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ANALYSIS OF FORCE PRODUCTION BY A
BIOLOGICALLY INSPIRED UNDERWATER FLAPPING
FOIL NEAR SOLID BOUNDARIES IN THREE
DIMENSIONAL FLOW
BY
DANE ELLES

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
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IN
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MASTER OF SCIENCE THESIS

OF

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2016

ABSTRACT

Force production from an underwater flapping foil near a solid boundary was experimentally studied in order to characterize the three dimensional flow effects. The experimental apparatus consisted of a dual canister system that actuated a harmonic oscillation of a NACA 0012 rectangular planform foil in pitch and roll. The flapping foil was towed at constant velocity through water in a tow tank in both a freestream and near boundary condition while forces and torques were measured by a six axis dynamometer. Experimental tests showed that for the chosen kinematic conditions and foil geometry, average maximum instantaneous lift forces increased 16-29% in ground effect compared to the freestream. It was also found that for the kinematic conditions evaluated there is a 9% increase in mean thrust production when in ground effect. Additionally, tests were performed at varying altitudes from the solid boundary with foil down biasing in an attempt to characterize the three dimensional flow changes as a function of height above bottom. Preliminary results have shown that the strength of ground effect observed through force sensing can be modulated through foil biasing and potentially provide useful information for altitude control of a flapping foil powered autonomous underwater vehicle (AUV).

Acknowledgments

I have always ascribed to a simple yet effective idea when approaching any undertaking in life, “Just do it!” Made popular by one of the world’s largest sports retailers, Nike; no fewer words have simply inspired so many to set forth and achieve something. My efforts throughout this thesis process challenged me in many ways that I never thought would present themselves, but I am truly grateful for opportunity and experience.

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1. Introduction

1.1 Motivation

Many animals within aquatic environments utilize flapping fins as a means of propulsion and maneuverability such as fish and turtles. Evolution has crafted a superb capability easily enabling them to inhabit and traverse areas of the ocean in which engineers have long considered to be operationally challenging or infeasible for unmanned underwater vehicles (UUVs). Littoral and tidal areas often have swift currents, shallow depths, and many obstructions to consider while navigating. These complex underwater environments are significant areas of interest for many scientific and industrial fields. Collecting of biological data in and around a reef, or inspection of pipelines or communication systems are just a few examples of where the employment of a traditional propeller-driven “torpedo shaped” UUV might be problematic. Whether it be agile navigation, or simply a desire to operate in close proximity to a solid boundary surface like the ocean floor or a ship’s hull, a UUV capitalizing on the natatorial movement like that of a sea turtle creates a very interesting biomimetic solution for these dynamic areas of operation. Hence where dynamic multi degree of freedom flapping foils come into play.

Pursuing the realm of near solid boundary operation, is where this work intends to expand upon much of the previous research and investigation into the response of a flapping foil propulsor in ground effect. It is hypothesized that the magnitude and direction of force production will be dependent upon the kinematics and geometry of foil position and that those magnitudes will be measurably different between ground effect and the free stream condition.

1.2 Thesis Content

Chapter 2 is a review of the associated literature surrounding the study of flapping foils and foils within ground effect. Background information is provided as a foundation to enhance the understanding of which this current work is based and sets forth to investigate. Chapter 3 presents the methodology, explaining the structure of the experimental system, enhancements and modifications made to the testing platform, and the overall experimental method for the work. Chapter 4 includes the results of the experimental setup and tests that were performed with corresponding findings. Chapter 5 addresses future design enhancements, acknowledges sources of error, and proposes future testing. Lastly, the summary and conclusions are presented defining the outcome of the overall effort, followed by the appendices and bibliography.

2. Background and Literature Review

2.1 Flapping Foil Propulsion

2.1.1 Foil Characteristics

Foils are characterized by a number of parameters based off the foil's geometry. Specifically, a foil can be summarized by its maximum camber, the asymmetry between the top and bottom surfaces, and its maximum thickness at a defined position relative to chord length. The chord (c) of the foil is the distance from the leading edge or nose to the trailing edge. The span (s) of a foil refers to its length measured from root to tip. In this work a NACA 0012 foil cross section with an overall shape of a rectangular planform area was used. The NACA four digit series of this foil defines it as a symmetrical foil (no camber) with a maximum thickness of 12% of the chord length. Many of the following concepts and equations will be based off these characteristic dimensions.

2.1.2 Foil Kinematics

The flapping foil test apparatus in this work is the same constructed by (Rauworth, 2014) and used in the work of (Chierico, 2014) in the investigation of ground effect. The test apparatus utilizes one of the four dual canisters developed for Finnegan the RoboTurtle, presented in (Licht, 2008). The system has two degrees of freedom denoted as pitch θ and roll ϕ . The two cylinder design consists of a roll motor, control card, and two power amplifiers located in the large stationary main cylinder, which drive the pitch cylinder through its roll motion about the X-axis. The pitch motor

and drive train components are located within the pitch cylinder and actuate the foil through its twist motion about the Y-axis as shown in Figure 1.

Figure 1: Existing Flapping Foil System

Flapping foil propulsion is generated through the formation of vortices in the wake pattern acting like a jet to provide thrust. This formation is referred to as a reverse Von-Kármán vortex street where the vortices created by the pitching and heaving foil are shed opposite one another in rotational direction and with an outward direction respective to the foil's top and bottom surfaces. This reversed shedding pattern creates a thrust channel behind the foil body rather than a mean velocity deficit, if the direction of vortex rotation is opposite as seen in Figure 2. The effective result of a flapping foil compared to a static body is the transformation of drag into thrust. Lift and drag forces can be created by a static foil simply by its geometry or orientation respective to the fluid flow. This enables foils to be used as control surfaces to generate lift for flight or to maneuver marine vehicles.

Figure 2: Reverse Von Karman Vortex Street created in wake of a flapping foil, (F. Hover)

The foil kinematics can be fully defined by a sinusoidal motion with equations for each parameter above using the same equations as those presented by (Polidoro, 2003). The equations for the roll of the pitch cylinder and the twisting of the foil are summarized by:

$$\phi(t) = \phi_0 \sin(\omega t)$$

Equation 1: Equation for roll of the foil

$$\theta(t) = \theta_0 \cos(\omega t)$$

Equation 2: Equation for pitch of the foil

where ϕ_0 is the roll amplitude in radians, θ_0 is the pitch amplitude in radians, and ω is the frequency of flapping motion in radians per second varied by time, t . A phase angle (ψ) between the pitch and roll motion of $\pi/2$ exists in all kinematics of this study so that maximum pitch occurs at both zero and maximum roll amplitude. Hence the cosine in the equation for pitch motion accounting for the phase difference.

The angle of attack (AoA) for a static foil is the angle between the chord line of the foil and a vector representing the apparent flow with respect to the body, Figure 3.

