For post-stall conditions, the $C_l$ was up to 50% greater than the unmodified section and with a comparable $C_d$. An increase in tubercle amplitude reduced the negative lift coefficient slope during post stall, which frequently resulted in greater $C_l$ at larger angles of attack ($\alpha \geq 26^\circ$). Smaller tubercle amplitude resulted in pre-stall $C_l$ data more comparable to that of the unmodified flipper and a large decrease of the $C_l$ at the point of separation.

Wavelength seemed to have a smaller impact on the resultant $C_l$ plot, but a wavelength of $\lambda = 25\%$ seemed to increase the generated force production.

Hansen et al. [14] investigated the parameter of tubercle amplitude over wavelength ($a/\lambda$) and compared the results with conventional vortex generators. In this study, both NACA 65-021 and NACA 0021 2D airfoil sections were tested with varying tubercle amplitude and wavelength at $Re = 1.2 \times 10^5$. Similar to Johari et al. [17], Hansen et al. [14] observed an increase of maximum $C_l$ with smaller amplitude tubercles, although the post-stall $C_l$ generation was improved for large amplitude tubercles. A decrease in wavelength was shown to positively impact the general $C_l$ until the optimum amplitude/wavelength was achieved. By comparing the results with those of conventional vortex generators, Hansen et al. [14] determined that the tubercles and conventional vortex generators do act similarly.

A recent investigation by Guerreiro et al. [13] tested five different leading edge tubercle geometries, varying amplitude and wavelength, (including a smooth baseline) for two different aspect ratios ($AR = 1$ and 1.5) and two Reynolds numbers ($Re = 7 \times 10^4$ and $1.4 \times 10^5$). Using the NASA LS(1)-0417, this investigation demonstrated that at low aspect ratios ($AR = 1$), leading edge tubercles have a minimal effect on lift production. $Re$, on the other hand, significantly effected lift and drag production for the different wing planforms. A significant reduction in lift and drag force generation was observed for the baseline, smooth, leading edge with a decrease in $Re$. On the other hand, a minimal force reduction was observed for the airfoil with large amplitude, large wavelength tubercles on the leading edge, suggesting that force produced by the leading edge tubercles is less influenced by Reynolds number.

Flow visualization has similarly illustrated that tubercles act as vortex generators that supply energy to the boundary layer over the tubercles, delaying separation in the downstream region [6, 17]. Using a 2D cross-section similar to Johari et al. [17], Custodio [6] studied the flow
over an airfoil with and without tubercles using dye injection flow visualization at a Re ≈ 1500. As seen in Fig. 1.5, these images show vortical structures developing on either sides of the tubercles, supplying moment to the boundary layer, which in turn delays separation on the airfoil with tubercles. The vortical structures observed on either side of the tubercles are similar to those of vortex generators. This figure also demonstrates the early separation for the tubercle model during the pre-stall regime (α ≤ 12°), causing a decrease in the $C_l$ for a 2D airfoil with tubercles. These flow characteristics were verified for higher Reynolds number flows by the research study of Pedro and Kobayashi [18]. Using a digitized model of the idealized humpback model from Miklosovic et al. [3], Pedro and Kobayashi [18] performed a numerical simulation with Re = 500,000 for α = 12.5° and 15° [18]. In these simulations vortical structures were observed that were similar to those of Custodio [6] and average shear streak-lines showed the flow separating at the troughs between tubercles and fanning out towards the trailing edge. They concluded that the presence of streamwise vortices improve the aerodynamic efficiency by supplying momentum to the boundary layer, confining the leading edge separation to the tip region of the models. Oil flow visualization conducted by Karthikeyan et al. [16] demonstrated similar compartmentalizing of separation due

![Dye injection flow visualization](image.jpg)

Figure 1.5: Dye injection flow visualization of an unmodified 2D airfoil (top) and a 2D airfoil with tubercles (bottom). Three different angles of attack were observed: post stall region (left) for unmodified airfoil (α = 18°), pre-stall region (middle) for unmodified airfoil (α = 12°), flow attached (right) to both airfoils (α = 0°). This image was selected from Custodio [6], used with author’s permission.
to streamwise flow on a NACA 4415 airfoil. Through the use of flow visualization and numerical studies, it was determined that the addition of leading edge tubercles generate streamwise vortices which carry momentum to the boundary layer and contain regions of separation.

Although previous investigations have explored the effect of idealized tubercles applied to idealized airfoils, no studies have been conducted using the actual geometry of an adult humpback whale flipper. Due to practical difficulties of obtaining an adult humpback whale flipper and digitizing the geometry, a 3D digitized model has not been previously available for experimentation. Even though these previous studies have determined that the leading edge tubercles perform analogous to vortex generators, these studies have not investigated the influence of varying amplitudes or locations along the chord length as seen on an adult humpback whale flipper (see Fig. 1.2).

By using a digitized model of a real adult humpback whale flipper, this thesis explores the effect of tubercles on real humpback whale flipper geometry, particularly natural spatial variations in tubercle size and location along the chord, on lift and drag production. The digitized model was reconstructed from 18 multi-view 2D images and was validated by comparing geometric data from the model with morphological data from Fish and Battle [2]. Two additional models were derived from the digitized model to determine the influence of leading edge geometry on force production for an adult humpback whale flipper. Variations in the geometry of these models were compared with the original flipper by using morphological measures. Force data were acquired and compared between the models with and without significant vibrations. Oil flow visualization was used to study the presence of vortex generation and qualitatively describe variations in separation between the models and vibration scenarios. These results are compared with those of previous studies, highlighting the effect of leading edge geometry on humpback whale flippers.

1.2 Flapping Flight Research

With the increase of interest in applications of unmanned air vehicles, Micro-Air Vehicles (MAVs), classified for their small size (about 15 cm) and low Reynolds flight region ($\leq 10^4$) [1,9,25,26] have become a source of scholarly interest due to the complexity of the aerodynamics. The reduction in size of a MAV has a dramatic effect on typical aerodynamic responses and flow phenomena such as flow unsteadiness, vortex effects, inertial forces, and centrifugal and Coriolis accelerations [25,27,28]; these enable flapping flight propulsion to be more suitable and efficient
for flight because rotary or fixed-wing flight drop in efficiency at low Reynolds numbers [29]. Even though flapping flight is viewed as a more suitable and efficient propulsion system, it was discovered that conventional aerodynamic theories disagree with measurements of instantaneous lift and thrust forces [26, 30], and many studies, some of which are summarized below, have been devoted to understanding flapping flight aerodynamics.

Due to the periodic motion of flapping flight, a leading edge vortex (LEV) similar to those generated by delta wings can be generated to augment force production. This unsteady flow feature was initially observed on the leading edge of natural fliers [30]. Further investigations have proposed that while attached to the leading edge, the LEV improves lift production by a “delayed stall effect” [25, 26]. The “delayed stall effect” is where the flow remains attached beyond the steady stall incidence due to the presence of the LEV [26]. Upon separation the LEV convects downstream and contributes to the growth of the trailing edge vortex (TEV), which at stroke reversal, separates from the wing and contributes to producing thrust through the generation of a reverse Von Karman vortex street [25, 26]. Previous research has suggested spanwise flow in the vortex core is used to stabilize the LEV [26], even though axial flow has not always been observed [31].

1.2.1 Flapping Flight Non-dimensional Analysis

While investigating flapping flight, scaling or non-dimensional numbers, such as the Reynolds number (Re), the Strouhal number (St), and reduced frequency (k), are used to compare different flow regime. The Reynolds number, a ratio of inertial to viscous forces, can be used to classify the influence of the boundary layer. During forward flapping flight, the free-stream velocity is used to calculate this dimensionless property, while during hovering flight the stroke velocity is used. With respect to flapping flight, changes in Re have been reported to increase force production and minimally impact flow topography or vortex generation, even though effects due to Re may influence laminar-turbulent transitions which results in an increase of lift [25]. The Strouhal number correlates the frequency of vortex shedding to the characteristic length and incoming flow velocity. The Strouhal number is applied in flapping flight to quantify the LEV shedding frequency to wing amplitude scale. Previous research investigations have shown that to maximize thrust efficiency the Strouhal number should be in the range of $0.2 \leq St \leq 0.4$ and can be observed by natural fliers during forward flight [25, 26]. Although the St number does have a significant impact on force pro-
duction, Baik et al. concluded that the St number only has a small effect on LEV circulation [26]. On the other hand, the reduced frequency has a reduced effect on force production, but the LEV formation growth rate decreases significantly as reduced frequency increases. Reduced frequency compares trajectory angular velocity to wing chord length and incoming flow. The reduced frequency of a trajectory has been shown to have a major effect on LEV formation [9].

The following non-dimensional numbers are here used as given below [9]:

\[
St = \frac{2\pi f c h_o}{U_\infty} = \frac{4\pi f c \phi_{\text{max}} b}{U_\infty},
\]

\[
Re = \frac{U_\infty c}{\nu},
\]

\[
k = \frac{\pi f c}{U_\infty},
\]

where \(h_o\) is the plunge amplitude defined here as the total sweep amplitude measured from the tip \((2\phi_{\text{max}} b)\), \(\phi_{\text{max}}\) is the maximum sweep amplitude in radians, \(b\) is the half-span length, \(f\) is the flapping frequency in Hz, \(U_\infty\) is the free-stream velocity, and \(c\) is the chord length.

### 1.2.2 Passive Vortex Generators in Flapping Flight

Passive control devices were initially identified in flapping flight on the wings of bats. Norberg [22] first suggested that the digits and arms projecting above the wing in addition to concentrations of hairs seemed to act as turbulence generators across the wings. As a turbulence generator, these passive control devices would transition the flow from laminar to turbulent, preventing separation and minimizing the pressure drag. A follow-up study suggested that these leading edge control devices acted similar to a vortex generator by maintaining lift and preventing stall at low speeds and high angles of attack [32].

Using a sinusoidal leading edge as a passive control device, recent investigations have shown the development of vortices along the chord for flapping flight. By imaging two flat rectangular flapping wings with and without a sinusoidal leading edge, Ozen et al. [1] demonstrated that a sinusoidal leading edge may be used to prevent spanwise flow generated during flapping flight. They also determined that although a sinusoidal leading edge does influence the spanwise flow, the formation and size of the tip vortex seems to be relatively unaffected. A following numerical simulation by Zhang et al. [33] used a airfoil section with a sinusoidal leading edge to determine
the influence on force production for both gliding and flapping motions. This investigation demonstrated that a sinusoidal leading edge improves performance during gliding with possibilities for improvements in flapping flight.

Although the streamwise vortices generated by a sinusoidal leading edge has been shown to act as a passive means of flow control on the leading edge where the LEV is formed, little is understood about how these vortices vary with flapping frequency. Initial observations have looked primarily in regimes of low Strouhal numbers. The intent of this investigation is to build upon this research and investigate the influence of a sinusoidal leading edge on vortex structure generation in different flow regimes by changing the flapping frequency.

1.3 Thesis Outline

1.3.1 Hydrodynamics of a Digitized Adult Humpback Whale Flipper (Chapter 2)

The hydrodynamics of a realistic humpback flipper model were explored. The model was developed by reconstructing a sequence of 18 images circumscribing the suspended flipper of a dissected, beached humpback whale. A physical prototype was constructed based on the resulting 3D model, along with two complementary model with the tubercles removed. Experimentally-obtained measurements of lift and drag were used to study the influence of the tubercles. In this thesis, flipper digitization and flow measurement methods are described and hydrodynamic results are presented and discussed.

1.3.2 Effect of Flapping Frequency and Leading Edge Profile on Airfoil Leading Edge Vortical Structures (Chapter 3)

This investigation explored the effects of flapping frequency on the passive flow control of a sinusoidal leading edge profile. Using the Brigham Young University flapping flight mechanism, the effect of flow regimes on the control of vortical structures on a sinusoidal leading edge was investigated. Two different wing planform designs, rectangular wings with straight and sinusoidal leading edges, were flapped at varying flow regimes by changing the flapping frequency. PIV images were acquired for different positions of the stroke at different flow regimes. Differences in
the passive flow control of a sinusoidal leading edge profile were observed. In this thesis, vorticity and velocity plots are provided and variations are discussed.

1.4 Overview of Thesis Contributions

The main contributions of this thesis are as follows:

1. The generation of a 3D digital model of an adult humpback whale flipper using 2D multi-view images

2. Validation of digitized flipper model with previously reported humpback whale flipper morphology

3. Lift and drag data from a scaled model of the adult humpback whale flipper at various angles of attack, including comparison with modified models without leading edge tubercles at various angles of attack

4. Qualitative flow visualization plots at various angles of attack for the digitized model and two modified models without leading edge tubercles

5. Quantitative velocity data showing the effects of a sinusoidal leading edge on vortex generation over a range of flapping frequencies and phase angles
CHAPTER 2. HYDRODYNAMICS OF A DIGITIZED ADULT HUMPBACK WHALE FLIPPER

2.1 Overview

Because of practical difficulties involved with generating a 3D reconstruction from an adult humpback whale flipper, no such 3D digitized model has previously been available. In this study, lift, drag and flow visualization data were acquired using a digitized adult humpback whale flipper model. The model was developed from multi-view 2D images and a commercial 3D reconstruction software tool (see Fig. 2.1). Two derivative models with modified leading edges were created and tested to explore the hydrodynamic effects of leading edge tubercles. Scale models were fabricated using the digitized models and used to acquire force and flow visualization data. The data demonstrated ways in which the addition of leading edge tubercles on humpback whale flippers improve hydrodynamic performance. In the following sections, the various methodologies used in this study, the resulting data, and a discussion of the results are presented.

Figure 2.1: Process overview for the 3D reconstruction of an adult humpback whale flipper. Left to right: Multi-view 2D images acquired of the humpback whale flipper; 3D reconstructed flipper; refined model, straightened, and smoothed model; original model with derivative models (original [left], filtered [middle], smoothed [right]); and fabricated 1:8 scale flipper models. Use of photos authorized under NMFS Permit No. 932-1905/MA-009526.
2.2 Methods

2.2.1 3D Flipper Reconstruction

Using 3D reconstruction software and multi-view images, a digitized model of an adult humpback whale flipper was developed. Eighteen multi-view 2D images were acquired by Dr. Scott Thomson during the necropsy of a deceased adult humpback whale that had beached on the shores of East Quogue (Long Island, New York; Fig. 2.2). Access to the whale was facilitated by Dr. Joy Reidenberg of the Mount Sinai Hospital and the Riverhead Foundation for Marine Research and Preservation. The whale, known as “Ishtar” to biologists who had observed her for over 40 years, weighed approximately 30-35 tons and 14.6 m long. The right flipper, estimated to be approximately 3.6 m long, was imaged while being hoisted by a trackhoe excavator. The images were acquired using a Nikon D5100 with focal lengths of 18 mm (15 images), 21 mm (1 image), and 24 mm (2 images) and shutter speeds ranging from 1/125 to 1/250 s. These images were reconstructed into a digitized 3D mesh using Autodesk 123d Catch software (http://www.123dapp.com/catch). After initial reconstruction an additional 29 manual points were added within 123d Catch to the image correlation to improve the resulting 3D mesh. Figure 2.3 shows the reconstructed flipper from different viewpoints.

In order to prepare the digitized model to be exported for subsequent fabrication and testing, modifications were made using the 3D modeling and animation software tool Blender (http://www.blender.org/). The initial reconstruction yielded a surface mesh with the presence of holes at the tip (due to contact with sand) and at the root of the flipper (where it had been separated from the whole body). The connective tissue was digitally cropped near the proximal end and holes were simply filled by connecting nodes surrounding the holes. The underside of the flipper tip was filled by following the general contour of the flipper surface leading to this incomplete section. A built-in 3D smoothing function was applied to the transition between the repaired section and the surrounding mesh. These reparations enabled the flipper to be regenerated as a solid object.
Figure 2.2: Multi-view 2D images of flipper. Use of photos authorized under NMFS Permit No. 932-1905/MA-009526.

Figure 2.3: Images of the reconstructed flipper from Autodesk 123d Catch. The flipper is curved due to being suspended by a chain and resting on the sand. Use of photos authorized under NMFS Permit No. 932-1905/MA-009526.
Straightening and smoothing operations were used to reduce noise and unnatural curves in the flipper. Straightening was required because of the flipper shape when imaged. A subsequent smoothing operation was performed to minimize the surface noise generated during the reconstruction. While the images were acquired, two general curves were prevalent in the flipper due to the method of supporting the flipper, as illustrated in Fig. 2.3. The first curve was a slight “S” shape due to the flipper being supported at the root end, with the tip resting on the beach. The second was due to the chain wrapped around the flipper root, causing a slight folding or curvature in that vicinity. The straightening techniques used in Blender consisted of creating a lattice structure along the flipper to rotate and translate groups of nodes (see Appendix B). Ten iterations of manipulating groups of nodes were performed to bend the flipper into a straight position. The first five iterations were focused on straightening the slight “S” shape, while the next five focused on finer straightening improvements and on the root end. Once straightened, the noise due to 3D reconstruction was reduced by using the smoothing tool in Blender. Ten steps of localized smoothing were performed to minimize the reconstruction noise. After each step in the straightening and smoothing process, the solid volume was verified to have remained within 3.5% of the original model volume. Figure 2.4 shows the flipper before and after the straightening techniques.

![Figure 2.4: Flipper model prior to straightening operations (left three images) and after straightening and smoothing (right three images; the box at the root was added for subsequent experiment mounting purposes).]
2.2.2 Flipper Model Variations

Two modified models of the straightened flipper were made to explore the influence of the tubercles on the flipper hydrodynamic response. The first modified model was generated by using filtering techniques to minimize the tubercles. The second model consisted of a smoothed, more “traditional” leading edge. The first “filtered” model was generated by exporting the original profile, low pass filtering the profile variations, applying the filtered leading edge to the original profile, and using lattice structures in Blender. The second “smoothed” model was generated by manipulating the filtered model’s leading edge with lattice structures until a more uniform leading edge was obtained. Both of these modified designs were generated to create a baseline model without leading edge tubercles for force and flow analysis. The following paragraphs describe these operations in more detail.

Two methods of generating a filtered leading edge profile were explored. The first method relied on the mean of two non-uniform rational B-spline (NURBS) curves generated using the peaks and troughs, respectively, along the profile (see Fig. 2.5). The second method included transforming the leading edge profile to a digital signal in order to filter out the leading edge tubercles (see Appendix C). The resulting mean chord length normalized by the half-span \( c/b \) was used to compare the two filtering profiles. The mean ratios of the resulting profiles were \( c/b = 0.2918 \) for the NURBS method and \( c/b = 0.2923 \) for the filtering method, compared to ratio for the original profile of \( c/b = 0.2920 \). Due to little variation of the chord length between each method, the profiles were further analyzed based on the influence of individual tubercles, particularly tubercles 1 and 4 (see Fig. 2.5). Both of the above methods resulted in acceptable profiles, but because the NURBS method resulted in a leading edge profile that was less influenced by single large amplitude tubercles, it was selected for the Blender transformation. The NURBS method is thus briefly described in more detail in the next paragraph.

