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Characterizing Tandem Fin Wake Using Lateral Line Inspired Sensors

by

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**CHARACTERIZING TANDEM FIN WAKE
USING LATERAL LINE INSPIRED SENSORS**

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Characterizing Tandem Fin Wake Interaction Using Lateral Line Inspired Sensors

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May 9, 2022

Abstract

Fish have demonstrated extreme agility underwater, a desirable trait for uncrewed underwater vehicles (UUVs) seeking to perform dexterous tasks in confined environments. Much of a fish's maneuverability can be attributed to the intricate interactions between the wakes generated by its biological control surfaces. One such interaction is between vortex wakes produced by dorsal and caudal fins. The phase difference between the oscillating fins influences the degree of thrust produced. The development of a robust feedback architecture capable of characterizing wake interaction will enable effective bioinspired vehicle motion using this phase difference.

This project replicates the lateral line organ in fish with commercially available pressure sensors and uses the lateral line's abilities to study the downstream effects of tandem foils, which represent simplifications of a bioinspired propulsion system. As these foils oscillate with variable phase difference, resulting force data show the production of thrust or drag. The lateral line response is analyzed for features which correlate with the foil phase difference, while computational fluid dynamics simulations provide insights on the observed wake. This process shows that, for decreasing phase and thrust, the magnitude of the dominant frequencies detected by the lateral line also decrease as a result of increased space between paired vortices or destructive interference between fin wakes. A trend line is developed to relate this feature to phase difference using a polynomial fit, finding a negative correlation with a coefficient of determination of 0.575.

Sensory systems capable of estimating tandem foil phase differences can directly relate such phase differences to foil thrust production, thereby providing the basis for a bioinspired feedback control system. Ultimately, a well-functioning control system enables more robust and agile underwater locomotion, required for difficult tasks such as closely studying coral reefs, maneuvering through subsea obstacles, and operating in formation with other UUVs.

Keywords: biomechanics, flapping foil, hydrodynamics, lateral line, maneuvering, sensing, tandem foils, uncrewed underwater vehicles

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1 Introduction

Uncrewed underwater vehicles (UUVs) provide valuable capabilities to the scientific community and the naval service, as they remove the human risk and constraints associated with deep-sea diving, reef exploration, mine clearing, hull inspections, reconnaissance, and other comparable activities. UUVs have typically used propellers for propulsion, requiring them to choose between efficient propulsion over long distances or maneuverability. In many cases, the propeller arrangement needed for long distance travel is not suitable for making tight turns or lateral movements.

These potential shortfalls in maneuverability can be addressed by drawing inspiration from biology, a concept known as bioinspired design. In nature, fish have developed the ability to maneuver through water with impressive agility, largely due to their flexibility and their fins' ability to create thrust in nearly any direction. The field of underwater robotics has drawn inspiration from natural systems with the hope of replicating the observed effectiveness in engineered designs. One example, shown in Figure 1, is the Pilotfish UUV from Nekton Research, LLC, which uses multiple flapping fins to achieve rapid vehicle reorientation and minimal stopping distance (Hobson et al., 1999).

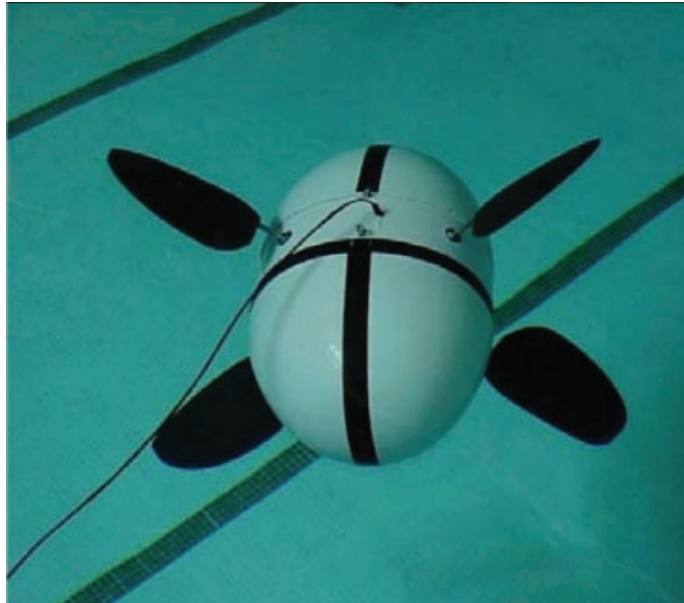


Figure 1: Pilotfish UUV design from Nekton Research, LLC, which made use of four, reorientable fins (Hobson et al., 1999).

While finned vehicles such as the Pilotfish present remarkable improvements on agility, they lack efficiency. This project explored the use of a tandem fin propulsion system for bioinspired robotics. Tandem fins differ from single fins, with two fins aligned in the streamwise direction that work together to achieve variable thrust. As these fins move, the degree of coordination between their movements, known as the phase difference, provides variable propulsion enhancements over single fins. An example of tandem fins is shown in Figure 2, with chronological cross sections of bluegill sunfish dorsal and caudal fins. These two fins, located inline with one another in the direction of streamwise flow, constitute tandem fins and are the propulsion system of greatest interest to this research project. In Figure 2 the progression of the angular position of the dorsal fin, θ , and caudal fin, θ_c , demonstrates that the fins move out of synchronization. The quantity of their respective cycles by which the fins differ is the phase difference.

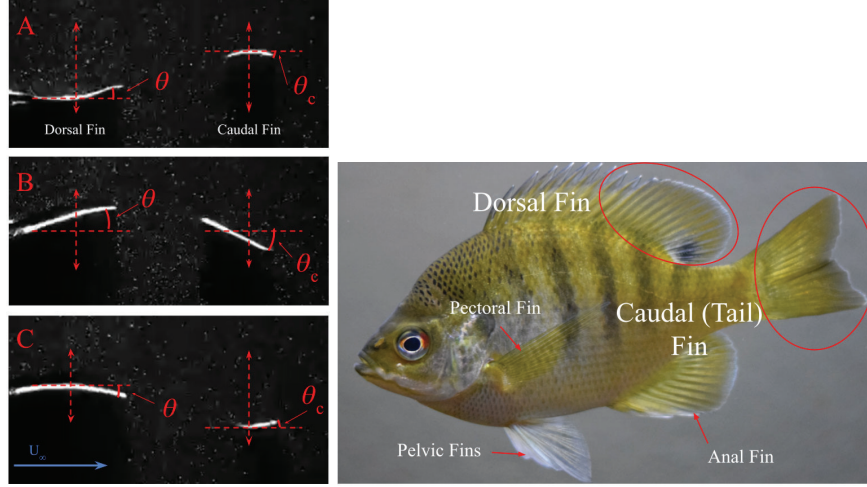


Figure 2: Chronological progression (A-C) of a dorsal and caudal fin cross section with fin angular position and free stream velocity, U_∞ , marked (left). Fin anatomy of a bluegill sunfish, the specimen used to create the left images (right).

If these fins are to be used in bioinspired robotics, they will require a method capable of fine-tuning their movements based on their performance. Previous research suggests that the behavior of these fins should be detectable using downstream pressure sensors, such as those inspired by the lateral line of fish (DeVries et al., 2015; Fernandez et al., 2011; Klein and Bleckmann, 2011). This presents a method for a bioinspired control system.

The goals of this project are to

- Develop means for a lateral line-inspired fin phase control loop.
- Identify numeric characteristics of tandem fin vortex wakes that can be observed using an artificial lateral line.
- Infer a relationship between measured vortex wake traits and tandem fin phase difference.
- Verify the propulsion benefits of tandem fin phase control.

These objectives support the development of a bioinspired feedback control loop, as well as justification for its benefits. A hypothetical bioinspired control system is shown in Figure 3. This loop represents the interactions between components in a robotic system that uses tandem fins for propulsion. The plant is the actionable structure in the system, the bioinspired propulsion structure. This plant receives electrical signals from a controller, which converts desired system effects into a signal compatible with machinery. The feedback loop is robust against outside disturbances because it compares the actual effects of the fins, their downstream wakes and induced forces, to the effects desired by the operator, referred to as the “reference signal”. The resultant “error signal” is delivered to the controller for “translation”. In order to do this, the system requires a sensor capable of estimating the effects of the fins based on their downstream effects. This section of the control loop is boxed in red, as it was the primary focus of this project. While the physical experimentation in this project leveraged a rudimentary plant and control system, the sensor development was prioritized as the primary deliverable.

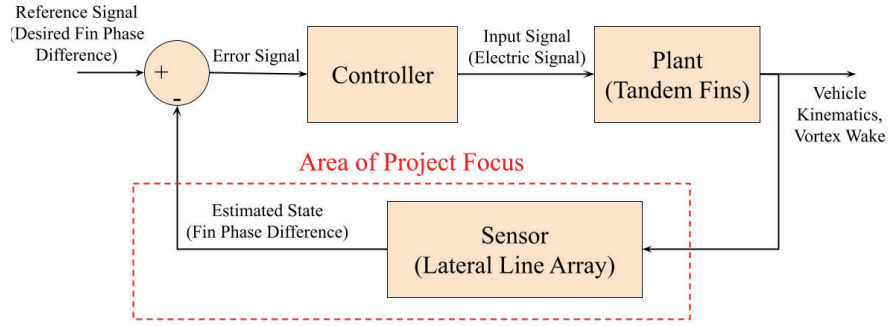


Figure 3: The basic structure of a feedback control loop, with the project focus boxed in red.

This research project enables future bioinspired systems to use tandem fin arrangements for propulsion benefits by developing a means for a feedback control loop. To do this, the complex fin movements and shapes used by fish are simplified as two-dimensional (2D), rigid, NACA0016 foils that oscillate back and forth. Experimentally, these foils are actuated with varying preset phase differences while a downstream pressure array recorded data. This pressure array was inspired by the lateral line sensory organ in fish. As presented later in this report, data sets from the sensors were analyzed for numeric traits, called features, that change with the preset phase differences between the foils. This develops the lateral line as the “sensor” in the bioinspired feedback control loop given in Figure 3. In addition, this project records the thrust force produced by the tandem foils at their various phase differences, which verify the potential thrust improvements of tandem fin systems.

2 Background on Biological Systems

To create a bioinspired control system for underwater locomotion, it is necessary to understand the basic morphology of fish and the physical properties of the water they manipulate to achieve their agility. After understanding the structures and behaviors observed in nature, they can be replicated in a laboratory environment and applied to engineered designs. Overall, drawing inspiration from a fish’s underwater sensory organs presents a method for detecting fin wake effects, which has distinct applications for the development of future feedback control systems.

2.1 Vortex Wakes

The interactions between a body and its surrounding fluid produces coherent structures in the fluid that are characteristic of the type of interactions present. For example, when a canoe paddle passes through water, it produces local areas of swirling water that linger for several seconds. When the paddle is pulled faster, the swirling is stronger and lasts longer. In this example, the paddle is a body, the water is a fluid, and the areas of swirling water are coherent structures that indicate the type of interaction between the paddle and the water.

For finned propulsion, the size, spacing, and density of downstream coherent structures produced also indicate the level of forward force, or thrust, developed by the fin. As shown in Figure 4, two-dimensional (2D) flapping fins produce trails of swirling water. Each swirling location, shown with pairs of black arrows in the figure, is called a vortex, and the trail of vortices is known as its wake. Each time the fin flaps, it produces a new vortex that circulates in the opposite direction of the previous vortex. The geometry of the resultant vortex wake indicates the direction of streamwise force generated. Streamwise refers to actions in the same direction as the overall fluid flow, which proceeds from left to right in Figure 4. When clockwise vortices are located above counterclockwise vortices, in terms of the coordinate system shown in Figure 4, they push the water between them back toward the foil. This water is called a momentum jet. Likewise, when the counterclockwise vortices are located

above the clockwise vortices, the momentum jets are directed away from the foil. These momentum jets can be related to the force on the foil using the momentum equation,

$$\int_{t_1}^{t_2} \vec{F} dt = m(\vec{v}_2 - \vec{v}_1),$$

where $\vec{F}$ is the average force on the foil, t_1 and t_2 are points in time before and after the water was placed in the momentum jet, m is the mass of the water in the jet, and $\vec{v}_1$ and $\vec{v}_2$ are the free stream water velocity and the velocity in the jets. Alternatively, by Newton's Third Law, a change in streamwise fluid momentum is met with an equal and opposite change in the foil's upstream momentum. In the case of Figure 4 (A), the momentum jets pointed toward the foil indicate that the foil is experiencing a drag force, while the momentum jets pointed downstream of the foil in Figure 4 (C) indicate an increase in the foil's upstream momentum. Likewise, the jets in Figure 4 (B) have no streamwise velocity component, showing that the foil has experienced no net streamwise force (Egan et al., 2014). This demonstrates that downstream characteristics of a foil's wake offer qualitative and quantitative insights about the foil's corresponding thrust development.

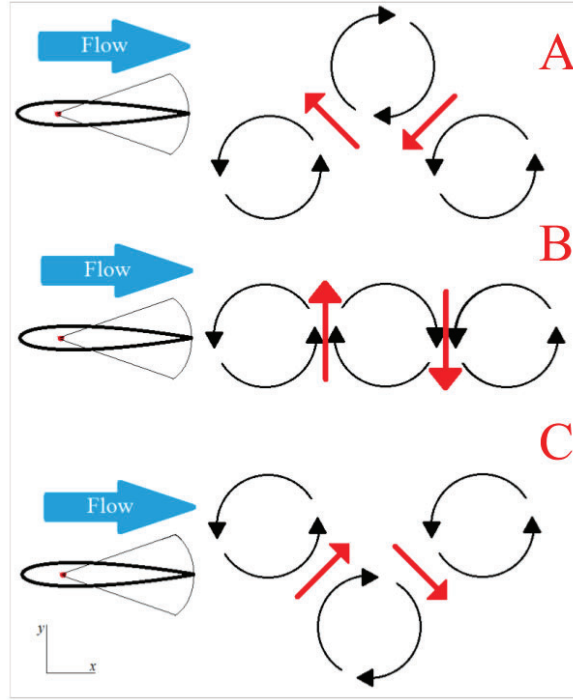


Figure 4: Three general vortex wakes produced by a pitching foil moving toward the left side of the figure, with the momentum jets between vortices marked with red arrows. The direction of each vortex's water circulation is shown with black arrows. (A) Vortex wake generated for backward force production, drag. (B) Wake for no streamwise force production. (C) Wake for forward force production, thrust. Adapted from Egan et al. (2014).

2.2 Fin Propulsion

Beneath the surface of the water, organisms must contend with higher viscosity and larger drag forces than organisms that live above the surface. In response to these challenges, marine animals, such as cartilaginous and bony fish, have developed the ability to use multiple control surfaces in tandem, enabling smaller turn radii and increased efficiency (Bandyopadhyay, 2002; Drucker and Lauder, 2001; Lauder and Drucker, 2004; Triantafyllou, 2020), which indicates improved agility. Figure 5 shows the basic fin placement for a ray-finned fish using the well studied bluegill sunfish. Drucker and Lauder (2001), and Akhtar et al. (2007) observed that, during forward propulsion, ray-finned fish beat the water with their dorsal fins and caudal fins in a periodic motion consisting of two steps: heave and pitch. Figure 5

illustrates a simplified caudal fin cross-section shown from the top, where the pitch motion is the angular change in the fin's orientation, while the heave motion is its lateral translation. The movement of this single fin is of the form

$$\text{Heave} : y(t) = A \sin(2\pi f_h t) \quad (1)$$

and

$$\text{Pitch} : \theta(t) = \theta_m \sin(2\pi f_h t + \psi), \quad (2)$$

where $y(t)$ is the position of the fin's leading edge, A is its amplitude, f_h is the flapping frequency in Hz, $\theta(t)$ is the orientation of the fin relative to an inertial reference frame aligned with the incoming uniform flow, θ_m is the maximum pitch, ψ is the phase shift between the two components of the fin motion, and t is the instantaneous time.