Figure 3: Static foil angle of attack (AoA)

The combination of rolling and pitching for a flapping foil causes a varying angle of attack along the foil span and is thereby referred to as having three dimensional kinematics (Polidoro, 2003). Following the previous works' notation of, (Polidoro, Rauworth, and Chierico) the three dimensional kinematics can be condensed into two dimensions denoted as heave and pitch by considering the instantaneous pitch angle and angle of incoming fluid acting at a particular cross section along the foil span. Most previous experimental work has taken a location at 70% of the foils span defining it as the center of pressure on the foil. This is taken from propeller design convention to use as a relevant dimensional parameter and used in this work as a starting point to define the three dimensional kinematics. $r_{0.7}$ is measured from the root of the foil and defined as,

$$r_{0.7} = r_0 + 0.7s$$

Equation 3: Equation for AoA location

where r_0 is the distance from the center of the roll axis to the root of the foil, and s is the foil span there by defining the selected location. Now that a particular location is chosen

the amplitude of the heave motion can be represented by the arc length created by the roll motion at $r_{0.7}$ and is defined by:

$$h_{0.7} = r_{0.7} \phi_0$$

Equation 4: Equation for heave amplitude

With heave amplitude adequately defined a heave velocity can be calculated. The heave velocity along with the angular motion equations and forward velocity can then be combined to define the instantaneous angle of attack, α as:

$$\alpha(t) = -\arctan\left(\frac{\omega r_{0.7} \phi_0 \cos(\omega t)}{U}\right) + \theta_0 \cos(\omega t)$$

Equation 5: Equation for dynamic AoA

where the first portion of the equation represents the roll induced AoA and the second portion represents the pitch induced AoA (Figure4).

Figure 4: Dynamic AoA at a span location (Polidoro, 2003)

For thrust producing motions, a maximum pitch amplitude is selected such that the maximum angle of attack, α_{max} is reduced at $r_{0.7}$ (Polidoro, 2003). The maximum angle of attack at $r_{0.7}$ is:

$$\alpha_{max} = \max(\alpha(t))$$

Equation 6: Equation for max AoA at $r_{0.7}$

2.1.3 Dimensionless Parameters

Utilizing scaling analysis, dimensionless numbers can be developed for parameters of the physics of interest. Relationships between these parameters allow for easy scaling and generalization of the experiment. The first dimensionless parameter of interest is the Strouhal number (St) and relates back to the formation of vortices in the wake pattern by the flapping foil. Strouhal number is used to characterize the vortex shedding and in our case is defined as a ratio of vortex size and frequency to the vehicle or fluid velocity. The defining equation is represented as:

$$St = \frac{2r_{0.7}\phi_0 f}{U}$$

Equation 7: Equation for Strouhal Number

The next dimensionless parameter in this study relates the amplitude of heave motion to the chord of the foil:

$$\frac{\text{heave amplitude}}{\text{chord length}} = \frac{h_0}{c}$$

Equation 8: Equation for heave to chord ratio

This is important as the width of the wake produced is mainly determined by the amplitude of the heave motion.

In an effort to validate this works' methodology, the results of testing will be similarly compared to the works of (Polidoro, 2003) and (Chierico, 2014). This requires identifying mean lift and thrust coefficients for different flapping kinematics. The mean lift coefficient is identified by:

$$\bar{C}_L = \frac{2\bar{L}}{\rho U^2 s c}$$

Equation 9: Equation for mean lift coefficient

Where ρ is the density of water and $\bar{L}$ is the measured mean lift force. Correspondingly, the mean thrust coefficient is identified by:

$$\bar{C}_T = \frac{2\bar{T}}{\rho U^2 s c}$$

Equation 10: Equation for mean thrust coefficient

The data comparison will map mean thrust coefficients ($\bar{C}_t$) using α_{max} and the Strouhal number as desired parameters. The Strouhal number will define the roll amplitude used which was constrained due to physical limitations of the test apparatus, and only leaves the pitch amplitude as the unknown parameter for the angle of attack formula.

The final nondimensional parameter used in this work to characterize the foil's physical location in the water volume with respect to the bottom is the height above bottom to chord ratio (H/c). This will be used to define when the foil is in ground effect where H is measured from the bottom of the tank to the mean roll position.

2.2 Bioinspiration and Fluid Dynamics

2.2.1 Ground Effect

2.2.1.1 Static Foils

‘Ground effect’, the change in force experienced by a static airfoil near a solid boundary, is a well understood phenomena in aerodynamics. Static airfoils begin to experience an increase in lift and decrease in drag (increased lift-to-drag ratio) approximately within a wingspan’s distance of a solid surface. Ground effect aerodynamics is mainly concerned with the changes to the three-dimensional flow field introduced by the presence of the near solid boundary and consequent impact on overall performance (Cui, 2010). This presents ground effect as a three-dimensional phenomenon, in which it should be studied due to the physical application of most foils.

Aerodynamic force on a static foil can be thought of as two components, lift normal to the freestream and drag parallel to the freestream. Lift is created due to the pressure difference between the upper and lower surface of the foil. Alternatively, one can think of lift as the creation of strong vortices near the foil’s solid surface whereby vorticity is used to explain lift (Garcia & Katz, 2003). This is often call ‘bound vorticity’ as opposed to ‘unbound vorticity’ found in a body’s wake pattern. In any circumstance, (Garcia & Katz, 2003) expand upon the idea of augmenting fluid dynamic loads using a “more vorticity, more lift” principle concluding that the trapped vortex is the most viable in lift augmentation. However, their background investigation found that stabilization of the bound vortex for aircraft lift augmentation was constrained to two-dimensional

laboratory tests and three-dimensional highly swept wings with very low angles of attack by capturing the leading edge vortices. A more practical application of the trapped vortex principle was found in the use of ground vehicles, specifically race cars, where the angle of attack relative to freestream falls within a small range similar to highly swept wing aircraft. When such vortices become trapped beneath a moving vehicle and the ground, an increase in negative lift can be attained. (Cui, 2010) mentions similar effects and it should be noted that the trapped vorticity is different from that of the Venturi effect whereby a constriction in the flow channel accelerates the fluid causing low pressure and a greater downforce, although this too is exploited in race car design. Overall the downforce of a foil in ground effect can significantly supplement the low mechanical downforce of light weight race cars vehicles without incurring any additional weight penalties.

An additional ground effect vehicle is known as the ‘wing-in-ground’ (WIG) vehicle whose specific design is intended to capitalize on the phenomenon for the intended purposes of operating with greater efficiency than conventional aircraft (Figure 5). While greater efficiency has been found, long durations of sustained low altitude flight have proven difficult due to random environmental conditions and surface fluctuations on the water. These conditions contribute to the instability of the vehicle. There are many successful operational WIG vehicles, however their limited operational capability due to vehicle stability has not proven economical. Modern engineering perspectives on design are typically focused on more efficient technology with increased performance. (Cui, 2010) notes that the clear benefits apparent with ground effect aerodynamics will ensure that the phenomenon will occupy a dominant role in

the optimization and development of vehicles subject to its influence. The scope will be expanded and deepened and the interaction with control systems are likely to receive extensive attention. This current work could certainly be a stepping point to do just that. Through the use of enhanced force sensing on an autonomous underwater vehicle (AUV) with flapping foil propulsion, control system design could be implemented to recognize the effects of ground effect for altitude control when near bottom operation is required.

