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DEVELOPMENT AND TESTING OF A PRESSURE SENSOR INTEGRATED

FOIL

BY

ALEXANDER ROBERT STOTT

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE

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ABSTRACT

Autonomous underwater vehicles are becoming increasingly more prevalent in exploring and studying the bodies of water found all over the world. Having a way to detect and identify the surrounding environment in close range would allow vehicles to move more efficiently and safely through hazardous environments or in groups of many. This study took biological inspiration from the fish sensory organ known as the lateral line to design, fabricate, and test a pressure sensor integrated foil. It examined the ability of pressure sensors to detect flow structures as well as variation in flow structures during a dynamic, flapping foil sinusoidal motion by changing the mean heave distance away from a wall. The experimental results showed that the foil's pressure sensors could detect a leading edge vortex at higher angles of attack and were able to detect the shedding vortex along the chord during dynamic motion with validation from PIV analysis and force sensors. The pressure sensors were also able to detect differences in pressure as a resultant from ground effect. These results could pave the way to creating vehicles that can interact and respond to the surrounding environment.

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It is with great thanks and gratitude that I acknowledge my advising professor, Dr. Jason Dahl, for all the support and guidance he provided during this very long journey. Not only was he always willing to take time to answer questions and make sure that I understood what he was saying, but he taught me how to question and consider all aspects of my research. I would also like to thank the other members of my committee for their help and patience. Dr. Stephen Licht always provided another point of view to help me bounce around ideas and was willing to give brief mini lectures in his office on topics I struggled with. Dr. Christopher Kincaid was a great professor with a unique and hands on way to teach his lectures which got me excited about what I was learning.

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DEDICATION

I want to dedicate this thesis to my loving and supportive family and friends, without whom I would have not made it to this point.

To my parents, Karen and Bob,

You have pushed me to be my absolute best and supported me in everything I have ever wanted to do. It is your unconditional love that has been my bedrock. Even during my most stubborn and frustrating moments, you were always there to help and set me in the right direction. I will never be able to love and thank you enough.

To Carrie,

This experience has been a tough and emotional roller-coaster for us, but you have stayed and loved me through thick and thin. I am so happy you have been by my side to highlight and remind me of my strengths and help me with my weaknesses. I cannot wait to start a new adventure with you.

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CHAPTER 1

Introduction

The oceans are vast unexplored and unknown. We understand relatively little about the organisms that reside in the giant expanses of water of our home planet and how our actions are impacting the natural cycles and processes that occur in the ocean. The harsh environment creates a significant challenge for exploration and, in the past, had limited our ability to observe the oceans and collect information. However, over the past few decades, ocean exploration and navigation has become increasingly more autonomous, requiring less human interaction with devices such as buoys [5], gliders [6], and other devices [7] making research in these difficult conditions more possible [8]. It is clear that automated underwater vehicles (AUVs) play a major role in the future of ocean exploration, and though these devices are advancing in energy, communications, autonomy, and navigation,[9] there are still limitations. Turbid water, narrow spaces, and fragile structures found in oceans and rivers make it difficult for AUVs to navigate and survive underwater. Cameras cannot function without a light source, and SONAR is prone to blind spots and does not work well in close quarters [10] [11] [12] [13]. In order to enhance navigation and obtain more information about our oceans, it is necessary to augment the current sensors system with additional capabilities that would fill in these gaps. By studying biology, research has shown that using pressure sensors is a feasible option for flow sensing, navigation, and object detection and recognition [11] [14]. This study aims to build on current artificial lateral line (ALL) research by developing a repeatable procedure for constructing objects with embedded pressure sensors as well as constructing a platform for detecting tangible flow features, such as vortices, in dynamic flow conditions.

1.1 Biological Inspiration

Evolution has been weeding out poor designs for hundreds of millions of years, producing interesting solutions to difficult problems. Birds and insects are able to fly, camouflage enables organisms to hide from predators or sneak up on prey, some deep sea organisms use fluorescence to attract prey; the list can go on. Scientists and engineers have studied these kinds of adaptations in hopes of gaining inspiration to solve complex problems. The two main fields are, biomimetics, the study of biological processes for the purpose of creating artificial copies that function like the ones in nature, and bio-inspired design, which takes the basic principles found in natural processes and applies them to engineering solutions.

1.1.1 Lateral Line System

Figure 1: A diagram of the bitterling, *Rhodeus sericeus amarus* (Cyprinidae) showing the distribution of superficial neuromasts (dots) and canal neuromasts (circles) [1]

The lateral line is a mechanosensory structure that allows fish and aquatic amphibians to sense changes in the flow field around them [1][15]. There is evidence that this organ is used for prey detection, predator avoidance, intra-specific communication, schooling, object discrimination, entrainment and rheotaxis [2]. It

is comprised of a network of receptor organs called neuromasts which are located on the head, trunk and tail of fish, as seen in Figure 1.

Neuromasts are small epithelial receptors that contain hundreds to thousands of hair cells [1] [15]. Those hair cells are the same as ones found in the auditory system of all vertebrates and, like all hair cells, each one has a ciliary bundle at the apical surface of the cell. The bundles are composed of stereocilia that are lined up in order of their ciliary height with the tallest positioned next to an elongated kinocilium [1][15] [2]. They are oriented in one of two opposing directions which defines the axis of most sensitivity [1]. All the hair cells within a neuromast are encased by a gelatinous mass, a cupula, which acts as the interface between all the hair cells and the flowing water [15].

Figure 2: Structural diagrams of both superficial neuromasts (left) and canal neuromasts (right). Superficial neuromasts are small and located on the surface of the body while canal neuromasts are much larger and located under the scales and skin. [2]

Figure 3: Diagrams showing how the different neuromasts are organized. Superficial neuromasts (a) move as a result of direct flow while canal neuromasts (b) move as a result of flow created by changes in pressure. [3]

The neuromasts can be separated into two types; the superficial neuromast (SN) and the canal neuromast (CN) which are shown in Figure 2. SNs are smaller and reside on the surface of the skin as depicted in Figure 3a. They are velocity-sensitive neuromasts that seem to respond to slow, uniform flows. CNs, on the other hand, appear to be acceleration or pressure-gradient-sensitive and respond more to rapidly changing motions [1].

1.2 Previous Research

The desire to create systems that interact seamlessly with the environment has been a driving force for scientists and engineers in the field of exploration. There have been many studies that have attempted to recreate the function of the lateral line by both mimicking it and taking inspiration from it. Some of those studies are reviewed below.

1.2.1 Hot Wire Anemometry (HWA)

Yang et al. [16] and Marting et al. [10] each conducted studies using a technique called hot wire anemometry (HWA) to detect subtle variations in fluid structures. Since the resistive properties of most metals are dependent on temperature, by heating thin wires of a known metal, it is possible to identify a relationship between the flow velocity of the fluid and the heat dissipation.

Yang et al. developed arrays of 16 miniature HWAs that had dimensions on the same order of magnitude as a biological SN, mimicking an ALL. They tested

its ability to localize a moving target by using a vibrating sphere. In addition they tested its ability to map a hydrodynamic wake by placing the array in the wake of the stationary cylinder. The sensor array was able to successfully locate the vibrating sphere when in close proximity to the array as well as distinguish the main features of the cylinder wake. Yang et al concluded that the ALL would enable safer and more flexible navigations.