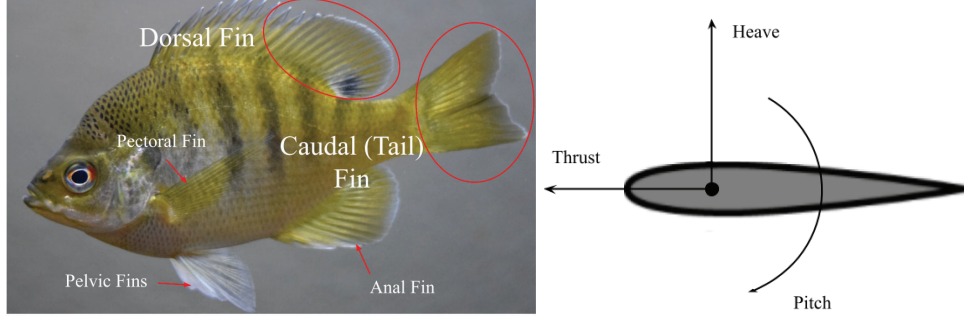


Figure 5: Diagram of the fin arrangement on bluegill sunfish (left). Top view of a 2D foil used to represent a fin cross-section, where a superimposed coordinate grid shows the direction of fin motions (right). The left side of the cross-section corresponds to the left side of the bluegill soft dorsal or caudal fin, which are circled in the left image.

2.2.1 Strouhal Number

During forward movement, fins create vortex wakes such as those described in Section 2.1. This motion is characterized by a nondimensional feature known as the Strouhal number. The Strouhal number represents the ratio between forces contributed by the fin and the inertial forces already present in the water. The Strouhal number is calculated as

$$St = \frac{Af}{U_\infty}, \quad (3)$$

where the characteristic length, A , is the peak-to-peak amplitude of the oscillating fin, U_∞ is the free stream water velocity, and f is the fin's flapping frequency. Strouhal values below one generally produce vortex wakes, while higher values produce disorganized, turbulent wakes. Typically, the Strouhal number varies from 0.2 to 0.4 for nearly all animals that flap foils for propulsion, including insects, birds, bats, and fish, and this range is associated with optimized energy input and thrust output (Triantafyllou et al., 1993). In the case of most bony fish, this value is near 0.25 for steady, forward propulsion (Drucker and Lauder, 2001; Nudds et al., 2014).

2.2.2 Tandem Fin Use

During forward movement, the vortex wake produced by the dorsal fin flows over the caudal fin, interacting with the caudal fin's vortices and inducing an increased suction zone on the downstream fin (Akhtar et al., 2007; Drucker and Lauder, 2001). This practice allows a fish to change the effective angle-of-attack of its caudal fin, relative to the free-stream velocity, and generate improved thrust, power, and efficiency. To maximize performance, the fins flap out of phase with one another (Drucker and Lauder, 2001), and the phase difference causes the effective coefficient of thrust on the caudal fin to change, as shown in Figure 6. This figure shows a combination of experimental and simulation-derived thrust coefficients for 2D cross-sections of a bluegill sunfish caudal and dorsal fins. The solid line shows the variation in caudal fin thrust coefficient with phase difference, while the dashed line shows the sum

of the caudal and dorsal fin thrust coefficients. This line appears lower than the solid line because the dorsal fin produced a negative thrust, although the caudal fin produced a large enough force to overcome this negative thrust. The thrust coefficient, C_T , is related to the fin's instantaneous thrust force by

$$C_T = \frac{F}{0.5\rho U_\infty^2 A_s}, \quad (4)$$

where F is the thrust force, ρ is the water density, U_∞ is the free stream water velocity, and A_s is the fin surface area exposed to the flow. The dorsal fin moves according to (1) and (2), while the caudal fin moves according to

$$\text{Heave} : y_c(t) = A_c \sin(2\pi f_h t + \phi) \quad (5)$$

and

$$\text{Pitch} : \theta_c(t) = \theta_{mc} \sin(2\pi f_h t + \psi_c + \phi), \quad (6)$$

where ϕ represents the phase difference between the two fins, A_c represents the caudal fin's heave amplitude, θ_{mc} represents its maximum pitch angle, and ψ_c represents the phase difference between its heave and pitch motions. In nature, A_c and θ_{mc} are slightly greater than their dorsal counterparts (Drucker and Lauder, 2001), although specific values vary depending on the fish species and behavior. The optimal ϕ for a pair of tandem fins differs depending on anatomy and fin spacing. As seen in Figure 6, a bluegill sunfish can achieve maximum thrust at a phase difference of $\phi = 48^\circ$, where the caudal fin experiences over three times the thrust possible with a single fin making the same motions. Other phase differences can achieve smaller increases or even decreases in thrust (Akhtar et al., 2007). While the results in Figure 6 are specific to the bluegill sunfish anatomy, tandem fins have been shown to improve thrust for a variety of different foil spacing (Boschitsch et al., 2014; Muscutt et al., 2017) and flapping frequencies (Muscutt et al., 2017). This concept is further explained in Section 3.1.2.

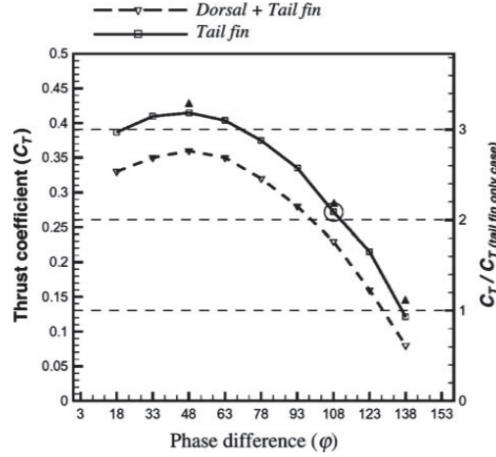


Figure 6: Variation of caudal, or tail, fin thrust coefficient with phase difference. The vertical axis is the thrust coefficient in absolute and normalized terms, while the phase difference is in degrees (Akhtar et al., 2007). The solid line shows the thrust coefficient on the caudal fin, while the dashed line shows the combined forward thrust coefficient for the caudal and dorsal fins.

The ability to achieve thrust improvements without changing the amplitude or frequency of the fins' motion is a desirable trait for UUVs. However, because the phase difference between the fins' motion can induce both improved and worsened propulsion, a future, tandem fin-propelled UUV will require a system capable of detecting the phase difference between its fins and fine-tuning this measured phase difference, in-situ, to meet the overall system needs. Based on the discussions above, the nature of the fin interactions with the water will leave distinct downstream wakes. Section 2.3 explores the lateral line wake detection

strategy used by fish, which has applications to coordinating tandem fin motions. Section 4 describes a methodology for using a lateral line to study the wakes behind two tandem hydrofoils. Although fish fins move according to both pitch and heave motions in nature, this project only oscillated foils according to pitch motion. This made an experimental study both feasible and achievable using equipment and infrastructure at the United States Naval Academy (USNA). The heave motion seen in natural systems may be implemented in future work, and the results should be similar.

2.3 The Lateral Line Organ

Fish possess a unique sensory organ that allows them to detect both smooth and oscillating flow over their bodies, called the lateral line. The lateral line consists of a network of superficial and canal-embedded neuromasts, which deflect when fluid flows past them and stretch clusters of hair cells. These hair cells, in turn, trigger neurons to fire and transmit signals to the fish's brain (Dijkgraaf, 1963). The general layout of the lateral line and the basic structure of the neuromasts are depicted in Figure 7. The superficial neuromasts (SN) exist on the fish's skin and protrude into the boundary layer. These biological sensors detect slow, steady changes in flow and have been characterized as velocity-sensitive (Montgomery et al., 2001). They typically detect flow changes that take place below 30 Hz (Coombs et al., 2001). The second group, the canal neuromasts (CN), exist as domed structures within small, fluid-filled canals that run beneath the surface of the fish's skin. This canal is exposed to the outside flow through a series of pores. A CN perceives oscillating flow as pressure differences; when the pressure at one pore is different from the pressure at a pore farther down the canal, the canal fluid moves toward the pore of lower pressure, causing a deflection in the CN. When pressure changes slowly, typically below 30 Hz, the viscous forces within the canals prevent fluid movement (Denton and Gray, 1989), effectively acting as a high-pass filter for pressure frequencies. Thus, CNs typically sense changes in flow that take place between 30 Hz and 150 Hz (Coombs et al., 2001). The pressure difference perceived by CNs can also be interpreted as a flow acceleration across the surface of the fish.

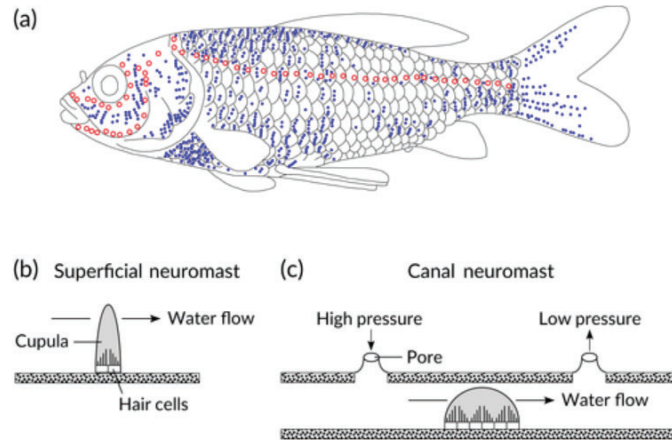


Figure 7: (a) Basic anatomy of the lateral line in a fish, where blue dots represent superficial neuromasts (SNs) and pink circles represent pores of the canal network. (b) Diagram of an SN. (c) Diagram of a canal neuromast (CN) (Mogdans, 2018).

The lateral line allows fish to detect flow characteristics and collect information about their surroundings that are undetectable by visual or acoustic means. By detecting acute pressure and velocity changes, the lateral line enables fish to "feel" objects that are several body lengths away, track prey by their wake (Montgomery et al., 1995), school with other fish, align with the local current (Montgomery and Baker, 1999), and adjust their gait for more efficient swimming in the presence of periodic flow (Liao et al., 2003). A particularly telling testimony to the effectiveness of lateral lines are the lifestyles of blind (Windsor et al., 2010) and abyss-dwelling fish, which have been observed tracking prey and sensing obstacles with a spatial resolution of 1 mm (Hassan, 1986). The ability of the lateral line to sense

the presence of structures and flow characteristics without the fish's body coming in direct contact with them is also known as "touch at a distance" (Dijkgraaf, 1963).

Most importantly, the lateral line enables fish to take advantage of wakes in the water to swim more efficiently. One such wake is the Karman vortex street, which is a simple trail of counter rotating vortices that are indicative of drag force production. This wake is similar to the sketch in Figure 4 (A), except it is formed behind a cylinder instead of a pitching foil. As Liao et al. (2003) observed, trout placed in a cylinder's Karman vortex street detected the vortices' positions and overall shedding frequency. The fish then adjusted their gaits to match the vortex shedding frequency and swam 180° out-of-phase with the vortex street, resulting in decreased muscle activity and, therefore, lower energy consumption. This behavior is depicted in a series of frames in Figure 8. Because the vortex wake was entirely invisible to the trout, the fish must have felt the flow characteristics and responded with a behavior that increased swimming efficiency (Liao et al., 2003). This figure shows the flow behind a cylinder as captured with particle image velocimetry (PIV). With this technique, a water tunnel was seeded with microscopic glass beads which were too small to sink to the bottom of the tank. A laser light sheet shone across the tank as the water flowed past the cylinder and trout, and a computer calculated the local velocity of the water by tracking each glass bead in the laser sheet. Areas with counterclockwise circulation are colored blue, while areas with clockwise circulation are colored red. This technique offers an excellent method for inferring wake characteristics, but it is time consuming and computationally expensive. For this reason, it was not conducted during this research project, but will be a useful component of future work.

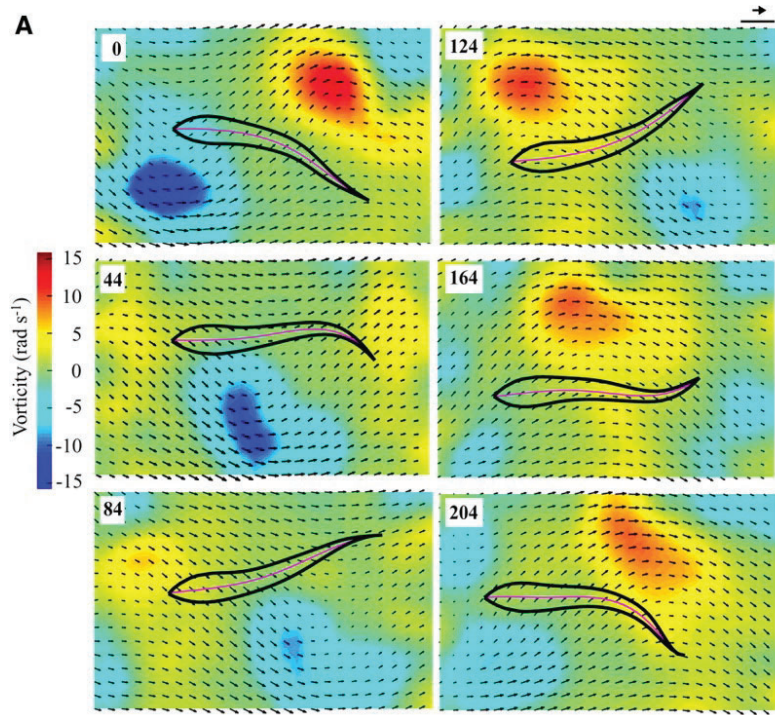


Figure 8: Top view of a trout body outline slaloming through a Karman vortex street. The flow field was created with particle image velocimetry (PIV), and subplots are ordered sequentially proceeding from top to bottom on the left, then top to bottom on the right (Liao et al., 2003).

2.4 Biological Inspiration

The slaloming behavior demonstrated by trout and the knowledge that fish fins induce similar vortices in their wake has spurred the underwater robotics research community to study and create control systems that utilize similar lateral line sensors to achieve more efficient or effective swimming in UUVs. Fish have already demonstrated that pressure-based control

loops can be used to swim more effectively, and a lateral line sensing mechanism can provide the wake feedback necessary to develop effective tandem fin propulsion. The overarching theme of this project was to draw inspiration from the propulsion and wake sensing systems observed in nature to enable a future control loop for tandem fin propulsion systems.

3 Background on Engineered Systems

Previous researchers have worked to understand and replicate the tandem fins and lateral line sensing described in Section 2 in both the laboratory and computational environments (Boschitsch et al., 2014; Fernandez et al., 2011; Gopalkrishnan et al., 1994; Muscutt et al., 2017). These studies investigated the effects of vortex wake interaction, the nature of 2D, pitching, tandem foil propulsion, and how artificial lateral lines can perceive vortex wakes. Based on a comprehensive literature review, however, no previous group has used lateral lines to perceive the wake behind tandem foils. These previous groups have solely demonstrated that the observed fish capabilities in Section 2 can be applied to human-made robotics, but tandem fin control systems remain largely unexploited by the underwater robotics community. Developing a method for tandem fin feedback control will enable future systems to take advantage of the research previous groups have already conducted on bioinspired robotics. Ultimately, this project seeks to bridge the identified gap between tandem foil and artificial lateral line research, as well as their broader implementation in robotic systems.

3.1 Two-Dimensional Wake Interaction

Although fish fins are flexible, three-dimensional (3D) shapes, simplifying their fluid interactions using 2D rigid bodies with similar cross-sections has allowed for expedited experimental analysis of their wake interactions. When vortex wakes interact, the individual vortices generally interact either constructively, destructively, or by pairing (Gopalkrishnan et al., 1994). When foils are phase shifted such that vortices with the same direction of circulation meet at the trailing edge of the downstream foil, the vortices build constructively into a single, larger vortex. The two foils effectively create one vortex street with increased circulation. When foils are phase shifted such that oppositely rotating vortices meet, the vortices combine destructively, resulting in dramatically decreased circulation. The resultant vortex street is of the same shape as the vortex street for a single foil, but with reduced circulation. When the foils are not in such a phase that would cause one of the wakes above, oppositely rotating vortices pair downstream of both foils and drift away from the center line. This creates a wider vortex street that a single foil would produce (Gopalkrishnan et al., 1994).

3.1.1 Effects of Two-Dimensional Wake Interaction

Due to the complex fluid dynamics equations governing the wake interactions between flapping foils, the effects of wake interaction have been largely studied through experimental means (Boschitsch et al., 2014). The wake interaction directly impacts the thrust and power coefficients on the trailing foil, with the largest coefficients associated with constructive vortex interactions and the lowest coefficients associated with destructive interactions (Boschitsch et al., 2014; Gopalkrishnan et al., 1994; Muscutt et al., 2017). Additionally, the foil spacing also influences the vortex interaction. When the spacing between two foils is greater than one half of their chord length, the wake interaction has negligible impact on the dynamics of the upstream foil (Boschitsch et al., 2014).