Figure 5: A wing in ground effect (WIG) aircraft

Another look at ground effect from a biological approach is cited in (Rayner, 1991). Observations of flying animals are made in relation to their performance in flying near a solid boundary (Figure 6). The author found that there may be a considerable performance advantage of flight in ground effect over a smooth solid surface which would reduce the cost of transport and mechanical flight power required, compared to values for flight out of ground effect. Additionally, slow flight performance in ground effect is very poor, due to the horizontal air velocities induced around the wing.

Figure 6: A pelican flying in ground effect over water

Comparing animal flight to that of aeronautical practice, Rayner considers the paradigm of ground effect for animals to be that of maintaining level flight at a constant height above ground in the most economical way; as opposed to conventional aircraft where during landings and takeoff, flight speed and height above ground are not constant. Based off this assumption of intended animal flight, a theoretical steady state lifting-line wing model was developed whereas conventional approaches to modeling an animal's wing in biological literature relied upon the method of images for a vortex pair acting on the wing which following general aeronautical practice where horizontal induced flow is ignored due to its relatively small effect. The lifting line model considers the induced velocity caused by the bound vortex and treats wings as fixed lifting surfaces. The form of the theory however does not take into account any thrust generation by flapping wings and he acknowledges that there are significant changes to the flight dynamics for that case.

2.2.1.2 Dynamic Foils

While much work has been done to understand the aerodynamics surrounding static airfoils both in and out of in ground effect, comparatively, far less large scale

research has been performed for dynamic foils. We have seen that animals can take advantage of ground effect, however all those animals primarily use the kinematics of flapping for general flight. The next logical study of ground effect from a biological approach is the flapping wing. (Wu, Shu, Zhao, & Yan, 2014) numerically simulated a flapping insect wing in forward flight using with NACA 0012 airfoil to model the insect's wing cross-section. The simulation was performed using the Immersed Boundary-Lattice Boltzmann Method (LB-LBM). A combined harmonic oscillation of pitch and heave are performed while constraining Reynolds number and amplitude of motion. This enabled the examination of distance between the foil and the ground together with the frequency of oscillation. Of significance in this work was the observation of the flow patterns shed from the foil. They were indeed altered due to the close proximity of the ground. Observing these flow patterns at varying heights above ground, they concluded that there is little effect at a $H/c > 3$, which was used as the basis for the freestream condition. At low Strouhal numbers within ground effect the size of the vortices shed is decreased however the strength was increased. As the frequency of flapping oscillation increased, greater vortex interaction with the ground is observed affecting the vortex shedding. The vortices were also compressed into an oblate shape and a distinct angle between the ground and center line of the vortex street was found. This is seen in Figure 7 as the minimum and maximum Strouhal numbers are observed over one flapping period within ground effect. The authors relate this angle to the mean lift vector direction induced from the increase in mean lift coefficient while in ground effect. Lastly, the mean drag coefficient was found to have increased for smaller Strouhal numbers while it decreased for larger Strouhal numbers. This would relate to

a finding of increased thrust at higher frequencies and decrease thrust at lower frequencies.

Figure 7: Vorticity distribution over one cycle in ground effect (Wu, Shu, Zhao, & Yan, 2014)

Another look at ground effect with from bioinspiration was performed by (Blevins & Lauder, 2013). They examined ground effects on an undulatory swimmer comparing it to that of other flapping fin animals with fixed kinematics. They utilized a physical model of a stingray to experimentally determine that ground effect does not necessarily enhance the performance on undulating fins. It was found that the influence

of ground effect varies with kinematics and that modulation of swimming patterns might be performed to minimize locomotion penalties for benthic swimmers near a substrate. While the kinematics of this physical analysis may be different, it is interesting to note once again that different kinematics will have significantly different outcome when in ground effect.

Using an similar test platform to the one in this current work, (Polidoro, 2003) collected data on three-dimensional flapping foils over a wide parametric space with the intent of identifying kinematics to maximize thrust production for flapping foil propulsion feasibility of an AUV. Data collected mapped thrust coefficient contours and time sequence lift and thrust data. While the dual canister system was physically similar to the one used in this current effort, its implementation was very different. Only the foil pierced the water's surface and force data was collected externally using a six axis dynamometer located between the foil and the canisters. Rauworth designed the current flapping foil test system to be employed completely submerged for studying ground effect. He also compared the lift and thrust data of Polidoro's work, which found similar trends, for the analysis of his system in the generation of force production.

In another work, (Licht, 2008) described the conception of Finnegan the RoboTurtle from observation of an actual sea turtle to full-scale testing of an AUV utilizing flapping foil propulsion. Finnegan provided the link between the testing of foils to their application on an underwater vehicle. His worked proved the concept of a highly dynamic and maneuverable alternative propulsor for underwater vehicles compared to that of conventional propeller driven vehicles. Finnegan was equipped with a suite of sensing equipment to provide information of the vehicle's location in the water,

however there were no instruments to sense the fluid flow surrounding the vehicle or the flapping foils. By instantaneously sensing forces on the foils, information about flow velocities and near boundary proximity could be measured in real time. Identifying boundary proximity through force sensing is one of the main efforts of this current work in order to enhance solid boundary detection for near bottom operation of flapping foil AUVs.

Additional work on flapping foils by (Techet, 2008) investigated thrust coefficient contours over a range of Strouhal numbers and maximum angles of attack using a similar test system to that of (Flores, 2003). Of significance from that paper was the generation of a contour plot with a heave to chord ratio of 1.5. This test data was used by both (Rauworth, 2014) and (Chierico, 2014) in their initial analysis. Techet noted that the center of hydrodynamic pressure on the foil varies while flapping and hence the 70% span length location was used for nondimensional calculations. Rauworth was able to create similar trends in mean thrust coefficient contour data, however the values were different due to different sensing methods and foils used. He found that the phase averaged data closely follows the expected theoretical results for flapping foil dynamics.

The next two reviews are of significant interest as they relate specifically to this current effort. A two dimensional foil (Licht & Dahl, 2013) was towed vertically with a heave and pitch oscillation through a small water tow tank approaching the vertical wall surface to sense ground effect. Their efforts presented a preliminary experimental study showing that for a typical set of thrust generating kinematics operating two chord lengths from the bottom, an increase in mean lift was detected by an amount consistent

with a one degree positive pitch bias of the foil. Also, for flapping near a solid boundary there is a peak magnitude increase of the downstroke vs. the upstroke instantaneous lift which can provide a detectable signal within a single flapping period and also negate the need for some previously measured baseline in open water to be operational useful.