The study conducted by Marting et al. proposed using HWAs to prevent an AUV from colliding with unseen objects. To test the idea, a HWA was placed on either side of a sphere that represented the nose of the AUV. The flow velocity of the surrounding fluid was measure while moving the sphere in a harmonic motion at different mean distances from the walls of the tank. Data obtained from the experiment matched qualitatively with that of theoretical calculations. It was concluded that the idea was feasible, but noise in the system remained a significant problem.

1.2.2 Cantilever Systems

An artificial lateral line canal (ALLC) was developed by Yang et al. [14]. The purpose of the study was to characterize the response properties of the canal, such as band pass filtering and noise rejections. Biomimetic neuromasts (BN) that were developed in previous work [17] were placed in a semicircular canal with pores much like a natural lateral line. Using a vibrating sphere, they compared the response of the ALLC and a superficial BN at various flow speeds ranging from 0 to 0.12 m/s. The ALLC was able to easily distinguish the vibrating sphere at all tested speeds while the superficial BN became overwhelmed at higher speeds. The study also identified the response of the sensors at various frequencies, identifying the peak response at 0.6 Hz. Yang et al. concluded that the canal had great noise immunity compared with the superficial BN, and that the system could be very

important for flow velocity sensing in the future.

Another system designed to mimic SNs was created by Abdulsadda and Tan [18]. The sensors were developed using ionic polymer-metal composites (IMPCs) and were on the millimeter scale. A 10 cm array comprising of 6 sensors was tested to determine its ability to identify the location of a vibrating sphere. The results indicated that the location of the sphere could be identified 1 to 2 body lengths away after training the sensors. Location identification was better with 6 sensors compared to the same test done with 2 and 4 sensors. The authors proposed further studies, such as using different signal processing, in order to do real time source localization and to track a moving source.

1.2.3 Pressure Sensor Arrays

As mentioned in section 1.1.1, the canal neuromast subsystem behaves more like an array of pressure sensors that can detect a pressure gradient along the length of the fish. Fernandez et al. [12]. The objective was to create small sensors that could contour to a wide range of shapes so they could be applied to vehicles. In order to identify objects, an array would need sensors that could detect pressures on the order of 1 Pa. They began development and testing of a silicon based, strain-gauge pressure sensor using MEMS techniques with diameters ranging from 1 to 4 mm. They tested the pressure sensors using a manometer that could create pressure differences with a precision of 10 Pa. Test results demonstrated that a sensor 2 mm in diameter with a resolution on the order of pascals was possible and would be the standard diameter for future testing.

Fernandez et al. have conducted various tests with a range of different pressure sensor arrays [19]. Their goals included being able to estimate external flow structures using vortex tracking and to identify leading edge vortices. The first test consisted of producing two vortices with a paddle that would travel parallel

to a pressure sensor array. The second involved creating a NACA 0018 foil with tapped pressure sensors and moving the foil in water at a 35 degree angle of attack at various speeds to track the leading edge vortex. Test results showed that the array of sensors in the first experiment was able to track the strength and direction of the vortex closest to it. In addition, the leading vortex on the foil could be detected. Authors of the study therefore concluded that vortex detection is limited by distance, modeling becomes significantly more complicated as the body becomes more complicated, and increased spatial resolution is necessary for estimating strength and location of self-generated vortex structures.

Another study, conducted by Lagor et al. [20], studied navigation using distributed pressure measurements. The goal of the paper was to create a feedback controller that used pressure measurements to orient a foil upstream. A foil with a sensor on either side of the leading edge was created to measure the pressure differences between each side as a flow moves past. The foil was placed in a recirculating tank at an initial angle of attack with a feedback system designed to orient the foil in the direction of oncoming flow. The results showed that the foil did reach the desired orientation, however, it took a relatively long time to do so and the signal was noisy. They concluded that though the proportional control law works, it lacks memory, resulting in sensitivity to sensor noise. In future work, the group looked to include velocity sensors in tandem with the pressure sensors to further mimic the biological lateral line.

Further work done by the same group [21] looked to develop a flexible foil with distributed pressure sensors. In order to create flexibility without having to create linked parts where more problems could result, the group molded a foil out of silicon rubber. Using the Bayesian filter techniques tested in the previous experiment, they placed the foil in the recirculating tank and moved the foil with

a sinusoidal angle of attack while recording the pressure data. The flow sensing algorithm was tested and validated in both simulation and experimentation. They intend to continue work to develop a closed loop control strategy.

1.2.4 Ground Effect

A well understood phenomena in aeronautical engineering literature is the 'ground effect' [22] which occurs when a foil is operated near the ground and produces either a repelling force or suction force depending on the distance away from the ground.

A study conducted by Mivehchi et al. [4] looked at the forces produced on an oscillating foil in a tow tank as the mean heave distance was brought closer to a wall. The purpose of that study was to investigate how the lift and drag forces changed depending on the motion and location of the foil relative to a wall. A foil was towed with a motion that was sinusoidal in pitch and angle of attack at multiple mean distances from a wall. In addition, varying strouhal numbers and maximum angles of attack were used. The study concluded that the mean distance from the wall had a significant impact on the measured mean lift and mean thrust acting on the foil. It was also concluded, however, that mean lift and thrust were not a good indication of proximity to a wall as the instantaneous forces could change over a phase cycle but still produce the same mean value.

1.3 Statement of Purpose

The purposes of this study involved designing, constructing and testing a foil where pressure sensors were integrated into it in such a way that they would be flush with the surface. By creating this foil, it would be possible to test the feasibility of detecting minute changes in flow structures that occur when the environment changes around a oscillating foil with simple pressure sensors. Testing the pressure

sensors for detecting a wall in the same ground effect scenario as Mivehchi et al. [4], would provide a controlled comparison. This study also used PIV analysis and force data to validate the pressure readings.

1.4 Organization of Thesis

Chapter 2 discusses the foil design and construction.

Chapter 3 describes the experimental setup and presents the results and discussion for the sensor tests.

Chapter 4 provides the general experimental setup for all experiments executed using the tow tank.

Chapter 5 describes the experimental setup for the static tests done in the tank. The results are also provided and discussed.

Chapter 6 discusses the experimental setup and analysis for the dynamic tests. The results are also presented and discussed.

Chapter 7 presents the conclusions made by the thesis along with recommendations and proposed ideas for future work.

CHAPTER 2

Foil Design and Construction

This chapter describes the design and construction of a foil with an array of pressure sensors integrated into the body. There were two iterations of the foil designed and both are discussed.