The NURBS method for filtering the leading edge tubercles focused on finding the mean of two NURBS curves. Using Blender, two NURBS curves were generated, with one NURBS curve intersecting the tubercle troughs, and the other NURBS curve intersecting the peaks, as shown in
Fig. 2.6. Using MATLAB, the curves were thresholded from the rest of the image and cropped (see Fig. 2.7). A chord-wise average length was calculated from both of the NURBS curves, and this constituted the filtered leading edge profile.

To generate the filtered model, the original whale flipper model was modified using a lattice structure to fit the NURBS-generated profile without tubercles. As seen in Fig. 2.8, the NURBS profile was imported into Blender and aligned to the centerline of the model to serve as a template for original flipper manipulation. Using a lattice structure, the original 3D model nodes at

Figure 2.5: Original flipper profile shown with the profiles generated by two methods: NURBS curve (red) and filtered method (blue).

Figure 2.6: Two NURBS curves in Blender. The upper NURBS curve passes through the troughs of the profile, while the lower NURBS curve passes through the peaks.

Figure 2.7: Cropped and thresholded image of the NURBS curves.
the mid-chord to the tip were condensed or expanded to fit the NURBS-generated profile while maintaining original volume to within 4%, as illustrated in Fig. 2.9. Translations occurred only in the y-direction (chord-wise direction), maintaining the x and z position of each vertex. The filtered model was additionally smoothed using sculpting tools in Blender to minimize residual tubercle influences such as slight leading edge irregularities resulting from the lattice structure transforms and span-wise variations of thickness.

The second modified model, the “smoothed” model, was transformed from the filtered model by further reducing waviness in the leading edge profile to generate a more “traditional” airfoil. Similar to the final manipulation of the filtered model, a lattice structure manipulated nodes in the y-direction in order to compress or expand the node’s position along the leading edge profile to suppress waviness. During the transformation of the leading edge, the volume was maintained to within ±2% and the mean chord over half-span ($c/b$) ratio was 0.2922 (compared with that of the original flipper of 0.2920).

**Figure 2.8**: Original flipper model superimposed on the mean NURBS curve profile (black) that was imported into blender to act as a template for manipulating the leading edge.

**Figure 2.9**: Illustration of Blender’s lattice structure operation being used to modify the leading edge in order to generate the filtered model.
Figure 2.10: Three flipper models: original (left), filtered (middle), and smoothed (right) flipper models.

Table 2.1: Geometric properties of the three flipper models normalized by half-span ($b$)

<table>
<thead>
<tr>
<th>Models</th>
<th>Initial Reconstruction</th>
<th>Original</th>
<th>Filtered</th>
<th>Smoothed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chord ($c/b$)</td>
<td>NA</td>
<td>0.2920</td>
<td>0.2918</td>
<td>0.2922</td>
</tr>
<tr>
<td>Planform area ($A/b^2$)</td>
<td>NA</td>
<td>0.2246</td>
<td>0.2238</td>
<td>0.2214</td>
</tr>
<tr>
<td>Volume ($\varphi/b^3$)</td>
<td>$8.75 \times 10^{-3}$</td>
<td>$8.74 \times 10^{-3}$</td>
<td>$8.78 \times 10^{-3}$</td>
<td>$8.59 \times 10^{-3}$</td>
</tr>
<tr>
<td>Final Volume Change ($% \varphi$)</td>
<td>NA</td>
<td>$-0.15%$</td>
<td>$0.35%$</td>
<td>$-1.87%$</td>
</tr>
</tbody>
</table>

The three flipper models are shown in Figure 2.10. Table 2.1 lists geometric properties normalized by the half-span length ($b$) for each model, as well as for the initial reconstruction (i.e., the leftmost three images of Fig 2.4). Chord length and planform area was not calculated for the initial reconstruction because of the previously discussed curvature of the flipper. A decrease in volume can be observed for the smoothed model due to the smoothing tool in blender which minimized leading edge variations. These geometric properties demonstrate good quantitative similarity between the different models even though the leading edge geometry was significantly altered. To further validate these models and the modifications, morphological graphs of the cross-section geometry are presented and compared with published humpback whale flipper data in the Section 2.4.1.
2.3 Experimental Setup and Procedure

2.3.1 Fabrication and Wind Tunnel Setup

Force (lift and drag) data were acquired using scaled oak wooden models from the three previously described digitized models in the Brigham Young University large wind tunnel. Using a CNC mill with a 1/4” straight bit and a final pass at 95% overlap, these models were fabricated at approximately 1:8 scale, resulting in a half-span \( b \) of 0.5 m and mean chord lengths \( c \) of about 0.145 m. These wooden models were sanded with 330 grit sandpaper prior to being painted. After applying several coats of primer and flat white paint, these models were smoothed with wet 500 grit sandpaper (see images in Appendix E).

Each model was tested in the wind tunnel to obtain force and flow measurements. The wind tunnel cross section was 0.6 m tall and 1.22 m wide. The flippers were mounted about 2 m downstream of the entrance nozzle. The free stream velocity was \( U_\infty \approx 46.8 \pm 1.0 \) m/s with air at 12-18°C \( (\nu \approx 1.60 \times 10^{-5}) \) for a Reynolds number of approximately \( \text{Re} \approx 430,000 \pm 20,000 \) based on the mean chord length; see Eq. (2.1) and Table 2.2.

\[
\text{Re} = \frac{U_\infty c}{\nu}
\]  

An AeroFMS MC-2S-3.5 5-Axis load cell was used to obtain lift and drag data for each flipper model at various angles of attack \( (\alpha) \) ranging from \(-45^\circ\) to \(45^\circ\) in \(1^\circ\) increments. An acquisition rate of 1000 Hz was acquired for at least 5 seconds at each \( \alpha \) after a two second wait time to allow the force signal to stabilize after changing \( \alpha \). The lift \( (L) \) and drag \( (D) \) mean and

<table>
<thead>
<tr>
<th>Models</th>
<th>Original</th>
<th>Filtered</th>
<th>Smoothed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chord ((c))</td>
<td>0.146 m</td>
<td>0.146 m</td>
<td>0.146 m</td>
</tr>
<tr>
<td>Planform area ((A))</td>
<td>0.561 m</td>
<td>0.559 m</td>
<td>0.553 m</td>
</tr>
<tr>
<td>Reynolds number ((\text{Re}))</td>
<td>4.3×10^6</td>
<td>4.3×10^6</td>
<td>4.3×10^6</td>
</tr>
</tbody>
</table>
standard deviation were calculated for each $\alpha$. The resultant force data for each of the models are compared in this thesis using the coefficients of lift ($C_l$) and drag ($C_d$), as follows:

$$C_l = \frac{2F_l}{\rho U_\infty^2 A} = \frac{F_l}{\Delta P A} \quad (2.2)$$

$$C_d = \frac{2F_d}{\rho U_\infty^2 A} = \frac{F_d}{\Delta P A} \quad (2.3)$$

where $F_l$ and $F_d$ are the respective lift and drag force measurements, $\rho$ is the calculated density, $U_\infty$ is the free-stream velocity, $\Delta P$ is the measured pressure difference used to calculate the free-stream velocity, and $A$ is the planform surface area previously reported.

### 2.3.2 Load Cell Mount

Tests were performed with the load cell fastened to an initial mount. However, because flipper vibrations were observed, a sturdier mount was constructed. The secondary mount resulted in a reduction of vibration amplitude and a different frequency. These vibrations were quantified by measuring the maximum tip amplitude for the original flipper model at various angles of attack. The maximum tip amplitude was measured by using a high speed Photron FastCam SA-3 camera at a respective frame rate of 125 frames/second with a resolution of $1200 \times 1000$ pixels. Five dots were marked on the tip of the flipper model and recorded for two seconds at five angles of attack ($0^\circ$, $10^\circ$, $15^\circ$, $20^\circ$, $25^\circ$). By tracing the movement of these markers, the maximum amplitude was determined. Table 2.3 gives the measured vibration data for both mounts with the original flipper model. Note that the first set of vibration data seemed to be caused by a flow induced vibration. This was concluded by finding the natural frequency by plucking the flipper mounted to the load cell (14 Hz), and comparing it to the observed vibration due to the free stream velocity with a similar vibration of 14 Hz. An increase in amplitude was also observed with increasing $\alpha$. The second vibration appeared to be generated by the wind tunnel shaking as the amplitude was consistent over $\alpha$. To summarize, the vibration from the first mount had a maximum amplitude of 0.8 mm at 14 Hz, while the second mount had a maximum amplitude of 0.3 mm at about 58 Hz.
Table 2.3: Observed vibration amplitudes for the original flipper with the two different load cell mounts

<table>
<thead>
<tr>
<th>(α)</th>
<th>Sturdier Mount (58 Hz)</th>
<th>Initial Mount (14 Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>0.3 mm ± 0.18 mm</td>
<td>0.4 mm ± 0.12 mm</td>
</tr>
<tr>
<td>10°</td>
<td>0.3 mm ± 0.18 mm</td>
<td>0.4 mm ± 0.12 mm</td>
</tr>
<tr>
<td>15°</td>
<td>0.3 mm ± 0.18 mm</td>
<td>0.6 mm ± 0.12 mm</td>
</tr>
<tr>
<td>20°</td>
<td>0.3 mm ± 0.18 mm</td>
<td>0.6 mm ± 0.12 mm</td>
</tr>
<tr>
<td>25°</td>
<td>0.3 mm ± 0.18 mm</td>
<td>0.8 mm ± 0.12 mm</td>
</tr>
</tbody>
</table>

(see Appendix A for the uncertainty analysis). The 58 Hz vibration was almost imperceptible with the naked eye, while the larger vibration could be seen at large α.

2.3.3 Flow Visualization

Using oil flow visualization, surface flow characteristics were qualitatively determined for each of these models. A 4:1 mixture of SAP O122-1 heavy paraffin oil (Fisher Scientific©) and General’s© pure powdered graphite (#970PG) was applied to the flipper at a predetermined angle of attack. The wind tunnel was subsequently brought up to speed and allowed to run for approximately two minutes. The wind tunnel was then decelerated and an image was acquired of the resulting oil flow pattern. These flow visualization tests were performed using both mounts at five different angles of attack (5°, 10°, 15°, 20°, 25°) for the original flipper and four different angles of attack (10°, 15°, 20°, 25°) for the other two models (filtered and smoothed).

2.4 Results and Discussion

2.4.1 Flipper Morphology

To validate the flipper reconstruction, morphological characteristics are here compared with prior results of [2]. The original flipper model was sliced into 71 sections and used to generate digital cross-sections (see Fig. 2.11). Images of the cross sections were analyzed using a custom MATLAB code to calculate the chord length (c), thickness (t), and streamwise position of maximum thickness from the leading edge (d), as illustrated in Fig. 2.12. Morphological plots are here
presented to compare the morphological data of the original flipper model to the reported data of a left flipper from a 9.02 m male adult humpback whale [2]. The reported flipper half-span of [2] was 2.5 m long. The flipper was sliced into 71 cross sections, each 2.5 cm thick, for imaging and measurement. Similar morphological plots are presented using the filtered and smoothed flipper models in order to further characterize the geometric changes resulting from the respective modifications previously mentioned.

As illustrated in Fig. 2.13, the spanwise variation of chord length is predominantly governed by the leading edge tubercles, the maximum thickness decreases at an approximately constant rate, and the distance from the leading edge to position of maximum thickness also follows the leading edge tubercle amplitude. Even though the primary feature in determining spanwise variations of the chord length is the leading edge tubercles, slight variations in the trailing edge do have a minor impact on the chord length variations. Due to the tubercles being formed from the cartilage of the manus (distal portion of the fore limb), previous research investigations such as Fish and Battle [2] have shown a low standard deviation in tubercle size and location. Consistent with the observation, the location and sizes of tubercles reported from [2] and the current model are indeed comparable (see Fig. 2.13). As expected with a wing-like appendage, the original flipper model decreases in thickness along the span from the proximal to the distal end. Figure 2.13 illustrates a fairly consistent decrease in flipper thickness along the span, suggesting that the maximum thickness decreases at almost a constant rate relative to the chord, which is also similar to the results reported of [2]. Finally, the location of maximum thickness appears to be a function of the leading edge tubercles. Although the amplitude of the leading edge tubercles vary slightly between the original flipper model and data of [2], the locations of maximum thickness are comparable between both data sets (see Fig. 2.13). Such variations would be expected due to natural biological variations within a species. Overall, these data sets show that the original flipper model geometry follows the same spanwise tendencies as the flipper studied by Fish and Battle [2].

In the data shown in Fig. 2.13 model and data from Fish and Battle, the position of maximum thickness is clearly seen to be a function of the leading edge tubercles (since the peaks
correlate with the presence of tubercles), suggesting that the position of maximum thickness may not vary significantly with respect to the mean chord length [2]. By normalizing the position of maximum thickness by the individual chord lengths, the shape of the airfoil can be more clearly defined. A negative trend is observed from tip (distal end) to shoulder (proximal end) in thickness location (as illustrated in Fig. 2.14) suggesting that the airfoil shape does vary slightly in the

Figure 2.11: (Above) Location of 71 slices of the original flipper model: (blue and green) cross sections 23 and 39, (orange) cross sections with numbers which are multiples of 5, and (yellow) other cross sections. (Below) Cross section profiles of number 23 and 39 from the original flipper model (left) and the respective images from [2] (right) used with author’s permission.

Figure 2.12: Illustration of morphological parameters for defining flipper geometry including chord length (green), maximum thickness (red) and streamwise position of maximum thickness (blue).
spanwise direction. Although these trends are seen in both the original flipper and the reported data in [2], there is a slight discrepancy at sections 1 through 3. Further inspection in this region showed that for the original flipper model cross sections 1 through 3 did resemble the same general shape as the images from [2]. However, due to error in the tip reconstruction (recall that it was in contact with sand requiring remodeling) the calculated position of maximum thickness differed from that of [2]; see Appendix D for further details. The most significant change in airfoil cross section was present in sections 1 and 2 for both the digitized models and those of [2], as these sections demonstrated almost a symmetric elliptical shape (images also shown in Appendix D).

It is here hypothesized that a possible reason for this trend, the transition in airfoil profile toward a symmetric elliptical shape near the tip, could result from the need to minimize structural loading and improve airfoil controllability. A slight variation in profile along the span with a more elliptical shape near the end could result in a change of the spanwise load distribution along the flipper. This generated load distribution could potentially move the lift moment arm closer to the inboard section, thereby minimizing the structural loading of the flipper. This reduction in structural loading would allow a humpback whale to maintain flipper position even during the
generation of large forces and potentially increase the controllability due to the improved stability. Further analysis would be required to test this hypothesis.

Figure 2.15 shows that the maximum thickness is about 23% of the chord length for both the original flipper model and data from [2]. This general trend holds true except for cross sections 1 through 3, due to variations in tip cross-section, and sections 38-60, due to the increase of chord length near the largest tubercle. The original flipper model again deviates slightly from [2] at cross sections 1 through 3 (the tip) due to the resulting error of tip remodeling, but as the general cross-section shape remains similar this error is deemed to be tolerable; see Appendix D.

Using the morphological data discussed above, the modified flipper models were compared with the original flipper to quantitatively describe the variations between the models. Recall that two complementary models were derived from the original model in order to further understand the effect of geometry on hydrodynamic performance. The filtered model was generated by minimizing the amplitude of the leading edge tubercles, whereas the smoothed model was transformed from the filtered model to minimize any leading edge waviness. The morphological plots and ac-

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Figure 2.14: Position of maximum thickness normalized by cross-section chord lengths (c) for the original model (left) and graph from Fish and Battle [2] (right). Reprinted with permission from Fish, Franke E., and Juliann M. Battle. "Hydrodynamic design of the humpback whale flipper." Journal of Morphology 225.1 (1995): 51-60. Copyright 1995, Wiley-Liss, Inc.
companying narrative below quantify and discuss these differences relative to the morphology of the original flipper model.

The filtered model demonstrates a smoothing of leading edge tubercles, while maintaining the general flipper shape, including the position of maximum thickness. As previously described, the filtered model used a filtering technique to minimize the tubercle amplitudes. In addition to showing the size reduction of the leading edge tubercles, Figure 2.16 shows both comparable decreases in thickness and approximately the same position of maximum thickness for the filtered and original models. Figure 2.17 shows a slight variation between the filtered model and original model with respect to maximum thickness position and magnitude, which variation was caused by smoothing. Nevertheless, both of these parameters resemble the same peaks and troughs as seen in the original flipper model. Importantly, the leading edge of the flipper model was filtered to reduce the presence of tubercles, but during this operation the position of maximum thickness and trends in maximum thickness maintained relatively unchanged for the filtered model.

For the smoothed model, the primary differences observed in the morphological plots (Figures 2.16 and 2.17) include a smoother leading edge and a mostly constant distance from the leading edge to the point of maximum thickness. While the maximum thickness follows a similar trend as the original model with minimized noise, it is important to note that the modifications

Figure 2.15: Maximum thickness normalized by cross-section chord lengths (c) for the original model (left) and graph from Fish and Battle [2] (right). Reprinted with permission from Fish, Franke E., and Juliann M. Battle. "Hydrodynamic design of the humpback whale flipper." Journal of Morphology 225.1 (1995): 51-60. Copyright 1995, Wiley-Liss, Inc
Figure 2.16: Spanwise variations of chord length (green line, solid green circles, open green circles), maximum thickness (red line, solid red circles, open red circles), and position of maximum thickness (blue line, solid blue circles, open blue circles) for the original, filtered, and smoothed models, labeled respectively.

Figure 2.17: (left) Spanwise variations of maximum thickness location for the original model (blue line), filtered model (solid blue circles), and the smoothed model (open blue circles). (right) Spanwise variations of maximum thickness for the original model (red line), filtered model (solid red circle), and the smoothed model (open red circles).

leading to the smoothed flipper increased the mean position of maximum thickness (Fig. 2.17). Figure 2.17 shows a reduction in maximum thickness for section numbers 15-30 due to eliminating the leading edge tubercles. This was previously observed in Fig. 2.16 by inspecting the plot
of maximum thickness of each section with respect to the overall maximum chord. The maximum thickness for each cross section tapers towards the tip as seen with the other models. By inspection of morphological plots, the smoothed flipper has eliminated slight variations due to the presence of tubercles, resulting in less variations in position of maximum thickness and a smooth leading edge, while maintaining the general tapering of maximum thickness near the tip.

To summarize the findings presented in this section, the geometry of the three flipper models were compared with each other and the flipper analyzed by Fish and Battle [2] using morphological plots. These observations showed that the original flipper model possessed comparable morphological structures with the flipper studied in [2], validating the 3D reconstruction. A trend of variation in cross-section profile shape was observed, resulting in a hypothesis of variation of load distribution to relieve structural loading. The filtered model minimized leading edge tubercles while maintaining the maximum thickness location dependence on the pre-existing tubercles. The smoothed model eliminated the presence of leading edge tubercles and other leading edge waviness while minimizing the maximum thickness location dependence on the pre-existing tubercles.