(Mivehchi et al, 2015) expanded the preliminary experimental work of Licht and Dahl by investigating ground effect in both two dimensional and three dimensional flow for a high aspect ratio flapping foil. Two sets of experimental tests were performed towing the vertically oriented foil through the same tow tank at varying distances from a solid boundary. In the first experiment two dimensional flow was investigated on an “infinite foil” such that a minimal average tip clearance of the bottom is achieved. The next experiment allowed for significant span-wise flow around the tip of the foil so that three dimensional flow could be investigated. It was summarized, as in most ground effect studies that distance has a significant impact on the lift and thrust forces generated by the foil, both in the time averaged mean forces and the phase averaged periodic forces. Additionally it was noted that instantaneous force profiles for some thrust producing kinematics may change significantly without altering the time averaged mean force. Hence for the experiment performed, it was concluded that the mean force measurement alone is not sufficient to indicate the proximity, or the effect, of the solid boundary. Lastly, the authors identified that while propulsive efficiency is slightly increased near the wall for some kinematics, in general this does not occur where a strong ground effect was observed and that maximum angle of attack plays a critical role in the orientation of that lift force. Smaller angles of attack tended to demonstrate a suction effect toward the wall for higher Strouhal numbers. In conclusion, the authors

acknowledge that the real world application of flapping foils will certainly include three dimensional span-wise flow and that ground effect on a foil is primarily a three dimensional phenomenon. Numerical approaches to studying ground effect tend to exclude span-wise flow due to computational constraints however experimental approaches struggle to eliminate it if not desired. This indicates that the path forward in the endeavor to fully understand and characterize flapping foils within ground effect certainly will include a three dimensional flow field whether done experimentally or computationally.

2.3 Existing Test Platform

The test platform used in this current work is fundamentally the same as that used in the work of (Rauworth, 2014) and (Chierico, 2014) but with some minor enhancements. Naturally, this effort can be seen as an extension to their work building upon the system Rauworth constructed and further investigating ground effect phenomena that Chierico pursued. The existing test platform utilized a dual canister system that enables harmonic pitching and rolling actuation, a carriage attachment structure for the dual canister, a National Instruments (NI) Data acquisition chassis with instrument cards, DC power supply, a laser distance measurer (LDM), two Kistler 9602 force sensors located in the pitch cylinder, and a computer to integrate all sensor and control components. A full breakdown of all components and construction of the physical test system can be found in (Rauworth, 2014).

Figure 8: URI Tow Tank flapping foil test platform (Rauworth, 2014)

Figure 9: Tow carriage with Flapping Foil Test Platform (Rauworth, 2014)

In (Chierico, 2014) a number of enhancements were made to the system. He started by creating a larger separation between the two three axis force sensors. The sensors were originally located closely together due to space constraints. In an attempt to increase the signal to noise ratio, by subjecting the sensors to larger moments generated by the flapping foil pitch shaft, larger separation between them was found by reconstructing the internal attachment components within the pitch cylinder. The next major improvement was the use of spherical bearings instead of rigid bearings on the pitch shaft. The rigid bearings acted like clamped connections and imparted additional moments about the body frame referenced x and z axes. Spherical bearings allowed for a pinned connection to the shaft that would permit the appropriate shaft rotation and minimally constrain movement in the other axes, eliminating additional moments. The next improvements that were made to the system were cleaning up cluttered sensor signal wires and power wires for the sensor. The sensor signals were transmitted from the sensors out of the dual canister via CAT 6 cable and terminated in a 68pin NI-SCB-68A connector block. The connector block then allowed for connection to the data acquisition (DAQ) card in the NI chassis. The sensors were powered from a NI DC power supply card in the chassis and dual canister motor actuation was powered using an external BK precision 1673 triple output DC power supply. The laser distance measurer used to provide location of the carriage down the length of the tank was also powered from this power supply. With the new configuration of the sensors and internal adjustments, a new calibration procedure was developed for the sensors. This had to be done since there was no previous factory calibration that came with the sensors to be validated.

With the newly modified test setup, (Chierico, 2014) performed a series of different kinematic flapping tests that showed for all cases there was an increase in mean lift coefficient for near bottom flapping compared to freestream and as noted by other work a minor thrust benefit only under certain kinematic conditions. Figure 10 displays one representative set of results for change in mean lift coefficient as a function of maximum angle of attack for various Strouhal numbers.

Figure 10: Change in mean lift coefficient as a function of α_{max} (Chierico, 2014)

The point at which Chierico evaluated ground effect is where this current effort intended to pick up. The same kinematic test matrix was used initially to verify new enhancements to the test system. Next an expansion of the study of flapping foil ground effect was performed in such a way that the test system is configured to mimic realistic operation of a flapping foil AUV, by simulating some of the physical constraints of a foil with pitching and heaving actuation near the bottom.

3. Methodology

3.1 Test System Modifications

Starting with the cited sources of error and recommendations of (Chierico,2014) for his investigation, a number of physical and operational changes were made including wiring upgrades, a new user interface, overall reduction of unwanted noise in the system, and most importantly the installation of a single six axis force and torque dynamometer. The same fixed body frame referenced coordinate system (Figure 11) established for the dual canister setup was utilized once internal geometry references were adjusted accordingly.

Figure 11: Fixed body frame referenced coordinate system

3.1.1 Six Axis Force and Torque Sensor

Starting with some of the maximum force values observed by Chierico and Rauworth, an appropriate force sensor was chosen as a replacement for the two Kistler sensors in the existing system. Additional requirements besides load rating included the physical size of the transducer since it had to fit into an already constrained space within the pitch cylinder, an appropriate overload capability for safe testing, and compatibility with the existing NI-DAQ card. For this effort, an ATI Industrial Automation, Inc. Gamma SI-65-5 DAQ Force/Torque sensor system was selected. The multi-axis system simultaneously measures forces (F_x , F_y , F_z) and torques (T_x , T_y , T_z). The system as a whole consists of a load transducer, power supply box, and associated cables.

Figure 12: DAQ F/T Transducer System (ATI F/T DAQ I&O Manual)

The transducer itself is a rugged monolithic structure made of aluminum that converts forces and torques into analog strain gage signals. Semiconductor strain gages are

attached to three symmetrically placed beams machined from a solid piece of metal decreasing hysteresis and increasing strength and repeatability. Due to the tri-beam construction calculations must be performed in order to obtain the loads being sensed hence, a force sensed in one axis is actually a composition of multiple strain gage values. The calculation is performed by the onboard electronics within the sensor. The transducer reports the loads as composite values converted into the six cartesian axes. The analog signals output by the transducer can be mapped directly into force and torque vectors through the factory provided calibration matrix. This calibration was validated prior to experimentation and will be discussed later. The tool adapter plate is machined with a standard bolt circle pattern and is where the origin of the sensor's coordinate system is located. A custom mounting adapter plate was made for the bottom of the sensor to affix it within the pitch cylinder.

Figure 13: Applied F/T vectors of SI-65-5 Gamma transducer

With a metric calibration range of 65 N in the x and y axes and 200 N in the z axis the only limitation in the load range was the moments which are limited to 5 N-m in all axes. While a greater calibration range could have been selected, this particular dynamometer's specification provided a nice sensing range to accommodate the

anticipated loads. Flapping kinematics could also be adjusted to ensure forces measured stayed within the calibrated range of the sensor while trying to investigate the maximum extent of the parameter space.