Figure 4: The general shape of the NACA foil family [23]

The design of the foil was intended to be lightweight, rigid, have a NACA 0012 shape, contain an array of sensors along the chord, and be simple enough to recreate or alter. A lightweight foil was necessary so that readings on the force sensor would not max out during the dynamic motion experiments. In order to directly compare results to those in the study conducted by Mivehchi et al. [4], a NACA 0012 shape and a rigid body was needed. A NACA 00xx shape is defined by Equation 1 and the general profile can be seen in Figure 4 [23]. The first two digits determine the camber, or curve of the foil, while the last two digits determine the thickness of the foil as a percentage of the chord length. The thickest point along the foil occurs at 30% of the chord length. Therefore, for a NACA 0012 foil, there is zero camber and the thickest part of the foil is 12% of the chord length.

$$\pm y_t = 0.29690\sqrt{x} - 0.12600x - 0.35160x^2 + 0.28430x^3 - 0.10150x^4 \quad (1)$$

The rigid body would also ensure that the sensors remained sealed within the foil. A chord length of 10 cm was used since there was a silicon mold available with those dimensions. This chord provided enough room within the foil for multiple sensors, along with the support structure needed to place the sensors flush with the surface of the foil. Unlike previous studies that used tubes to connect the sensor to the surface, this design kept the sensors at the surface of the foil to limit error due to air trapped in tubing. As a tube is submerged, the amount of air trapped in the tube can vary depending on its orientation. If an array of sensors with tubes were deployed, there is the potential for different amounts of air getting trapped in each tube, slightly altering the readings of each pressure sensor as air is compressible. By eliminating the entrainment of air, each pressure sensor is recording the pressure exerted directly by the water.

In order to fit inside the foil and have the ability to detect the small changes in surrounding pressure, the pressure sensors used needed to be compact, durable, fast, and have high resolution that was on the order of 5 Pa as specified by Fernandez et al. Therefore, the type of pressure sensor selected was the MS5803-01BA07 absolute pressure sensor, developed by Measurement Specialties (Fremont, CA). This sensor was created with gel protection and anti-magnetic stainless steel for harsh environments. It had a maximum resolution of 1.2 Pa, was temperature compensated, had an on-board A/D converter, and communicated using I2C/SPI serial interface. A digital sensor as opposed to an analog sensor was used to help prevent electrical noise entering the signal. It also reduced the number of wires necessary to communicate with multiple sensors. In order to wire the sensors, small 8 pin MSOP to DPID surface mount breakout boards were used.

Figure 5: MS5803-01BA07 pressure sensors (left) and Adafruit breakout board (right)

2.1 First Iteration

To develop a repeatable process for integrating sensors into a foil, only a single sensor was embedded into a foil for the first design. The design was refined for a second iteration to include multiple pressure sensors. The intentions of only using a single sensor was to develop the method without losing many sensors in the process. A surface mount lab was utilized for attaching the pressure sensor to the breakout board connecting the wires. How the wires were attached to the sensor depended on the type of interface desired. For the first iteration foil, the lone sensor was wired following the specification for I2C (Inter-Integral Circuit) communication. This type of circuit is a multi-master, multi-slave device. It allows for communication to multiple sensors using only two lines, one for master in, slave out (MISO) and the other for master out, slave in (MOSI). In order to communicate to specific sensors, each sensor had a specific address and responded to the master when called upon. The I2C circuit was chosen to reduce the number of wires protruding from the foil.

To meet the requirements for weight and rigidity, a lightweight urethane casting resin, called Feather Lite by Smooth-On (Macungie, PA), was used. It has a low specific gravity of 0.67 g/cc along with a low viscosity of 410 cps for easier pouring into a narrow mold. When fully hardened the urethane has a shore D hardness of 58 which is comparable to the hardness of a golf ball. This made the

(a) side

(b) top

(c) bottom

Figure 6: The first iteration inner structure. The side view (a) shows the ledge where the sensor rests and the hole allowing the wires to pass through. The top (b) and bottom (c) view show sensor sitting in the foil and the wires sitting along a recessed channel.

foil more durable and reduced the risk of damage during testing. The backbone of the foil was a 0.25 thick aluminum bar that spanned the length of the foil. In addition to adding structural support, the bar held the sensor in place during the molding process. A hole was milled completely through the middle of the bar and a track was created along the length of the bar so that the wires for the sensor could be recessed into it. This prevented the wires from protruding from the surface. A wider hole was milled over the initial hole, creating an edge for the sensor to sit just deep enough so the top of it was flush with the surface of the foil. The edge was wide enough for the breakout board to sit on the aluminum without having any of the aluminum come in contact with the circuitry. Two holes on either end of the aluminum were drilled and tapped to create connection points to the plastic box that held the silicon mold of the foil.

Once the aluminum bar with sensor was placed in the silicon mold, the rigid,

Figure 7: The silicon mold (a) and the support box structure (b).

plastic box holding the mold in place was firmly bolted around it. A 3D printed endcap held one end of the aluminum bar. Another endcap held the other end and contained a hole to allow air to escape during the molding process and another large hole to pour the resin through. The resin cures in 8 minutes and so the process went quickly. While pouring the resin, it became apparent that the pour hole was not large enough as it repeatedly became blocked. This slowed down the rate at which the mold was filling and the current batch of resin became more viscous as it started to harden close to the 8-minute mark. In an attempt to salvage the foil, more resin was mixed, the hole was cleared and the new resin was poured into the mold. The same problems occurred and the foil did not become fully molded.

The foil had multiple characteristics that were not desirable as seen in Figure 8. Due to slow pour rate, bubbles were trapped higher up the mold. Holes were present along the trailing edge of the foil and the top part of the foil was incomplete. It could clearly be seen where the two batches of resin ended and began and the

newer resin was not mixed adequately, resulting in a softer, more pliable texture. The sensor was fortunately covered by the first batch of resin and it appeared to seal well around it. Unfortunately, the sensor was not seated properly and it stuck out above the surface of the foil.

Figure 8: The first iteration foil when removed from the mold. (a) The pressure sensor sits above the surface (red circle). (b) There are large air bubbles trapped within the foil (white arrow). (c) The trailing edge of the foil is brittle (white box); discontinuity with the mold (blue arrow); air holes (black circle).

Despite the appearances of the foil, conclusions were made during the process. Firstly, precisely manufacturing the aluminum bar to hold a sensor in place and accurately tap holes proved to be difficult and hard to replicate. In addition, the bar would not easily lend itself to include multiple sensors along the chord of the foil. The use of I2C circuitry would also lead to difficulty when more than two sensors were involved as the sensors were only created to have two different addresses. Multiple buses would need to be used in order to communicate with more than two sensors. The pouring process would need to be altered in order

to get a complete mold without defects. It would be necessary to widen the pour hole to prevent clogging and to tilt the mold at an angle so that the resin can slide down the edge of the mold, reducing bubbles.

The most important aspect of this process was that the sensor survived the molding process. Once out of the mold, the sensor was hooked up to an Arduino and fully submerged in water. Quick measurements provided reasonable pressure and temperature readings of the ambient air. This indicated that the resin seals in the electronics without damaging it, protecting it from water damage.

2.2 Second Iteration

The second design iteration addressed many of the problems from the first design. Firstly, the wiring of the MS5803-01BA07 sensors followed the SPI circuit design found in the sensor specifications document as opposed to I2C. Serial Peripheral Interface (SPI) is a synchronous serial communication interface that uses one master to control multiple slave devices. The change in circuitry was a result of the number of sensors being used and the higher transfer speed available when using SPI communication. For the foil design, a three sensor array was placed along the chord length. Only three sensors were used due to the limitation of space within the foil. For I2C communication, the sensors had only two addresses which were identified by wiring a signal permanently high or low. To speak to more than two sensors, SPI communication calls each sensor using a process called "chip select" where an extra wire is attached to each sensor and a conductor is dedicated to each sensor. As the master device calls to the sensors, it sends a signal down the chip select line of the desired sensor to signal it to send information along a common line. This feature enables one master device to communicate with as many devices as it can handle. The National Instruments USB-8452 SPI/I2C DAQ was used as the master device to communicate with the sensors. For future

constructions it could be used to communicate with up to 8 sensors. The only major downside with this communication type is that instead of having only four wires protruding from the foil, there were four wires in addition to a chip select wire for every sensor being used. For example, since there were three sensors in this foil, there were 7 wires protruding out the end.