3.1.2 Parameters Governing Two-Dimensional Wake Interaction

The degree of wake interaction is dependent on the phase difference between the foils, the Strouhal number, and the foil spacing (Boschitsch et al., 2014; Muscutt et al., 2017). These parameters dictate the mode of wake interaction between the foils, as well as the strength of their impact on the downstream foil thrust coefficient, which can be observed in Figure 9. This figure compares the coefficients of thrust, C_T , for a single fin with those of a downstream fin in a tandem configuration. As the lighter regions indicate, various combinations of phase difference, ϕ , and fin spacing, $\frac{s}{C}$, cause large improvements in downstream foil performance, e.g. the area labeled A, with C_T^* at $\frac{s}{C} = 1.5$ and $\phi = \frac{7\pi}{4}$. In Figure 9, s represents the foil spacing in meters, while C represents the foil chord length in meters, making $\frac{s}{C}$ the

chord-normalized foil spacing. Location B in Figure 9 shows a phase difference where the same foil spacing had unimpacted or worsened thrust. Boschitsch et al. (2014) used foils that only made pitching motions to create Figure 9, but similar results also occur for foils that pitch and heave (Gopalkrishnan et al., 1994; Muscutt et al., 2017). Because the same foil spacing can achieve either improved or worsened thrust, depending on the exact phase difference between pitching foils, it is desirable to develop a system capable of detecting and controlling this value.

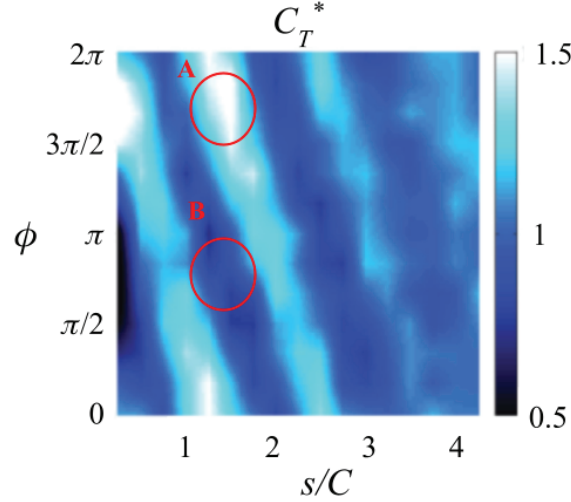


Figure 9: Variation of normalized thrust coefficient on a downstream foil with respect to phase difference in radians, ϕ , and foil spacing in units of foil chord lengths, $\frac{s}{C}$. The coefficients are normalized by dividing by the coefficients experienced by a single flapping foil under the same parameters, as $C_T^* = \frac{C_{single\,foil}}{C_{tandem\,foil}}$. Lighter regions indicate parameter combinations that offered improved thrust relative to a single flapping foil, and darker regions indicate combinations that worsened thrust (Boschitsch et al., 2014). (A) provides an example of a phase shift and foil combination where the downstream foil achieved improved thrust, while (B) refers to a combination that yielded worsened thrust.

3.2 Artificial Lateral Lines

Several groups have developed artificial canal neuromasts using micro-electromechanical systems (MEMS) (Chen et al., 2007; Fan et al., 2002; Kottapalli et al., 2014) or optical sensors (Klein and Bleckmann, 2011). However, because CNs detect pressure differences across the surface of fish, many researchers have implemented off-the-shelf pressure sensors to achieve similar effects (DeVries et al., 2015; Venturelli et al., 2012; Zhang et al., 2015). These configurations eliminate the need for a canal, as the differential pressure between two points can be calculated by simply subtracting the measurements from adjacent sensors. The lateral lines become linear arrangements of sensors, such as the arrays built by Venturelli et al. (2012) and Fernandez et al. (2011), shown in Figure 10. Figure 10 (left) shows a linear sensor array quite similar to the one this project constructed in Section 4.3.1. It consists of two rows of pressure sensors mounted inside a plastic tube, and the upstream side of the tube is streamlined. The sensors make contact with the water through holes in the body's surface, and the tube is supported by a metal rod perpendicular to its center axis. The array on Figure 10 (right) is a similar design with sensors mounted inside one side of a plastic tube. Section 3.3 describes their abilities to detect vortex wakes and perceive useful features from object wakes.

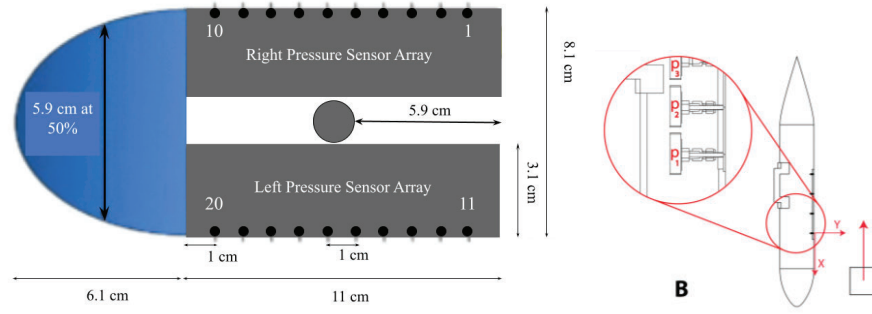


Figure 10: Linear pressure sensor array designed to detect oncoming vortices using absolute pressures, where each black dot represents an MS5401-BM pressure sensor (left) (Venturelli et al., 2012). Linear array of Honeywell 19C015PG4K pressure sensors used for classifying nearby objects (right) (Fernandez et al., 2011).

3.3 Vortex Wake Feature Extraction with Lateral Lines

Pressure sensor arrays have demonstrated the ability to draw both qualitative and quantitative characteristics from object wakes. As described in Section 2.1, vortices produce low pressure regions in the water. Vortex streets create perceptible undulations in the readings from differential pressure sensor arrays, as seen in Figure 11. In this figure, the pressure data for each sensor is shown over five seconds by using blue to indicate low pressure, and red to indicate high pressure. A single sensor's output can be seen by beginning at a point on the left side of the plot and proceeding strictly horizontally while consulting the color key for the detected pressure. This data was generated by Venturelli et al. (2012) when they placed the array shown in Figure 10 (left) behind a cylinder in steady flow. Because the vortices generated create low pressure regions in the water, they caused spikes in pressure sensor readings as they passed individual units. This can be seen in the alternating bands of red and blue over the course of each sensor's readings, and an example of this is shown in the figure within a black, dotted box. When the same vortex was detected by progressively more distant sensors, the time taken between each detection of the vortex provided information about the flow speed carrying it past the sensors. This can be visualized in Figure 11, as the diagonal progression of the blue and red signatures when proceeding from the top of a plot to the bottom. This time is indicated for an example vortex using blue arrows on the left plot. Similarly, the time between each vortex detected at the same unit provided the vortex shedding frequency.

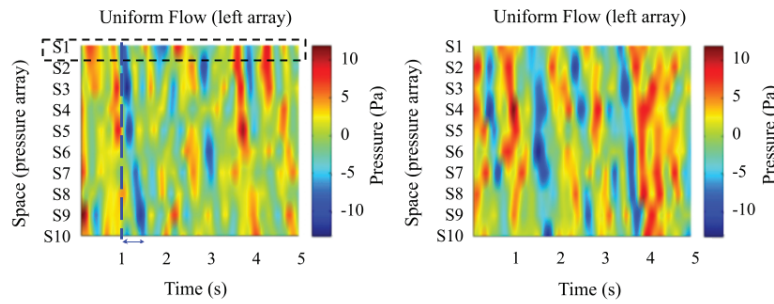


Figure 11: Pressure readings from each sensor on the artificial lateral line shown in Figure 10 (left). Higher numbered sensors on the same plot are farther downstream than the lower numbered sensors. Pressure readings are encoded by color and correspond to the vortices shed by an upstream cylinder (Venturelli et al., 2012). The pressure reading for a single sensor over the course of the entire trial is shown in a black, dotted box. A blue, dashed line shows the time when a vortex was first detected, and the blue arrows show the time the vortex spent traveling across the sensor array.

A single sensor pair exposed to a vortex wake produces a periodic differential pressure response, and this can be observed in Figure 12 (middle). The pressure sensors are able to detect the vortices at varying distances, although the magnitude of the vortex pressure signatures decreases with distance. In Figure 12, a lateral line moved near to and away from a cylinder's vortex wake detected the vortices with nearly constant frequency. The frequency perceived by a sensing array is relatively constant when its movement within the street is small, as inconsistent frequencies occurred primarily at points in time when the array was moving fastest (Chambers et al., 2014). In the case of flapping foils, the vortex shedding frequency, f , and free stream flow speed, U_∞ , are two of the three terms related to the Strouhal number, according to Equation (3). This Strouhal number corresponds directly to the efficiency, thrust, and power of the foil. As shown by these studies, linear pressure sensor arrays have the potential to indicate the effective Strouhal number of a system and, thus, offer real-time feedback on the performance of a system.

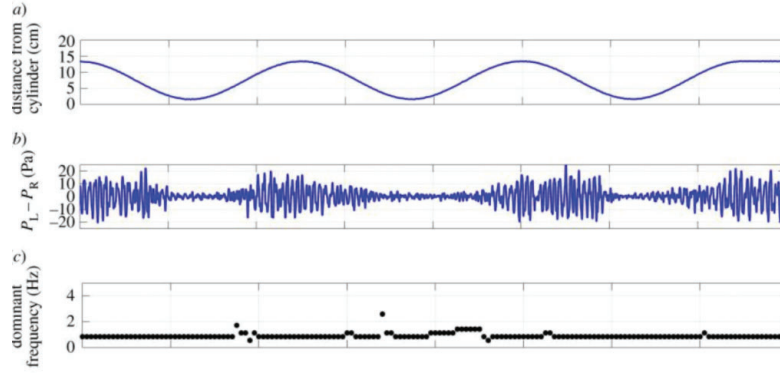


Figure 12: A pressure sensing array's lateral displacement from a Karman vortex street with respect to time (top). Differential pressure readings between the left and right sides of an array as it moved into and out of the vortex street (middle). The dominant frequency observed at each moment in the array's path (bottom) (Chambers et al., 2014).

Lateral line-inspired systems consisting of commercially available, off-the-shelf (COTS) pressure sensors have demonstrated the ability to detect wake characteristics with an accuracy that enables object identification based solely on the pressure readings. The work of Fernandez et al. (2011) shows one example of this. When either a square or circular cylinder passed alongside the sensor array shown in Figure 10 (right), the pressure sensors would generate pressure waves such as those shown in Figure 13. The two types of cylinders produced distinct waves, from which Fernandez et al. (2011) derived salient features that determined the contour of the cylinder with only 1.2% error (Fernandez et al., 2011).

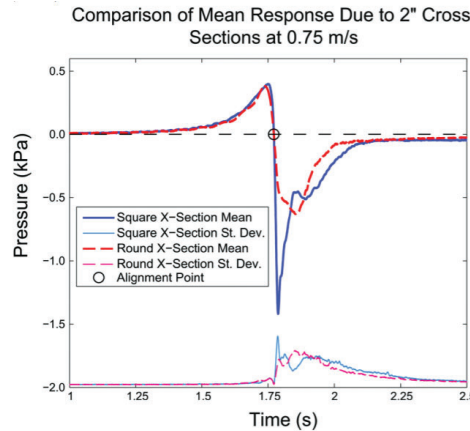


Figure 13: Average pressure response for square and circular cylinders, with the standard deviation offset by -2.0 kPa (Fernandez et al., 2011).

While the artificial lateral line response to a single Karman vortex wake is well documented, no studies to date have characterized the system response in the presence of two interacting vortex wakes. Previous work also demonstrates the potential for artificial lateral lines to collect wake features capable of identifying their sources.

4 Materials and Methods

The experimental component of this research followed the flow chart given in Figure 14. As the chart shows, a viable sensor model was selected and incorporated into a lateral line network. A simplified, bioinspired propulsion system provided a vortex wake for this lateral line to detect, and the dataset was analyzed in pursuit of the objectives outlined in Section 1.

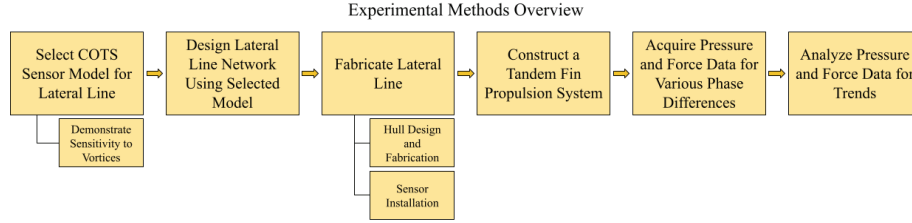


Figure 14: Stages of the experimental component of this research project. Several main checkpoints are given, with smaller secondary checkpoints on two items.

4.1 Sensor Model Evaluation

Three commercially available pressure sensor models were evaluated for use in the lateral line: the Millar Mikrotip Pressure Transducer employed in DeVries, et al. (2015), the Measurement Specialties MS5407-AM used in Venturelli, et al. (2012), and the Blue Robotics Bar-02, selected for its resolution and low hardware requirements. These pressure units are depicted in Figure 15. The units were ranked on their sensitivity, noise, drift, and sampling rate using the decision matrix shown in Figure 16. The MS5407-AM and Millar unit were both analog, requiring experimentation to test their feasibility. The Bar-02, as a digital sensor, was primarily evaluated using its data sheet. The full description of these testing procedures is given in Appendix A. After calibrating the analog sensors and comparing their noise, the Bar-02 and Millar were selected for the lateral line. Before incorporating them into the structure, a proof-of-concept was conducted to verify their abilities to detect vortices.



Figure 15: Pressure sensors considered for the lateral line. The Millar Microtip Pressure Transducer (left), Measurement Specialties MS5407-AM (center), and Blue Robotics Bar-02 (right).

Trait	Importance	Sensor Model		
		Mikrotip Catheter	MS5407-AM	Bar02
Low Noise	3	2	3	2
High Sensitivity	4	2	3	2
High Sampling Frequency	2	2	2	3
Low Bias Drift	1	2	2	3
	Score	20	27	23

Figure 16: Completed decision matrix used to select pressure sensors for the lateral line. Each unit was ranked on the traits in the left column. Importance was multiplied by the corresponding rank of each sensor in its row before taking the sum of each category for a given sensor. The final score indicated the desirability of the sensors, with lower values being preferred.

4.2 Vortex Detection Proof of Concept

The Millar sensor was mounted on a rod and placed in the Naval Academy Hydromechanics Laboratory's (NAHL's) Large Re-Circulating Water Tunnel, 10 cm downstream from the trailing edge of a foil. This configuration is shown in Figure 17. This foil was aligned to an angle sensor using a laser sheet. The foil was then manually flapped in a sinusoidal pattern at 1 Hz using a metronome. The Millar sensor recorded pressure data at a 200 Hz sample rate. The foil was first flapped at an amplitude of $\pm 20^\circ$, then $\pm 10^\circ$, and finally $\pm 5^\circ$. Pressure and foil angle were recorded for these trials. The pressure response was processed using a low-pass filter with a cut-off frequency of 15 Hz, as well as a moving average filter with a nine point span.



Figure 17: Millar sensor placed behind a half foil for wake detection.

For all three trials, pressure spikes were recorded at regular delays of about one second from the foil angle zero-crossing points, as can be seen by the selected points in Figure 18. Separated into its component frequencies, the sensor response had a dominant frequency at 0.93 Hz, with a relative non-dimensional magnitude of 0.0013 when exposed to a foil oscillated at $\pm 20^\circ$ and 1Hz. When the amplitude decreased to $\pm 10^\circ$, the sensor detected a dominant frequency of 1 Hz with a relative non-dimensional magnitude of 0.0086. These results are depicted in Figure 19. When the fin amplitude was further decreased to $\pm 5^\circ$, it continued to detect a dominant frequency at 1 Hz with a relative non-dimensional magnitude of 0.00068, as shown in Figure 20. In each trial, the dominant frequency matched the foil oscillation rate, and magnitude also varied directly with foil amplitude, thus verifying that the Millar sensor would detect characteristic vortices.

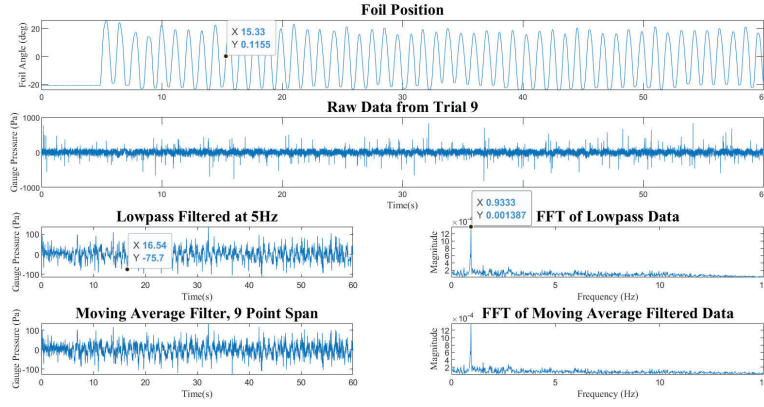


Figure 18: Data collected from an angle sensor (top) and Millar pressure unit (below) as a fin flapped at 1 Hz with an amplitude of $\pm 20^\circ$. The low pass and moving average filtered data are shown (bottom, left) with their frequency components (bottom, right). Points are selected to show the foil zero-crossing, a pressure spike, and the dominant frequency for the low pass filtered data.