The power supply box of the sensor is connected in line between the DAQ card on the chassis and the sensor itself. The DAQ card is capable of outputting 5VDC which is transmitted to the power supply box through the power supply cable. The power supply box then amplifies the power signal and provides voltage to the sensor through the transducer cable. Every effort was made in the installation of this new force sensing system to maintain the integrity of the factory provided cables. Any modification to the cables could introduce unwanted noise to force signals.

To install the new sensor within the pitch canister, a complete redesign of the internal components was performed. The new sensor is substantially thicker than the previous units, so the Delrin pitch cylinder had to be modified to account for its size. All internal components had to be assembled and mounted in a way that only connection the tool adapter plate is permitted (Figure 14) so that all forces on the foil would transmit directly. The sensor was oriented in the pitch cylinder with its positive x axis in line with the body frame x axis. When the dual canister system is mounted to the tow tank carriage the actual orientation of the sensor is upside down so that forces sensed in the z and y axis have to be resolved and translated to the body frame of reference.

Figure 14: Pitch drive train assembly mounted to ATI sensor

3.1.2 Wiring Improvements

Maintaining factory wiring for the sensor was already mentioned in order to eliminate any question of noise in the force signals. A number of additional wiring improvements were made to the existing communication and power cables. The existing systems had two main entrances through the front of the pitch cylinder for the pitch motor power, motor controller communications cable, two sensor signal cables, encoder position signal wires, pitch shaft homing flag sensor wires, and leak detector wires (Figure 15). All power and signaling for the components within the pitch cylinder come from the roll canister where the motor control card and motor amplifiers are located. The wires for this were routed out of the back end of the roll canister and through the front of the pitch cylinder using waterproof Impulse connectors. In the new redesign, all these wires were run through the roll shaft located on the back of the pitch cylinder that connects to the roll motor in the roll canister.

This eliminated circuitous routing of wires from one canister to the other outside of the system and separated motor power from the force signaling cable.

Figure 15: Existing pitch canister wiring

Since all of the wiring for the pitch actuation was removed from the front of the pitch cylinder, two access holes were left. Only a single cable for the sensor signal is needed so utilizing one of the tapped holes from the previous Impulse connector locations, a simple Heyco-Tite liquid tight bulkhead connector designed for pre-assembled cables with a split gland was used. This allowed for sensor cable installation without removing the factory 26-pin connector. The other tapped hole was used as a vacuum port for leak testing to ensure water tightness of the system prior to its operation. During operation, the vacuum port is sealed.

Figure 16: Redesign of the pitch canister wiring

3.1.3 User interface

Part of the redesign of the test system was to create a new user interface for controlling the flapping foil, viewing, and recording force and position data. The NI chassis contains the ethernet card for communications to the motor controller, the NI DC power card, and the DAQ card all connected to the wave tank desktop computer. A LabVIEW virtual instrument program was created to control the various system functions of the components all from one user interface. Power for the LDM was taken off the external BK Precision power supply and connected to the NI-DC power card. This enabled full remote functionality of the LDM from the desktop computer. The external BK Precision power supply was now free to solely provide power to the dual canister motors. The new LabVIEW graphical user interface (GUI) integrated

GalilTools software that is used for motor control commands, the distance and velocity measurements of the carriage from the LDM, and the sensor force data (Figure 17). A waveform graph displays the instantaneous force and torque information from the sensor. When recording of data is required, force and torque data, carriage velocity and distance, and motor position and velocity information are recorded to 3 separate data files representing the raw data for one run down the length of the tow tank.

Figure 17: LabVIEW flapping foil GUI

3.1.4 Foil Design

The foil used in the ground effect study by (Chierico, 2014) was one of the fins from Finnegan (Licht, 2008). The biologically inspired design was constructed of a titanium framework surrounded by a polyurethane elastomer with a NACA 0012 profile (Figure 18).

Figure 18: Existing foil (Chierico, 2014)

Due to its construction and placement of the framework, one-third of the chord closest to the trailing edge was compliant. This property had not been quantified nor studied on this particular foil shape and introduced an unknown in how the foil behaves hydrodynamically. Due to its shape, a mean chord length was used in calculations. The 70% span location was used as the assumption of the effective hydrodynamic center of pressure on the foil as a starting point. While consistent with preceding works (Polidoro, 2003), (Techet, 2008), (Rauworth, 2014) the actual location was never accurately determined due to the low resolution and high noise in the system. To remove question about the foil itself a new foil was constructed. Instead of a compliant material, a ridged material in the shape of a rectangular planform with a NACA 0012 profile was used. This foil shape is well documented and understood. Using the existing titanium framework within a pre-constructed rectangular planform mold the new foil was cast using Smooth-On Feather Lite lightweight casting resin. The material has a low density and a shore D hardness of 58 when fully cured. After curing the foil was given a rounded aft swept tip. The final foil dimensions were 0.3975m in span and 0.095m in chord

resulting in a high aspect ratio (AR) of 4.1. The foil was then coated with yellow epoxy paint and wet sanded to produce a very smooth surface finish (Figure 19).

Figure 19: New rectangular planform foil

3.1.5 Sensor Calibration

The ATI sensor (serial FT16647) used in this work does not require any calibration after shipment from the factory. It is provided with a factory calibration per the specified range of which it is listed for. The measure of uncertainty or maximum amount of error for the sensor per its certificate of calibration for each axis expressed as the percentage of its full-scale load is 0.75% in the Fx axis, 1.25% in the Fy axis, 0.75% in the Fz axis, 1% in the Tx axis, 1% in the Ty axis, and 1.5% in the Tz axis. A calibration or sensitivity matrix was also provided to perform the calculation of converting strain gage voltages into force and torque data. Since it is highly unattainable to recreate the National Institute of Standards and Technology (NIST) level of accuracy

provided by the factory calibration given the resources available, a validation that the sensor exhibited good linearity for its calibrated range was performed. A series of static and dynamic tests were conducted by loading the sensor with known weights and observing its force and torque readings. For the static tests the sensor was affixed to a small rotary table used for machine work (Figure 20).

Figure 20: Isolated axis static calibration loading

Initial static testing isolated each axis where known masses were applied from 0.04 kg to 0.5 kg to measure forces. The same masses were observed with measured moment arms to observe torque readings. Results from simple static testing where each axis was attempted to be isolated and loaded are shown below.

Figure 21: Static loading results of force in the x-axis

Figure 22: Static loading results of force in the y-axis

Figure 23: Static loading results of Torque about the x-axis

You can see for the single axis force loading that the data exhibits a very linear trend.

Next the sensor was validated through compound loading where multiple axes were deliberately loaded in a static position that simulates the middle of a flapping cycle. The bearing mount plate along with the bearings was attached to the sensor face. A shaft was installed in the bearings to represent the pitch shaft for the foil. Known masses from 0.1 kg to 1.1 kg were hung on the shaft at five different locations along the shaft and plotted. The intent of this was to see if the force and torque reads exhibited the same linearity as before. The following plots display the loaded force and torque values. Upon calculating the sampled force data it was found that the sensed forces fell well within the measurement uncertainty ascertained for the factory calibration.