The aluminum bar in the first iteration took up a lot of space, was hard to manipulate, and presented a risk for short circuiting. The second iteration used 1/8th inch steel rods, cut to length, as the skeleton of the foil. Like the aluminum bar, the rods had a dual purpose; to strengthen the foil and to hold the sensors in place. Because the rods are thin and long, flexing and sagging would be an issue for the 0.46 m span of the foil. To ensure that the rods remain parallel, ribs were designed and 3D printed with acrylonitrile butadiene styrene (ABS) plastic to match the contour of the mold to hold the rods in place. The ribs also helped keep the silicon mold in place, ensuring that the sensors were flush with the surface. The ribs were hollowed out as much as possible to allow for the resin to flow through and reduce the risk of air getting trapped during molding.

In order to hold the sensors in place, modeling software was also used to design clips that attached in between two steel rods. Each clip was designed to interlock with another clip to prevent any one of them from sliding out of place during the molding process and ensuring that the array remained in a straight line. Depending on the location of the sensor along the chord length, the angle at which the sensor was held could be adjusted in the modeling software before printing. Since there were 3 sensors being used in this specific design, 4 steel rods needed to be inserted into the foil to hold the clips in place. Once the sensors were assembled, they were glued into the clips to prevent any shifting within the clip during the molding process.

Figure 9: The support structure for the second iteration foil (c). The clips (a) attached to the steel rods and held the sensors in place at the correct angle. Ribs (b) held the rods in place and supported the silicon mold.

The molding process was similar to that of the first foil. The end caps were adjusted to hold the four rods and the pour hole sizes were increased to prevent the clogging issue from reoccurring. The sensors were covered in aluminum HVAC tape to protect the gel coated sensor cavity, and the cable containing the common wires that would exit the end of the foil was wrapped with fishing line between two of the steel rods to keep it in the middle of the foil. During pouring, the mold was tilted at an angle to reduce bubble entrainment and limit the risk of trapping air behind the ribs. After letting the mold sit for 24 hours the hardened foil was removed from the mold and the post molding process began.

Some air got trapped behind three of the ribs and created large gaps on the tail and smaller ones on the leading edge. Bondo was used to fill in the gaps and was sanded down to eliminate any bumps. The trailing edge of the foil was uneven

(a) just after molding

(b) sanded foil

(c) foil after painting

Figure 10: The foil during the final stages of development. The foil just out of the mold (a) required Bondo to patch some holes created by trapped air. A granite stone with sandpaper was used to smooth out any irregularities (b). The final foil was spray painted red (c) and sealed with clear finish to limit reflection of the green laser.

and there were a few bumps created by little pockets in the silicon rubber mold. To correct the imperfections, the molded foil was passed over sandpaper that was taped to a granite surface block. This process made the uneven parts of the foil more visible. After multiple passes with progressively finer grit sandpaper, the

HVAC tape was removed from the sensors and replaced with painters tape. The foil was hung and spray painted with a grey automobile primer and then sanded when dry. The purpose of this was to fill in any low lying spots that could not be fixed with sanding. Once the foil was smooth and consistently level, the foil was given one last coat of grey primer and then spray painted with multiple coats of flat red paint and primer. Between each coat, the foil was lightly sanded to remove any uneven spots. The red flat paint was chosen to reduce the amount of reflection produced when a green laser is shown on it. True red does not reflect green light and is therefore the most ideal color to paint the foil when using a green laser for flow visualization. Making the texture of the paint application flat instead of glossy also helped reduce glare. The type of paint used was not waterproof so to prevent the paint from staining the water, Rust-oleum American Accents Ultra Cover, a clear matte application, was applied to the foil to seal the paint and reduce water absorption by the foil.

Initially, the four rods extending beyond the tip of the foil were going to be kept by attaching a 3D printed foil tip. This would allow for studies involving different foil tip shapes to be easily executed without having to mold a different foil each time. Unfortunately, with limited time and complications with ensuring that the tip will stay in place while maintaining easy removal, this aspect was scrapped and the rods at the one end of the foil were removed.

The design of the second foil relative to the first iteration is much more versatile and useful. Because the major pieces that support the foil can be easily adjusted in a design program like SolidWorks and then 3D printed, cost and time to make the foil are significantly reduced. There is no machining necessary to make the parts and due to their small size, it takes little material to print. The number, size and location of the rods in the foil can be easily adjusted. Sensor clips can be

added anywhere along the span of the foil, on either side, since they only need to clip to the support rods.

CHAPTER 3

Sensor Test

The purpose of the following test was to ensure that the sensors worked properly when secured in the foil and could accurately measure changes in absolute pressure. This test also made it possible to observe the resolution of the sensor.

Figure 11: The dip test consisted of clamping the foil to the side of the tank at measured depths

3.1 Depth Test

The foil was clamped to the side of a tank with the position of the sensors discretely varied in water. Initially, the sensors sat just below the surface of the water. One minute of data at a recording rate of 48 Hz was collected for six different depths at 1 cm increments from 0 to 5 cm. For each reading, the sensor calibration was applied to the raw data. All sensors needed time to settle after being turned on so the first 40 seconds of data were removed. The mean value

for the remaining 20 seconds of data was calculated. To look at the differences in pressure, all points were referenced to the initial average pressure. Since the foil is at rest, experimental values were compared to theoretical values calculated using Equation 2 for hydrostatic pressure,

$$p - p_0 = \rho gh \quad (2)$$

where p_0 is the pressure recorded at the first depth, ρ is the fluid density, g is gravity, and h is the depth of the sensors.

3.2 Results

Figure 12 shows the difference in pressure from the initial reference value collected at 0 cm for each sensor. It is expected that the sensors measure a linear increase in pressure as the depth increases as calculated using Equation 2. All sensors follow a linear trend, though the linear fit trend is slightly off of the theoretical line. All pressure readings for every sensor indicate a distance of less than 1.5 mm away from the true depth which is well within a reasonable distance for human error.

3.3 Discussion

The water test provided good insight into the ability of the sensors to detect minor pressure changes. Despite the linear trend being slightly off from the theoretical value, 1 standard deviation for each point was no greater than 2.2 Pa. That is less than twice the resolution of the sensor. In addition it can be seen that the sensors drift above or below the theoretical line in the same direction for each point. Since each sensor is a separate reading of the depth, the fact that all three measure a drift from the theoretical in the same way supports the idea that the foil was not placed at exactly the right depth. In addition, the position of the

(a)

(b)

(c)

Figure 12: Differences in pressure from an initial reference depth of 0 cm. Collecting pressure readings with foil integrated MS5803-01BA07 absolute pressure sensors at known changes in depth of 1 cm from 0 to 5 cm. Sensors 1-3 (a-c) are shown with sensor 1 at the leading edge of the foil.

sensors could have also been affected by any slight rotation of the foil resulting in significantly different changes in pressure between the sensors. In hindsight, the experiment could have been improved by keeping the foil in place and simply increasing the water level. This would have kept the orientation of the foil the same for every recording but changed the depth at which the sensors were located.