After the Millar sensor was tested behind an oscillating foil, the unit was replaced by a Bar-02 sensor. The Bar-02 was set to a 58 Hz sampling rate, which was fixed by the sensor's digital processing speed. This sensor was then exposed to the vortex wake behind the half foil as it was flapped at 1 Hz with $\pm 20^\circ$, $\pm 10^\circ$, and $\pm 5^\circ$ amplitudes. The pressure dataset was analyzed using the same methods as the Millar sensor.

The Bar-02 sensor behaved similarly to the Millar sensor. As shown in Figure 21, when exposed to a foil amplitude of $\pm 20^\circ$ the sensor recorded a dominant frequency of 1.935 Hz with a relative non-dimensional magnitude of 14.97. The sensor unit also recorded pressure spikes about one second after the foil's zero-crossing locations, visible by the selected points of Figure 21. When the foil amplitude was $\pm 10^\circ$ the sensor recorded a dominant frequency of 1.935 Hz with a relative non-dimensional magnitude of 1.643, depicted in Figure 22. Lastly, when the foil amplitude was $\pm 5^\circ$ the sensor recorded a dominant frequency of 1.935 Hz with a relative non-dimensional magnitude of 1.428. This result is shown in Figure 23. Overall, the Bar-02 proved capable of detecting a consistent dominant frequency when placed behind the oscillating foil and its magnitude varied directly with foil amplitude.

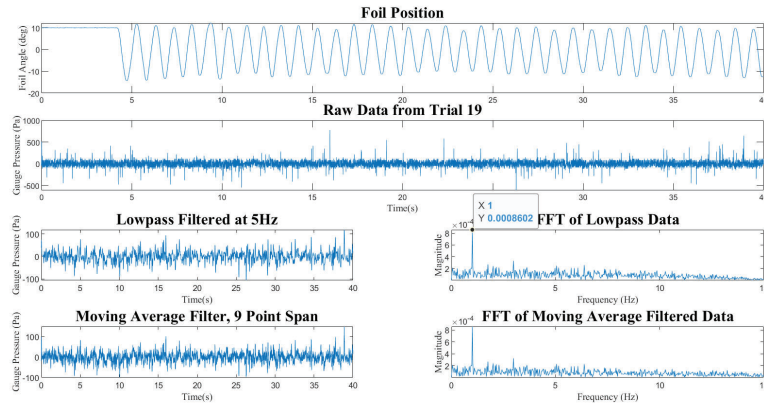


Figure 19: Data collected from an angle sensor (top) and Millar pressure unit (below) as a fin flapped at 1 Hz with an amplitude of $\pm 10^\circ$. The low pass and moving average filtered data are shown (bottom, left) with their frequency components (bottom, right). The dominant frequency is selected for the low pass filtered data.

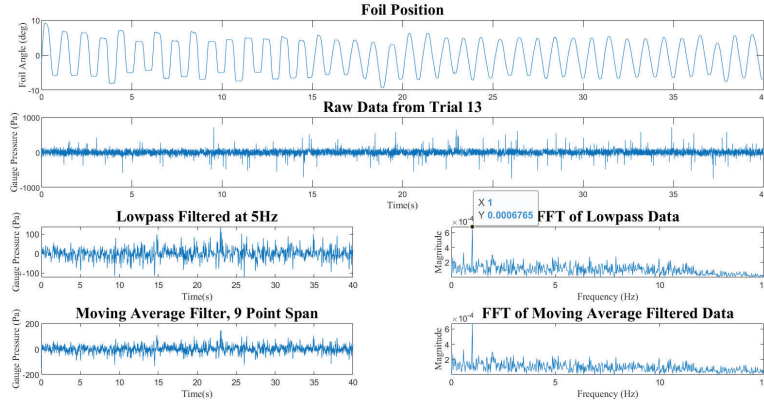


Figure 20: Data collected from an angle sensor (top) and Millar pressure unit (below) as a fin flapped at 1 Hz with an amplitude of $\pm 5^\circ$. The low pass and moving average filtered data are shown (bottom, left) with their frequency components (bottom, right). The dominant frequency is selected for the low pass filtered data.

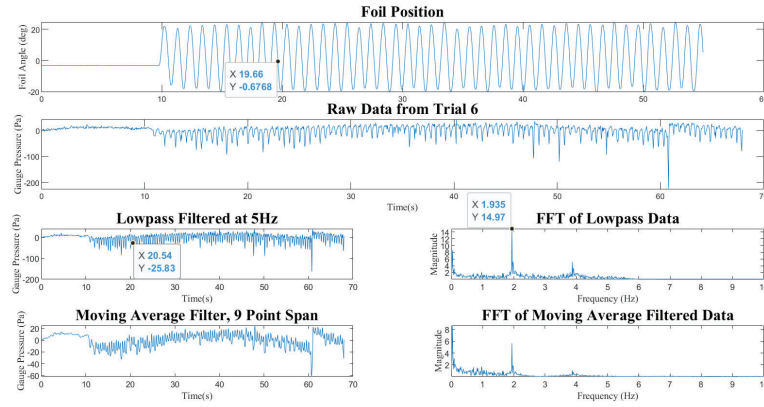


Figure 21: Data collected from an angle sensor (top) and Bar-02 pressure unit (below) as a fin flapped at 1 Hz with an amplitude of $\pm 20^\circ$. The low pass and moving average filtered data are shown (bottom, left) with their frequency components (bottom, right). The dominant frequency is selected for the low pass filtered data. Points are selected to show the foil zero-crossing, a pressure spike, and the dominant frequency for the low pass filtered data.

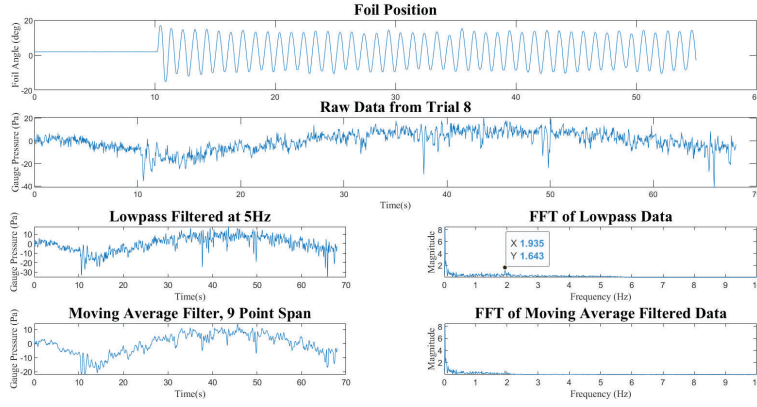


Figure 22: Data collected from an angle sensor (top) and Bar-02 pressure unit (below) as a fin flapped at 1 Hz with an amplitude of $\pm 10^\circ$. The low pass and moving average filtered data are shown (bottom, left) with their frequency components (bottom, right). The dominant frequency is selected for the low pass filtered data.

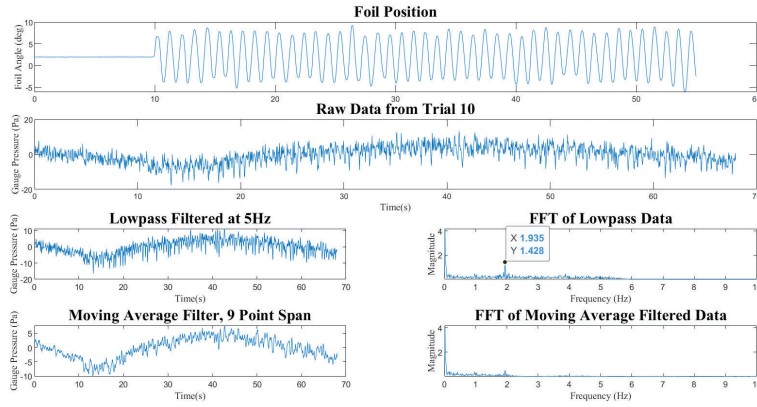


Figure 23: Data collected from an angle sensor (top) and Bar-02 pressure unit (below) as a fin flapped at 1 Hz with an amplitude of $\pm 5^\circ$. The low pass and moving average filtered data are shown (bottom, left) with their frequency components (bottom, right). The dominant frequency is selected for the low pass filtered data.

4.3 Lateral Line Design

4.3.1 Sensor Implementation

After verifying the functionality of individual COTS sensor units, multiple sensor units were consolidated into a cohesive lateral line architecture. The resultant sensor suite housed twenty Bar-02 sensors and two Millar units, placed on two sides of a hydrodynamic body. A National Instruments USB-3633 data acquisition (DAQ) box sampled the analog Millar sensors, while also providing a clock pulse to four Mbed LPC1768 microprocessors. Each Mbed was connected to five Bar-02 digital sensors via I2C communication and used a TCA9548A multiplexer to deconflict addresses. Under this configuration, a laptop computer controlled data flow from each sensor while an external clock maintained the synchronization of the system. The overall sensory system architecture is shown graphically in Figure 24.

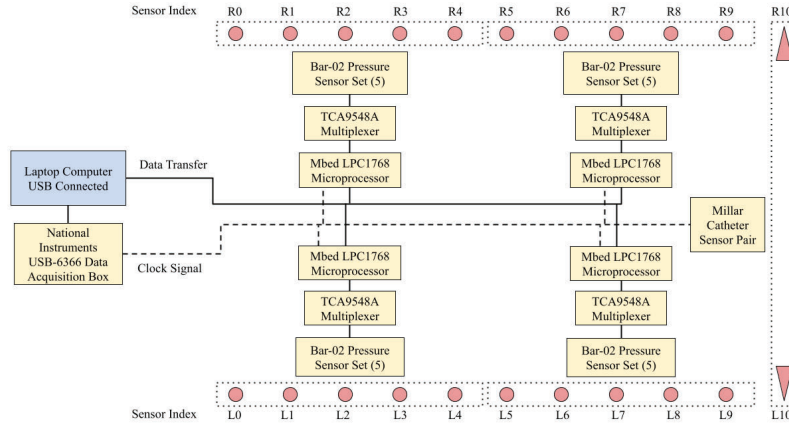


Figure 24: Block diagram of the lateral line components, showing both the clock line and data transfer between devices. Sensor indices provide a method to reference individual units, with L0 and R0 located on the most upstream component of the line.

4.3.2 Lateral Line Hydrodynamic Housing

The full sensory architecture was potted in an additively-manufactured housing fabricated in the USNA Makerspace. The structure was designed as two halves of a hydrodynamic structure. The halves connected with overlapping faces to facilitate waterproofing. As shown in Figure 25 (left), the hull was formed by two convolved parabolas and an ellipsoidal cylinder. This cross section had a major axis of 10 cm and a minor axis of 6 cm. Pressure taps were placed at 1.5 cm spacing, with ten on each half for the Bar-02 sensors and one for the Millar unit. The first pressure tap was placed 6.5 cm from the leading edge of the structure. A 3 mm overlap section was added to each half of the structure so that the halves would fasten together and allow for simple waterproofing. This overlap is depicted in Figure 25 (right), while a full assembly of the structure is shown in Figure 26. A second, inner compartment was implemented to house the electronics and contained ports for wires to enter and exit.

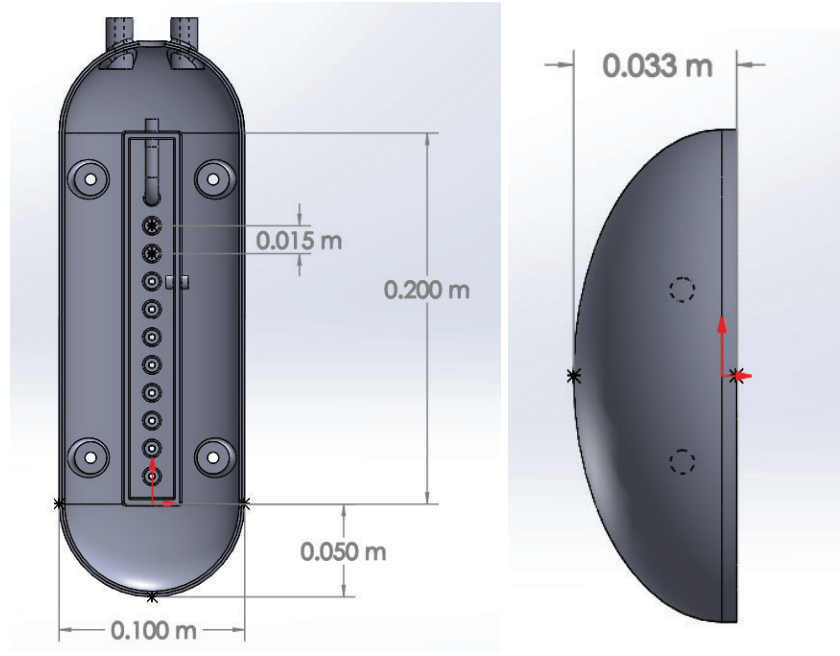


Figure 25: 3D sketches of the lateral line, depicting the horizontal cross section (left) and vertical cross section (right) of one half.

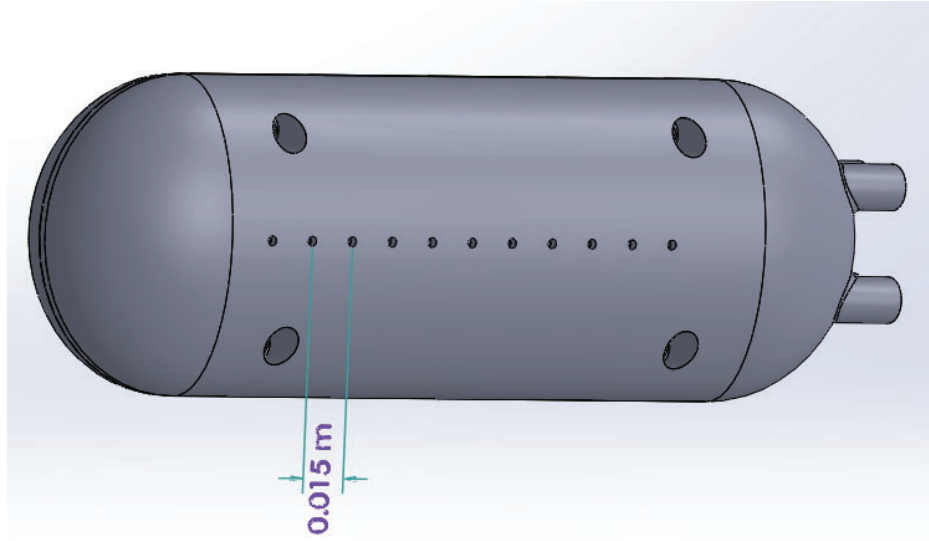


Figure 26: 3D sketch of the full lateral line housing, with pressure tap spacing marked.

The sensor housing was printed in Formlabs Tough 2000 resin using an advanced stereolithography (SLA) printer. Support structures were added prior to printing, but contact points were edited so that no points remained on the outside of the structure or on articulated edges. This process is shown in Figure 27. This allowed for the smoothest possible outer hull and a smooth fit between overlapping parts. After printing, the structure was rinsed with 90% isopropyl alcohol and set under an ultraviolet (UV) lamp at room temperature to cure. Due to the large size of the housing, it could not cure in a heated machine and required a significantly longer cure time than smaller parts. The support structure was carefully removed after the outside of the hull became firm, 17 hours after being placed under the lamp. The hull cured under the UV light for an additional 66 hours until it had lost all tackiness. The curing process and finished products are shown in Figure 28.



Figure 27: Lateral line support structure contact points removed from the outer hull and articulated edges before printing.