2.4.2 Lift, Drag, and Hydrodynamic Efficiency

The steady state hydrodynamic efficiency of the original flipper model was defined by measuring the resultant lift and drag force generation at different angles of attack and making comparisons with lift and drag data similarly acquired using the two modified models. First, the lesser vibration case (second mount) is presented for all three models, as in this case vibrations had a reduced effect on resultant force generation. The resultant force data for each of the models are compared using the lift coefficient \( C_l \) and drag coefficient \( C_d \) to determine the effect of geometry on force generation; see Appendix A for plots of standard deviations. Hydrodynamic efficiency is then represented by plotting \( C_l/C_d \) vs. \( C_l \), providing a measure of efficiency vs \( C_l \). Following this initial description of force generation, the greater vibration case (first mount) is presented and compared with the lesser vibration case data. It is shown that as has been previously observed in
other research studies, the addition of tubercles improved the post-stall force generation for these models. Induced vibrations had a greater effect on the force generation of the filtered and smoothed models than of the original model.

Force data obtained from the three flipper models demonstrate that the leading edge tubercles are a prominent feature in delaying stall and increasing post-stall $C_l$ for positive angles of attack. Figures 2.18 and 2.19 show $C_l$ and $C_d$ vs. $\alpha$ for each model. During pre-stall conditions ($\alpha \leq 16^\circ$), all three models exhibit a nearly linear trend of increasing lift with a more modest increase in drag, as would be expected with attached flow. At $\alpha = 14^\circ$ the original flipper model begins to taper towards a maximum $C_l$ of 1.1, while the filtered and smoothed model $C_l$ values increase together until $\alpha = 17^\circ$, at which point $C_l \approx 1.2$. At post-stall angles of attack up to around $\alpha = 19^\circ$, the original model maintains a relatively constant $C_l$, while the filtered and smoothed models experience shaper reductions in $C_l$. During the post stall regime ($\alpha \geq 20^\circ$), the original flipper sustains a higher $C_l$ compared to the filtered and smoothed flipper models. For $\alpha \approx 30^\circ$, the original model produces up to 30% more $C_l$ than the respective values from the other two models.

A similar difference in stall characteristics was observed on idealized airfoils with tubercles by Johari et al. [17] in which 2D airfoils with tubercles on the leading edge were observed to decrease in maximum $C_l$, but exhibit a significantly larger $C_l$ production in the post-stall regime. Flow visualization of idealized tubercles have demonstrated that 3D vortical structures that develop on the sides of the tubercles enable the flow across tubercles to remain attached well past stall angles for baseline airfoils without tubercles [6, 17, 18]. At large angles of attack ($\alpha \geq 36^\circ$), all three flippers demonstrate a comparable value of $C_l$ which does not vary with an increase of $\alpha$, suggesting significant separation has occurred on all three airfoils. With respect to the drag coefficient, during the large angles of attack at which the tubercles act as vortex generators to prevent separation a slight increase of drag coefficient is observed. These combined results demonstrate that the leading edge tubercles are a predominant feature in increasing post-stall $C_l$ in the original flipper model.
Similar trends are observed for the models at negative angles of attack. The force plots for negative angles of attack demonstrate the effects of non-symmetric geometries (see Figs. 2.18 and 2.19). As seen during pre-stall conditions for positive $\alpha$, all three models exhibit the same linear trend towards increasing $C_l$ with increasing angle of attack. Because of the slight concavity of the geometry, for negative $\alpha$ the smoothed model initially stalls at $\alpha \leq 10^\circ$ and the filtered model stalls at $\alpha \leq 12^\circ$. These points of separation are all significantly lower than the respective positive angle cases. In contrast to the positive angle of attack case, the original flipper continues to increase $C_l$ until $\alpha = 20^\circ$, although a temporary drop in $C_l$ is seen at $\alpha = 6^\circ$. These force data sug-
gest that the leading edge tubercles generate vortices which transfer momentum to the boundary layer, preventing stall between $6^\circ \leq \alpha \leq 20^\circ$. Within this regime of tubercle-generated vortices transferring momentum, an increase of drag coefficient is exhibited, similar to that which occurs for positive angles of attack.

By comparing these force results to those of previous research studies, it becomes evident that the addition of tubercles attached to real geometry yields a response that is similar to those of ideal tubercles present on ideal airfoils. With the 3D idealized models of Miklosovic et al. [3], in the pre-stall regime, the model with the leading edge tubercles yielded a similar force generation as the model without leading edge tubercles. In the post-stall regime, Miklosovic et al. [3] observed a delay of stall for the idealized model with tubercles. Similar to that study, the present results suggest that tubercles on a real humpback whale flipper (the original model) generates a similar $C_l$ for pre-stall angles of attack and improves $C_l$ for a range of post-stall angles of attack compared with flippers without tubercles (filtered and smoothed models). In addition, a slight decrease of maximum $C_l$ is also noted for the original model. This is similar to observations made on a 2D hydrofoil with idealized tubercles on the leading edge, in which Johari et al. [17] noted a decrease in maximum $C_l$ followed by up to a 50% $C_l$ increase compared to the baseline model without tubercles during the post-stall regime. With respect to the drag coefficient (Fig. 2.19), a similar trend is observed for all three models, which corresponds to observations made by Miklosovic et al. [3] in the idealized airfoil study.

Plotting the hydrodynamic efficiency ($C_l/C_d$) vs. $C_l$ demonstrates the improved hydrodynamic efficiency of an adult humpback whale flipper over that of a flipper model without any leading edge tubercle influence. Figure 2.20 shows the hydrodynamic efficiency at different $C_l$. The backward sweep of data in the hydrodynamic plot is due to the post-stall force production. A green line separates the pre-stall and post-stall regimes. This plot demonstrates improvements for both the original and filtered models in hydrodynamic efficiency through most $C_l$ over the smoothed flipper during the pre-stall regime. Due to the decrease in maximum $C_l$ for the original flipper, the hydrodynamic efficiency at the highest $C_l$ are significantly less than those observed for the filtered
and smoothed models. Because of the additional force generation for the original flipper in the post-stall regime, a greater range of $C_l$ are observed. Even though a larger range of $C_l$ are observed for the original flipper, these $C_l$ are less efficient than comparable lift coefficients of the filtered and smoothed models, perhaps suggesting that the vortices generated by the leading edge of an adult humpback whale flipper may actually decrease the hydrodynamic efficiency at large angles of attack. The original model, therefore, has an improved hydrodynamic efficiency during the pre-stall regime, but a decrease in hydrodynamic efficiency during the post-stall regime. Similar results are observed in the published results of Miklosovic et al. [3], with an idealized airfoil with tubercles demonstrated an increase of $(C_l/C_d)$ over the baseline airfoil without tubercles during the pre-stall regime. Because Miklosovic et al. plotted $(C_l/C_d)$ vs $\alpha$, little information can be determined about the post-stall regime in which the $C_l$ values of the baseline and tubercle model vary significantly. With respect to a humpback whale, if a decrease in efficiency for high $C_l$ at high angles of attack ($\alpha \geq 20^\circ$) was only needed for short periods of time (turning), then this decrease in efficiency may not significantly impact the whale. However, for the pursuit of bio-inspired designs, this decrease in efficiency could have a potential impact and should be further examined.

Although the increase in induced vibration had a significant effect on the filtered and smoothed flipper models, the induced vibration had a minimal effect on force production for the original model with leading edge tubercles. In the case of the more significant vibration (14 Hz), the maximum $C_l$ decreased for the smoothed flipper model, while the original and filtered models maximum $C_l$ varied insignificantly (Fig. 2.21). During the post-stall regime, the smoothed flipper model exhibited an additional decrease in $C_l$. With respect to the additional lift generated by the filtered flipper due to tubercle influence in the post-stall regime, the vibration had a minimal effect. After this initial additional lift generation, the filtered model followed a similar trend as that of the smoothed flipper. The original flipper model force generation was comparatively similar to the previous force results, including the same fluctuations during the post-stall regime. Although induced vibrations are observed to have a negative impact on the $C_l$, the drag coefficients remain relatively unchanged. These results suggest that the leading edge tubercles on the leading edge of
an adult humpback whale flipper may enable it to prevent loss in $C_l$ due to small amplitude vibrations, which is similar to the conclusion of Lau [15], that leading edge tubercles are less sensitive to changes in flow velocity. Nevertheless, further study in this is needed.

To summarize, similar to what has been determined in previous studies with idealized geometry, a real humpback whale flipper geometry produces an increase of $C_l$ during post-stall angles of attack, suggesting that the leading edge tubercles prevent separation by supplying momentum to the boundary layer. Force results presented here demonstrated that the presence of the tubercles can increase the delay in stall, suggesting that larger tubercles enable flow to remain attached at larger angles of attack, as has been shown in the idealized case. The original model yielded improved hydrodynamic efficiency through most pre-stall lift coefficients, but diminished hydrodynamic efficiency during the post-stall regime, even though there existed an increase in lift production compared to the modified flipper models without leading edge tubercles. The filtered model with small leading edge waviness resulted in a similar hydrodynamic efficiency through the pre-stall lift coefficients, but a decrease of $C_l$ during post-stall angles of attack. By comparing the
two different vibration cases, observations indicated that the presence of leading edge tubercles may have reduced the effect of vibrations on $C_l$.

![Figure 2.21: Lift coefficient ($C_l$) vs. angle of attack ($\alpha$), for positive (left) and negative (right) angles of attack, for the three flipper models (original [black], filtered [blue], and smoothed [red]) with a maximum vibration of ±0.8mm.](image)

![Figure 2.22: Drag coefficient ($C_d$) vs. angle of attack ($\alpha$), for positive (left) and negative (right) angles of attack, for the three flipper models (original [black], filtered [blue], and smoothed [red]) with a maximum vibration of ±0.8mm.](image)
2.4.3 Boundary Layer Separation

Oil flow visualization was used to study the developing surface flow characteristics for each flipper model over a range of $\alpha$. Previous flow visualization studies have shown a separation bubble occurring near the leading edge of the airfoil for both airfoils with and without tubercles [6, 12, 13, 16]. After this initial separation, a transition to turbulent flow may result due to an unstable shear layer, which may result in the reattachment of the boundary layer [16]. With respect to airfoils with tubercles, these studies have shown that separation occurs in between tubercles primarily in the distal (tip) region [6, 12, 13, 16, 18, 34]. As the spanwise vortices are formed along the edge of the tubercles, they convect down towards the valleys and create a point of separation (Fig. 2.23) [6].

Although the vortices cause separation in the valleys of the tubercles, this 3D flow formation supplies momentum in the boundary layer on each tubercle, inhibiting separation on the tubercles. Because the tubercles act similar to small delta wings along the leading edge, a spanwise flow is developed in the form of streamwise vortices [6]. The counter rotating vortices along either side of a tubercle (shown in Fig. 2.23) supply momentum in the boundary layer to prevent separation. In addition, a high pressure region is established in the tubercle valleys, resulting in a decrease of momentum to the boundary layer between the tubercles. This decrease in momentum

![Flow](image)

Figure 2.23: Leading edge tubercles act as vortex generators creating alternating vortices in between tubercles. These vortices preserve momentum of the boundary layer at the tubercles and have been recognized as a mechanism to delay flow separation resulting in a delay of stall. Image of vortex generators was acquired from Custodio [6] and used with author’s permission.
can cause earlier separation downstream of the valleys. Airfoils with an idealized sinusoidal leading edge have demonstrated that separation at the trailing edge of airfoils can interact with flow at the leading edge, generating bi-periodic turbulent flow separation patterns [6].

Oil flow visualizations qualitatively show positions of boundary layer development across the different models. Karthikeyan et al. [16] used oil flow visualization at Re = 120,000 to identify complex flow characteristics developing across a 2D airfoil with leading edge tubercles, including laminar separation, flow reattachment, inclined flow from peak to trough, separation bubbles, and flow reversal. The laminar separation resulted from an increase in adverse pressure gradient due to the airfoil curvature. Once the flow had separated, an unsteady shear layer caused the flow to transition to a turbulent flow, which resulted in reattachment to the foil. Continual increase of adverse pressure gradient caused the turbulent flow to separate and the possible formation of flow reversal.

Similarly, this study used oil flow visualization at Re = 370,000 to reveal the complex flow features around the three flipper models. Several key features observed included a stagnation point, flow from peak to trough, attached turbulent flow regions, streamwise separation possibly due to alternating vortices, flow separation, separation bubbles, and flow reversal (Fig. 2.24). Due to the large Re, laminar to turbulent transitional separation and reattachment was not observed in this study, as opposed to results from Karthikeyan et al. [16]. An initial stagnation point is seen along the leading edge just prior the point of maximum thickness. An increase in adverse pressure gradient results in a separation point (solid black line of graphite) along the trailing edge of the flipper resulting in a separation bubble (stagnant graphite) or flow reversal (graphite movement in the opposite direction), labeled in Fig. 2.24.

In addition to the identification of boundary layer development, these oil flow visualizations can be used to identify locations and development of alternating vorticies. As observed by Karthikeyan et al. [16], the development of streamwise vortices result in an inclined flow from the tubercle to the valley (Fig. 2.24). Similarly, the formation of a stagnation point in the tubercle valleys indicate that momentum is being transferred from the valley boundary layer to the boundary layer over the tubercle, also seen in Fig. 2.24.
Figure 2.24: [left to right] Original, filtered, and smooth models at $\alpha = 15^\circ$ (top row) and $20^\circ$ (bottom row). Several primary points of interest are identified including: 1. Stagnation point, 2. Flow from peak to trough, 3. Attached turbulent flow, 4. Streamwise separation possibly due to alternating vortices, 5. Separation point, 6. Separation bubble/flow reversal.
By comparing the oil flow visualization of the original flipper at different $\alpha$, qualitative flow characteristics, including boundary layer separation and the presence of alternating vortices, can be discerned. Figure 2.25 shows oil flow visualization at various angles of attack ($\alpha = 5^\circ$, $10^\circ$, $15^\circ$, $20^\circ$, and $25^\circ$) while Figure 2.26 shows oil flow visualization at the same angles of attack but with the higher vibration case. For low angles of attack, $\alpha = 5^\circ$ and $10^\circ$, flow moved from peaks to troughs, stagnation points were located in between tubercles, and separation was only observed on the trailing edge of the airfoils or at the trailing edge in the proximal region of the flipper (likely resulting from the mounting method). At $\alpha \geq 15^\circ$, additional separation occurred in between tubercles beginning at the tip section of the model.

Compartmentalized distal and trailing edge separation is observed at higher angles of attack for the original model. As $\alpha$ increased the amount of separation occurring along the distal (tip) and trailing edge of the flipper increased (see Figs. 2.25 and 2.26). Trailing edge separation was initially observed at $\alpha = 10^\circ$, while separation at the tip occurred at $\alpha = 15^\circ$. Similar to observations of idealized tubercle flow visualizations, the trailing edge separation was divided by attached flow behind individual tubercles. Low pressure regions over the tubercles formed from alternating vortices supply momentum to the boundary layer and help prevent separation. Areas with a decrease in shear stress are subsequently created between the tubercles resulting in a leading edge stagnation of flow and a decrease in momentum to the boundary layer down stream augmenting the possibility of separation at the valleys. With higher angles of attack, these areas of separation begin to combine into larger areas of separation.

The variation of tubercle amplitude size along the original model’s leading edge appears to correlate with the conglomeration of the divided separation regions observed at high angles of attack. At $\alpha = 15^\circ$, the triangular trailing edge separation between tubercles 4 and 6 combined. Because tubercle 5 is significantly smaller than the surrounding tubercles (4 and 6), it becomes apparent that the size of tubercle might correlate with whether or not these areas of separation will combine. On the other hand, at larger angles of attack ($\alpha = 20^\circ$ and $25^\circ$), the flow appears to have remained attached behind the larger tubercles resulting in the conglomeration of flow separation in
between the larger tubercles. The flow seems to have remained attached behind tubercle 4, one of the larger tubercles at all $\alpha$. At $\alpha = 25^\circ$, the flow separation regions combined above and below the flow behind tubercle 4 creating two primary separation regions (distal and proximal), as shown in Figs. 2.25 and 2.26.

A proposed reason for the flow remaining attached behind larger tubercles is due to the fact that larger tubercles generate an increased vorticity magnitude supplying more momentum to the boundary layer, further delaying separation, while smaller tubercles generate a lesser quantity of vorticity magnitude, supplying less momentum to the boundary layer, which would result in separation at lower angles of attack. By delaying separation at larger $\alpha$, larger $C_l$ would be produced at larger angles of attack for tubercles with larger amplitude. This proposed explanation could correlate with previous research studies in which larger tubercle amplitudes generally generated a larger $C_l$ than smaller amplitude tubercles [13]. For larger angles of attack, large tubercles remain attached to the flow, while smaller tubercles separate due to the generation of comparably smaller vortical structures, supplying less momentum to the boundary layer.

In addition to correlating with the compartmentalization of separation areas, spanwise flow is observed between tubercles of varying size. Spanwise flow is initially observed in the distal direction at the proximal end of the flipper at $\alpha = 5^\circ$. As $\alpha$ increases, the magnitude of this spanwise flow also increases, resulting in graphite being swept toward the distal end (Figs. 2.25 and 2.26). At $\alpha = 25^\circ$, the spanwise flow is sufficient to generate a swirl-like motion at the proximal end behind tubercles 1 and 2. This general spanwise flow appears to be generated by the large amplitude of tubercle 1. For higher angles of attack $\alpha \geq 15^\circ$, spanwise flow appears to be induced by the presence of other tubercles. Tubercle 4 at $\alpha \geq 20^\circ$ seems to generate a spanwise flow toward the base of the model. Spanwise flow has not been previously observed in the placement of idealized tubercles on 2D foils, suggesting that this phenomenon maybe due to the varying amplitudes of tubercles or the general shape of the flipper. One possible explanation for the formation of the observed spanwise flow is that the different tubercle sizes generate vortices of unequal magnitude, directing the flow in a specific region toward the proximal (base) or distal (tip) ends. Further re-
search with respect to the influence of neighboring tubercles with unequal size would be important in order to further understand the development of this spanwise flow.

By comparing the flow visualization between the smaller and larger vibration cases, it appears that vibration has little influence on flow separation for the orginal flipper. Minimal variation was observed between the vibration cases for all tested $\alpha$ with the largest variation observed being an increased area of separation around tubercle 5 at $\alpha = 20^\circ$. Even though this area of separation was slightly larger, in general the original flipper model had similar oil flow results, further supporting the prior conclusion that vibration had a minimal effect on the original model.