The sensors have such a high resolution that they were able to clearly show any variation from the original orientation during the movement of the foil. Studies have shown that pressure differences generated by a moving foil at an angle of attack can easily reach values well into the hundreds of pascals [19] [20]. Given that the foil would be moving and producing pressures well above 100 Pa, the ability of the sensors to measure changes in pressures within two standard deviations, under 5 Pa, was a good indication that the foil would accurately measure pressures and detect fluid structures in further testing.

CHAPTER 4

Experimental Apparatus

For the next two chapters, the experiments being described take place in the flow visualization tow tank lab. In the lab resides a 0.9 x 0.9 x 4.3 m glass walled tank which allows for viewing from all directions. On top of the tank sits a carriage that contains two linear motors that provide motion in heave and surge while a rotational motor provides pitch. A motor moves the carriage along the length of the tank (x-axis) using a chain system, controlling the forward velocity of the carriage. Motion files created in a computer next to the tank are loaded into a program called Pwin32Pro2 which communicates and controls the motions of the carriage.

Figure 13: Schematic of test tank and foil apparatus [4]

The foil was connected to the tank using a clamp that was designed using modeling software and 3D printed with ABS plastic. By using a clamp method, the

risk of drilling into the foil with irreversible damage was eliminated. The process of 3D printing also made the construction of the clamp easier for those without the proper machining experience. The clamp held onto the four protruding rods and the first half inch of mold at the top of the foil. Bolts held the two halves of the clamp in place and an aluminum extension rod with flanges on either end was attached to the clamp. An aluminum extension rod with flanges on either end was attached to the clamp.

Figure 14: The mounting system for the foil. It is clamped and attached to an extension rod that is attached to the force sensor.

The extension rod lowered the foil further into the water so that the sensors could be as far into the water as possible, reducing surface effects. The flange and the other end of the rod was attached to the motor mount via a 6 axis strain gauge dynamometer (factory calibrated ATI Gamma SI-65-15) which was used to measure the forces exerted on the foil during each run.

The force data was recorded using a NI USB-6289 DAQ. Like the sensor tests, the pressure and temperature data was recorded using the NI USB-8452 SPI/I2C module. All data was consolidated in LabView and saved as a CSV file to be processed.

CHAPTER 5

Static Tests

Prior to conducting highly dynamic motion experiments, it was observed that when the motors were turned on, the noise level increased dramatically within the data collected. Before very involved tests were begun, it was necessary to test the ability of the sensors to detect the flow structure of a leading edge vortex above the noise from the motors.

5.1 Test setup and analysis

To test the noise threshold of the sensors and the foils ability to detect flow structures, the foil was moved through the tank in a straight line. The constant angle of attack was varied from 0 to 40 degrees at increments of 5 degrees while the pressure sensors were located on the side of the foil facing away from the incoming flow. The linear runs were conducted at a forward velocity of 0.3 m/s and the pressure was sampled at a rate of about 48 Hz. Each setup was only run once.

Once the runs were completed, the factory calibration matrices were applied to the pressure data. Each run was cropped to begin at the start of forward acceleration and the mean value of the data collected before the start of the run was subtracted from each sensor. A Butterworth, zero-phase digital filter was then applied to the data and plotted using MATLAB.

5.2 Results

The pressure signals in Figure 16 indicate that for low angles of attack, a vortex is either unable to be detected due to noise or one is not created at all. The first indication that the sensors detect any type of flow structure is when the angle of attack is increased to 15 degrees. Sensor 1 dips below 0.1 kPa before slowly

Figure 15: Schematic for the static test. The foil was towed in a straight line at a constant pitch resulting in a constant angle of attack. The angle was varied from 0 to 40 degrees.

rising back up to nearly 0 kPa. Sensors 2 and 3 dip down in pressure roughly 0.2 and 0.5 seconds later respectively. As the angle of attack is increased the change in pressure increases. The largest changes in pressure occurred when the angle of attack was between 30 and 40 degrees. In addition, the maximum pressure change for each sensor occurs earlier as the angle of attack is increased.

5.3 Discussion

The purpose of this test was to determine whether or not the sensors would be able to detect the changes in pressure created by a fluid structure, such as a shedding vortex, over the noise created by the motors. What was expected in the pressure signals was a dip in pressure as a shedding vortex moved over the sensors. Given that the sensors were positioned along the foil, there would be a time delay between when the sensors detected a shedding vortex as it moved downstream, starting at the leading edge. In addition, the signal strength of the detected vortex would diminish at each sensor. This is because the sensors are angled away from the path of the vortex which would travel straight behind the leading edge.

Fernandez et al. [19] have an example of this result where they accelerated a foil up to 0.3 m/s at an angle of 35 degrees. The greatest change in pressure they observed for their first sensor was around -0.25 kPa which is very similar to

Figure 16: The change in pressure at different angles of attack. The foil was accelerated to 0.3 m/s in 0.5 seconds with a constant angle of attack ranging from 0 to 40 degrees, (a) to (i) respectively. The formation of a leading edge vortex is detected when $AOA \geq 15$.

the pressure change of -0.26 kpa observed in Figure 16h when the foil was at 35 degrees. There is expected to be slight differences in the pressure readings between the studies, given that the sensors are not in the exact same place. However, the general trend is the same.

The higher frequency undulations of the filtered pressure sensor data, even when the angle of attack was positioned at 0 degrees, could have been a result of fluctuating hydrostatic pressure as the foil moved through the water. The movement of the foil produced a slight wake, resulting in changes in relative sensor depth. This would lead to the fluctuating pressure changes present for all sensors during every run.

This experiment provided enough evidence to show that the sensors were able to pick up the specific pressure signals created by flow structures. The signals were strong enough that they overcome the noise generated by the motor.

CHAPTER 6

Dynamic Tests

6.1 Test setup

The following experiment conducted was designed to examine the ability of the foil to detect minute changes in the flow structure when there is a physical change in the surrounding environment.

Figure 17: A schematic showing the setup using PIV (a) and an image of the cameras below the tank (b). Two cameras were placed underneath the tank on a carriage looking up at different angles to view the light sheet projected on the sensors. The foil was off-center in order to view the foil and the wake.