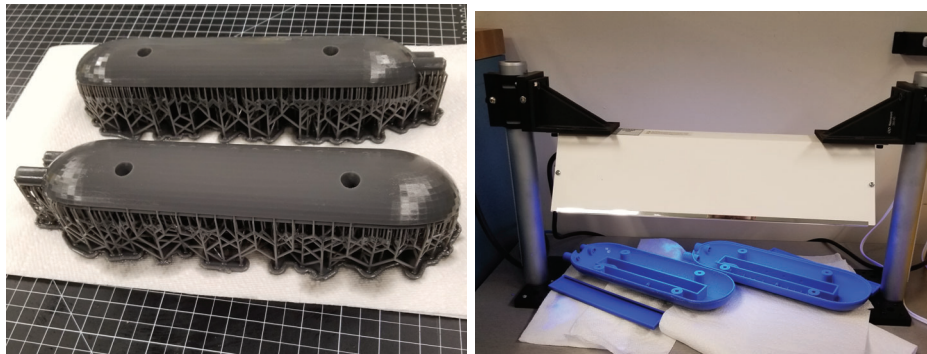


Figure 28: Newly printed lateral line with support structure intact (left) and UV curing at room temperature (right).

4.3.3 Pressure Sensor Installation

Pull up resistors and smoothing capacitors were soldered directly to the Bar-02 circuit boards and fitted to the lateral line inner hull using O-rings, as shown in Figure 29. The individual sensors were then coated in RTV-112 for waterproofing and the inner hull was filled with wax. The communication and power leads extending from the sensor suite were encased in tygon tubing and connected to the microprocessor network. Millar transducers were inserted into the sensor suite via an enclosed channel and encased in tygon tubing.

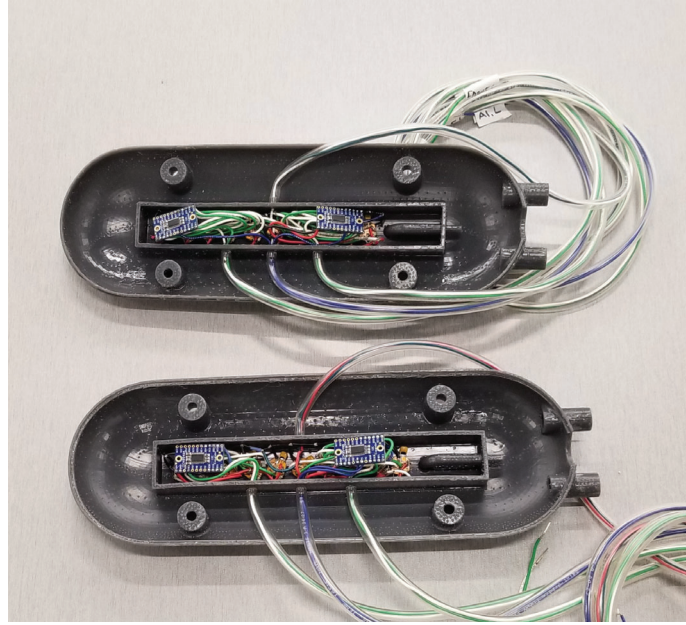


Figure 29: Inside of lateral line housing with sensors and multiplexers installed.

The lateral line was sealed using waterproof tape and putty, then affixed to an aluminum frame. The frame was hydrodynamically faired with foam cut as a NACA 0020 cross section using a four-axis hot wire machine. Figure 30 depicts the final product, affixed to its support strut and waterproofed. In this configuration, the lateral line would experience flow from the left of the figure to the right, exposing the Millar units to the wake last.

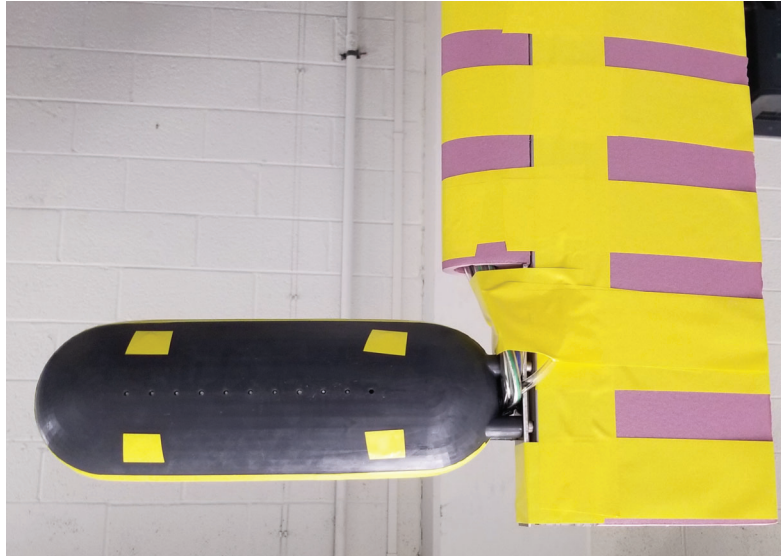


Figure 30: Unsubmerged artificial lateral line affixed to a streamlined strut.

4.4 Propulsion System Design

4.4.1 Foil Construction

Based on the previous work in Section 3, two mechanical hydrofoils were designed with constant NACA0016 cross section. As shown in Figure 31, the foils were given a chord length, c , of 10 cm and a span, d , of 41 cm, which was equal to the height of the test section

of the NAHL Large Re-Circulating Water Tunnel. The foils were milled from 6061 aluminum and anodized. The finished foils are shown in Figure 31.

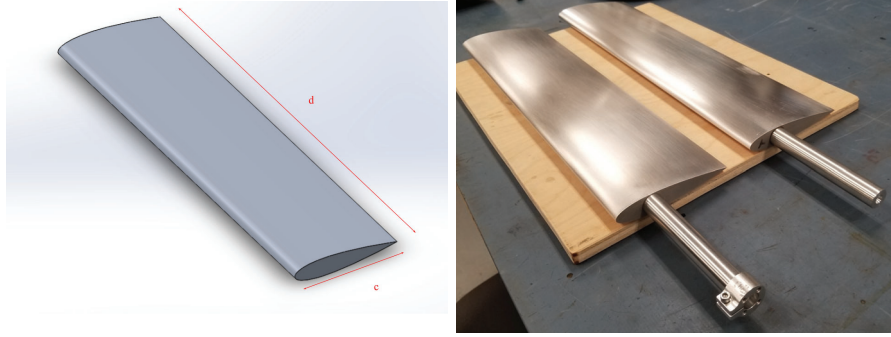


Figure 31: 3D sketch of the NACA0016 foil which was used to approximate a fish fin cross section, with chord and span marked (left). Finished foils, unanodized (right).

4.4.2 Actuation System

A motor was selected that would be able to actuate the foils with a sufficient factor-of-safety. This motor was selected for a holding torque greater than the torque of the foil at its maximum angle-of-attack. Based on a foil height of 0.41 m, a chord length of 0.10 m, and a maximum pitch angle of 16° , and a coefficient of lift for a NACA0016 foil, C_L , of 1.201, the lift force became

$$F_L = 0.5C_L\rho Av^2 = 0.5(1.201)(998.2\text{kg/m}^3)(0.41\text{m} * 0.1\text{m})(0.13\text{m})^2 = 0.415\text{N}.$$

The center of pressure on the foil body was not known, but the moment calculations about the axis of rotation utilized the longest possible moment arm as a factor-of-safety. The foil actuation rod was located 0.025 m behind the leading edge, making this moment arm 0.075 m. The resultant torque generated by the lift force about the axis of foil rotation was

$$\tau_L = F_L * d = (0.415\text{N})(0.075\text{m}) = 0.031\text{N} - \text{m}.$$

An American Industries 23D-6204A stepper motor was selected to actuate the foil. This unit operated with a static torque of 0.70 N-m. The motors were controlled with a Pololu Amis-30543 motor driver and Mbed LPC1768 microprocessor.

To achieve sinusoidal motion using stepper motors, the foils were actuated with a constant step size of 0.45° and variable times between steps. The total time for each step was calculated recursively as the absolute difference between times for successive angles. The time was calculated for a given step based on Equation 2, solved for time:

$$t = \arcsin\left(\frac{\theta(t)}{\theta_m}\right) / (2\pi f_h + \psi) \quad (7)$$

The simulated foil response using this algorithm is shown in Figure 32, where the phase difference is generated by holding one foil motionless for a set amount of time.

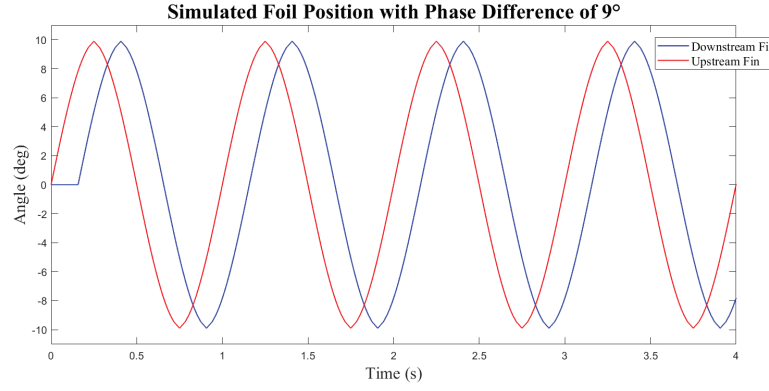


Figure 32: Simulated tandem fin position response with a phase difference of 9° , generated by maintaining constant step size and varying only wait time between each angle.

4.4.3 Experimental Rig Development

The experimental test rig was designed to have adjustable foil heights and variable distance between foils, which would allow them to be configured easily when placed in the NAHL Large Re-Circulating Water Tunnel. The rig was suspended over the water tunnel and connected via two Hydronautics 2 in force gauges, as shown in Figure 33. The gauges were oriented orthogonally, such that one gauge measured streamwise force and the other measured side force on the floating plate. The full setup was designed first as a 3D sketch, as shown in Figure 33. The USNA Model Shop then fabricated motor shaft adapters, plates to mount the motors, and a base plate, cut from 0.635 cm aluminum. Components were attached to the base plate using aluminum 80-20 segments.

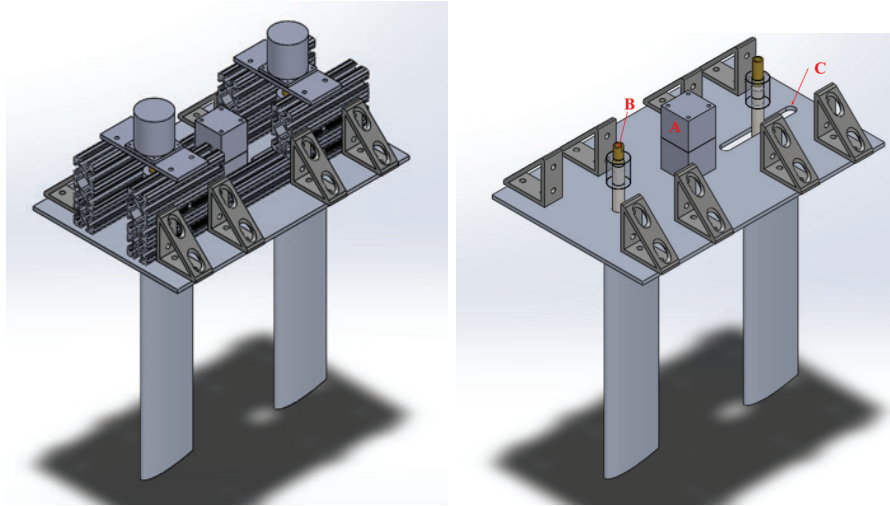


Figure 33: 3D sketch of the full experimental setup (left) and cutaway (right) to expose the force gauges (A), motor shaft adapters (B), and slot for the downstream foil (C).

4.5 Data Acquisition

Propulsive force and lateral line pressure were collected as the foils oscillated for a set of phase differences between 0° and 180° . The lateral line assembly was placed behind the tandem fins in the NAHL Large Re-Circulating Water Tunnel with the leading sensors 12.7 cm behind the trailing edge of the downstream foil. This arrangement is shown in Figure 34. Although the first sensor would have ideally been 10.0 cm behind the trailing edge, this distance was impossible to achieve due to the configuration of the tank. The foils and lateral line assembly were aligned using a laser sheet, as shown in Figure 35, and the starting position of the foils

was marked on their shafts to facilitate manual resetting. The water tunnel was set to 13.7 cm/s and allowed to settle for several minutes before data collection began.

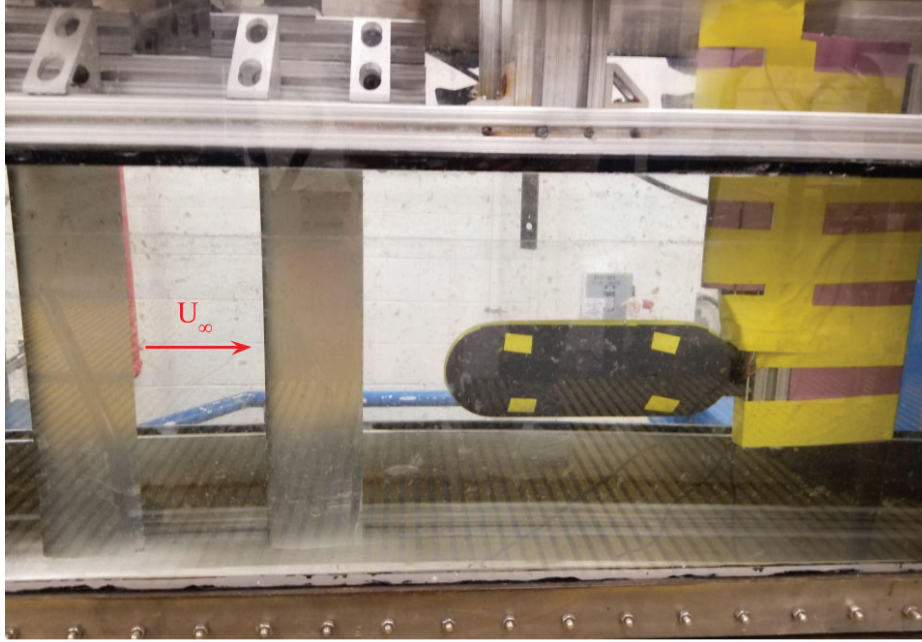


Figure 34: Side view of experimental setup, with flow proceeding from the left of the figure to the right.

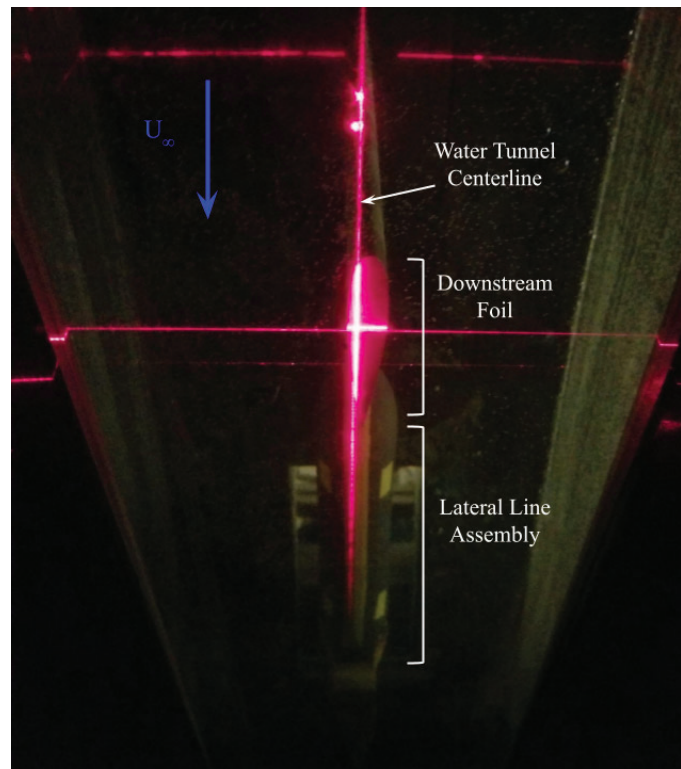


Figure 35: Lateral line and foils aligned using a laser sheet. The downstream foil is located at the top of this image and the lateral line is located below it.