Oil flow visualization using the modified models further indicates that the presence of leading edge tubercles are the primary mechanism in delaying stall for the original model. The filtered model demonstrates several similar flow characteristics as both the original and smoothed flipper; see Figs. 2.25 through 2.30. Along the span of the filtered flipper is the presence of small amplitude waviness which seems to perform similar to small amplitude leading edge tubercles in some parts of the flipper. For $\alpha = 15^\circ$, the filtered flipper has less separated surface area when compared to the original and smoothed flipper models, which may be in part due to the leading edge waviness (Figs. 2.27 and 2.28). This decrease in separation could be due to the idea that the smaller vortices generated by leading edge waviness remove less momentum from the valleys minimizing valley separation, while supplying enough momentum from outside the boundary layer to prevent separation. This waviness was shown to delay stall at low angles of attack. At higher angles of attack, $\alpha \geq 20^\circ$, the waviness was unable to supply enough momentum to the boundary layer, causing separation similar to the smoothed flipper (Figs. 2.27 and 2.28).

The comparison of the minimal vibration and significant vibration set indicated that at higher angles of attack, $\alpha \geq 20^\circ$, vibration had an influence on the amount of separation. As the filtered model approached high angles of attack, the resultant force production decreased as the induced vibrations augmented separation. Because of almost no presence of the original leading edge tubercle, the smoothed flipper model was illustrated to be susceptible to separation with and
without induced vibrations. Because of the initial “hump” located at the base of the smoothed profile, a small section of flow remained attached.

Observations of the oil flow visualizations changing with $\alpha$ correlate with the measured force data. Lift across an airfoil is primarily produced by an accelerated flow across the top developing a lower pressure region. The lift produced is proportional to the velocity of the flow across the airfoil and the attached surface area. At $\alpha = 10^\circ$, the flow across all three models was attached along the practical length of the models, resulting in a similar $C_l$ generation. As $\alpha$ increases, the surface area of separation varies for each model. Variations can be seen explicitly at $\alpha = 15^\circ$, where trailing edge separation has begun to occur for the smoothed flipper model. An increased amount of separation is observed for the original flipper between tubercles (due to the vortices removing momentum from this region), while behind the tubercles, the flow remains attached. A decrease in $C_l$ is observed for the original flipper compared to the smoothed flipper, suggesting the momentum exchanged from the valleys to the tubercles is generating an increase of separation between the tubercles which is not being compensated for by attached flow over the tubercles. However, the waviness of the filtered leading edge appears to have reduced the trailing edge separation resulting in an increase in $C_l$ production. For larger angles of attack, $\alpha \geq 20^\circ$, a similar correlation exists between $C_l$ production and area of separation. These observations correlate with previous idealized cases in which it was observed that large amplitude tubercles produced a decrease of maximum $C_l$, but a smaller amplitude tubercle could increase the maximum $C_l$ [3, 6, 13, 14, 17]. Further research is required to better understand the effect of tubercle size on flow separation and force generation. The $C_l$ generation of the smoothed model drops significantly by $\alpha = 20^\circ$, which correlates with the oil flow visualization in which a significant amount of the flow across the model is seen to have separated. Both the filtered and original models have a significantly more attached flow surface area then the smoothed flipper resulting in a higher $C_l$ at $\alpha = 20^\circ$. At $\alpha = 25^\circ$, a significant amount of separation is observed along the filtered flipper, while the original flipper remains attached behind tubercle 4. A corresponding drop in $C_l$ results from this decrease in separation.


2.5 Conclusion

Lift, drag, and hydrodynamic efficiency data of the model of a digitized adult humpback whale flipper were analyzed. Using 18 multi-view images, the first 3D digitized humpback whale flipper model was obtained. This model was modified to create two additional models to further study the influence of leading edge tubercles. Morphological plots demonstrated that the digitized model generated demonstrated comparable geometric characteristics as the flipper studied by Fish and Battle [2]. Similar plots were used to quantitatively compare the geometric transformations of the modified models to the original model. At pre-stall angles of attack, $C_l$ production was comparable between the three models, while the original flipper generated up to 30% more $C_l$ at post-stall angles of attack. A general trend of increasing $C_d$ was observed for all of the flipper cases. Further analysis of these force results demonstrated that the addition of leading edge tubercles enhance the hydrodynamic efficiency through pre-stall $C_l$, while a decrease in hydrodynamic efficiency was observed in the post-stall regime. These force results suggest that an adult humpback whale flipper enables an adult humpback whale to maintain lift at high angles of attack, $\alpha \geq 25^\circ$. Additional force results were obtained with a larger observed vibration. These results demonstrated that leading edge tubercles resist a decrease in force production due to induced vibrations. Using oil flow visualization on the digitized model, the first flow visualization across an actual humpback whale geometry was obtained. The comparison of oil flow visualization for the three flipper models demonstrate that the presence of leading edge geometry has a significant effect on 3D flow development for adult humpback whale flippers.
Figure 2.25: Oil flow visualization images on the original flipper model for (left to right) $\alpha = 5^\circ$, $10^\circ$, $15^\circ$, $20^\circ$, and $25^\circ$.

Figure 2.26: Oil flow visualization images on the original flipper model for (left to right) $\alpha = 5^\circ$, $10^\circ$, $15^\circ$, $20^\circ$, and $25^\circ$ with a maximum vibration of $\pm 0.8\text{mm}$.
Figure 2.27: Oil flow visualization images on the filtered flipper model for (left to right) \( \alpha = 10^\circ, 15^\circ, 20^\circ, \) and \( 25^\circ \).

Figure 2.28: Oil flow visualization images on the filtered flipper model for (left to right) \( \alpha = 10^\circ, 15^\circ, 20^\circ, \) and \( 25^\circ \) with larger observed vibrations.
Figure 2.29: Oil flow visualization images on the smooth flipper model for (left to right) $\alpha = 10^\circ, 15^\circ, 20^\circ, \text{ and } 25^\circ$.

Figure 2.30: Oil flow visualization images on the smooth flipper model for (left to right) $\alpha = 10^\circ, 15^\circ, 20^\circ, \text{ and } 25^\circ$ with larger observed vibrations.
CHAPTER 3.  EFFECT OF FLAPPING FREQUENCY AND LEADING EDGE PRO-
FILE ON AIRFOIL LEADING EDGE VORTICAL STRUCTURES

3.1 Overview

Using the Brigham Young University flapping mechanism, vortical structures were ana-
yzed for two rectangular wings, one with a straight edge and the other with a sinusoidal-varying leading edge, at different flapping frequencies. Changes in the flapping frequency alter the flow around the airfoil. Nondimensional numbers such as the Strouhal number (St) and reduced frequency (k) are used to describe the setup and input parameters influencing the general fluid flow. An increase in flapping frequency resulted in an increase in wing velocity, transforming the previously noted vortical structures seen by Ozen and Rockwell [1]. Quantitative vorticity and velocity data are compared for each of the different cases to document the effect of flapping frequency on these observed vortical structures. Noted trends are included in the analysis.

3.2 Methods

Using a free-surface water tunnel with free stream velocity \(U_\infty\) of 25.4 mm/s, Ozen and Rockwell [1] observed the streamwise vortical structures of a rectangular wing, one with a straight edge and the other with a sinusoidally-varying leading edge. The wing had a mean chord length \(c\) of 50.8 mm, thickness of 1.59 mm and half-span \(b\) of 101.6 mm. For the wing with a sinusoidal leading edge, the leading edge was defined as a sinusoid with \(a/c = 0.098 \) and \(\lambda/c = 0.246\). With a pitching angle of 8° relative to the horizontal free stream velocity, the wing was oscillated at 0.047 Hz in a flapping motion by following a triangular trajectory with a maximum angle of 30°.

By varying the flapping frequency of a similar experimental setup as Ozen and Rockwell [1], the previously observed vortical structures were transformed. Table 3.1 compares the
Table 3.1: Experimental parameters for each flapping frequency \( f \) compared to those used by Ozen and Rockwell [1].

<table>
<thead>
<tr>
<th>Parameters</th>
<th>0.05 Hz</th>
<th>0.075 Hz</th>
<th>0.1 Hz</th>
<th>0.2 Hz</th>
<th>0.047 Hz [1]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free stream velocity ( U_\infty )</td>
<td>23 mm/s</td>
<td>23 mm/s</td>
<td>23 mm/s</td>
<td>23 mm/s</td>
<td>25 mm/s</td>
</tr>
<tr>
<td>Chord length ( c )</td>
<td>50.8 mm</td>
<td>50.8 mm</td>
<td>50.8 mm</td>
<td>50.8 mm</td>
<td>50.8 mm</td>
</tr>
<tr>
<td>Wing length ( R )</td>
<td>101.6 mm</td>
<td>101.6 mm</td>
<td>101.6 mm</td>
<td>101.6 mm</td>
<td>95.25 mm</td>
</tr>
<tr>
<td>Mount length ( p )</td>
<td>25.4 mm</td>
<td>25.4 mm</td>
<td>25.4 mm</td>
<td>25.4 mm</td>
<td>6.35 mm</td>
</tr>
<tr>
<td>Half-span ( b )</td>
<td>127 mm</td>
<td>127 mm</td>
<td>127 mm</td>
<td>127 mm</td>
<td>101.6 mm</td>
</tr>
<tr>
<td>Thickness ( t )</td>
<td>2 mm</td>
<td>2 mm</td>
<td>2 mm</td>
<td>2 mm</td>
<td>1.59 mm</td>
</tr>
<tr>
<td>Sinusoidal amplitude ( a/c )</td>
<td>0.98 mm</td>
<td>0.98 mm</td>
<td>0.98 mm</td>
<td>0.98 mm</td>
<td>0.98 mm</td>
</tr>
<tr>
<td>Sinusoidal wavelength ( a/c )</td>
<td>0.246 mm</td>
<td>0.246 mm</td>
<td>0.246 mm</td>
<td>0.246 mm</td>
<td>0.246 mm</td>
</tr>
<tr>
<td>Max sweep ( A_\phi )</td>
<td>30°</td>
<td>30°</td>
<td>30°</td>
<td>30°</td>
<td>30°</td>
</tr>
</tbody>
</table>

variations in parameters for the different flapping frequency cases and the parameters used by Ozen and Rockwell [1]. A flapping frequency of \( f = 0.05 \) Hz is the most comparable set to those parameters conducted by Ozen and Rockwell [1]. Even though the tested variations of the leading edge are comparable, the free stream velocity, half-span, and flapping frequency deviated slightly from the original study by Ozen and Rockwell [1].

### 3.2.1 Water Tunnel

The following experiments were performed in a free-surface water tunnel, simulating a slow forward trajectory. The cross section at the test location was about 0.95 m wide and 0.46 m deep. To reduce flow disturbances, an entrance diffuser, entrance honey comb, exit honey comb, and exit guides were installed; see Fig. 3.1. The entrance diffuser was comprised of an inlet guide to more evenly distribute the flow and a gravel structure to breakup large vortical structures (Fig. 3.1). After these slight modifications, PIV measurements were acquired at six different chordwise locations spaced from the centerline in the region of interest to determine the mean free stream velocity \( U_\infty = 23 \pm 3 \) mm/s and the maximum turbulence intensity level \((\leq 3\%)\) in the area of interest (see Appendix F). The flapping mechanism was placed in the middle of the measured volume, about 0.41 m from the upstream honey comb and about 0.61 m from the downstream honey comb.
3.2.2 Flapping Mechanism

The flapping mechanism previously developed at Brigham Young University [35], pictured in Fig. 3.2, was used to perform the flapping kinematics. Motors connected to three shafts drove each wing with three independent rotational degrees of freedom (pitch, sweep, and deviation). A surface coating of black oxide was applied to the shafts and drive box, and the wing mount was black anodized in order to minimize the reflection properties for improved PIV results.

Two wing planforms, one with a straight and the other with a sinusoidal leading edge (see Fig. 3.3), were separately used. Each had a mean chord length of $c = 50.8$ mm, a wing length of $R = 101.6$ mm, and were 2 mm thick, which differed slightly from Ozen and Rockwell; see Table 3.1. The wing mount was 25.4 mm long, yielding a half-span of $b = 127$ mm. The leading edge sinusoids featured an amplitude of $a/c = 0.1$ and wavelength of $\lambda/c = 0.025$, comparable with those of Ozen and Rockwell [1], as seen in Fig. 3.3.

3.2.3 Wing Kinematics

The kinematic description of the flapping motion is similar to that of [10], as shown in Fig. 3.4 with the flow in the negative $x$-direction. In this description, $\phi$ denotes sweep motion, $\beta$
Figure 3.2: Flapping mechanism used for performing flapping kinematics with three independent rotational degrees of freedom including (pitch, sweep, and deviation).

Figure 3.3: Wing planform designs demonstrating the straight and sinusoidal leading edges, in addition to the location of the laser sheet and direction of the PIV camera view (illustration courtesy Keenan Eves).

denotes stroke plane deviation, and \( \psi \) is the stroke plane angle relative to the vertical. The pitch angle of the wing, \( \theta \) (not shown in Fig. 3.4), is referenced from the current stroke plane angle, \( \psi \). The stroke plane deviation (\( \beta \)) and the stroke plane angle (\( \psi \)) values were set to zero, resulting in

52
a simple vertical flapping motion with a constant pitch angle. The vertical sweeping motion, $\phi$, was determined by a rounded triangular input, as calculated by Equation (3.1), while the pitching remained constant at $\theta = 8^\circ$, as illustrated in Fig. 3.5. A rounded triangular input was used to reduce wear on the mechanism hardware, even though Ozen and Rockwell [1] used a triangular input without the rounding at wing reversal.

$$\phi = \frac{30^\circ}{\sin^{-1}(0.8221)} \sin^{-1}(0.8221 \sin(2\pi ft))$$

The PID gains were tuned to yield adequate tracking between prescribed position and actual encoder values throughout the stroke. Fig. 3.5 illustrates the overlay of motor positions to encoder values for one complete period ($T$). The generated sweep trajectory was a rounded triangular input in which the motors followed the prescribed input command satisfactory.
Figure 3.5: Wing sweep ($\phi$), stroke plane deviation ($\beta$), and pitch angle ($\theta$) trajectories for both prescribed encoder values and actual motor position over one flapping cycle.

During this experiment the flapping frequency was varied in order to understand how this parameter affects the vortical structures. As previously described, the sweep kinematics, as calculated by Equation (3.1), were dependent on the flapping frequency, which included discrete values of $f = 0.2$ Hz, 0.1 Hz, 0.075 Hz, and 0.05 Hz. Because the wing tip velocity, $V_t$, and effective angle of attack ($\alpha_e$) of the wing are dependent on the flapping frequency, these were calculated for each flapping frequency according to Equations (3.2) and (3.3) used by Ozen et al., where $\alpha = 8^\circ$ (the static angle of attack) and $U_\infty$ is the free stream velocity. The calculated values are presented in Table 3.2.

\[
V_t = 2\pi\phi_{\text{max}} f
\]

\[
\alpha_e = \alpha_0 + \tan^{-1}\left(\frac{V_t}{U_\infty}\right)
\]

Variations in flapping frequency influenced the period but not the trajectory waveform of wing kinematics. By changing the flapping frequency, the non-dimensional numbers which described flow characteristics were altered. Table 3.2 presents these non-dimensional parameters for each flapping frequency and compares these parameters with those established by Ozen and Rockwell.
Table 3.2: Experimental nondimensional parameters compared to those used by Ozen and Rockwell [1].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>0.05 Hz</th>
<th>0.075 Hz</th>
<th>0.1 Hz</th>
<th>0.2 Hz</th>
<th>0.047 Hz [1]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flapping frequency ($f$)</td>
<td>0.05 Hz</td>
<td>0.075 Hz</td>
<td>0.1 Hz</td>
<td>0.2 Hz</td>
<td>0.047 Hz [1]</td>
</tr>
<tr>
<td>Tangential tip velocity ($V_t$)</td>
<td>13.3 mm/s</td>
<td>19.9 mm/s</td>
<td>26.6 mm/s</td>
<td>53.2 mm/s</td>
<td>10.6 mm/s</td>
</tr>
<tr>
<td>Effective angle of attack ($\alpha_e$)</td>
<td>38.0°</td>
<td>48.9°</td>
<td>57.1°</td>
<td>74.6°</td>
<td>30.7°</td>
</tr>
<tr>
<td>Reynolds number (Re)</td>
<td>1170</td>
<td>1170</td>
<td>1170</td>
<td>1170</td>
<td>1300</td>
</tr>
<tr>
<td>Strouhal number (St)</td>
<td>0.29</td>
<td>0.43</td>
<td>0.69</td>
<td>1.38</td>
<td>0.22</td>
</tr>
<tr>
<td>Reduced frequency ($k$)</td>
<td>0.35</td>
<td>0.52</td>
<td>0.58</td>
<td>1.15</td>
<td>0.22</td>
</tr>
</tbody>
</table>

[1]. As the flapping frequency increased from 0.05 Hz to 0.2 Hz, the Strouhal number (St) and reduced frequency ($k$) also increased from 0.29 and 0.35 to 1.38 and 1.15, respectively.

3.2.4 PIV Acquisition

Quantitative cross-flow velocity and vorticity measurements were acquired using a LaVision particle image velocimetry (PIV) system. The flow was seeded with 11 µm diameter hollow glass spheres (Potter Industries Inc., Sphericel 110P8). The LaVision PIV system included a double-pulsed Nd:YAG laser (532 nm) which generated an approximately 1.5 mm thick sheet across the wing as illustrated in Figs. 3.3 and 3.7. A mirror was placed approximately 0.46 m downstream in order to reflect the spanwise image up to the mounted PIV camera; see Fig. 3.7. The PIV camera (LaVision, VC-Imager Intense, 1376×1040) was mounted with a Nikkor 105 mm lens. To synchronize the PIV system with the flapping mechanism, a TTL trigger was sent from the PIV system to the flapping mechanism to determine when to acquire images. The time delay between the camera images was changed depending on the flapping frequency and adjusted such that the mean pixel movement was between about 6 to 10 pixels in selected areas of interest (see Appendix G for tabulated values). The PIV measurements were computed using multi-pass cross-correlation with a decreasing window size from 64 × 64 pixels to 16 × 16 pixels with 50% overlap. Using ensemble phase averaging of 35 images, vorticity and velocity plots were generated. Spurious vectors of magnitude 1.2 times the RMS of the eight neighboring velocities were eliminated and replaced with the next highest correlation peak which met this criteria. Subsequently, the vor-
Vorticity (ω) was calculated as the curl of the resulting velocity. As the PIV camera images through the water surface, the images were manually sorted to eliminate free surface effects. For each of the cases described above, vorticity and y-direction velocity scalar plots and velocity vector plots are presented and compared (see Appendix A for the uncertainty analysis).