Figure 24: Static compound loading results of force in the x-axis for 5 different torque distances

Figure 25: Static compound loading results of force in the z-axis for 5 different torque distances

Figure 26: Static compound loading results of torque about the x-axis at 5 different distances

Figure 27: Static compound loading results of torque about the z-axis at 5 different distances

Lastly, for the validation of the sensor calibration, an in situ dynamic test was performed. The dual canister system was clamped to a test bench so that the pitch and roll oscillation of the canisters would not cause the test system to fall. Next the sensor was installed and prepared for operation (Figure 28).

Figure 28: In situ dynamic flapping sensor validation testing adjacent to tow tank

The system was commanded to execute the harmonic oscillation to produce a flapping kinematic with a Strouhal number of 0.3. This represented a 12 degree roll amplitude (ϕ_0) and pitch amplitude of 23 degrees (θ_0) with a frequency of 0.81Hz. Knowing the mass of the components attached to the sensor face, as the pitch canister executed its roll actuation the maximum corresponding force and torque values were observed. Additionally, these tests were done with the shaft seal in place to observe the

physical effect that the seal would have on the sensor readings. As expected there was a slight damping effect and a static bias that was noted in the force data after the seal was installed. The compliant seal would however find an equilibrium position and impart less of a bias force on to the shaft once initial movement had begun breaking static friction. There was always some minimal bias force imparted onto the shaft though due to the shaft and the seal not being perfectly concentric with one another. After a homing routine is performed prior to a test run, equilibrium is found for the shaft seal, and the biased force is neglected as the sensor is tared before every run down the length of the tank. The static bias by the seal was later addressed in post processing.

This gave insight into the effect that the shaft seal would have on the force measurements. Figure 29 displays a notable bias force of approximately 1 N in the y direction and also displays the damping effect to the sensed force in the y-axis.

Figure 29: Comparing dynamic Fy data w/ and w/o shaft seal installed

3.2 Experimental Method

3.2.1 Test Setup

The tow/wave tank in the Ocean Engineering Sheets Laboratory on URI's Bay Campus was utilized for all testing. The 30m long tank is equipped with a tow carriage that translates the length of the tank on rails. The tank is equipped with movable panels along the bottom to simulate different beach heights. Figure 30 shows the depth profile of the tank used in all experiments. A single run down the tank consists of first the freestream zone at the beginning followed by the transition, and then the ground effect zone.

Figure 30: Tank water depth profile

Throughout the 8 m long freestream zone, the mean $H/c = 9.7$. (Wu, Shu, Zhao, & Yan, 2014) found that for $H/c > 3$, there was no influence on lift force from ground effect. Assuming this effort translates well to their results, the freestream zone forces should not indicate any presence of ground effect. In the shallow end of the tank, the lowest possible ratio attained was $H/c = 1.3$, throughout the 9 m long ground effect zone. The transition region from freestream to ground effect was neglected for this work. $H/c = 1.3$ is the lower limit for this experiment due to the geometry of the dual canister body

when a 1 cm minimum clearance is used. At this closest point using the 39 cm long foil a maximum roll amplitude of 12 degrees in the negative (down) roll direction was possible without the tip hitting the bottom. All kinematics performed in this work maintain the same roll amplitude for comparative analysis to one another. These physical limitations represent part of the realistic operating parameters that a flapping foil AUV in near bottom operation might experience. Following (Techet et al, 2008) and assuming initially that hydrodynamic center is located at the 70% span location for the maximum allowable roll amplitude.

A series of tests were performed following the test matrix presented by (Chierico, 2014) as a starting point with the intent to confirm similar force readings from the new sensor. Strouhal numbers and maximum angles of attack were varied between 0.3 - 0.6 and 20° to 35°, respectively.

A midrange set of test parameters ($St = 0.4$, $\alpha_{max} = 20^\circ, 35^\circ$) were selected in order to compare operation at different heights from the bottom. Six different height cases were evaluated. For each pair of Strouhal number and maximum angle of attack, tests were performed with zero roll bias and then with a roll bias to allow the foil tip to maintain the same proximity to the bottom (1cm). This allowed the foil tip to maintain a distance from the bottom to maximize ground effect forces even though the majority of the foil span and vehicle body were elevated away from the ground. Figure 31 illustrates three positions of varied height from the bottom and the corresponding down bias to achieve the foil tip clearance desired.

Figure 31: Down biasing at varied altitudes

3.2.2 Experimental Procedure

At the start of each testing day and prior to installation on the carriage attachment, the system was connected to the data acquisition chassis and shore based desktop computer to verify proper operation. Motion commands were performed to evaluate proper movement and operation. The system was then disconnected and attached to the carriage attachment in the water. Upon reconnection of the system cables it was operationally checked once again. Next the carriage speed was dialed in to translate at 0.5m/s. This was done by adjusting the potentiometer on the carriage control box until the desired velocity was met as measured by the LDM. Once this was achieved the dial remained untouched for the duration of testing. Each test run began with the carriage positioned to maximum extent of the freestream zone by manually pushing it up against a hard stop. This ensured that every run started from the same location and allowed for the maximum amount of freestream data to be collected. At the end of each run the carriage was stopped at a location so that the dual canister would not impact the bottom of the last sloping panel providing for the maximum amount of ground effect data to be collected. These locations were physically surveyed on the tank as distances

and then correlated to the depth. The distances were then validated against the LDM readings. During post processing, force data could accurately be associated with distance and velocity so that data within the distinct zones of interest could be selected from each run.

The same process to gather a dataset for one run was followed for every test and is prescribed as follows:

1. The carriage is set in the starting location, a homing routine is performed to orient the foil and create a zero based origin on each axis to perform any needed bias for different runs or to take account of the zero foil pitch bias, to be discussed later.
2. The sensor is tared to subtract the weight of the foil and drive train components in the force measurements.
3. Data collection is initiated recording force data, distance, velocity, and motor position.
4. The flapping motion is begun for the specific kinematic to be run.
5. After a least three cycles are performed the carriage is started and accelerates to its predefined constant speed down the length of the tank.
6. At the end of the run first the carriage is stopped, then the flapping motion of the foil is stopped, and finally the data acquisition is stopped.

Each run takes approximately 40 seconds to complete and upon resetting the carriage an 8 minute settling time is allowed for the water in the tank before the next run.