6.1.1 Particle Image Velocimetry

In order to detect the changes in the flow structures, a technique called Particle Image Velocimetry (PIV) was used to correlate pressure readings with physical flow structures. PIV uses a laser and high speed cameras to illuminate the motion of seeded particles to derive a series of velocity fields which can be used to quantify a flow field. [24]. For this experiment, a green laser, attached to another moving carriage located underneath the tank, was passed through multiple lenses

to create a large horizontal laser sheet. The sheet needed to be wide enough to illuminate both the area directly around the foil as well as the wake behind the foil. The water was seeded with $20\mu m$ particles at a density of about 20 particles per interrogation window size of 32×32 pixels. Using the results found by Willet and Gharib, this results in an velocity RMSE of 0.0089 m/s. [24] On the same carriage, two cameras were positioned to look upward to get the cross-sectional view of the NACA 0012 foil. The cameras were angled to have a difference of 30 degrees to produce a stereoscopic view of the foil and the surrounding particles. A single camera view is only capable of providing information regarding Δx and Δy . A stereoscopic view, like human eyes, provide two different views of an object which produces two additional equations that can be used to calculate Δz [25]. Scheimpflug adapters were attached to the cameras to reduce any blurriness within the image by adjusting the angle of the plane that is being viewed while green light filters of the same frequency as the laser were used to reduce the impact of reflected and refracted light. [25] In order to ensure that every run was recording the same instance, a TTL trigger was attached to the side of the tank that would start the PIV recording process when a specific point on the carriage passed over it. The recording captured the motion of the foil during the third cycle of motion.

6.1.2 False Wall

The location of the support structure of the tank blocked the view of a camera from seeing the space between the foil and the wall. By making a rigid, false wall the cameras would be able to get a clear view of the particles moving in this narrow space. To make the false wall, four, 0.5 inch, clear, acrylic panels were used. Holes were drilled close to the corners of the panels for connection points. Suction cups were utilized to hold the panels to the glass wall while threaded rod extended the acrylic panels out from the wall. This eliminated having to use sticky substances

that would leave residue on the glass and the parts could also be reused. A series of jam nuts and coupling nuts were used to make the wall adjustable. A guide wheel installed on the carriage kept the foil the same distance from the wall despite any bend in the glass that occurs due to water pressure. This made it possible to measure all connectors to the same length before installation to ensure a uniform distance. When installed, the false wall reduced the distance to that side by 0.149 m. To remove any bend in the center of the acrylic, suction cups with attached hard tubes cut to length were placed near the middle of the panels and could be moved if needed, depending on the location of the laser.

Figure 18: The suction cup attachments (a) and the acrylic false wall attached to the side of the glass tank(b)

6.1.3 Calibration

Calibration between each set of runs was necessary in order to account for the change in refracted light when the foil and cameras were moved closer to the wall. First the laser sheet and cameras were turned on and the lights turned off. The

cameras were then manually focused on the particles floating in the laser sheet. Once focused, the lights were turned on and the calibration plate was attached to the carriage so that the laser sheet fit within the slots of the plate. A picture was taken from each camera and then run through a calibration program provided in the PIV software. The calibration setting were saved to the file that would contain the data for that particular set of runs.

6.2 Test Matrix

All experiments were conducted with a sinusoidal motion in pitch and angle of attack to match the motions used by Mivehchi et al. [18]. The only parameter altered throughout testing was the nondimensional mean heave distance to chord length (H^*) as shown in Table 2.

Figure 19: (a) Top view of the foil showing the sinusoidal motion in heave along the tank. (b) Front view of the foil showing the mean heave position and location of sensors. Images modified from Mivehchi et al. [4]

The motion of the foil is fully defined by Eqs. 3 - 7. Eqs. 3 and 4 describe the two kinematic constraints where both pitch and angle of attack are sinusoidal.

$$\theta(t) = \theta_0 \sin(\omega t) \quad (3)$$

Table 1: Kinematics

Chord length	c
Heave amplitude	h_0
Angle of attack amplitude	α_0
Pitch amplitude	θ_0
Oscillation frequency	ω
Mean heave position	H
Carriage Velocity	U

$$\alpha(t) = \alpha_0 \sin(\omega t) \quad (4)$$

The instantaneous angle of attack can be defined by the pitch angle and the velocity of the foil through the water as seen in Eqs. 5:

$$\alpha(t) = \theta_0(t) - \arctan\left(\frac{\dot{h}(t)}{U}\right) \quad (5)$$

By breaking up the velocity into it's components, it is possible to solve for the heave velocity knowing the constant forward velocity. The heave position can then be calculated by integrating heave velocity from time 0 to time t.

$$h(t) = H + \int_0^t \dot{h}(t) dt \quad (6)$$

where

$$h^{max} - h^{min} = h_0 \quad (7)$$

This calculation is an iterative process where the defined parameters $(\alpha_0, h_0, H, U, \omega)$ do not change and the unknown value of θ_0 is iteratively changed in order to obtain a value for h_0 that does not exceed the parameters of Eqn. 7.

The results for this experiment are presented as a function of non-dimensional parameters. These parameters are listed in Table 2.

Table 2: List of parameters and experimental values

Strouhal number	$St = \frac{h_0 f}{U}$	0.4
Maximum nominal angle of attack	α_0	40
Heave amplitude to chord length	$h^* = \frac{h_0}{c}$	1
Mean heave distance to chord length	$H^* = \frac{\bar{h}}{c}$	[1.33, 4]

6.3 Analysis

The analysis is described in two parts. The first part explains the processing of the images taken with PIV techniques while the second describes the process of matching the PIV vector fields with the pressure and force data.

6.3.1 PIV processing

PIV analysis works by correlating the position of the particles captured by two images within a specific particle window size (example: 48x48 pixels) for a specified difference in time. Knowing the difference in time and the change in position of the particles, the correlation identifies the direction and magnitude of the velocity vector for that particular window in the image.

The recorded images collected using PIV were put through a processing algorithm in DaVis 8.1.4. The algorithm used a time series pyramid sum of correlation method as seen in Figure 20. During this process, the cross-correlations that have the same time separation are averaged together to obtain the averaged correlation maps. These averaged maps are then rescaled using a transformation equation so that they may be directly combined. The mean of these newly scaled images produces the final correlation image for time t_0 . This process is well explained in the article produced by Sciacchitano et al. [26]. The pyramid is shifted over by

one time-step and the process is repeated. It is the most accurate image processing algorithm but is very time consuming [26]. For this study, only a 3 image time length, Gaussian weighted, with a pyramid height of 1 was used.

Figure 20: Time-series pyramid sum of correlation diagram

No image pre-processing was conducted. Next defined were the Vector calculation parameters. The 'standard' correlation was used, a 3D vector validation limit of 5 pixels was selected along with multi-pass stereo cross-correlation with decreasing size. Two passes were done at an interrogation window size of 64x64 pixels followed by two passes with a window size of 48x48 pixels, all with an overlap of 50%. Vector post-processing was then conducted to remove all vectors that had a RMS value greater than 2 relative neighboring vectors. The removed vectors would be reinserted if the RMS value was less than 3. All empty spaces were filled with interpolated data and one pass of a 3x3 smoothing filter was applied.

6.3.2 Phase Averaging

Once all the images had been processed, the force, pressure and motor data needed to be filtered, re-sampled, aligned and averaged. First the raw data for force and pressure was calibrated using the respective factory calibrations. That data along with the heave and pitch information was filtered using a Butterworth,

zero-phase, digital filter. The mean values for each set of information was found using the information collected before the start of the motion and subtracted. The data was initially cropped when the carriage speed reached 0.2 m/s and re-sampled to match the rate at which the PIV images were collected.

To phase average the PIV data, after re-sampling, the time and heave motion data were cropped again to match the time period when PIV data was being collected. This was accomplished using the PIV trigger data and the number of velocity fields created. Each pressure value then lined up with a single velocity field.