Two sets of PIV data were acquired to characterize the influence of flapping frequency on the observed streamwise vortical structures. Set 1 focused on identifying the primary differences of vortical structures between a straight and sinusoidal leading edge at different flow domains. PIV images were acquired for each flapping frequency and wing at a phase angle of 13.3°, as was initially investigated by Ozen and Rockwell [1]. A follow-up study (Set 2) was conducted with the sinusoidal leading edge profile to track the development of streamwise vortices throughout different phase angles. For flapping frequencies $f = 0.2$ Hz, $0.1$ Hz, $0.075$ Hz, and $0.05$ Hz, images were acquired at phase angles of $28^\circ$, $23^\circ$, $18^\circ$, and $13^\circ$. An additional two phase angles, $25^\circ$ and $20^\circ$, were explored for $f = 0.075$ Hz and $0.1$ Hz.
3.3 Results

3.3.1 PIV Results Set 1

The streamwise vortical structures generated by both sinusoidal leading edge and straight leading edge were documented at different flapping frequencies. At low flapping frequency \((f = 0.05 \text{ Hz})\) for a wing with a sinusoidal leading edge, a repetitive pattern of small scale alternating vortices were observed in the vicinity of the sinusoidal leading edge, as illustrated in Fig. 3.8, similar to observations made by Ozen and Rockwell [1]. Because the half-spans differ between this investigation and Ozen and Rockwell, the first three vortices (from right to left side) along the wing of this current study correlate to the last three vortices (excluding the tip vortex from tip to left side) from Ozen and Rockwell [1]. The non-dimensional vorticity magnitude and size of these vortices appear to be comparable, even though there are slight discrepancies in the setup. By examining the development of these streamwise vortices of this current study along the tip, it appears that the vortices close to the wing tip begin to stretch upward due to the increased wing velocity (cross-radial velocity) near the tip. The cross-radial velocity is the resulting velocity from sweeping motion of the wing. Another possible explanation is that the change in vorticity may be
Figure 3.8: (left) Vorticity plot of a rectangular wing with a sinusoidal leading edge for $f = 0.05$ Hz and $\phi = 13.3^\circ$. The gray lines illustrate the position of the wing. (right-above) Basic schematic of the setup used by Ozen and Rockwell [1]. (right-bottom) Vorticity plot from Ozen and Rockwell [1] of a rectangular wing with a sinusoidal leading edge. Freestream flow is out of the page for both vorticity plots. Reprinted with permission from Ozen, C. A., and D. Rockwell. "Control of vortical structures on a flapping wing via a sinusoidal leading-edge." Physics of Fluids (1994-present) 22.2 (2010): 021701. Copyright 2010, AIP Publishing LLC.

caused by a higher frequency vortex shedding, as opposed to attached vortices at lower frequencies. Further investigation would be required to better understand this development of the flow field. The previously described streamwise vortices appear to have a similar structure as the vortices observed by Custodio [6] at the leading edge of a stationary 2D airfoil with idealized tubercles at $Re \approx 1500$. As the flow passed on either side of the sinusoidal peaks, alternating vortices were developed (Fig. 3.8). The vortices observed at this lower frequency corresponds to the respective locations of sinusoidal peaks along the leading edge of the wing.

With respect to a straight leading edge, a comparable vortex formation was observed in this study as reported by Ozen and Rockwell [1]. The plots of vorticity indicate the development of a spanwise flow (see Fig. 3.9). A positive and negative vortex is identified indicating the development of spanwise flow. Although the magnitude of vorticity is fairly similar for a sinusoidal leading edge between the current study and the reported data by Ozen and Rockwell [1], the vorticity magnitude of this study is significantly greater for a straight leading edge, potentially resulting in a much greater spanwise velocity (Fig. 3.9). A possible reason for this dramatic increase in spanwise flow is the increase of half-span length, although further investigation would be needed to determine influence of wing length to spanwise flow.
As the flapping frequency increases, the cross-radial wing velocity appears to influence the development of the observed streamwise vortices. With respect to a straight leading edge at \( f = 0.05 \) Hz and \( 0.075 \) Hz (Figs. 3.10b and 3.10d), spanwise flow generates opposing vortices near the tip, as identified in Fig. 3.9. As the flapping frequency increases beyond \( f = 0.05 \) Hz, the cross-radial velocity appears to contribute to the dissipation of this jet, resulting in a decrease of spanwise velocity, while an increase in vorticity near the center of the wing is also observed (Fig. 3.10b, 3.10d, and 3.10f and 3.12b, 3.12d, and 3.12f). At \( f = 0.2 \) Hz, the vorticities become significantly larger, resulting in a much larger spanwise flow (Figs. 3.10h and 3.12h). The magnitude of vorticity for the sinusoidal leading edge wing seemed to increase with increasing flapping frequency (Fig. 3.10 a, c, e, and g and Fig. 3.11). This increase in magnitude could potentially result from an increase of flow past the sinusoidal peaks from the increase in cross-radial velocity. Although an increase in vorticity magnitude was observed due to the cross-radial velocity, the vorticity is stretched tangential to the wing (Fig. 3.10a, 3.10c, 3.10e, and 3.10g and Fig. 3.11). Contrary to the straight leading edge, the spanwise flow increases with flapping frequency (Fig. 3.11). At \( f \geq 0.15 \) Hz (Fig. 3.11i) the alternating vorticities begin to break down near the tip.
As the wing velocity continues to increase with flapping frequency, instabilities develop around the perimeter of the vortices. For higher frequencies such as \( f = 0.2 \), these instabilities cause the streamwise vortices to break down into smaller vortices. The observed instabilities appear to develop due to a velocity shear in a continuous fluid and seem to transition the flow towards turbulence. Observations of this shearing of vortices can be seen in Figs. 3.10e, 3.10f, 3.10g, and 3.10h and 3.11e as waviness on the edges of the streamwise vortices. The waviness increases with flapping frequency \( f \), as would be expected due to an increased flapping frequencies produced increased velocity shear which would cause the instabilities to grow. At \( f = 0.2 \), the ordered pattern of alternating vortices has broken down between the peaks, but several large alternating vortices are observed in place of the usual pattern (Figs. 3.10g and 3.11e). Initial observations indicate that with the increase of flow velocity, Rayleigh instabilities have broken down the individual vortices at the peaks and generated these large alternating vortices. An evaluation of the calculated RMS shows that at higher flapping frequencies, the presence of Rayleigh instabilities plays an increased role in the disruption of vortices (Appendix H).

Even though the streamwise vortical structure varies with flapping frequency, an increase in flapping frequency had a limited effect on the passive spanwise control. With a straight leading edge, a \( y \)-direction (spanwise) flow is observed towards the tip at all frequencies tested. Contrary to the straight leading edge, the sinusoidal leading edge results in an observed decrease in \( y \)-direction velocity (Figs. 3.12, 3.13, and 3.11). A decrease in spanwise flow is observed at \( f = 0.1 \) Hz, due the relatively large wing velocity (cross-radial velocity), but by \( f = 0.2 \) Hz the spanwise flow has increased in magnitude. Even though a decrease of spanwise flow is observed as a general trend, at flapping frequencies of \( f = 0.15 \) Hz and 0.2 Hz, a significant spanwise velocity component is observed in the locations without the presence of alternating vortices. Thus, this pattern of alternating vortices appears to minimize spanwise flow even with the presence of instabilities. But, once the pattern of alternating vortices completely breaks down, spanwise flow consequently increases.
Figure 3.10: Vorticity plots for straight (left) and sinusoidal (right) leading edge profiles at phase angle $\phi = 13.3^\circ$. 
Figure 3.11: Vorticity (left) and y-direction scalar velocity (right) plots for the sinusoidal leading edge at phase angle $\phi = 13.3^\circ$. This set includes $f = 0.15$, illustrating the transition from a more uniform pattern of lower flapping frequencies to the disordered nature at higher frequencies.
Figure 3.12: $y$-direction component of velocity for straight (left) and sinusoidal (right) leading edge profiles at phase angle $\phi = 13.3^\circ$. 
Figure 3.13: Velocity vectors for straight (left) and sinusoidal (right) leading edge profiles at phase angle $\phi = 13.3^\circ$. 
Figure 3.14: Velocity vectors for a sinusoidal leading edge at phase angle $\phi = 13.3^\circ$. This set includes $f = 0.15$, illustrating the transition from a more uniform pattern of lower flapping frequencies to the disordered nature at higher frequencies.
3.3.2 PIV Results Set 2

By evaluating the flow field at different sweep angles, the development of the flow field was evaluated for the sinusoidal leading edge at various flapping frequencies. Plots of vorticity, y component of velocity, and velocity magnitude are presented to document the development of streamwise vortices from the top of the down stroke, $\phi = 30^\circ$, down to the angle observed by Ozen and Rockwell [1], $\phi = 13.3^\circ$ (Figs. 3.15 to 3.23). At $\phi = 28^\circ$, alternating streamwise vortices are present along the leading edge for every flapping frequency. As the stroke progresses, these alternating vortices begin to shed or stretch at the higher flapping frequencies. The presence of instabilities at the perimeter contributes to this break down of vortices due to the formation of a velocity shear from the increase in cross-radial velocity. RMS plots are included in Appendix H, demonstrating little variation within the ensemble averages for all frequencies except $f = 0.1$ Hz and 0.2 Hz, at which point the increase in variation is observed on the periphery of the vortices, further suggesting the presence of instabilities at the perimeter.

The development of these streamwise vortices seems to be independent of flapping flight frequency, even though the interactions of the shed vortices vary significantly. Figs. 3.15, 3.16 and 3.21 show that the leading edge alternating vortex structures are stretched or shed at similar phase angles along the flap. Although vortices appear to be shed or stretched at similar locations, because of the different vorticity magnitude and tangential flow velocity, the vortices interact differently at increasing flapping frequency. At $f = 0.05$ Hz, the vortices shed have a smaller influence on the attached vortices (e.g. from $\phi = 18^\circ$ to $\phi = 13^\circ$), while at a larger flapping frequency, $f = 0.1$ Hz, the shed vortices near the tip interfere with the development of the alternating vortices along the wing resulting in a decrease in vorticity along the wing. For a flapping frequency of $f = 0.2$ Hz, a pattern of alternating vortices is initially developed along the wing, but due to a substantial tip vortex and cross radial (tangential) velocity, this pattern is quickly diminished.

As the pattern of alternating vortices along the wing dissipates for higher flapping frequencies, the spanwise component of velocity increases (Figs. 3.18, 3.20, 3.22, and 3.23). For $f = 0.02$ Hz, minimal spanwise flow is present with the existence of alternating vortices ($\alpha = 28^\circ$). Once
the flow around these vortices causes them to break up, a significant spanwise flow is present (as shown in Fig. 3.18) even though this spanwise flow diminishes at $\alpha = 13.3^\circ$. On the other hand, at lower frequencies, $f = 0.1$ Hz and $0.075$ Hz, spanwise flow is only present in the wing tip region once the alternating vortices have separated from the wing at about $\alpha = 13.3^\circ$. The spanwise flow present at these lower velocities is significantly less. For $f = 0.05$ Hz, significant spanwise flow is not present.

### 3.4 Conclusion

By comparing two wing profiles, one with a straight and one with a sinusoidal leading edge, at different flapping frequencies, the development of passive flow phenomena were further investigated. A sinusoidal leading edge can be used to minimize spanwise flow by the generation of alternating streamwise vortices. At larger flapping frequencies ($f \geq 0.2$Hz), the tangential wing velocity breaks down the alternating vortices. Because of the breakdown in alternating vortical structures, spanwise flow is present, although slightly less than the sinusoidal leading edge. Even though the alternating vortices begin to separate from the wing for mid-range flapping frequencies, $f = 0.1$ and $0.075$ Hz, the spanwise flow is almost insignificant. Observations on the development of the alternating vortices indicate a shedding of vorticity for all the flapping frequencies examined at roughly the same phase angle.
Figure 3.15: Vorticity plots for a sinusoidal leading edge at flapping frequencies, $f = 0.05$ Hz (left) and $0.075$ Hz (right) and phase angles $\phi = 28^\circ, 23^\circ, 18^\circ, \text{and } 13.3^\circ$. 
Figure 3.16: Vorticity plots for a sinusoidal leading edge at flapping frequencies, $f = 0.1$ Hz (left) and $0.2$ Hz (right) and phase angles $\phi = 28^\circ, 23^\circ, 18^\circ, \text{and } 13.3^\circ$. 
Figure 3.17: y-direction component of velocity for a sinusoidal leading edge at flapping frequencies, $f = 0.05$ Hz (left) and 0.075 Hz (right) and phase angles $\phi = 28^\circ, 23^\circ, 18^\circ, \text{and } 13.3^\circ$. 

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Figure 3.18: \( y \)-direction component of velocity for a sinusoidal leading edge at flapping frequencies, \( f = 0.1 \) Hz (left) and 0.2 Hz (right) and phase angles \( \phi = 28^\circ, 23^\circ, 18^\circ, \) and \( 13.3^\circ \).
Figure 3.19: Velocity vectors for a sinusoidal leading edge at flapping frequencies, $f = 0.05$ Hz (left) and 0.075 Hz (right) and phase angles $\phi = 28^\circ, 23^\circ, 18^\circ,$ and $13.3^\circ$. 
Figure 3.20: Velocity vectors for a sinusoidal leading edge at flapping frequencies, $f = 0.1$ Hz (left) and 0.2 Hz (right) and phase angles $\phi = 28^\circ, 23^\circ, 18^\circ, \text{ and } 13.3^\circ$. 
Figure 3.21: Vorticity plots for a sinusoidal leading edge at flapping frequencies, 0.1 Hz (right) and 0.075 Hz (left) and phase angles $\phi = 28^\circ$, $25^\circ$, $23^\circ$, $20^\circ$, $18^\circ$, and $13.3^\circ$. 
Figure 3.22: $y$-direction component of velocity for a sinusoidal leading edge at flapping frequencies, 0.1 Hz (right) and 0.075 Hz (left), and phase angles $\phi = 28^\circ$, $25^\circ$, $23^\circ$, $20^\circ$, $18^\circ$, and $13.3^\circ$. 

- $f = 0.075$ Hz
- $f = 0.100$ Hz
- $\phi = 28^\circ$, $25^\circ$, $23^\circ$, $20^\circ$, $18^\circ$, and $13.3^\circ$.
Figure 3.23: Velocity vectors for a sinusoidal leading edge at flapping frequencies, 0.1 Hz (right) and 0.075 Hz (left), and phase angles $\phi = 28^\circ, 25^\circ, 23^\circ, 20^\circ, 18^\circ, \text{and } 13.3^\circ$. 
CHAPTER 4. CONCLUSION

Force production and flow characteristics resulting from vortices generated on different leading edge profiles were examined in their respective flow regimes. The first profile examined was an adult humpback whale flipper which generates a streamwise vortex on either side of the leading edge tubercles. Previous studies have shown that sinusoidal tubercles located on idealized airfoil models and 2D airfoil sections can improve force generation characteristics for a wing by delaying separation resulting in an increase of $C_l$ production at post-stall angles of attack. Using the first generated 3D model of an adult humpback whale flipper, this study presented the first data set of force production and flow characteristics across the real geometry. The second mechanism investigated was the effect of a sinusoidal leading edge of a flat flapping wing. The development of spanwise flow and streamwise vorticity was studied for various flapping frequencies at a single spanwise location using particle image velocimetry (PIV).

4.1 Hydrodynamics of a Digitized Adult Humpback Whale Flipper (Chapter 2)

4.1.1 Conclusions and Contributions

The first 3D digitized adult humpback whale flipper model was generated by reconstructing a series of 2D images. Using a commercial 3D reconstruction software, 18 multi-view 2D images were digitized into a 3D mesh. Connective tissue was digitally cropped near the proximal end, and holes, including those at the underside of the tip, were filled to complete the 3D model. Additional smoothing and straightening techniques were used to refine the flipper for subsequent fabrication and testing. Two complementary models with smooth leading edges were generated from this original model to study the impact of leading edge tubercles on the flipper hydrodynamics.
To validate the original flipper model reconstruction, geometric data was compared with
reported data from a flipper studied by [2]. Strong similarities were observed in the chord length,
maximum thickness and position of maximum thickness for 71 cross sections along the length
with a previously sectioned and measured flipper. Both sets of data showed a decrease of max-
imum thickness along the span of the flipper, as would be expected for a wing-like appendage.
This maximum thickness was measured as approximately 23% of the cross section chord length.
The position of maximum thickness was shown to be a function of leading edge tubercles, also
previously observed by [2]. By normalizing the position of maximum thickness by the individ-
ual chord lengths, geometric data from the original model demonstrated a fairly consistent airfoil
cross section along the length, transitioning to a slightly elliptical cross section near the distal end.
Although a discrepancy existed in this correlation for the three cross sections closest to the tip, on
the whole, the cross sections of the original model and the data from [2] showed a similar basic
shape.

The same geometric parameters were used to quantitatively compare the original model
with the two modified models. The two transformed models included a model with a wavy leading
edge (filtered model) and a model with a smooth leading edge (smoothed model). The filtered
model was shown to have a wavy leading edge with similarly reported maximum thickness and
position of maximum thickness over the half-span as reported by the original model, while the
smoothed model had a smoother leading edge resulting in a more “traditional” airfoil shape. Even
though the smoothed model showed similar geometric characteristics as the original and filtered
models, the mean position of maximum thickness increased, while for the local maximum thick-
ness a decrease was observed for cross sections 15 to 30 relative to the other two models. Calcu-
lations of the mean chord length, planform area, and volume further verified that the models were
comparable.

The coefficients of lift ($C_l$) and drag ($C_d$) were computed for each of the models and used to
calculate the hydrodynamic efficiency. The original model with leading edge tubercles was shown
to have a decrease in maximum $C_l$ compared to the maximum $C_l$ for the other two models. The fil-
tered and smoothed model began to stall at $\alpha = 17^\circ$, while the original model with tubercles did not begin to stall in a similar manner. During the post-stall regime, the original model demonstrated an increase of $C_l$ up to 30% over the other two models. The original model slowly decreased $C_l$ production in the post-stall regime. At high angles of attack ($\alpha \geq 36^\circ$), a similar $C_l$ is measured for all three models. Comparable $C_d$ was reported for all three cases. These force results are comparable with previously published studies on idealized airfoils with idealized tubercles [3, 6, 14, 17].

Further analysis of these force results was performed by comparing the hydrodynamic efficiency ($C_l/C_d$). The original and filtered models had a larger hydrodynamic efficiency through most pre-stall lift coefficients. Even though larger $C_l$ were observed during the post-stall regime for the original flipper, the hydrodynamic efficiency was less in this range than that of the other two models. These force results suggest that an adult humpback whale flipper allows for an increase of hydrodynamic efficiency at low angles of attack, while maintaining increased lift at high angles of attack, $\alpha \geq 25^\circ$. With respect to a humpback whale, if a decrease in efficiency for high $C_l$ at high angles of attack ($\alpha \geq 20^\circ$) was only needed for short periods of time (e.g., during turning), then this decrease in efficiency may not significantly impact the whale. However, for the pursuit of bio-inspired designs, this decrease in efficiency could have a potential impact and should be further examined.