3.2.3 Finding zero foil pitch bias

In order to collect accurate lift force data a nominally zero foil pitch position must first be found at which zero mean lift is produced. This ensures that there is no additional pitch bias imparted on the foil when the assumption is that there is not. The zeroed origin of the motor positions correspond to the locations of the optical homing flags on each rotation axis. This origin only represents an initial best estimate of zero pitch angle. In order to determine the true zero pitch bias location, a series of static foil tests were performed in which the foil was towed down the length of the tank at varying pitch angles without flapping. The nominal zero pitch position was determined through a linear regression to find the position at which zero mean lift was produced. Every effort was made to remove as much mechanical backlash in the pitch drive train however, the connection point of the foil to the pitch shaft permits some variation in pitch angle. The tests were performed from -5° to 5° of pitch at one degree increments (Table 1). A homing routine was performed each time prior to the setting of each pitch bias to limit any compounding error in position that could possibly occur.

Test #	Velocity (m/s)	Pitch Bias ($^{\circ}$)
1	0.5	5
2	0.5	4
3	0.5	3
4	0.5	2
5	0.5	1
6	0.5	0
7	0.5	-1
8	0.5	-2
9	0.5	-3
10	0.5	-4
11	0.5	-5

Table 1: Pitch bias test runs

Only the lift force generated in the freestream was used in the calculation of the lift coefficient. Due to the linearity and resolution of the new sensor it was thought that simple static tests would suffice to determine the zero mean lift coefficient rather than performing flapping tests. Results are presented in Figure 32.

Figure 32: Mean lift coefficient as a function of pitch bias

The objective was to identify where the pitch bias exhibits a zero mean lift coefficient. The results of the tests showed that the zero mean pitch bias was located at the positive one degree in pitch angle. The data displays a deviation from linear fit between -2° and 0° . There are a few assumptions as why this occurs. The first being caused by the play in the foil to pitch shaft connection. More linear trends are exhibited when the foil is pitched to either 2° or -3° . Beyond these angles the fluid force on the

foil is great enough to take up the backlash and prevent foil transient motion. The next assumption is that the foil could possibly be slightly asymmetric in its profile, having some minor camber that would create lift in the mean position.

While determining the zero mean lift coefficient the interest was only focused on the freestream zone, it was however interesting to see the increase in lift force generated within the ground effect zone. When the entire length of the run is plotted, a 15% mean increase in lift force was observed for the 3° case shown in Figure 33. Additional static pitch bias plots can be found in Appendix 1.

Figure 33: Instantaneous lift for a pitch bias of 3 degrees

3.2.4 Data Post Processing

Since the GUI built for this work is completely different than anything used previously, the output files are completely different as well. Additionally, the sensor is directly sensing torque values as opposed to the work of (Chierico, 2014) and (Rauworth, 2014) where the moments were calculated from the assumed hydrodynamic center and forces recorded at the sensor. New processing codes were developed in Matlab™ to parse the data from the raw data files, organize it, and then perform analysis of the results. The equations of motion were calculated based off a non-rigid body analysis to account for the pitching of the foil in addition to its roll rotation. The equations yielded reaction forces from the mass of the foil and drive train components based off of the time varying pitch and roll angles. A detailed analysis of the free body diagrams and equations can be found in Appendix 2. The reaction forces were then used to remove the effects of inertia and gravity from the force readings. It is important to note that the effects of the shaft seal are not accounted for in these reaction forces. Since it is a compliant seal, the assumption was made that it had a minimal effect. This allows for the sole analysis of fluid forcing on the foil. Next, the transformation of the force and torque values from the sensor frame of reference to the body frame of reference was performed. Figure 34 shows the relation of the sensor frame to the body frame of reference.

$R_{0.7}$ was used to quantify the heave amplitude in the calculation of the Strouhal number. Since moments are recorded from the sensor the location of the center of pressure can be identified experimentally.

Figure 34: Sensor frame in reference to body frame

Analysis consisted of finding the phase average lift and thrust in both the freestream and ground effect zones. The cycles of motion within their respective zones are averaged together based off the motor position period to provide an averaged instantaneous lift and thrust force throughout a single cycle within each zone for a run. The mean of the instantaneous lift and thrust coefficients throughout the cycle are then

computed. Mean coefficients of lift and thrust can then be compared across varying heights and varying heights with down biasing in the roll axis

4. Results and Discussion

4.1 Test Results

Two sets of experiments were performed as the basis for analysis in this work. In the first experiment, the intention was to evaluate the new sensor and foil against the previous experimental results of (Chierico, 2014) and (Rauworth, 2014). Table 2 was developed for Strouhal 0.3 to 0.6 and varying maximum angles of attack from 20° to 35°. This planned test matrix is similar to the previously mentioned work, but accounts for the new foil dimensions by altering the frequency (f) and the pitch amplitude (AMY) to maintain the same Strouhal numbers.

Test #	f (Hz)	AMX (°)	AMY (°)	St #	$\alpha_{\max}$ (°)
1	0.81	12	23.3	0.3	20
2	0.81	12	18.3	0.3	25
3	0.81	12	13.3	0.3	30
4	0.81	12	8.3	0.3	35
5	1.08	12	31.7	0.4	20
6	1.08	12	26.5	0.4	25
7	1.08	12	21.5	0.4	30
8	1.08	12	16.5	0.4	35
9	1.35	12	39.6	0.5	20
10	1.35	12	33.1	0.5	25
11	1.35	12	27.6	0.5	30
12	1.35	12	22.5	0.5	35
13	1.62	12	47.5	0.6	20
14	1.62	12	39.8	0.6	25
15	1.62	12	33.1	0.6	30
16	1.62	12	27.2	0.6	35

Table 2: Comparative Test Table

In the second experiment, tests were performed at varying heights above the bottom of the tank for a midrange set of test parameters ($St = 0.4$, $\alpha_{\max} = 20^\circ, 35^\circ$). Six different height cases were evaluated. For each pair of Strouhal number and maximum angle of attack, tests were performed first with zero roll bias and then with roll bias to maintain the same foil tip proximity to the bottom (1cm) at the maximum amplitude of the downstroke.

The results of the Table 2 experiment were corrupted by significant experimental problems. However, the results did provide qualitative context and are included in Appendix 3 for further discussion. The results of the second varying height experiment are the primary focus and are fully described here.

4.1.1 Varying Height Tests without Down Bias

Table 3 shows the kinematic parameters and H/c ratios for all tests performed without down biasing. While in the ground effect zone, six heights were tested for each of the two foil kinematics ($St=0.4$, $\alpha_{\max}=20^\circ$) and ($St=0.4$, $\alpha_{\max} = 35^\circ$). Two representative phase averaged lift and thrust plots ($H/c = 1.3$ and 3.3) from the table are presented along with the mean lift coefficient plots for all heights. Additional phase averaged lift and thrust plots for Table 3 can be found in Appendix 4. Figure 35 illustrates three of the varying heights from Table 3.