Since the pressure and force data was collected over multiple cycles in each run as opposed to one cycle for the PIV data, the raw data did not need to be cropped as much. Only the first cycle was removed in order to ensure that only cycles where the fluid motions had stabilized were being analyzed.

Using the sinusoidal heave motion of the foil, the velocity fields, pressure, force, heave and pitch data could be placed in to bins relative to the phase of the heave motion. This was done using the Hilbert transform on the heave motion and obtaining the angle of the output for each point. The bin size selected was 10 degrees, starting at 0 and ending at 360 degrees resulting in 36 bins. The average value from each bin was obtained for each of the five runs. The five values for each phase step were averaged together to obtain one set of 36 values for heave, pitch, pressure, force and velocity fields. This was done for both values of H^* .

Finally, the forces were converted to the non-dimensional lift and thrust coefficients (C_L, C_T) using the following equations:

$$C_L = \frac{F_y}{0.5\rho U^2 A} \quad (8)$$

$$C_T = \frac{F_x}{0.5\rho U^2 A} \quad (9)$$

where ρ is the density of the fluid, U is the forward velocity of the foil, and $A = sc$ is the planform area of the submerged foil where s is the span and c is the chord length.

6.4 Results

6.4.1 Pressure Data

The foil is closer to the wall for decreasing H^* . When H^* is equal to 4, the foil is effectively in free stream with little effect from a wall. On the other hand, a H^* value of 1.33 means that the foil is very close to the wall at one extreme of its trajectory. Figure 21 compares the pressure measurements recorded when $H^* = 1.3$ and 4 for each sensor. At the start of the motion, as the foil moved in the direction of the wall, the pressure on the side of the sensors increased. As conservation of mass would suggest, as the foil moves towards the wall, the flow would have to move faster in order to get the same fluid mass through a smaller area, causing a decrease in pressure. However, the foil closer to the wall recorded a significantly higher pressure signal on all three sensors compared to the free stream case. This unusual observation is related to the decreased velocity between the wall and the foil and is further discussed in the discussion section. Before the foil reached the wall, completing the first half of the motion cycle, the pressure decreased on all three sensors as the foil leveled out to a zero angle of attack. The pressure for when $H^* = 4$ decreased at an earlier point compared to when $H^* = 1.33$. At that instance, the largest difference in pressure occurred for all three sensors.

For sensor 1, as Figure 21a shows, the pressure decreased dramatically to its lowest point for both cases at 4.625 radians. When the foil was further away from

(a)

(b)

(c)

Figure 21: Comparing the average pressure readings for sensor 1(a), sensor 2(b), and sensor 3(c) over one motion cycle for when $H^* = 1.33$ and 4.

the wall, there was a significantly larger decrease. In plot b of the same figure, sensor 2 registered a slight drop in pressure just as sensor 3 in plot c recorded an increase in pressure. The third sensor indicated a drop in pressure shortly after sensor 2. When the foil was closer to the wall, the pressure dropped sooner and significantly more than when the foil was away from the wall.

6.4.2 Force Data

Figure 22: Comparing the non-dimensional lift (a) and thrust (b) coefficients ($\Delta C_L, \delta C_T$) for $H^* = 1.3$ and 4

In Figure 22, the non-dimensional forces (C_L, C_T) are compared for the two cases of H^* . At the start of the motion, the foil moved in the direction of the wall and the angle of attack increased. Consequently, both lift and thrust increases for both values of H^* . A quarter way through the cycle as the foil reached the maximum angle of attack, the force on the foil peaked and the effects of the wall caused a greater force in lift and thrust for the foil closest to it compared to the free stream case. The lift force increased in magnitude in the negative direction as the foil moved away from the wall while the thrust increased positively. While moving away from the wall the foil closest to the wall had a smaller lift and thrust compared to the foil in free stream until it got far enough away from the wall.

6.4.3 PIV Results

PIV analysis was used to visualize the flow field around the foil and in its wake. This helped confirm what flow structures were present near and down stream of the foil during the sinusoidal motion. Figure 8, provides snapshots of the motion at the instances where the pressure drop was at its lowest point for each sensor, indicating the presence of a vortex. The lowest pressures occur at different phases for sensors 2 and 3 for different values of H^* but the shapshots are provided for both cases at every instance.

During the second half of the motion cycle, PIV analysis clearly indicated the presence of a shed vortex along the pressure sensor side of the foil. In both cases, a vortex formed on the leading edge of the foil, on the side of the pressure sensors, as it moved in the direction away from the wall. In the images collected, The first sensor detected the vortex at roughly the same phase. The vortex for $H^* = 4$ was closer to the foil relative to the one seen for $H^* = 1.33$ but not as well formed.

As the foil continued to move away from the wall, the vortex progressed along the foil, weakening in strength. The strength of the vortex appeared to be stronger when the foil was closer to the wall, possibly a result of the proximity of the other two vortices.

The alignment of the vortex with the pressure sensors does not completely line up. The first sensor detected the vortex location accurately as it measured a steep drop in pressure right as the vortex began to break from the leading edge. Sensor 2 recorded a drop in pressure just slightly before the time when the center of the vortex is above the sensor for both cases. The location of the vortex was located more closely over sensor 2 than sensor 3 for both values of H^* when sensor 3 registered a drop in pressure.

In Figure 22b,d,f,h,j, there appeared to be an additional counter-clockwise

(a) $H^* = 4$

(b) $H^* = 1.33$

(c) $H^* = 4$

(d) $H^* = 1.33$

(e) $H^* = 4$

(f) $H^* = 1.33$

(g) $H^* = 4$

(h) $H^* = 1.33$

(i) $H^* = 4$

(j) $H^* = 1.33$

Figure 22: PIV imaging of vortex shedding during dynamic motion. The foil was accelerated to a 0.2 m/s forward motion with a sinusoidal heave with a maximum angle of attack of 40 degrees. Images a,c,e,g,i correspond with a $H^* = 4$ (free stream) and images b,d,f,h,j correspond with $H^* = 1.33$ (close to wall). The PIV images chosen match the points in time when the sensors detected a vortex.

vortex that formed between the wall and the trailing clockwise vortex in blue. The additional vortex did not appear in the free stream case at any point. The strength of the clockwise vortex also seemed much stronger and the propagation much slower. The flow between the trailing vortex and the foil also appeared to increase dramatically relative to the free stream case.

6.5 Discussion

The proximity of an object to an oscillating foil will change the flow structure characteristics in the area surrounding the foil. The presence of a wall near an oscillating foil resulted in different instantaneous pressures and forces that could be used to help in navigation and obstacle avoidance.

6.5.1 Pressure sensors successfully detected structure change

The foil was very successful in being able to detect changes in pressure over the dynamic signal produced by foil. Figure 21 clearly showed the propagation of pressure drops for each sensor, indicate the movement of a shedding vortex across the foil for both values of H^* . As seen in Figure 23, the signals were very similar to those seen in Figure 16i where sensor 1 recorded the largest change in pressure first followed shortly by a smaller reading from sensor 2 and then sensor 3.