The additional force results obtained with a larger observed vibration in the flipper demonstrated that leading edge tubercles may better resist alteration in force production due to vibrations of the flow. The smoothed model resulted in the largest decrease of $C_l$ with an increase in vibration, while the filtered model did not demonstrate a decrease in $C_l$ until after the post-stall region. The original flipper model force generation was comparatively similar to the previous force results, including the same fluctuations during the post-stall regime. These results suggest that the tubercles on the leading edge of an adult humpback whale flipper may enable it to prevent loss in $C_l$ due to small amplitude vibrations, which is similar to the conclusion of Lau [15], that leading edge tubercles are less sensitive to changes in flow velocity.
Oil flow visualization was used to study the developing surface flow characteristics for each flipper model over a range of angles of attack. Similar to previously reported studies with sinusoidal tubercles on idealized geometry, the formation of streamwise vortices contributed to the momentum of the boundary layer over the leading edge tubercles. These streamwise vortices generated low pressure regions over the tubercles shown by the lack of graphite residue, and high pressure regions in the valleys identified by stagnant graphite. At $\alpha = 15^\circ$, the reduced momentum boundary layer region between tubercles resulted in an early onset of trailing edge separation correlating with a slight decrease in maximum $C_l$ production for the original flipper. While larger angles of attack, such as $\alpha \geq 20^\circ$, the attached flow behind the leading edge tubercles leads to the segregation of the trailing edge separation, resulting in a larger $C_l$ production. The comparison of oil flow visualization for the three flipper models demonstrate that the presence of leading edge geometry has a significant effect on 3D flow development for adult humpback whale flippers.

4.1.2 Future Work

1. Evaluate the effect of individual leading edge tubercle amplitude on delay of separation across an entire adult flipper model

2. Obtain quantitative velocity data of flow across the original model using 3D PIV in order to evaluate whole-field flow characteristics

3. Evaluate the effect of leading edge tubercle flexibility on delaying separation and vortical formation

4. Evaluate the lift profile and the effect of variable airfoil cross-section on lift profile

5. Perform methodical, quantitative analysis of the effect of leading edge tubercles on reducing vibration effects
4.2 Effect of Flapping Frequency and Leading Edge Profile on Airfoil Leading Edge Vortical Structures (Chapter 3)

4.2.1 Conclusions

By comparing two wing profiles, one with a straight and the other with a sinusoidal leading edge, at different flapping frequencies, the development of passive control devices were further investigated. At a flapping frequency of $f = 0.05$ Hz, a similar vortical formation is observed for both a straight and sinusoidal leading edge as previously reported by [1]. A sinusoidal leading edge can be used to minimize spanwise flow by the generation of alternating streamwise vortices, but as flapping frequency increases these streamwise vortices are shed or stretched in the trailing path of the wing. Even after being elongated or shed, these streamwise vortices minimize spanwise flow, until they begin to break down due to instabilities about the vortices’ perimeters as seen at $f \geq 0.1$ Hz. The peripheral instabilities are formed due to the presence of a velocity shear generated by the increase in flapping frequency and resulting cross-radial velocity.

An inspection of different phase angles indicates that alternating streamwise vortices result in a decrease of spanwise flow at different stroke angles. The development of alternating vortices are observed at $\phi = 28^\circ$. As the stroke progresses, separation between the wing and these alternating vortices are observed near the tip at flapping frequencies greater than $f = 0.05$ Hz. In addition, the generated vortices begin to break down at the periphery at a flapping frequency of $f = 0.2$ Hz due to peripheral instabilities resulting velocity shearing. Except for $f = 0.2$ Hz, spanwise flow is minimized at different flapping frequencies even with the vortices being separated from the wing.

4.2.2 Future Work

1. Quantify the effect of half-span length on spanwise flow features, including streamwise vortices
2. Determine the effects of $St$ and $k$ on streamwise vortex development
3. Evaluate the development of alternating vortices during a complete stroke (up and down)
4. Acquire force data to determine the overall effect of these streamwise vortices on lift and drag production
REFERENCES


APPENDIX A. UNCERTAINTY ANALYSIS

A.1 Humpback Whale Flipper

A.1.1 Vibration Analysis

The vibration of the different load cell mounts were evaluated by measuring flipper movements in images collected by a high speed Photon camera. These images were calibrated prior to acquisition using a 10 mm × 10 mm checkerboard pattern calibration grid with a checkerboard pattern. Due to the camera not being located directly over the airfoil section, perspective errors were introduced into the calibration, these errors have been calculated and accounted for in the uncertainty analysis below:

Calculation of Perspective Error:

In order to calculate the error due to perspective, four pixels were selected near the corners of the images. X and Y lengths were calculated between each point and variation in both directions were compared to approximate the overall perspective error.

X-Direction:

\[
U_{px} = \max((X(2) - X(1))/d_x(12), ((X(4) - X(3))/d_x(43)))
\]

\[
U_{px} = \max(0.145, 0.132)
\]

\[
U_{px} = 0.145 \, \delta \text{pixel/pixel}
\] (A.1)
X-Direction (load cell mount with larger observed vibrations):

\[
U_{pxv} = \max((X_v(2) - X_v(1))/d_{xv}(12)), ((X_v(4) - X_v(3))/d_{xv}(43))
\]

\[U_{pxv} = \max(0.07919), (0.0817)\]

\[U_{pxv} = 0.0817 \delta \text{ pixel/pixel}\]  

(A.2)

Y-Direction:

\[
U_{py} = \max((Y(2) - Y(1))/d_y(12)), ((Y(4) - Y(3))/d_y(43))
\]

\[U_{py} = \max(0.0749), (0.0741)\]

\[U_{py} = 0.0749 \delta \text{ pixel/pixel}\]  

(A.3)

Y-Direction (load cell mount with larger observed vibrations):

\[
U_{pyv} = \max((Y_v(2) - Y_v(1))/d_{yv}(12)), ((Y_v(4) - Y_v(3))/d_{yv}(43))
\]

\[U_{pyv} = \max(0.00528), (0.00542)\]

\[U_{pyv} = 0.0054 \delta \text{ pixel/pixel}\]  

(A.4)

Where \(X()\) and \(Y()\) are the respective pixels \(x\) and \(y\)-locations, \(d_x()\) and \(d_y()\) are the distances between the respective pixels in the \(x\) and \(y\)-directions, and \(U_{px}\) and \(U_{py}\) are the uncertainties due to perspective error in the \(x\) and \(y\)-directions for both the load cell with smaller vibration. A subscript \(v\) is used to indicate the load cell with larger observed vibrations.

**Calculation of Pixel Approximation Error**

The flipper movement was calculated by finding the equivalent distance of each pixel. This was evaluated by finding the \(X\) and \(Y\) distances between the previously selected 4 points and dividing the number of calibration squares between the points in both directions by this distance. The associated uncertainty with pixel approximation was \(1/2\) the minimal step size (distance of each pixel).
X-Direction:
\[ \Delta x = \max\left(\frac{d_x(21)}{N_x}, \frac{d_x(43)}{N_x}\right) \]
\[ \Delta x = \max(0.2355, 0.2052) \]
\[ \Delta x = 0.2355 \text{ mm/pixel} \quad \text{(A.5)} \]
\[ U_{ax} = \frac{\Delta x}{2} \]
\[ U_{ax} = 0.118 \text{ mm/pixel} \]

X-Direction (load cell mount with larger observed vibrations):
\[ \Delta x_v = \max\left(\frac{d_{xv}(21)}{N_{xv}}, \frac{d_{xv}(43)}{N_{xv}}\right) \]
\[ \Delta x_v = \max(0.1436, 0.1557) \]
\[ \Delta x_v = 0.156 \text{ mm/pixel} \quad \text{(A.6)} \]
\[ U_{axv} = \frac{\Delta x_v}{2} \]
\[ U_{axv} = 0.078 \text{ mm/pixel} \]

Y-Direction:
\[ \Delta y = \max\left(\frac{d_y(21)}{N_y}, \frac{d_y(43)}{N_y}\right) \]
\[ \Delta y = \max(0.2284, 0.2108) \]
\[ \Delta y = 0.228 \text{ mm/pixel} \quad \text{(A.7)} \]
\[ U_{ay} = \frac{\Delta y}{2} \]
\[ U_{ay} = 0.114 \text{ mm/pixel} \]

Y-Direction (load cell mount with larger observed vibrations):
\[ \Delta y_v = \max\left(\frac{d_{yv}(21)}{N_{yv}}, \frac{d_{yv}(43)}{N_{yv}}\right) \]
\[ \Delta y_v = \max(0.171, 0.171) \]
\[ \Delta y_v = 0.171 \text{ mm/pixel} \quad \text{(A.8)} \]
\[ U_{ayv} = \frac{\Delta y_v}{2} \]
\[ U_{ayv} = 0.0789 \text{ mm/pixel} \]
where \(d_x()\) and \(d_y()\) are the distances between the respective pixels in the \(x\) and \(y\)-directions, \(N_x\) and \(N_y\) are the number of squares in the \(x\) or \(y\)-directions and \(U_{ax}\) and \(U_{ay}\) are the uncertainties due to pixel approximation in the \(x\) and \(y\)-directions for both the load cell with smaller vibration. A subscript \(v\) is used to indicate the load cell with larger observed vibrations.

**Total Error:**
The total component error for each direction was determined by the sum of the squares of the two uncertainties, and then a total error was calculated by a sum of the squared components. As the vibration determined by the maximum distance traveled, the total error will be equal to the root mean square of each component.

**X-Direction:**
\[
U_x = \sqrt{(U_{px} \Delta x)^2 + U_{ax}^2}
\]
\[
U_x = \sqrt{(0.145 \times 0.235)^2 + (0.118)^2}
\]
\[
U_x = 0.123 \text{ mm/pixel}
\]  
(A.9)

**X-Direction (load cell mount with larger observed vibrations):**
\[
U_{xv} = \sqrt{(U_{pxv} \Delta x_v)^2 + U_{axv}^2}
\]
\[
U_{xv} = \sqrt{(0.0817 \times 0.156)^2 + (0.0789)^2}
\]
\[
U_{xv} = 0.156 \text{ mm/pixel}
\]  
(A.10)

**Y-Direction:**
\[
U_y = \sqrt{(U_{py} \Delta y)^2 + U_{ay}^2}
\]
\[
U_y = \sqrt{(0.00749 \times 0.228)^2 + (0.114)^2}
\]
\[
U_y = 0.136 \text{ mm/pixel}
\]  
(A.11)

**Y-Direction (load cell mount with larger observed vibrations):**
\[
U_{yv} = \sqrt{(U_{pyv} \Delta y_v)^2 + U_{ayv}^2}
\]
\[
U_{yv} = \sqrt{(0.00542 \times 0.156)^2 + (0.1707)^2}
\]
\[
U_{yv} = 0.156 \text{ mm/pixel}
\]  
(A.12)
Total:

\[ U_t = \sqrt{U_x^2 + U_y^2} \]
\[ U_t = 0.18 \text{ mm/pixel} \quad \text{(A.13)} \]

Total (Vibration):

\[ U_{tv} = \sqrt{U_{xv}^2 + U_{yv}^2} \]
\[ U_{tv} = 0.12 \text{ mm/pixel} \quad \text{(A.14)} \]

where \( \Delta X \) and \( \Delta Y \) are the conversion between pixels to mm in the respective directions, \( U_x \) and \( U_y \) are the uncertainties for the respective component, and \( U_t \) was the total uncertainty. A subscript \( v \) is used to indicate the load cell with larger observed vibrations.

A.1.2 Force Acquisition

Force measurements and the respective variables for the nondimensional numbers were calculated based upon temperature, pressure, length and force measurements. The barometric pressure uncertainty \( (\partial P = \pm 0.1 \text{ in Hg}) \), atmospheric temperature uncertainty \( (\partial T = \pm 2.2^\circ \text{C}) \), pressure difference uncertainty \( (\partial \Delta P = \pm 0.05 \text{ in } H_2O) \), and force uncertainty \( (\partial F = \pm 0.974 \text{ N}) \) were determined by the instrument error. The respective shape uncertainties, planform area \( (\partial A = \pm 2.52 \text{ mm}^2) \) and chord length \( (\partial c = \pm 1.59 \text{ mm}) \), were determined by the fabrication tolerance. Kinematic viscosity and the associated uncertainty \( (\partial \nu = \pm 0.32 \times 10^{-6}) \) was calculated from the temperature measurements.
Density Uncertainty:

\[ U_\rho = \sqrt{\left(\frac{\partial \rho}{\partial P}\right)^2 + \left(\frac{\partial \rho}{\partial T}\right)^2} \]

\[ \left(\frac{\partial \rho}{\partial P}\right)^2 = \left(\frac{\partial P}{RT}\right)^2 \]

\[ \left(\frac{\partial \rho}{\partial T}\right)^2 = \left(\frac{169.3 \text{ Pa}}{(287.058 \text{ J/kgK})(291.15 \text{ K})}\right)^2 \]

\[ \left(\frac{\partial \rho}{\partial P}\right)^2 = (2.026 \times 10^{-3} \text{ kg/m}^3)^2 \]

\[ \left(\frac{\partial \rho}{\partial T}\right)^2 = \left(\frac{-\partial TP}{RT^2}\right)^2 \]

\[ U_\rho = \sqrt{\left(\frac{\partial \rho}{\partial P}\right)^2 + \left(\frac{\partial \rho}{\partial T}\right)^2} \]

\[ U_\rho = \sqrt{(2.026 \times 10^{-3} \text{ kg/m}^3)^2 + (-7.944 \times 10^{-3} \text{ kg/m}^3)^2} \]

\[ U_\rho = 0.0082 \text{ kg/m}^3 \]

\[ U_{\rho_v} = \sqrt{\left(\frac{\partial \rho_v}{\partial P_v}\right)^2 + \left(\frac{\partial \rho_v}{\partial T_v}\right)^2} \]

\[ \left(\frac{\partial \rho_v}{\partial P_v}\right)^2 = \left(\frac{169.3 \text{ Pa}}{(287.058 \text{ J/kgK})(285.15 \text{ K})}\right)^2 \]

\[ \left(\frac{\partial \rho_v}{\partial T_v}\right)^2 = (2.068 \times 10^{-3} \text{ kg/m}^3)^2 \]

\[ \left(\frac{\partial \rho_v}{\partial P_v}\right)^2 = \left(\frac{-\partial TP_v}{RT_v^2}\right)^2 \]

\[ \left(\frac{\partial \rho_v}{\partial T_v}\right)^2 = \left(\frac{-7.944 \times 10^{-3} \text{ kg/m}^3}{(86.918.6 \text{ N/m}^2)(285.15 \text{ K})}\right)^2 \]

\[ U_{\rho_v} = \sqrt{\left(\frac{\partial \rho_v}{\partial P_v}\right)^2 + \left(\frac{\partial \rho_v}{\partial T_v}\right)^2} \]

\[ U_{\rho_v} = \sqrt{(2.068 \times 10^{-3} \text{ kg/m}^3)^2 + (-8.193 \times 10^{-3} \text{ kg/m}^3)^2} \]

\[ U_{\rho_v} = 0.0084 \text{ kg/m}^3 \]

where \( R \) is the specific air gas constant, \( T \) is mean measured temperature, and \( P \) is the mean measured barometric pressure. A subscript \( v \) is used to indicate the load cell with larger observed vibrations.
Velocity Uncertainty:

\[ U_{U_w} = \sqrt{\left( \frac{\partial U_w}{\partial \Delta P} \right)^2 + \left( \frac{\partial U_w}{\partial \rho} \right)^2} \]

\[ \left( \frac{\partial U_w}{\partial \Delta P} \right)^2 = \left( \frac{\sqrt{2} \Delta P}{2 \sqrt{\Delta P \rho}} \right)^2 \]

\[ \left( \frac{\partial U_w}{\partial \rho} \right)^2 = \left( \frac{\sqrt{2} \Delta P}{2 \rho^{3/2}} \right)^2 \]

\[ \left( \frac{\partial U_w}{\partial \rho} \right)^2 = \left( -\frac{\sqrt{2} \Delta P \rho}{2 \rho^{3/2}} \right)^2 \]

\[ U_{U_w} = \sqrt{(0.51 m^2/s)^2 + (-0.36 m^2/s)^2} = 0.62 m/s \]

\[ U_{U_{w,v}} = \sqrt{\left( \frac{\partial U_{w,v}}{\partial \Delta P} \right)^2 + \left( \frac{\partial U_{w,v}}{\partial \rho_{v}} \right)^2} \]

\[ \left( \frac{\partial U_{w,v}}{\partial \Delta P} \right)^2 = \left( \frac{\sqrt{2} \Delta P \rho_{v}}{2 \sqrt{\Delta P \rho_{v}} \rho_{v}} \right)^2 \]

\[ \left( \frac{\partial U_{w,v}}{\partial \rho_{v}} \right)^2 = \left( -\frac{\sqrt{2} \Delta P \rho_{v} \rho_{v}}{2 \rho_{v}^{3/2}} \right)^2 \]

\[ U_{U_{w,v}} = \sqrt{(0.50 m^2/s)^2 + (-0.37 m^2/s)^2} = 0.62 m/s \]

where \( T \) is mean measured temperature, \( \rho \) is the mean air density, and \( \Delta P \) is the mean measured barometric pressure. A subscript \( v \) is used to indicate the load cell with larger observed vibrations.
Reynolds Number Uncertainty:

\[ U_{Re} = \sqrt{\left( \frac{\partial Re}{\partial \nu} \right)^2 + \left( \frac{\partial Re}{\partial U_\infty} \right)^2 + \left( \frac{\partial Re}{\partial c} \right)^2} \]

\[ \left( \frac{\partial Re}{\partial \nu} \right)^2 = \left( -U_\infty c \frac{\partial v}{v^2} \right)^2 \]

\[ \left( \frac{\partial Re}{\partial U_\infty} \right)^2 = \left( \frac{\left( -46.69 \frac{m}{s} \right) \left( 0.146 m \right) \left( 0.32 \times 10^{-6} \right)}{1.61 \times 10^{-5} \frac{m^2}{s}} \right)^2 \]

\[ \left( \frac{\partial Re}{\partial c} \right)^2 = (-8470)^2 \]

\[ \left( \frac{\partial Re}{\partial U_\infty} \right)^2 = \left( \frac{c \partial U_\infty}{v} \right)^2 \]

\[ \left( \frac{\partial Re}{\partial c} \right)^2 = \left( \frac{\left( 0.146 m \right) \left( 0.62 \frac{m}{s} \right)}{1.61 \times 10^{-5}} \right)^2 \]

\[ \left( \frac{\partial Re}{\partial c} \right)^2 = \left( 5650 \right)^2 \]  \hspace{1cm} (A.19)

\[ \left( \frac{\partial Re}{\partial c} \right)^2 = \left( \frac{\left( 46.69 \frac{m}{s} \right) \left( 0.00159 m \right)}{1.61 \times 10^{-5}} \right)^2 \]

\[ \left( \frac{\partial Re}{\partial c} \right)^2 = \left( 4600 \right)^2 \]

\[ U_{Re} = \sqrt{\left( \frac{\partial Re}{\partial \nu} \right)^2 + \left( \frac{\partial Re}{\partial U_\infty} \right)^2 + \left( \frac{\partial Re}{\partial c} \right)^2} \]

\[ U_{Re} = \sqrt{(-8470)^2 + (5650)^2 + (4600)^2} \]

\[ U_{Re} = 11,170 \approx 11,200 \]
\[ U_{Rev} = \sqrt{\left( \frac{\partial Re_v}{\partial V_v} \right)^2 + \left( \frac{\partial Re_v}{\partial U_{\infty,v}} \right)^2 + \left( \frac{\partial Re_v}{\partial c} \right)^2} \]

\[ \left( \frac{\partial Re_v}{\partial V_v} \right)^2 = \left( \frac{-U_{\infty,v} c \partial V_v}{V_v^2} \right)^2 \]

\[ \left( \frac{\partial Re_v}{\partial U_{\infty,v}} \right)^2 = \left( \frac{-(46.96 m/s)(0.146 m)(0.32 \times 10^{-6})}{1.58 \times 10^{-5} m/s} \right)^2 \]

\[ \left( \frac{\partial Re_v}{\partial c} \right)^2 = (-8870)^2 \]

\[ \left( \frac{\partial Re_v}{\partial U_{\infty,v}} \right)^2 = \left( \frac{c \partial U_{\infty,v}}{V_v} \right)^2 \]

\[ \left( \frac{\partial Re_v}{\partial c} \right)^2 = \left( \frac{0.146 m)(0.62 m/s)}{1.58 \times 10^{-5}} \right)^2 \]

\[ \left( \frac{\partial Re_v}{\partial c} \right)^2 = (5760)^2 \]

\[ \left( \frac{\partial Re_v}{\partial c} \right)^2 = \left( \frac{46.96 m/s)(0.00159 m)}{1.58 \times 10^{-5}} \right)^2 \]

\[ \left( \frac{\partial Re_v}{\partial c} \right)^2 = (4720)^2 \]

\[ U_{Rev} = \sqrt{\left( \frac{\partial Re_v}{\partial V_v} \right)^2 + \left( \frac{\partial Re_v}{\partial U_{\infty,v}} \right)^2 + \left( \frac{\partial Re_v}{\partial c} \right)^2} \]

\[ U_{Rev} = \sqrt{(-8870)^2 + (5760)^2 + (4720)^2} \]

\[ U_{Rev} = 11,580 \approx 11,600 \]

where \( U_{\infty} \) is the calculated mean free-stream velocity, \( \nu \) is the calculated kinematic viscosity, and \( c \) is the mean chord length. A subscript \( v \) is used to indicate the load cell with larger observed vibrations.
Force Calculations Uncertainty:

The following force uncertainties were calculated based on an estimated maximum force (75 N).

\[
U_{C_l} = \sqrt{\left(\frac{\partial C_l}{\partial F_l}\right)^2 + \left(\frac{\partial C_l}{\partial \rho}\right)^2 + \left(\frac{\partial C_l}{\partial A}\right)^2 + \left(\frac{\partial C_l}{\partial U_\infty}\right)^2}
\]

\[
\left(\frac{\partial C_l}{\partial F_l}\right)^2 = \left(\frac{2F_l}{\rho U_\infty A}\right)^2
\]

\[
\left(\frac{\partial C_l}{\partial \rho}\right)^2 = \frac{\rho}{2(75N)(0.0082kg/m^3)A(0.0558m^2)}^2
\]

\[
\left(\frac{\partial C_l}{\partial A}\right)^2 = \left(-\frac{2F_l}{\rho U_\infty A}\right)^2
\]

\[
\left(\frac{\partial C_l}{\partial U_\infty}\right)^2 = \frac{\rho}{4(75N)(0.62m/s)A(0.0558m^2)}^2
\]

\[
U_{C_l} = 0.0583
\]
\[ U_{C_i,v} = \sqrt{\left( \frac{\partial C_i,v}{\partial F_{i,v}} \right)^2 + \left( \frac{\partial C_i,v}{\partial \rho_v} \right)^2 + \left( \frac{\partial C_i,v}{\partial A_v} \right)^2 + \left( \frac{\partial C_i,v}{\partial U_{w,v}} \right)^2} \]

\[
\left( \frac{\partial C_i,v}{\partial F_{i,v}} \right)^2 = \left( \frac{2 F_{i,v}}{\rho U_{w,v}^2 A} \right)^2
\]

\[
\left( \frac{\partial C_i,v}{\partial \rho_v} \right)^2 = \left( 2(0.974N)/(1.068kg/m^3)(46.96m/s)(0.0558m^2) \right)^2
\]

\[
\left( \frac{\partial C_i,v}{\partial A_v} \right)^2 = (0.0149)^2
\]

\[
\left( \frac{\partial C_i,v}{\partial U_{w,v}} \right)^2 = \left( -2 F_{i,v} \rho \partial \rho_v \right)^2
\]

\[
\left( \frac{\partial C_i,v}{\partial \rho_v} \right)^2 = \left( \frac{-2(75N)(0.0084kg/m^3)}{(1.068kg/m^3)(46.96m/s)(0.0558m^2)} \right)^2
\]

\[
\left( \frac{\partial C_i,v}{\partial A_v} \right)^2 = (-9.14 \times 10^{-4})^2
\]

\[
\left( \frac{\partial C_i,v}{\partial U_{w,v}} \right)^2 = \left( -2 F_{i,v} \rho \partial A_v \right)^2
\]

\[
\left( \frac{\partial C_i,v}{\partial A_v} \right)^2 = \left( \frac{-2(75N)(2.52mm^2)}{(1.068kg/m^3)(46.96m/s)(0.0558m^2)} \right)^2
\]

\[
\left( \frac{\partial C_i,v}{\partial \rho_v} \right)^2 = (-0.0467)^2
\]

\[
\left( \frac{\partial C_i,v}{\partial U_{w,v}} \right)^2 = \left( -4 F_{i,v} \partial U_{w,v} \right)^2
\]

\[
\left( \frac{\partial C_i,v}{\partial A_v} \right)^2 = \left( \frac{-4(75N)(0.62m/s)}{(1.068kg/m^3)(46.96m/s)(0.0558m)} \right)^2
\]

\[
\left( \frac{\partial C_i,v}{\partial U_{w,v}} \right)^2 = (-0.0289)^2
\]

\[ U_{C_i,v} = \sqrt{(0.0149)^2 + (-9.14 \times 10^{-4})^2 + (-0.0467)^2 + (-0.0289)^2} \]

\[ U_{C_i,v} = 0.0569 \]
\[ U_{C_d} = \sqrt{\frac{\partial C_d}{\partial F_d}^2 + \left( \frac{\partial C_d}{\partial \rho} \right)^2 + \left( \frac{\partial C_d}{\partial A} \right)^2 + \left( \frac{\partial C_d}{\partial U_{\infty}} \right)^2} \]

\[ \left( \frac{\partial C_d}{\partial F_d} \right)^2 = \left( \frac{2 \partial F_d}{\rho U_{\infty} A} \right)^2 \]

\[ \left( \frac{\partial C_d}{\partial F_d} \right)^2 = \left( \frac{2 \partial F_d}{\rho U_{\infty} A} \right)^2 \]

\[ \left( \frac{\partial C_d}{\partial \rho} \right)^2 = \left( 2(0.974N)/(1.051kg/m^3)(46.69m/s)(0.0558m^2)) \right)^2 \]

\[ \left( \frac{\partial C_d}{\partial A} \right)^2 = (0.0152)^2 \]

\[ \left( \frac{\partial C_d}{\partial U_{\infty}} \right)^2 = \left( \frac{-2 F_d}{\rho U_{\infty} A} \right)^2 \]

\[ \left( \frac{\partial C_d}{\partial \rho} \right)^2 = \left( \frac{-2(75N)(0.0082kg/m^3)}{1.051kg/m^3)(46.69m/s)(0.0558m^2)} \right)^2 \]

\[ \left( \frac{\partial C_d}{\partial A} \right)^2 = \left( -9.15 \times 10^{-4} \right)^2 \]

\[ \left( \frac{\partial C_d}{\partial \rho} \right)^2 = \left( \frac{-2 F_d}{\rho U_{\infty} A} \right)^2 \]

\[ \left( \frac{\partial C_d}{\partial A} \right)^2 = \left( \frac{2(75N)(2.52mm^2)}{1.051kg/m^3)(46.69m/s)(0.0558m^2)} \right)^2 \]

\[ \left( \frac{\partial C_d}{\partial \rho} \right)^2 = \left( -0.0477 \right)^2 \]

\[ \left( \frac{\partial C_d}{\partial A} \right)^2 = \left( \frac{-4 F_d}{\rho U_{\infty} A} \right)^2 \]

\[ \left( \frac{\partial C_d}{\partial U_{\infty}} \right)^2 = \left( \frac{-4(75N)(0.62m/s)}{1.051kg/m^3)(46.69m/s)(0.0558m)} \right)^2 \]

\[ \left( \frac{\partial C_d}{\partial U_{\infty}} \right)^2 = \left( -0.0298 \right)^2 \]

\[ U_{C_d} = \sqrt{\left( \frac{\partial C_d}{\partial F_d} \right)^2 + \left( \frac{\partial C_d}{\partial \rho} \right)^2 + \left( \frac{\partial C_d}{\partial A} \right)^2 + \left( \frac{\partial C_d}{\partial U_{\infty}} \right)^2} \]

\[ U_{C_d} = \sqrt{(0.0152)^2 + (-9.15 \times 10^{-4})^2 + (-0.0477)^2 + (-0.0298)^2} \]

\[ U_{C_d} = 0.0583 \]
\[ U_{C_d,v} = \sqrt{\left( \frac{\partial C_{d,v}}{\partial F_{d,v}} \right)^2 + \left( \frac{\partial C_{d,v}}{\partial \rho_v} \right)^2 + \left( \frac{\partial C_{d,v}}{\partial A_v} \right)^2 + \left( \frac{\partial C_{d,v}}{\partial U_{w,v}} \right)^2} \]

\[ \left( \frac{\partial C_{d,v}}{\partial F_{d,v}} \right)^2 = \left( \frac{2F_{d,v}}{\rho U_{w,v}^2 A} \right)^2 \]

\[ \left( \frac{\partial C_{d,v}}{\partial \rho_v} \right)^2 = \frac{2(0.974N)/((1.068kg/m^3)(46.96m/s)(0.0558m^2)))^2}{(1.068kg/m^3)(46.96m/s)^2(0.0558m^2)} \]

\[ \left( \frac{\partial C_{d,v}}{\partial A_v} \right)^2 = (0.0149)^2 \]

\[ \left( \frac{\partial C_{d,v}}{\partial U_{w,v}} \right)^2 = \frac{-2F_{d,v}\rho_v}{\rho U_{w,v}^2 A^2} \]

\[ \left( \frac{\partial C_{d,v}}{\partial A_v} \right)^2 = \frac{-2(75N)(2.52mm^2)}{(1.068kg/m^3)(46.96m/s)^2(0.0558m^2)^2) \]

\[ \left( \frac{\partial C_{d,v}}{\partial U_{w,v}} \right)^2 = \frac{-4F_{d,v}\rho_v}{\rho U_{w,v}^2 A^2} \]

\[ \left( \frac{\partial C_{d,v}}{\partial U_{w,v}} \right)^2 = \frac{-4(75N)(0.62m/s)}{(1.068kg/m^3)(46.96m/s)^2(0.0558m)^2} \]

\[ \left( \frac{\partial C_{d,v}}{\partial U_{w,v}} \right)^2 = \frac{-0.0289)^2}{(0.0149)^2 + (-9.14 \times 10^{-4})^2 + (-0.0467)^2 + (-0.0289)^2} \]

\[ U_{C_d,v} = 0.0569 \]

where \( U_{\infty} \) is the calculated mean free-stream velocity, \( \rho \) is the measured mean density, and \( A \) is the mean surface planform area. A subscript \( v \) is used to indicate the load cell with larger observed vibrations.

A 3rd-order Butterworth filter with a cutoff frequency 10 Hz was used to mitigate vibration noise in the force signal. For the statistical analysis, a student-t value (\( t_{v,p} = 1.645 \)) was used for generating a precision interval (\( \pm t_{v,p}S_x \), where \( S_x \) is one standard deviation of the measured forces), given at the probability (\( P\% = 90\% \)). Below are the force plots with the associated precision intervals for each angle of attack:
Figure A.1: Precision interval of lift coefficient ($C_l$) vs. angle of attack ($\alpha$), positive (left) and negative (right) angles of attack, for the three flipper models (original [black], filtered [blue], and smoothed [red] models).

Figure A.2: Precision interval of drag coefficient ($C_d$) plotted vs. angle of attack ($\alpha$), positive (left) and negative (right) angles of attack, for the three flipper models (original [black], filtered [blue], and smoothed [red] models).
Figure A.3: Precision interval of lift coefficient ($C_l$) plotted vs. angle of attack ($\alpha$), positive (left) and negative (right) angles of attack, for the three flipper models (original [black], filtered [blue], and smoothed [red] models) with a maximum vibration of ±0.8mm.

Figure A.4: Precision interval of drag coefficient ($C_d$) plotted vs. angle of attack ($\alpha$), positive (left) and negative (right) angles of attack, for the three flipper models (original [black], filtered [blue], and smoothed [red] models). with a maximum vibration of ±0.8mm.
A.2 Flapping Flight

A.2.1 PIV Acquisition

The uncertainty for the particle image velocimetry was calculated by determining the settling velocity of the particles, particle inertia, and resolution of the images. Because the same particles were used for both Set 1 and Set 2 of data, as well as the water tunnel flow measurements, the particles settling velocity and particle inertia was calculated once for all three sets of data. The resolution and total uncertainty are calculated for each of the above listed data sets.

Diameter of particle: \( d = 0.011 \text{ mm}, \ d/2 = 0.005 \text{ mm}, \)
Gravty: \( g = 9.81 \text{ m/s}^2, \)
Dynamic Viscosity: \( \mu = 1.002 \times 10^{-3} \text{Ns/m}^3, \)
Particle Density: \( \rho_p = 1,110 \text{ kg/m}^3, \)
Fluid Density: \( \rho_f = 1,000 \text{ kg/m}^3, \)
free-stream velocity \( U_{infy} = 0.023 \text{ m/s} \)

Hollow Glass Sphere Settling Velocity Calculation

\[
U_s = \frac{2(\rho_p-\rho_f)a^2g}{(9\mu)}
\]

\[
U_s = \frac{2((1,110 \text{ kg/m}^3)-(1,000 \text{ kg/m}^3))(0.05\times10^{-3})^2(9.81 \text{ m/s}^2)}{9(1.002\times10^{-3})}
\]

\[
U_s = -5.98 \times 10^{-6} \text{ m/s}
\]

Because \( U_s \) is so small compared to \( U_{infy} \), the uncertainty due to the particle settling velocity is negligible.

Hollow Glass Sphere Inertia Calculation

\[
\tau = \frac{2(a)^2(\rho_p)}{9(\mu/\rho_p)}
\]

\[
\tau = \frac{2(0.005\times10^{-3})^2(1.100 \text{ kg/m}^3)}{9(1.002\times10^{-3})}
\]

\[
\tau = 6.154 \times 10^{-6} \text{ s}
\]

Because the time between images only varies between \( 1.2 \times 10^{-2} \) to \( 6.4 \times 10^{-3} \), the inertia of the hollow glass sphere is also negligible.
Uncertainty due to Calculations and Resolution for PIV

The uncertainty due to the calculations and resolution was determined by the norm of the change in maximum velocity with respect to location \((dv/dd)\), which is the \(dt\) in this case times the position uncertainty or pixel resolution \((U_d)\) and the change in velocity with respect to time multiplied by the time uncertainty, which was calculated by taking the maximum velocity \(v = 0.06\) m/s divided by the \(dt\). Because the \(dt\) ranges from 6400 \(\mu\)s to 12000 \(\mu\)s depending on flapping frequency, this uncertainty will vary. The most stringent criteria (6400 \(\mu\)s) is calculated below, while the least stringent (12000 \(\mu\)s) is also reported as \(U_{c2}\). Uncertainty due to Calculations and Resolution for Set 1

\[
U_c = \sqrt{(dv/dd)^2(U_d)^2 + (dv/dt)^2(U_i)^2}
\]

\[
U_c = \sqrt{(u*l/dt*L)^2(U_d)^2 + (v/dt)^2(U_t)^2}
\]

\[
U_c = \sqrt{(1/0.0064s^{-1})^2(2.2 \times 10^{-5}m)^2 + ((0.06m/s)/(0.0064s))^2(10^{-9})^2}
\]

\[
U_c = \sqrt{1.11 \times 10^{-5}m/s + 7.724 \times 10^{-15}m/s}
\]

\[
U_c = 0.0033m/sU_{c2} = 0.0018m/s
\]

Total Uncertainty Calculation for Set 1

\[
U_i = \sqrt{U_c^2 + U_s^2 + U_i^2}
\]

\[
U_i = \sqrt{(0.0034m/s)^2 + (0)^2 + (0)^2}
\]

\[
U_i = 0.0033m/sU_{i2} = 0.0018m/s
\]

Uncertainty due to Calculations and Resolution for Set 2

\[
U_c = \sqrt{(dv/dd)^2(U_d)^2 + (dv/dt)^2(U_i)^2}
\]

\[
U_c = \sqrt{(u*l/dt*L)^2(U_d)^2 + (v/dt)^2(U_t)^2}
\]

\[
U_c = \sqrt{(1/0.0064s)^2(2.3 \times 10^{-5}m)^2 + ((0.06m/s)/(0.0064s))^2(10^{-9})^2}
\]

\[
U_c = \sqrt{1.291 \times 10^{-5}m/s + 7.724 \times 10^{-15}m/s}
\]

\[
U_c = 0.0036m/sU_{c2} = 0.0019m/s
\]
Total Uncertainty Calculation for Set 1

\[
U_t = \sqrt{U_c^2 + U_s^2 + U_i^2}
\]

\[
U_t = \sqrt{(0.0036m/s)^2 + (0)^2 + (0)^2}
\]  

(A.30)

\[
U_t = 0.0036m/s
\]

Uncertainty due to Calculations and Resolution for Water Tunnel Analysis

\[
U_c = \sqrt{(dv/dd)^2(U_d)^2 + (dv/dt)^2(U_f)^2}
\]

\[
U_c = \sqrt{(u\,*\,l/dt\,*\,L)^2(U_d)^2 + (dv/dt)^2(U_f)^2}
\]

\[
U_c = \sqrt{(1/0.0064s)^2(2.3\,*\,10^{-5}m)^2 + ((0.024m/s/(0.0064s))^2(10^{-9})^2}
\]

(A.31)

\[
U_c = \sqrt{1.11\,*\,10^{-5}m/s + 1.36\,*\,10^{-10}m/s}
\]

\[
U_c = 0.0036m/s
\]

Total Uncertainty Calculation for Water Tunnel Analysis

\[
U_t = \sqrt{U_c^2 + U_s^2 + U_i^2}
\]

\[
U_t = \sqrt{(0.0036m/s)^2 + (0)^2 + (0)^2}
\]  

(A.32)

\[
U_t = 0.0036m/s
\]

A.2.2 PIV RMS

RMS plots are included in Appendix I for each of the acquired PIV data sets.
Prior to straightening the 3D reconstruction, the generated mesh needed to fill several holes in order to complete the 3D model. The most prominent hole, the underside of the tip, resulted from the tip resting on the beach. This hole was remodeled by following the general contour of the rest of the flipper. Figure B.1 shows the remodeling of the tip. Two primary curves were present in the original 3D reconstruction. Due to the flipper being hoisted by a backhoe while the tip remained on the ground, the entire flipper had a general “S” shape, the first curve, shown in Figure B.2. The flipper was hoisted from a chain wrapped around the proximal end of the flipper, resulting in a slight fold, the second curve, as seen in Figures B.2 and B.3. Prior to force and flow analysis, these primary curves needed to be eliminated from the flipper.