During each trial the tandem foils oscillated according to Equation 7 at a preset phase value between 0° and 180° and a frequency of 1 Hz. Successive trials differed by 4.5° , a value which allowed the stepper motors to achieve each phase difference with an integer number of steps. Each trial began with five seconds of fin oscillation before data collection began. Data were collected for 23 seconds at 60 Hz and the foils continued to flap for three seconds after data collection had ceased. The foils were re-aligned manually at the end of each trial. This experimental procedure achieved a Strouhal number of

$$St = \frac{fA}{U_\infty} = \frac{1Hz * 2 * 10\sin(10)cm}{13.1cm/s} = 0.265$$

Overall, the physical experimentation of this research operated under several assumptions:

1. A single inflow velocity was tested
2. A single hydrofoil cross-section was tested
3. A single hydrofoil spacing was tested
4. Water temperature remained constant
5. Foils would only pitch with no heave motion

4.6 CFD Simulation

Simulations of tandem fins were conducted in Lilypad by expanding on the models used in Muscutt, et al. (2017). Lilypad is an open source CFD program developed by Dr. G Weymouth for quick, 2D flow simulations (Weymouth, 2015). It solves the Navier-Stokes equations and applies body boundary conditions over surfaces using the boundary data immersion method, while maintaining a Cartesian grid for calculations (Weymouth and Yue, 2011). Tandem fins were initialized at a spacing equal to their chord length and with only a pitching component of motion. The Strouhal number was set to 0.265, which matched the experimental procedures in this research project. Vortices were marked using a heat map, with blue and red corresponding to counterclockwise and clockwise rotating vortices, respectively. Color saturation corresponded with vortex intensity. Recordings and still motion captures were made of these images to provide insight on the physical phenomena responsible for the experimental results.

5 Results

5.1 Force Data

Streamwise force on the foils was collected for each trial and featured a periodic generation of thrust and drag. An example dataset is shown in Figure 36. Force noise was contributed by shaking in the foils as their actuation rods contacted the base plate. The force data from each run was averaged and plotted for the corresponding phase value, as shown in Figure 37. This represented the net force on the foils for a given phase difference. Between 0° and 103.5° phase difference the tandem foils produced net thrust, but produced net drag from 103.5° to 180° . This result agrees with work done by Akhtar, et al. (2007) and Boschitsch, et al. (2014). The computational work performed by Akhtar showed that, for 2D foils that undergo pitch and heave motions for propulsion, maximum generated force occurred at 48° . This plot is shown in Figure 6. Similarly, the data in Figure 37 shows 48° phase difference to be in the center of the range for thrust production, although it is not a clear maximum. Meanwhile, as shown by the Boschitsch plot in Figure 9, pitching foils with a chord to foil spacing ratio of 1 will produce increased thrust for the phase range of 0° to 90° phase difference, followed by a decrease in thrust or potentially drag creation. This result is also consistent with Figure 37. However, discrepancies exist in exact values between Figure 37 and the work by Akhtar and Boschitsch because this research project conducted trials at a slightly higher Strouhal and Reynolds number than the previous work. Additionally, the computational work performed by Akhtar includes a heave component in foil motion and an upstream foil that was shorter

than the downstream foil. For these reasons, exact values may not align between their work and the present research project, but the shared trends support confidence in these findings.

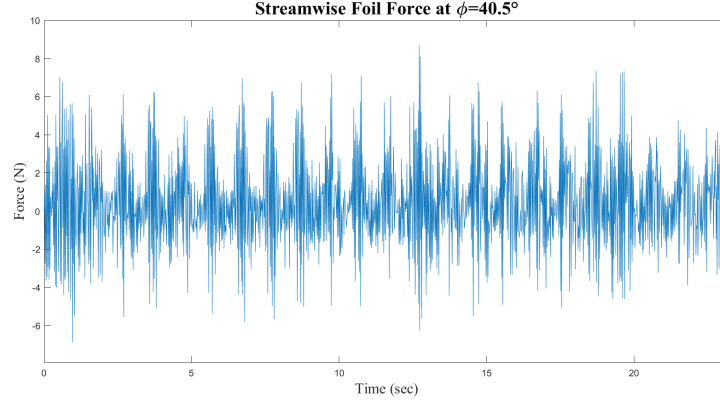


Figure 36: Raw force data for fins oscillated with a phase difference of 40.5° .

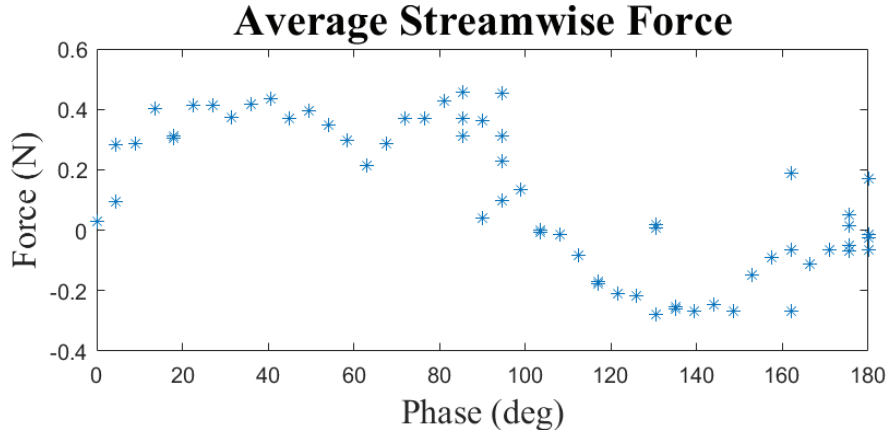


Figure 37: Average streamwise force on tandem foils for a range of phase differences from 0° to 180° .

5.2 Pressure Data

Pressure data from each sensor were processed using a first order detrending function, which removed any data offset and the linear component of drift. The first five seconds of each trial were removed, as the Bar-02 sensors utilized an internal polynomial fit function that required several initial readings to settle on the true pressure value. An example of the remaining data is shown in Figure 38 (top), which displays pressure data offset over a range for visualization. These data are displayed without units, as the data processing relied on trends rather than absolute values. The absolute pressures of the Bar-02 sensors, when held at a static pressure, were within ± 400 Pa of one another. The legend in this plot references the sensors with the indices shown in the 3D sketch of the experimental setup in Figure 38 (bottom). The sudden pressure dip between 11.5 and 12.5 seconds for sensors L1 through L9 is an instance of electrical noise, as these sensors were powered by the same electrical bus.

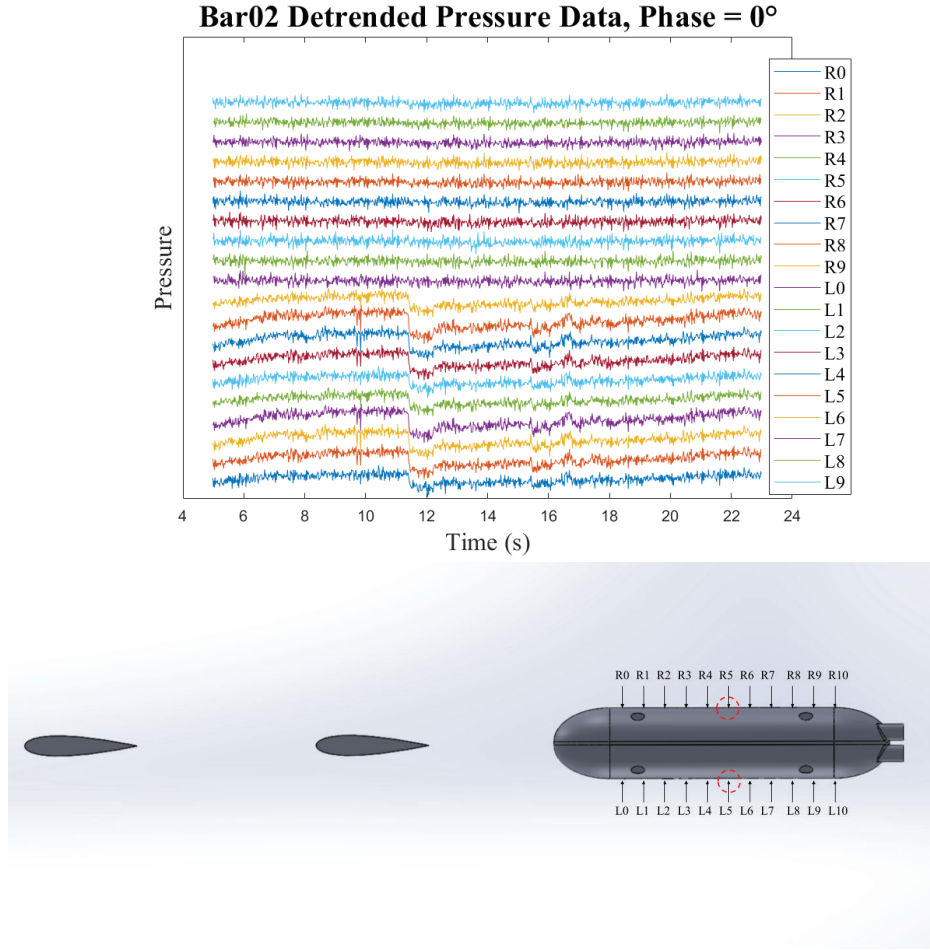


Figure 38: Top: Detrended pressure data from the lateral line during a phase difference of 0° . Each pressure unit response is offset for visualization and displayed against time. Bottom: 3D sketch of the lateral line assembly behind two foils with pressure sensor locations annotated. Two opposite pressure sensors are circled to show that they would be compared to extract differential pressure. The legend in the top subplot references the sensors shown in the bottom subplot.

Although the lateral line assembly used in this project was biologically based, the pressure data was post processed in a different manner than has been observed in fish. Fish detect pressure changes between adjacent pores on their lateral lines, while this research project calculated the differential pressure between opposite sensors to derive features. This technique is common in engineered systems, however, as it enables researchers to cancel tank and electrical noise and increase the signal produced by vortices (DeVries et al., 2015; Venturelli et al., 2012).

Detrended pressure data from the starboard side of the lateral line were subtracted from the port side, yielding differential pressure. This technique operated on the assumption that both sides of the lateral line would not experience vortices simultaneously, as this would cause the signatures from both vortices to cancel. This technique used sensors opposite from one another on the line, as shown in Figure 38. The effect of this process is shown in Figure 39 using data from L5 and R5 during a trial at 31.5° phase difference between foils. Figure 39, left, shows the raw data from these two sensors, while Figure 39, right, shows the differential pressure between the two. The component frequencies are shown in the corresponding plots of Figure 40.

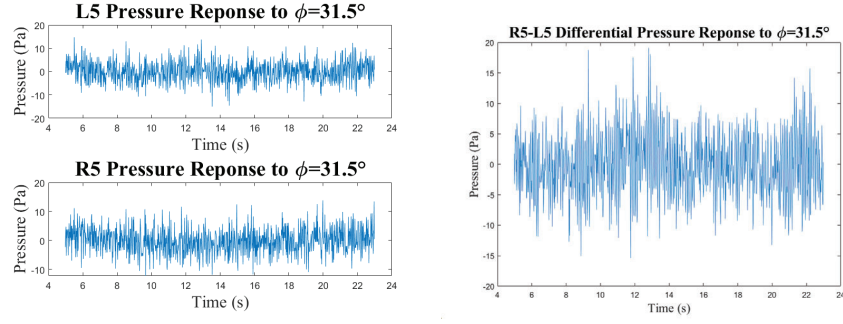


Figure 39: Detrended pressure from sensors L5 (left, top) and R5 (left, bottom) during a trial at 31.5° phase difference. The differential pressure between these opposite sensors is shown (right).

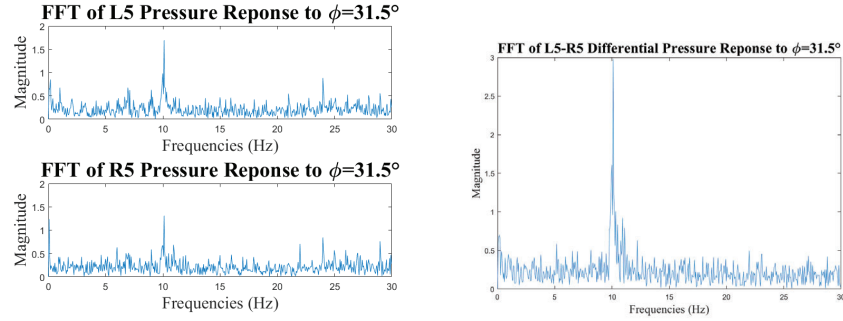


Figure 40: FFT of pressure from sensors L5 (left, top) and R5 (left, bottom) during a trial at 31.5° phase difference. The FFT of their differential pressure is shown (right).

The pressure data was further analyzed by selecting the dominant frequencies between 0.7 Hz and 16 Hz. Values above and below this range were assumed to be due to sensor noise and drift, respectively. As shown in Figure 41, the majority of differential pressure data showed dominant frequencies at 10 Hz and 1 Hz, with magnitudes that varied for each trial. This figure shows the frequency data for one pair of sensors, and similar plots were created for the five aft-most sensor pairs. Water damage impaired the sensors on the front half of the structure and their data could not be used. The differential plots show similar trends in the frequency data, and the 10 Hz signal from each is shown in Figure 42.

Dominant Frequencies for Corresponding Phases, L5-R5

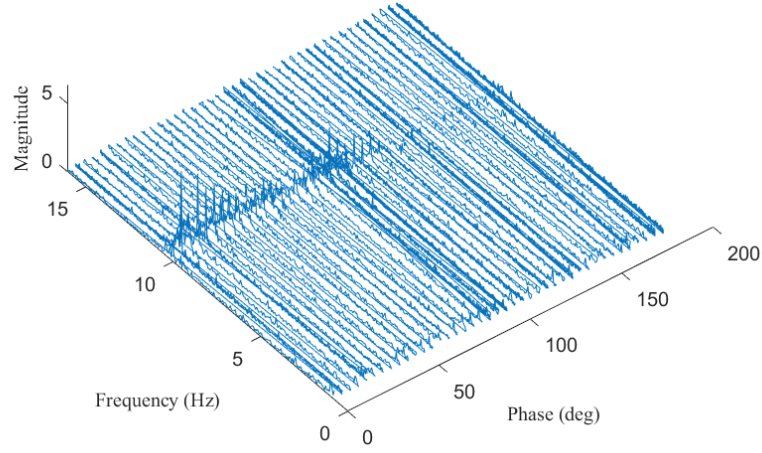


Figure 41: 3D plot of differential pressure vs time data from each experimental trial converted to the frequency domain, ranging for foil phase differences between 0° and 180° . The data shown is for the L5 and R5 sensor pair.

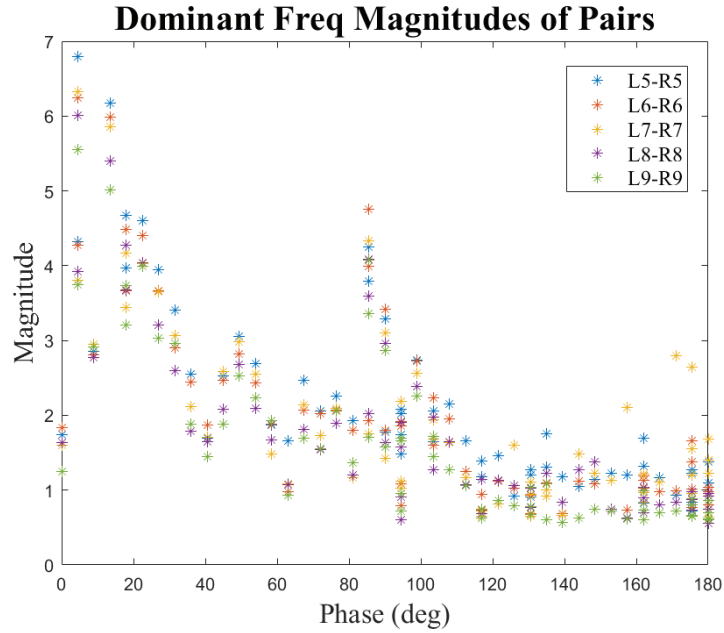


Figure 42: Magnitude of the largest dominant frequency of each pressure sensor pair, plotted for each phase difference. The legend indicates the particular sensor pair that detected each magnitude. The largest dominant frequency for each trial was 10 Hz.

6 Analysis

The data presented in Section 5 was analyzed to determine its application to bioinspired propulsion control systems. The components of this goal and the processes performed to reach them are shown in Figure 43. To be applicable to bioinspired control systems, the

artificial lateral line needed to demonstrate the ability to indirectly measure thrust. In effect, the lateral line would show an ability to measure the propulsive system behavior without necessarily being a physical component of the propulsion system. This would demonstrate the colloquial “touch at a distance” that lateral lines contribute to fish (Dijkgraaf, 1963).