As mentioned in the results, there was what appeared to be a phase shift in the pressure readings from $H^* = 1.3$. Figure 23 shows the lowest point for each pressure drop, indicating the center of the vortex as it moves over each sensor. It is possible that this phase shift is a result of the additional vortex that is formed when the foil is near the wall. The wall was a barrier that prevented the flow from moving freely, concentrating the shed vortex that formed during the approach, making it stronger. Due to viscous forces, and the direction of the rotation, an additional vortex formed that rotated in the opposite direction. This created a back-flow,

Figure 23: Showing second half of the motion when the sensors detected a shedding vortex. The vertical lines show the low points for each sensor, indicating the point at which the center of the vortex was directly above the sensor.

forcing the oncoming flow to speed up underneath the foil to pass between the trailing vortex and the newly shed vortex as seen in Figure 24.

Figure 24: Blockage of flow created by a vortex pair (circled) that formed along the wall. The pair generated flow in the opposite direction (blue arrow) and redirected flow causing it to speed up (red arrow)

The increased flow velocity generated in this area could have pushed the shedding vortex along the chord of the foil more quickly resulting in a phase shift further down the foil. This would also explain why there was not a phase difference at the first sensor.

Effects from the trailing vortex lasted a lot longer when the foil was closer to the wall. It propagated much more slowly along the wall compared to the free stream case. This again, was a result of the viscous forces present at the wall and the back-flow that was generated.

The change in pressure detected when the foil approached the wall is characteristic of the ground effect. The pressure sensors indicated an increase in pressure relative to the free stream case which would create a larger pressure difference between the two sides foil resulting in greater lift. The force sensor measured an increase in lift at roughly the same segment in the cycle. Figure 25, shows the differences in the vector fields between the two cases as the foil approaches the wall. It is clear that the flow moves slower between the foil and the wall when proximity decreases, indicative of a pressure increase.

Figure 25: The difference in flow speed for $H^* = 1.3$ and 4 (a) between the foil and the wall (in square) and the corresponding pressure from sensor 1 (b). The flow speed decreases when the foil is near the wall resulting in higher pressure.

6.5.2 PIV and pressure alignment does not match

Though the PIV analysis can validate the presence of a shedding vortex and the changes in the flow field, the location of the vortex during propagation along the foil is not clear. The drop in pressure indicating the presence of a vortex and the images for sensors 2 and 3 do not line up very precisely. This however, does not mean that the pressure sensors are wrong. One explanation could be that the phase averaging of the images into bins of 10 degrees shifted the location of the vortex if there was a run that did not produce a clear image. Another could be that reflections off the surface of the water were detected as particles and altered the location of the vortex. There was difficulty in limiting the amount of reflection that occurred from surface vortices which created concave indents at the surface resulting in reflected light downward towards the cameras. This could also be the reason the vortex seems to grow in size and lose strength as it progresses along the foil. The reflected light could be creating too much noise in the PIV signal.

6.5.3 Force data measurements match pressure data

The change in force between $H^* = 4$ and $H^* = 1.33$ verified the changes in pressure measured on the foil. The force exerted on the foil was greater when the pressure difference increased as the foil approached the wall and then decreased as the pressure difference was less relative to the free stream case. The mean lift for our study was significantly higher when the foil had a closer proximity to the wall relative to a foil in free stream with values of 0.448 and -0.045 respectively. The general trend of an exponential increase matched that found by Mevichchi et al. [4], though the values in this study were significantly higher. Mivehchi found a mean lift of 0.15 at $H^* = 1.33$ which is less than half of the value found in this study.

The thrust coefficient appeared to have the inverse linear relationship of the

one found in the study by Mivehchi et al.. They found that as the foil moved further away from the wall, the average thrust coefficient decreased. In this study, it was calculated that C_T increased with a higher H^* value with a value of 0.903 for $H^* = 1.33$ and 0.918 for $H^* = 4$

After examining the PIV images more closely, it became apparent that the distance between the chord of the foil and the wall when parallel to one another was closer than expected. The distance should have measured 3.13 cm but the actual distance was 2.55 cm. This would result in an actual H^* value of 1.26. The decrease in distance could significantly alter the how the fluid moved around the foil. If we were to project the trend lines found for lift and thrust in the Mivehchi study, the lift would be still be much smaller than that found in this study and the thrust would increase and not decrease. The difficulty in measuring the mean values is that the differences are very small. Any small offset angle could easily shift the mean value up or down.

CHAPTER 7

Conclusion

A pressure sensor integrated foil was designed and developed using an iterative method in order to produce a simple and variable product. The foil used 3D printable parts and a urethane mold to create a rigid structure that held sensors flush with the surface of the foil. A series of tests were also conducted in order to test the ability of the sensor to detect fluid structures as well as the variation between fluid structures as the proximity of the foil to a wall was altered. The foil successfully detected shed vortices during both simple and highly dynamic motions. The pressure results were compared to force results and the vortices were verified using PIV techniques. Even though the timing of the pressure sensors and PIV images did not completely line up, the general procession of the vortex was accurate. The force and pressure sensors also detected changes in the flow field that were a result of ground effect. These qualities in a pressure sensor integrated foil are vital to creating a feedback system that could help AUVs navigate in difficult, more hazardous environments.

The foil designed in this study is not a final product. There are a few suggested changes that could be implemented into the next foil iteration. Since the foil is thin, placing pressure sensors on both sides of the foil at the same location along the span of the foil would be unrealistic with the NACA 0012. However, it would be possible to offset the sensors by a few centimeters to obtain readings from both sides of the foil. It could also be possible to integrate the sensors into ribs themselves. This would allow more flexibility in positioning the sensors to key locations along the chord length as identified in the study conducted by Persichetti [9].

For future testing, it is hoped that the noise produced by the motors could be further reduced to see what the pressure readings would be like at lower angles of attack and reduce the amount of filtering needed to get a clear picture of the signal. Another goal would be to create a foil with pressure sensors on both sides for a better understanding of what is happening around the entire foil.

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APPENDIX

Appendix A

This Appendix contains a list of the MATLAB files used to process the collected data, along with a brief description of what each one does.

SENSOR_TEST

Sorts and plots pressure data collected from the sensor tests for the purpose of checking the accuracy of the sensors.

STATIC_TEST

Plots pressure data for the static tests conducted on the sensor integrated foil for the purpose of assessing the ability of the foil to detect fluid structures (shedding LEVs).

PHASE_AVG

Filters, crops, re-samples, and phase averages data and saves the new data as .MAT files. The program can be used for pressure, force and PIV data.

PRESSURE_PLOTS

Generates plots for the pressure data comparing two different runs and saves them as .PNG images to a specified folder.

FORCE_COEFFICIENTS

This m.file calculates the lift and thrust coefficients and saves the data as a .MAT file.

FORCE_COEFFICIENTS_PLOTS

Generates plots for the lift and thrust coefficients. Compares the coefficients between two runs. Plots are saved as .PNG images to a specified folder.

DYNAMIC_VIDEOS

Generates videos from the PIV vector data. It generates a black foil with white shadow to represent the position of the foil in the laser sheet. A pressure plot and location plot are also generated into each frame. The video is saved as an .AVI file.

DYNAMIC_VECTOR_PLOTS

Generates velocity vector plots using the PIV vector fields. They are saved as .PNG files to the designated save location.

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