Using lattice structures in Blender, the adult humpback whale flipper was straightened. A lattice structure, is a simplified structure that can be used to vary the points of a large selection,

Figure B.1: The initial 3D mesh (left) with a hole at the underside of the tip and the remodeled tip (right).
Figure B.2: Two general bends were associated with the original 3D reconstruction. A general “S” curve was present along the entire flipper (left and center) due to the hoisting of the flipper. The flipper was also folded (right) near the proximal end due to the chain wrapped around.

Figure B.3: This is a rotated image of the flipper showing the fold near the proximal end due to the chain being wrapped around.
while also interpolating the geometry back to the non transformed regions. 10 iterations of manipulating groups of nodes were performed to correctly bend the flipper into a straight position. The first 5 iterations were focused on straightening the slight “S” shape, while the next 5 focused on finer straightening improvements including the proximal end. Below are the first three iterations samplings of the blender python code and images for each of the lattice structure transformation steps:

Figure B.4: The initial straightening step was focused on the larger “S” curve but near the proximal end.
Figure B.5: A second lattice structure was made around the proximal end to refine the initial transformation.

Figure B.6: The rest of the flipper is initially straightened to minimize the larger “S” curve.
APPENDIX C. MODIFICATION OF 3D MODEL: FILTERING METHOD

For the filtering method the leading edge profile was first identified from the mid-chord of the flipper. The entire flipper profile, shown in Figure 1, was cropped at the rectangular base (green line in Figure C.1) and at the mid-chord of the flipper (blue line in Figure C.1). The mid-chord of the flipper was defined using the stream-wise midpoint of the flipper tip.

The cropped leading edge profile, shown in Figure C.2, was transformed into a filterable data signal by taking the horizontal and vertical location of each pixel (Figure C.3). This data signal was split into three sections with a linear interpolation of 30 pixels enabling a smooth transition between the three sections (marked as orange in Figure C.3). The final 45 pixels were unfiltered.

Figure C.1: Two different crops were made on the original profile in order to isolate the leading edge. The first crop was to eliminate the rectangular base (green line) and the second crop was to isolate the leading edge from the rest of the flipper at the mid-chord of the flipper (blue line).

Figure C.2: The cropped leading edge, used to calculate the filtered plot.
because no tubercles were present. The cut-off frequency for the filtering was determined from the product of a filtering constant \((F_c)\) and the frequency of the section of the signal. The frequency constant was varied between 1.5, 1.1, 1.0, and 0.9. The frequency of the signal was calculated as the maximum frequency (derived from the period (pixel distance) between each of the peaks) in the filtered section.

By visual inspection, a filtering constant of 1.0 was determined as remaining most true to general shape. As seen in Figure 4, a filtering constant of 1.5 (blue line) negates to account for the concavity at tubercle 6. A filtering constant of 0.9 (purple line), 1.0 (orange line), and 1.1 (green line) are relatively similar. A filtering constant of 0.9 also accounts for the concavity at tubercle 6, but seems to be influenced by the individual tubercles. A filtering constant of 1.1 doesn't completely account for the concavity at tubercle 6, but has less influence of the individual tubercles. A filtering constant of 1.0 was selected due to accounting for the concavity at tubercle 6, while maintaining relatively independent of individual tubercles.

Figure C.4: Overlay of different filtering constants, \(F_c = 1.5\) (blue), 1.1 (green), 1.0 (blue), and 0.9 (purple)
Matlab code for filtering profile generation:

```matlab
%% Profile of Leading Edge
clear all;
I = imread('WhaleFlipperProfile.png');
BWI = im2bw(uint8(I(1:size(I,1)-5,1:size(I,2),1)),0.70);
BW = im2bw(uint8(I(162:size(I,1)-5,162:size(I,2),1)),0.85);
[Y, X] = find(BW);
[B, A] = butter(3,0.0045);
[B2, A2] = butter(3,0.012);
LE_f = filtfilt(B, A, [X(1:925), Y(1:925)]) - 2;
LE_f2 = filtfilt(B2, A2, [X(800:end), Y(800:end)]) + 2;
figure()
plot(X(1:814), LE_f(1:814, 2), 'g')
hold on
plot(X(814:925), LE_f2(15:126, 2), 'g')
plot(X, Y-5, 'r')
hold off
BW2 = zeros(size(BW,1), size(BW,2));
for i = 1:814
    BW2(round(LE_f(i, 2)), X(i)) = 1;
end
for i = 814:926
    BW2(round(LE_f2(i-799, 2)), X(i)) = 1;
end
I2 = padarray(BW2, [162 162], 'pre');
I2(1:162, 1:size(BWI, 2)) = BWI(1:162, :);
I2(1:size(BWI, 1), 1:162) = BWI(:, 1:162);
I2(825:size(BWI, 1), 1:162) = BWI(825:end, 1:162);
I2(1:size(BWI, 1), 1070:size(BWI, 2)) = BWI(:, 1070:end);
```

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imshow(I2)
figure()
imshow(BWI)

%% Calculate Mean Chord Length
[Y1, X1] = find(BWI(:,162:1093));
[Y2, X2] = find(I2(:,162:1093));
for i = 1:2:length(X2)-1
    C1(i) = (Y1(i)-Y1(i+1))^2;
    C2(i) = (Y2(i)-Y2(i+1))^2;
end
C1 = sqrt(C1);
C2 = sqrt(C2);
C1(C1==0) = [];
C2(C2==0) = [];
C1(C1==1) = [];
C2(C2==1) = [];

%% Conversion to Inches
FlipperLength = 934; %Pixels from Root to End
ModelLength = 18.25; %Inches from Root to End of Model
ConP2in = ModelLength/FlipperLength;
MChord1 = mean(C1)*ConP2in
MChord2 = mean(C2)*ConP2in
APPENDIX D. COMPARISON OF FLIPPER CROSS SECTIONS

Because the tip of the flipper imaged was resting on the beach during the acquisition of the 2D images, tip reconstruction was required. This reconstruction was performed by filling in the whole with the same general contour as the rest of the flipper near this section. By comparing the cross-sections of the reconstructed tip and correlating cross-sections from a flipper studied by [2], a similar geometry is observed. Even though Figs. D.1 and fig:Comparison2 show that the images take by [2] have a thinner leading and trailing edge, a similar elliptical shape is observed.

Figure D.1: Cross section 1 of the original model (left) and an image from Fish and Battle [2] (right) used with author’s permission.

Figure D.2: Cross section 2 of the original model (left) and an image from Fish and Battle [2] (right) used with author’s permission.
Additional images are presented below demonstrating further demonstrating the correlation between the initial reconstruction (after straightening prior to smoothing), images from Fish and Battle [2], and the original model.

Figure D.3: Cross section 5 of the post-straightening, pre-smoothing, initial reconstruction (left), image from Fish and Battle [2] (middle), and the original model (right) used with author’s permission.

Figure D.4: Cross section 10 of the post-straightening, pre-smoothing, initial reconstruction (left), image from Fish and Battle [2] (middle), and the original model (right) used with author’s permission.

Figure D.5: Cross section 20 of the post-straightening, pre-smoothing, initial reconstruction (left), image from Fish and Battle [2] (middle), and the original model (right) used with author’s permission.
Figure D.6: Cross section 30 of the post-straightening, pre-smoothing, initial reconstruction (left), image from Fish and Battle [2] (middle), and the original model (right) used with author’s permission.

Figure D.7: Cross section 40 of the post-straightening, pre-smoothing, initial reconstruction (left), image from Fish and Battle [2] (middle), and the original model (right) used with author’s permission.

Figure D.8: Cross section 50 of the post-straightening, pre-smoothing, initial reconstruction (left), image from Fish and Battle [2] (middle), and the original model (right) used with author’s permission.
APPENDIX E. IMAGES OF THE FABRICATED MODELS

Below are several images of the humpback whale flipper models after fabrication. These images were taken under harsh lighting conditions in order to illuminate any natural geometric variations.

Figure E.1: Top of the fabricated models
Figure E.2: Bottom of the fabricated models

Figure E.3: Fabricated models with the leading edge illuminated.
APPENDIX F. WATER TUNNEL FLOW ANALYSIS

To adequately determine the flow parameters of the free surface water tunnel, particle image velocimetry (PIV) measurements were acquired at six different chordwise locations. Measured from the center of the tank the six chord wise locations were 50.8 mm, 76.2 mm, 101.6 mm, 127 mm, 152.4 mm, and 203.2 mm. The flapping mechanism was placed in the center of the tank, so that the wing was centered in the image frame and matched with the locations shown in Fig. F.1. Using a similar PIV setup as reported in Chapter 3, the camera was mounted parallel with the flapping mechanism as to acquire a streamwise image. F.1 The same double-pulsed Nd:YAG laser (532nm) illuminated a sheet from underneath the mechanism. 500 continuous images were taken at a rate of 0.5 Hz with a dt of 0.03 s. The PIV camera was mounted with a Nikon Nikkor 50 mm lens. The PIV measurements were computed twice using a decreasing window size from 64×64 pixels to 32×32 pixels with 50% overlap. Spurious vectors of magnitude 1.2 times the 8 neighbors RMS were eliminated and replaced with the next highest correlation peak which met this criteria.

To evaluate the flow characteristics, the average velocity and standard deviation was calculated for the 500 images for each velocity vector (see Figs. F.2 and F.3). The turbulence intensity was calculated as the standard deviation divided by the mean velocity (see Fig. F.4). Table F.1 reports the average velocity and the maximum standard deviation and turbulence intensity for each location evaluated.
Figure F.1: Water tunnel PIV evaluation laser locations: (1) 203.2 mm, (2) 152.4 mm, (3) 127 mm, (4) 101.6 mm, (5) 76.2 mm, and (6) 50.8 mm.

Table F.1: The average velocity, average standard deviation, and maximum turbulence intensity for each location evaluated in the water tunnel.

<table>
<thead>
<tr>
<th>Number</th>
<th>Location</th>
<th>Average Velocity</th>
<th>Standard Deviation</th>
<th>Turbulence Intensity (%)</th>
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<tr>
<td>1</td>
<td>203.2 mm</td>
<td>0.02371 m/s</td>
<td>0.000412 m/s</td>
<td>2.2</td>
</tr>
<tr>
<td>2</td>
<td>152.4 mm</td>
<td>0.0237 m/s</td>
<td>0.000428 m/s</td>
<td>2.3</td>
</tr>
<tr>
<td>3</td>
<td>127 mm</td>
<td>0.0233 m/s</td>
<td>0.000405 m/s</td>
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</tr>
<tr>
<td>4</td>
<td>101.6 mm</td>
<td>0.0228 m/s</td>
<td>0.000467 m/s</td>
<td>2.4</td>
</tr>
<tr>
<td>5</td>
<td>76.2 mm</td>
<td>0.0219 m/s</td>
<td>0.000443 m/s</td>
<td>2.5</td>
</tr>
<tr>
<td>6</td>
<td>50.8 mm</td>
<td>0.0215 m/s</td>
<td>0.000485 m/s</td>
<td>3</td>
</tr>
<tr>
<td>Evaluation</td>
<td>NA</td>
<td>0.0228 m/s</td>
<td>0.000485 m/s</td>
<td>3</td>
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</table>
Figure F.2: Water tunnel average velocity (left) and standard deviation (right) for the different locations, (1) 203.2 mm, (2) 152.4 mm, and (3) 127 mm from the middle.
Figure F.3: Water tunnel average velocity (left) and standard deviation (right) for the different locations, (4) 101.6 mm, (5) 76.2 mm, and (6) 50.8 mm from the middle.
Figure F.4: Water tunnel turbulence intensity for the different locations, (1) 203.2 mm, (2) 152.4 mm, (3) 127 mm, (4) 101.6 mm, (5) 76.2 mm, and (6) 50.8 mm from the middle.
APPENDIX G. PIV PARAMETERS

Table G.1: PIV parameters

<table>
<thead>
<tr>
<th>$f$</th>
<th>$\phi$</th>
<th>$dt$</th>
<th>PIV Set</th>
<th>Encoder Data Points</th>
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<td>Both</td>
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<td>8000\mu s</td>
<td>Both</td>
<td>6000</td>
</tr>
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<td>13</td>
<td>9600\mu s</td>
<td>Both</td>
<td>9000</td>
</tr>
<tr>
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<td>11500\mu s</td>
<td>Both</td>
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</tr>
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<td>13</td>
<td>12000\mu s</td>
<td>Both</td>
<td>18000</td>
</tr>
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<td>Set 2</td>
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</tr>
<tr>
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<td>Set 2</td>
<td>9000</td>
</tr>
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</tr>
<tr>
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<td>10000\mu s</td>
<td>Set 2</td>
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</tr>
<tr>
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<td>12000\mu s</td>
<td>Set 2</td>
<td>12000</td>
</tr>
<tr>
<td>0.05</td>
<td>23</td>
<td>12000\mu s</td>
<td>Set 2</td>
<td>18000</td>
</tr>
<tr>
<td>0.1</td>
<td>20</td>
<td>12000\mu s</td>
<td>Set 2</td>
<td>9000</td>
</tr>
<tr>
<td>0.075</td>
<td>20</td>
<td>12000\mu s</td>
<td>Set 2</td>
<td>12000</td>
</tr>
<tr>
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<td>18</td>
<td>6400\mu s</td>
<td>Set 2</td>
<td>4500</td>
</tr>
<tr>
<td>0.1</td>
<td>18</td>
<td>9600\mu s</td>
<td>Set 2</td>
<td>9000</td>
</tr>
<tr>
<td>0.075</td>
<td>18</td>
<td>12000\mu s</td>
<td>Set 2</td>
<td>12000</td>
</tr>
<tr>
<td>0.05</td>
<td>18</td>
<td>12000\mu s</td>
<td>Set 2</td>
<td>18000</td>
</tr>
</tbody>
</table>
Figure H.1: Vorticity and \( y \)-direction velocity component plots for sinusoidal leading edge profile at \( f = 0.1 \) Hz and different \( \phi \) values.
Figure H.2: Velocity vectors for sinusoidal leading edge profile at $f = 0.1$ Hz and different $\phi$ values.
Figure H.3: RMS vorticity plots for straight and sinusoidal leading edge profiles at phase angle $\phi = 13.3^\circ$. 

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Figure H.4: RMS $y$-direction velocity component for straight and sinusoidal leading edge profile at phase angle $\phi = 13.3^\circ$. 
Figure H.5: RMS velocity vectors for straight and sinusoidal leading edge profile at phase angle $\phi = 13.3^\circ$. 
Figure H.6: RMS vorticity plots (left) and y-direction scalar velocity plots (right) for sinusoidal leading edge at phase angle $\phi = 13.3^\circ$. This set includes $f = 0.15$ illustrating the transition from a more uniform pattern of lower flapping frequencies to the chaotic nature at higher frequencies.
Figure H.7: RMS velocity vectors for sinusoidal leading edge profile at phase angle $\phi = 13.3^\circ$. 
Figure H.8: RMS vorticity plots for a sinusoidal leading edge profile at flapping frequencies, $f = 0.05$ Hz and $0.075$ Hz and phase angles $\phi = 28^\circ$, $23^\circ$, $18^\circ$, and $13.3^\circ$. 
Figure H.9: RMS vorticity plots for a sinusoidal leading edge profile at flapping frequencies, $f = 0.1$ Hz and 0.2 Hz and phase angles $\phi = 28^\circ$, 23°, 18°, and 13.3°.
Figure H.10: RMS $y$-direction component of velocity for a sinusoidal leading edge profile at flapping frequencies, $f = 0.05$ Hz and $0.075$ Hz and phase angles $\phi = 28^\circ, 23^\circ, 18^\circ,$ and $13.3^\circ$. 
Figure H.11: RMS y-direction component of velocity for a sinusoidal leading edge profile at flapping frequencies, $f = 0.1$ Hz and $0.2$ Hz and phase angles $\phi = 28^\circ, 23^\circ, 18^\circ$, and $13.3^\circ$. 

Figure H.11: RMS y-direction component of velocity for a sinusoidal leading edge profile at flapping frequencies, $f = 0.1$ Hz and $0.2$ Hz and phase angles $\phi = 28^\circ, 23^\circ, 18^\circ$, and $13.3^\circ$. 

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Figure H.12: RMS velocity vectors for a sinusoidal leading edge profile at flapping frequencies, $f = 0.05 \text{ Hz}, 0.075 \text{ Hz}, 0.075 \text{ Hz}, 0.05 \text{ Hz},$ and phase angles $\phi = 28^\circ, 23^\circ, 18^\circ,$ and $13.3^\circ.$
Figure H.13: RMS velocity vectors for a sinusoidal leading edge profile at flapping frequencies, \( f = 0.1 \) Hz and 0.2 Hz and phase angles \( \phi = 28^\circ, 23^\circ, 18^\circ, \) and 13.3\(^\circ\).

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Figure H.14: The RMS vorticity plots for a sinusoidal leading edge profile at flapping frequencies, 0.1 Hz and 0.075 Hz, and phase angles $\phi = 28^\circ, 25^\circ, 23^\circ, 20^\circ, 18^\circ$, and $13.3^\circ$. 

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Figure H.15: The RMS $y$-direction component of velocity for a sinusoidal leading edge at flapping frequencies, 0.1 Hz and 0.075 Hz, and phase angles $\phi = 28^\circ, 25^\circ, 23^\circ, 20^\circ, 18^\circ$, and $13.3^\circ$. 
Figure H.16: The velocity vectors for a sinusoidal leading edge profile at flapping frequencies, 0.1 Hz and 0.075 Hz, and phase angles $\phi = 28^\circ, 25^\circ, 23^\circ, 20^\circ, 18^\circ$, and $13.3^\circ$. 
Figure H.17: RMS vorticity and y-direction velocity component plots for sinusoidal leading edge at $f = 0.1$ Hz and different $\phi$ values.
Figure H.18: RMS velocity vectors for sinusoidal leading edge profile at $f = 0.1$ Hz and different $\phi$ values.