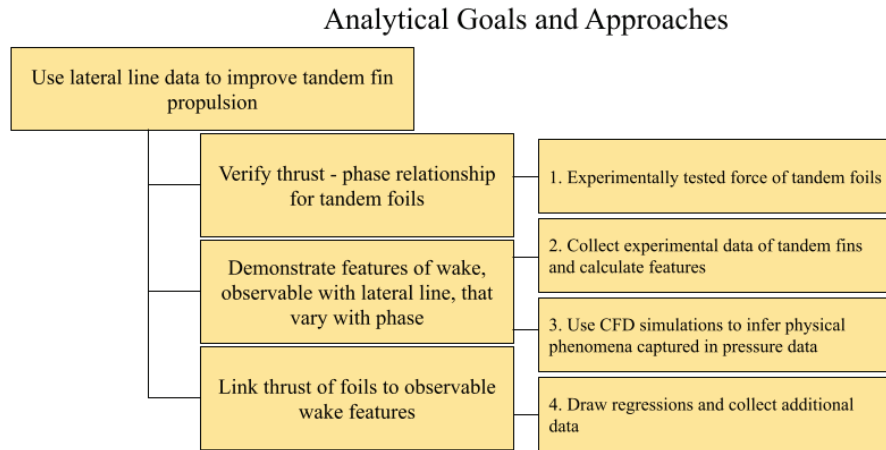


Figure 43: Hierarchy of goals and how the data was analyzed to support the different components of this research project.

6.1 Correlations and Regression of Pressure Data

To demonstrate a correlation between force, phase, and the dominant frequency magnitude of pressure data, Figure 37 and Figure 42 are replotted with the same x-axis in Figure 44. The red-boxed force value is a local maximum of 0.4337 N, corresponding to a dominant frequency of 1.695 magnitude. The green-boxed force value shows zero net force, a crossing point at which the foils began to produce drag. The corresponding dominant frequency had a magnitude of 1.448. The blue-boxed point was the local minimum force generated; it was the phase at which the foils produced the most drag. This force corresponds to a dominant frequency of 0.683 magnitude. The selected points between these plots show that, as streamwise force decreased, the strength of the dominant frequency detected by the lateral line assembly decreased. This correlation demonstrates a link between a measured feature of the foil wake and corresponding foil thrust. This data set showed that phase control can alter the thrust produced by tandem foils and that downstream sensors could be used in this control if they are able to relate a numeric wake feature to foil phase difference.

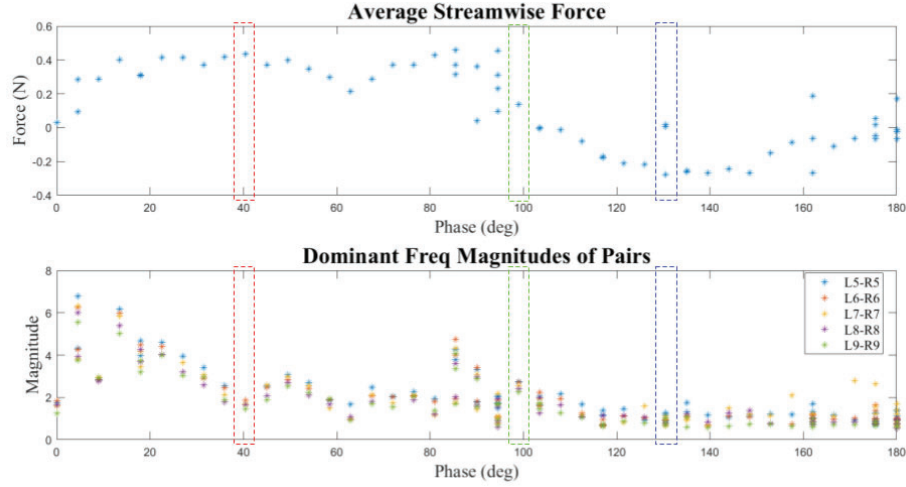


Figure 44: Average force of tandem foil propulsion system versus phase difference (top). Magnitude of the dominant differential pressure frequency detected by the lateral line assembly (bottom). Selected points indicate corresponding force measurements, frequency magnitudes, and the phase differences at which they occurred.

The dominant frequency magnitude plot in Figure 42 was fitted with first and second order polynomial lines to provide a mathematical link between phase and the magnitudes of dominant frequencies. These functions constituted regressions between the phase differences and these features. The result is shown in Figure 45. The coefficient of determination, R^2 , was calculated for these curves, with the first order regression resulting in an R^2 of 0.530 and the second order regression resulting in an R^2 of 0.575. For these two values the coefficient of correlation, R , was -0.728 and -0.758, respectively. This showed a negative correlation between phase difference and the magnitude of the dominant frequencies.

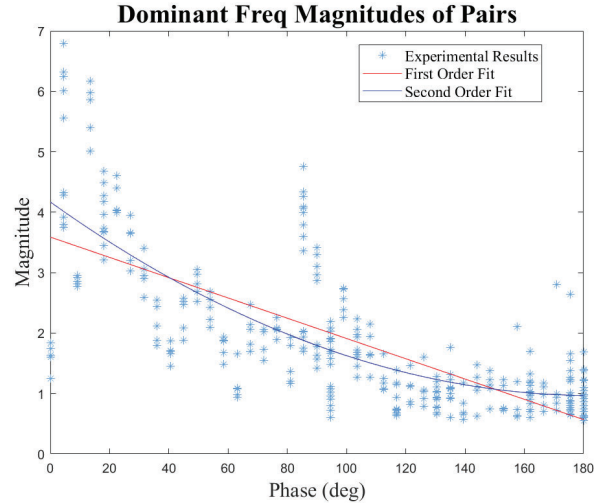


Figure 45: First and second order regression curves between phase and dominant frequency magnitude for the aft sensor pairs on the lateral line. For the first order curve, $R^2 = 0.530$. For the second order curve $R^2 = 0.575$.

6.2 Comparison with CFD

The source of this trend may be explained by the results of CFD simulations using Lilypad (Weymouth and Yue, 2011). Figure 46 depicts three examples, selected as points of interest from the force versus phase plot in Figure 37. The top image depicts the simulated flow for

two 2D foils oscillating at a Strouhal number of 0.265 and a phase difference of 0.0° , which corresponds to minimal force production in Figure 37. The middle image shows this behavior for a phase of 85.5° , where Figure 37 indicates maximum force production. The bottom image shows flow for a phase of 139.5° , where Figure 37 displays drag production. Counterclockwise and clockwise flow are colored by blue and red, respectively, in these images, with saturated regions corresponding to vortices.

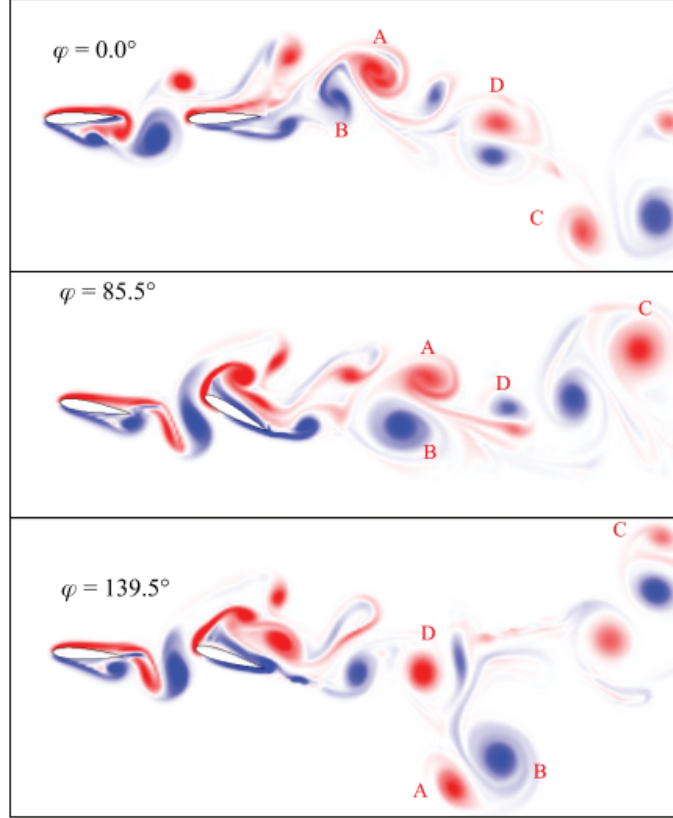


Figure 46: CFD simulations of tandem foil wake at three phase differences. Counterclockwise and clockwise vortices are shown as blue and red, respectively, and letters indicate vortices of note. A and B mark the first paired vortices of each cycle, C marks the second pair of vortices for each cycle, and D marks vortices produced by wake interaction. This program was developed by Weymouth (2015).

Based on the dominant frequency plot shown in Figure 41, the sensors detected 1 Hz and 10 Hz for many of the phases before the foils began producing excess drag, with occasional intermediate frequencies. Higher frequencies occur for rapid changes in pressure, as would be detected between vortices marked A and B in Figure 46. These counter rotating vortices are pulled toward one another and are paired, keeping them relatively close together as they advect past the foils. This phenomena likely contributed the 10 Hz signal.

As the foils oscillated in a periodic motion at 1 Hz, the vortex patterns comprising their wake repeated at this frequency. The lengths of vortex sequences are shown in Figure 46 as the distance between vortices marked A and C. This spacing likely led to the 1 Hz signals.

The complicated interaction of the foil wakes created singular or smaller vortex pairs, which had spacing between 1 Hz and 10 Hz. Examples of these vortices and distances are marked with letter D in Figure 46.

As shown in Figure 42, the magnitude of the dominant frequency decreased as the foil phase difference increased. As phase difference increased, paired vortices came more in-line with one another in the direction normal to the streamwise flow. This is depicted in Figure 46 as the vertical alignment of vortices labeled A and D. Comparison between the top and bottom CFD wakes shows the secondary pair of vortices, labeled D, moving closer to and eventually behind the primary vortex pair, labeled A and B. Because the lateral line

extended in the streamwise direction, vortices aligned in this manner would not register on the lateral line as two distinct pairs, but as a single, small pair, decreasing the prevalence of the 10 Hz signal. For the middle simulation, the primary vortex pair rotated to have the primary vortex pair, A and B, opposite one another. Because post-processing took the differential pressure across the lateral line before converting the pressure signal to the frequency domain, opposite vortices such as these were nearly canceled out, also contributing to lower magnitudes of the 10 Hz signal for the 85.5° phase difference.

7 Conclusion

This research project explored the means for a bioinspired control loop consisting of an artificial lateral line and a tandem fin propulsion system. To do this, it was necessary to demonstrate the relationship between tandem foil phase difference and thrust, the ability of the lateral line to estimate the foil phase difference based on a measured feature, and simulations of the physical phenomena responsible for this relationship. The experimental results of this research project showed that tandem fins will produce variable thrust or drag depending on the phase difference between foils, with maximum and minimum thrust development agreeing with previous research. These results verified the need for tandem fin phase control. An artificial lateral line proved able to detect a wake feature which correlated with foil phase difference, and a general mathematical relationship was attempted with regression lines. While this feature could not be mathematically mapped to the force developed by tandem foils, it was shown to vary, generally, with the streamwise force. As the force developed by tandem foils decreased, the magnitude of 10 Hz frequency detected by the lateral line also decreased. CFD simulations of the propulsion system allowed for an understanding of the physical phenomena responsible for this relationship. These simulations showed that paired vortices present at lower phase differences contributed higher-frequency signals to the pressure response, and the alignment of vortex pairs at higher phase differences caused the lateral line to detect fewer pairs. Together, these elements showed that variable tandem foil phase difference created unique vortex wakes, which contained pressure data that varied with the phase difference and force generated by the foil. Moreover, an artificial lateral line was able to detect these trends, demonstrating its potential for use in future bioinspired control loops.

A set of simplifications and assumptions were made for this data which may impact future work. The foils were simplified from their biological counterparts by excluding the heave component of fin motion and consisted of rigid structures, while fish fins are quite flexible. For foil motion, the heave phase generates the majority of the thrust compared to the pitch motion. Research using flexible, heaving foils will see different vortex wakes with unique features not seen in this project, as well as higher thrust. Additionally, the differential pressure between opposite sensors assumed that vortices would not impact both sensors simultaneously, as this would cause both to cancel in the differential pressure calculation. Future work might study the features of individual pressure sensors or the differential pressure between adjacent, rather than opposite, pressure units. Future research could use PIV to add validity to the CFD simulations and determine expected lateral line features. Micro electromechanical sensors could also be developed with higher sensitivity than the COTS units used in this project, and would be capable of detecting smaller pressure differences and features.

Ultimately, this research showed that an artificial lateral line could be constructed using commercially available pressure sensors, and that this line could be used in a bioinspired control loop. A lateral line capable of discerning tandem fin phase based on downstream effects would allow a system to adjust its fin behavior to achieve specific thrust, a quality essential to tandem fin propulsion if it will be used on robotic vehicles. The benefits of this would be two-fold. Lateral line-enabled tandem fin propulsion could dramatically improve the agility of underwater vehicles. Additionally, the lateral line presented a means to indirectly measure the thrust of a simplified tandem foil propulsion system without being part of the propulsion system itself. This capability could allow UUVs to passively detect behaviors of upstream vehicles and enable a vehicle to school with other bioinspired systems by observing their wakes and adjusting its own behavior accordingly. Tandem fin propulsion and lateral line sensing have independently enabled a multitude of undersea lifestyles, and their combination stands to propel underwater robotics to greater depths.

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Appendices

A Sensor Evaluation

This test calibrated and evaluated the noise and sensitivity of the analog pressure sensors: the Millar transducer and MS5407-AM. The MS5407-AM was connected to a breadboard using an INA118 instrumentation amplifier and an Mbed LPC1768 microprocessor which performed analog to digital conversions. The amplifier used a $4.8\text{ k}\Omega$ resistor to scale the sensor output voltage to the Mbed pins' maximum value.

This sensor was then fitted with a tygon tube and exposed to a range of known pressures by filling the hose with water. The sensor's output voltage was collected over a 1 kPa range, sampling at 40Hz. The applied pressure increased by increments 0.33 kPa and rested for twenty seconds at each pressure. This experimental setup can be seen in Figure 47.

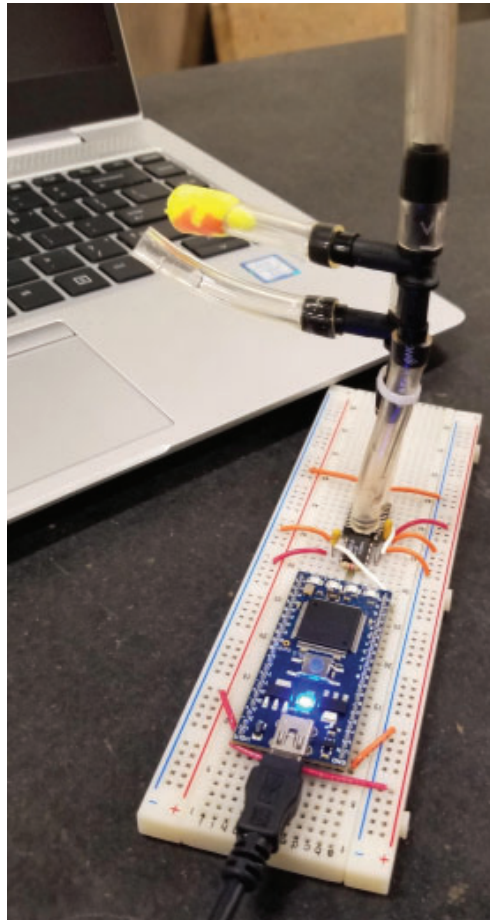


Figure 47: Implementation of the MS5407-AM sensor during trials at fixed pressures.

The Millar sensor was connected to a Millar PCU-2000 amplification system and read with a National Instruments USB-6009. This sensor was then lowered into a graduated cylinder filled with water. By controlling the depth of the water, the sensor was exposed to a 2.25 kPa pressure range and sampled at 50 Hz. The unit was then compared qualitatively to the MS5407-AM and calibrated.

When exposed to a 1 kPa pressure range, the MS5407-AM increased by an average voltage of 4.4 mV. The sensor signal and noise are reflected in Figure 48. The average output voltage and standard deviation were calculated for each static pressure value, with the average standard deviation for each static pressure found to be 1.11 mV.

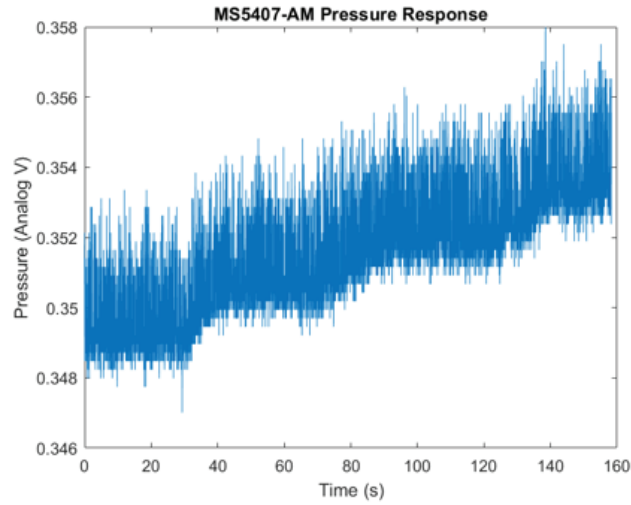


Figure 48: Pressure response of the MS5407-AM unit over a 1 kPa range.

Meanwhile, the Millar unit increased by 145 mV over a 2.25 kPa range. Like the MS5407-AM, the output voltage was averaged at each static pressure. This is shown in Figure 49, where the red and blue bars indicate the range that the sensor was averaged over. The average standard deviation was likewise found to be 4.47 mV.

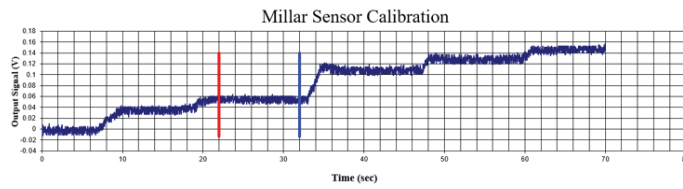


Figure 49: Pressure response of the Millar unit over a 2.25 kPa range.

B Calibration Sheets

NAHL Calibration of: Millar Cath A
 Least Squares Fit of Calibration Data
 Full Scale Gage Capacity (FS): 2112.72 Pa
 Date: 4/8/2022

U.S. Naval Academy
 Hydromechanics Laboratory
 590 Holloway Road
 Annapolis, MD 21402

Applied Load Pa	Gage Output volts	Fit Output volts	Difference Pa	Percent Full Scale
0.00	-0.004	0.00	30.9755	1.466
124.28	0.008	0.01	-9.0452	-0.428
248.55	0.019	0.02	-26.6882	-1.263
372.83	0.028	0.03	-27.6221	-1.307
497.11	0.035	0.04	5.4189	0.256
621.39	0.044	0.04	8.8120	0.417
745.66	0.053	0.05	5.0290	0.238
869.94	0.062	0.06	5.6277	0.266
994.22	0.072	0.07	4.0573	0.192
1118.50	0.081	0.08	1.7193	0.081
1242.77	0.090	0.09	7.6975	0.364
1367.05	0.099	0.10	6.9352	0.328
1491.33	0.109	0.11	3.9340	0.186
1615.61	0.119	0.12	-10.9721	-0.519
1739.88	0.127	0.13	3.6750	0.174
1864.16	0.137	0.14	0.8605	0.041
1988.44	0.147	0.15	-16.9048	-0.800
2112.72	0.155	0.16	6.4904	0.307

Gage No.	-
Amp No.	-
Gage Cal	-
Gain	-

Water Dens 997.82 kg/m³

Water Temp 71.1 F

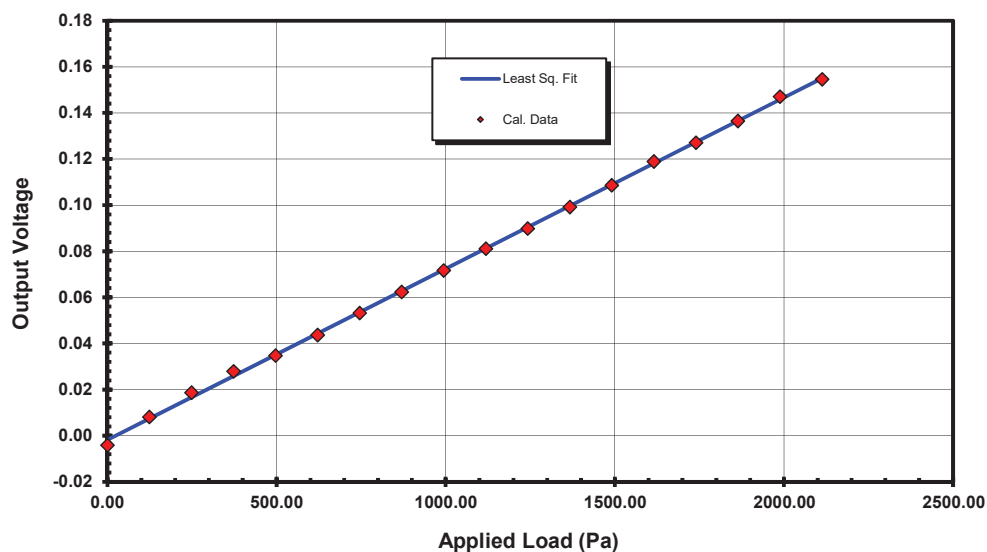
Gage Sensitivity: **0.000074227706** volts / Pa

Offset: -0.001800151753 volts

Calibration Linearity Statistics:

Max Deviation:	1.466	% Full Scale
Max Deviation:	30.976	Pa
Std. Deviation:	13.5099	Pa

LEAST SQUARES FIT OF CALIBRATION DATA



NAHL Calibration of: Millar Catheter B
 Least Squares Fit of Calibration Data
 Full Scale Gage Capacity (FS): 2112.72 Pa
 Date: 4/8/2022

U.S. Naval Academy
 Hydromechanics Laboratory
 590 Holloway Road
 Annapolis, MD 21402

Applied Load Pa	Gage Output volts	Fit Output volts	Difference Pa	Percent Full Scale
0.00	-0.001	0.00	19.9230	0.943
124.28	0.010	0.01	-5.4082	-0.256
248.55	0.021	0.02	-19.4508	-0.921
372.83	0.030	0.03	-22.0444	-1.043
497.11	0.037	0.04	10.5287	0.498
621.39	0.047	0.05	8.1928	0.388
745.66	0.057	0.06	-0.5836	-0.028
869.94	0.066	0.07	-0.6300	-0.030
994.22	0.075	0.08	0.0700	0.003
1118.50	0.085	0.08	-1.0800	-0.051
1242.77	0.094	0.09	8.3378	0.395
1367.05	0.103	0.10	9.0102	0.426
1491.33	0.112	0.11	6.8396	0.324
1615.61	0.123	0.12	-4.0143	-0.190
1739.88	0.131	0.13	7.2351	0.342
1864.16	0.141	0.14	-0.0109	-0.001
1988.44	0.152	0.15	-18.4823	-0.875
2112.72	0.160	0.16	1.5673	0.074

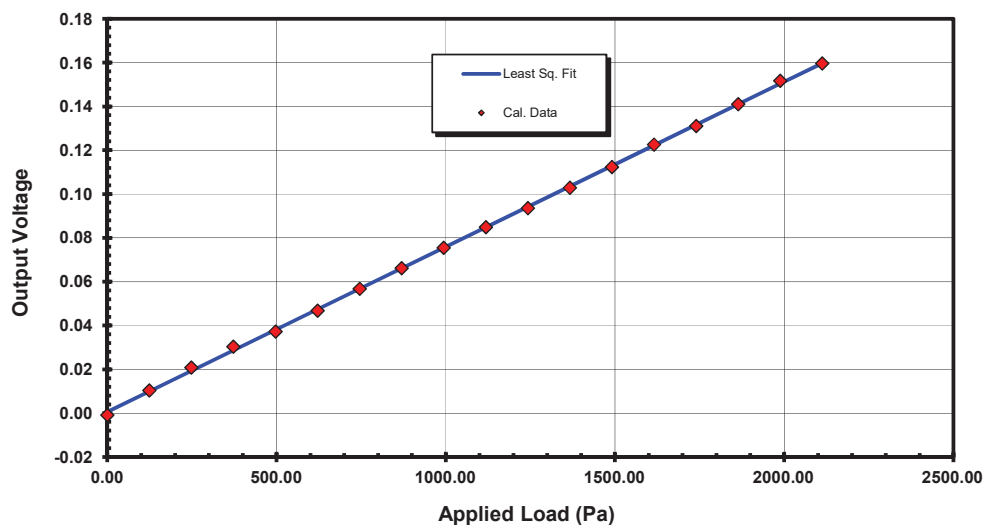
Gage No.	-
Amp No.	-
Gage Cal	-
Gain	-
Water Density	997.82 kg/m ³
Water Temp	71.1 F

Gage Sensitivity: **0.000075309360** volts / Pa
 Offset: 0.000604634914 volts

Calibration Linearity Statistics:

Max Deviation:	1.043	% Full Scale
Max Deviation:	22.044	Pa
Std. Deviation:	10.7506	Pa

LEAST SQUARES FIT OF CALIBRATION DATA



NAHL Calibration of: Streamwise Force Block Gauge
 Least Squares Fit of Calibration Data
 Full Scale Gage Capacity (FS): 10 lb
 Date: 4/8/2022

U.S. Naval Academy
 Hydromechanics Laboratory
 590 Holloway Road
 Annapolis, MD 21402

Applied Load lb	Gage Output volts	Fit Output volts	Difference lb	Percent Full Scale
0.00	-0.163	-0.17	-0.0054	-0.054
1.00	0.377	0.37	-0.0031	-0.031
2.00	0.914	0.92	0.0036	0.036
3.00	1.460	1.46	-0.0053	-0.053
4.00	1.995	2.00	0.0057	0.057
5.00	2.535	2.54	0.0086	0.086
6.00	3.083	3.08	-0.0045	-0.045
7.00	3.619	3.62	0.0041	0.041
8.00	4.158	4.16	0.0077	0.077
9.00	4.701	4.70	0.0040	0.040
10.00	5.253	5.24	-0.0153	-0.153

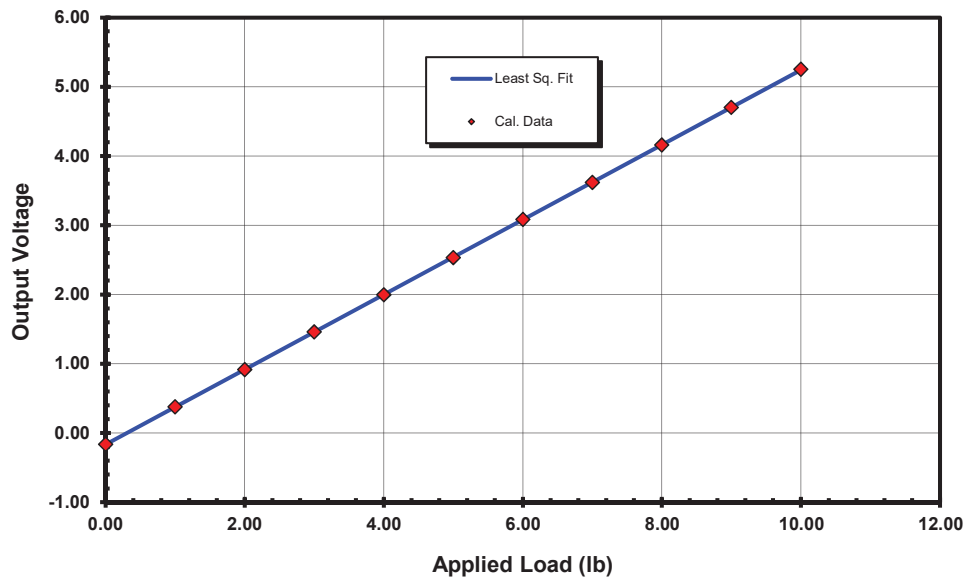
Gage No.	-
Amp No.	-
Gage Cal	-
Gain	-
Cal Pot	-
Cable ID	-

Gage Sensitivity: **0.5411** volts / lb
 Offset: -0.16615 volts

Calibration Linearity Statistics:

Max Deviation: 0.153 % Full Scale
 Max Deviation: 0.015 lb
 Std. Deviation: 0.0070 lb

LEAST SQUARES FIT OF CALIBRATION DATA



NAHL Calibration of: Side Force Block Gauge
 Least Squares Fit of Calibration Data
 Full Scale Gage Capacity (FS): 5 lb
 Date: 4/8/2022

U.S. Naval Academy
 Hydromechanics Laboratory
 590 Holloway Road
 Annapolis, MD 21402

Applied Load lb	Gage Output volts	Fit Output volts	Difference lb	Percent Full Scale
0.00	0.210	0.21	0.0026	0.053
0.50	0.729	0.73	0.0044	0.088
1.00	1.264	1.25	-0.0094	-0.187
1.50	1.786	1.78	-0.0098	-0.196
2.00	2.292	2.30	0.0045	0.089
2.50	2.816	2.82	0.0018	0.036
3.00	3.330	3.34	0.0085	0.170
3.50	3.861	3.86	-0.0011	-0.021
4.00	4.375	4.38	0.0060	0.120
4.50	4.903	4.90	-0.0012	-0.023
5.00	5.430	5.42	-0.0064	-0.128

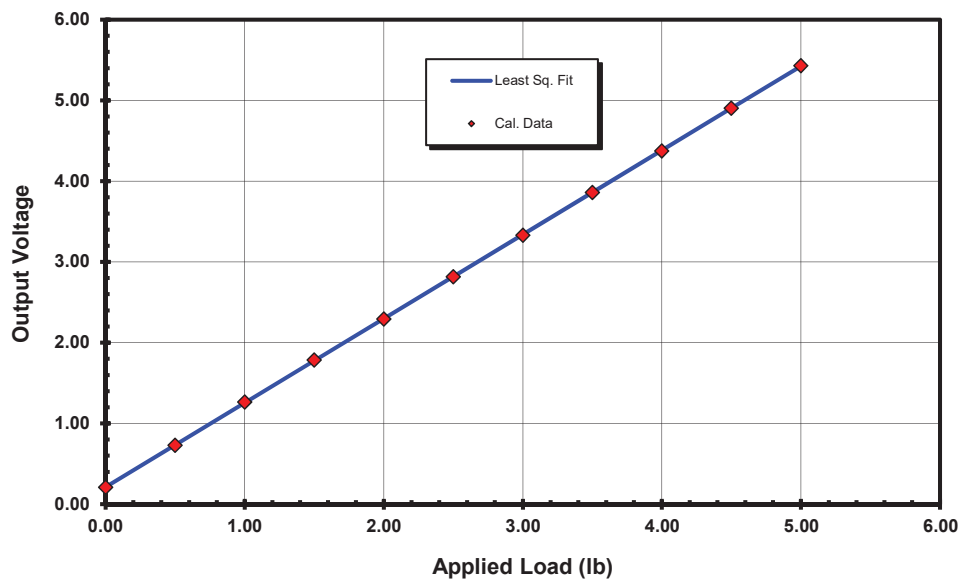
Gage No.	-
Amp No.	-
Gage Cal	-
Gain	-
Cal Pot	-
Cable ID	-

Gage Sensitivity: **1.0421** volts / lb
 Offset: 0.21255 volts

Calibration Linearity Statistics:

Max Deviation: 0.196 % Full Scale
 Max Deviation: 0.010 lb
 Std. Deviation: 0.0059 lb

LEAST SQUARES FIT OF CALIBRATION DATA



C Characterization of USNA Water Tunnel

The NAHL Large Re-Circulating Water Tunnel used a pitot static pressure tube to calculate exact tank speeds. The speed setting on the control panel was a percentage of the maximum tank drive capacity, which could be changed by the operator and had a resolution of 0.1% of the tank drive. A lookup table and trend line exist to relate most tank speeds to drive percentage settings. However, the water tunnel had not often been used for slow speeds and its data sheets did not contain a lookup table for achieving them. At slow speeds the pitot static tube calculations become inaccurate, or the sensor lacks the resolution to effectively indicate the current speed. An acoustic-doppler velocimeter (ADV) was used to accurately measure the speed of the tunnel at its lowest settings, as shown in Figure 50.



Figure 50: Acoustic-doppler velocimeter detecting exact tank speeds at various slow settings.

Before the ADV was employed, a simple experiment was undertaken to estimate the tunnel flow speed at various settings. The tunnel was run at 2.2% for five minutes before being dialed down to 2%. The tunnel was allowed to run at this speed for five minutes. Speed tests began after this period and consisted of dropping a small, floating object at the beginning of a measured window on the tank's free surface, then timing its progression across a 90 cm section of the tank. When ten trials were completed at 2%, the tank speed was dialed to 1.2% for eight additional trials.

These timed runs served as comparisons for the ADV. In order to use the ADV, the water was seeded with neutrally buoyant microbeads and run at 2.2% for forty-five minutes. Then, the water tunnel was set for 2% and given five minutes to settle. The ADV then recorded speed data until the speed settled on a value that only changed by ± 0.001 cm/s over the course of one minute, and this speed was recorded as the steady state speed for the water tunnel at that given setting. This process was repeated for the tunnel at the 1.8%, 1.6%, 1.4%, 1.3%, and 1.2% settings of its total drive capacity, creating a lookup table for future tests. Speeds between these values were found using interpolation.