Test #	St #	$\alpha_{\max}$ (°)	H/c
1	0.4	20	1.3
2	0.4	35	1.3
3	0.4	20	1.8
4	0.4	35	1.8
5	0.4	20	2.3
6	0.4	35	2.3
7	0.4	20	2.8
8	0.4	35	2.8
9	0.4	20	3.3
10	0.4	35	3.3
11	0.4	20	3.8
12	0.4	35	3.8

Table 3: Varying height tests

Figure 35: Varying height without down biasing

4.1.1.1 Phase Averaged Lift and Thrust Forces without down bias

The instantaneous phase averaged lift and thrust for $St=0.4$, $\alpha_{\max}=20^\circ$ are shown for $H/c=1.3$ and $H/c=3.3$ in Figures 36 and 37, respectively. Figure 36 shows a 29% increase in instantaneous maximum lift force near the bottom compared to Figure 37 which displays a 6% increase. The mean thrust force increases by 7% from freestream to ground effect in Figure 36 and by 9% in Figure 37. Comparing Figure 36 to Figure

37, the effect is definitely greater the closer the foil is operating to the solid boundary. The data in these plots also shows some of the backlash in the system interacting with the force sensing. In Figure 36 just past $\pi/2$ on the x axis you can see the slight hump in the lift force indicating the backlash in the roll motor. As the foil completes its downstroke and begins the upstroke the play in the system is taken out resulting in slight hump displayed in the data. This effect is more prominent in the lower maximum angle of attack runs as the sensor is more susceptible to the mechanical noise.

Figure 36: Phase averaged lift and thrust force, $\alpha_{max}=20^\circ$, $H/c = 1.3$

Figure 37: Phase average lift and thrust force, $\alpha_{\max}=20^\circ$, $H/c = 3.3$

In Figures 38 and 39 the backlash of the system is less prominent due to the higher signal to noise ratio attained through more aggressive kinematics. Figures 38 and 39 also show that that overall maximum magnitude of lift is greater for the higher angle of attack case. A 13% increase in maximum lift and a 4% increase in mean thrust is found at the lowest $H/c = 1.3$ (Figure 38). No significant change in instantaneous lift or thrust is found for these kinematics at the $H/c = 3.3$ (Figure 39).

Figure 38: Phase averaged lift and thrust force, $\alpha_{\max}=35^\circ$, $H/c = 1.3$

Figure 39: Phase averaged lift and thrust force, $\alpha_{\max}=35^\circ$, $H/c = 3.3$

4.1.1.2 Mean Coefficients of Lift at varying height without down bias

The mean lift coefficients for all tests are shown in Figure 40 for the freestream and the ground effect zones. Each point represents a different height above bottom. The value of H/c on the x-axis corresponds to the value in the ground effect region for that particular test. As H/c increases the presence of ground effect decreases.

Figure 40: Coefficients of lift in the freestream vs ground effect zones

Figure 40 also seems to show that lift for the freestream and ground effect zones begin to converge at the greatest height above bottom, $H/c = 3.8$. Additional H/c ratios could provide a more concise picture. The data also suggests that height alone may not be sufficient to characterize ground effect for three dimensional flapping foils. Between the two maximum angles of attack examined it would seem that for different kinematics the presence of ground effect may diminish sooner for less aggressive motions. To

remove effects of unintended mean pitch bias, the changes in mean lift coefficient for each maximum angle of attack from freestream to ground effect regions are plotted in Figure 41.

Figure 41: Change in mean lift coefficient from FS to GE at varying height

4.1.2 Varying Height Tests with Down Bias

In addition to varying the height of the foil and observing the ground effect, the foil was also down biased in the roll axis at each corresponding height so that the tip maintained the same ground clearance (1 cm) for all tests. Given the heights and span of the foil, negative down angle was applied to the roll axis to maintain the same foil tip bottom clearance for each test. In general, as height is increased more of the foil body is removed from close proximity to the ground however, these tests allow for more

influence from ground effect as the tip maintains a constant height for all tests. Table 4 shows each of the varying height tests with the corresponding down bias angle.

Test #	St #	$\alpha_{\max}$ (°)	H/c	Down Bias (°)
1	0.4	20	1.3	0
2	0.4	35	1.3	0
3	0.4	20	1.8	-4
4	0.4	35	1.8	-4
5	0.4	20	2.3	-7
6	0.4	35	2.3	-7
7	0.4	20	2.8	-14
8	0.4	35	2.8	-14
9	0.4	20	3.3	-19
10	0.4	35	3.3	-19
11	0.4	20	3.8	-23
12	0.4	35	3.8	-23

Table 4: Varying height test with down biasing of the foil

4.1.2.1 Phase Averaged Lift and Thrust Forces with down bias

The instantaneous phase averaged lift and thrust for $St=0.4$, $\alpha_{\max}=20^\circ$ and 35° with down biasing are shown for $H/c=3.3$ in Figures 42 and 43, respectively. The configuration of the foil for $H/c=1.3$ for both maximum angles of attack for the down bias tests are the same as the varying height tests without down bias and yielded the same percent increase in instantaneous maximum lift and mean thrust force. For $H/c = 3.3$, $\alpha_{\max}=20^\circ$, a 13% increase in maximum instantaneous lift and 4% increase in mean thrust force was found from freestream to ground effect, (Figure 42). Again, gains in maximum lift force are found the closer the foil is in proximity to the bottom. Comparing the $\alpha_{\max}=20^\circ$, $H/c=3.3$ case with -19° down bias (Figure 42) to the same case without down bias (Figure 37) there is a slight increase of 4% in maximum

instantaneous lift force as a result of the down biasing. The mean thrust force generated with down bias compared to no down bias showed no significant change.

For $St=0.4$, $\alpha_{\max}=35^\circ$ at $H/c=3.3$ there is minimal change (3%) in instantaneous lift and minimal change in mean thrust (1%) throughout the motion cycle even with down biasing, as shown in Figure 43.

Figure 42: Phase averaged lift and thrust force, $\alpha_{\max}=20^\circ$, $H/c = 3.3$ with down bias

Figure 43: Phase averaged lift and thrust force, $\alpha_{\max}=35^\circ$, $H/c = 3.3$ with down bias

4.1.2.2 Mean Coefficients of Lift at varying height with down bias

The mean lift coefficients for all down bias tests are shown in Figure 44 for the freestream and the ground effect zones. Each point represents a different height above bottom. The value of H/c on the x-axis corresponds to the value in the ground effect region for that particular test. As H/c increases the presence of ground effect decreases just as in the varying height tests without down bias. Lift for the freestream and ground effect zones begin to converge at the greatest height above bottom, $H/c = 3.8$. To remove effects of unintended mean pitch bias, the changes in mean lift coefficient for each maximum angle of attack from freestream to ground effect regions are plotted in Figure 45 along with the results from previous tests without down biasing.

The mean lift coefficient at $H/c = 1.3$ is the same data point as the varying height tests without down biasing. This is the closest vehicle case. All lift coefficients in the ground effect zone are more positive for the down bias case. This is indicative of more of the foil being influenced by ground effect due to down biasing. The change is more dramatic for the larger maximum angle of attack especially at the smaller H/c ratio due to higher lift generating kinematics. Clearly, down biasing the foil permits an increase in the influence of ground effect in lift production.

Figure 44: Mean lift coefficients from FS to GE with foil down bias

Figure 45: Change in mean lift coefficient FS to GE at varying height w/ & w/o down bias

An interesting observation in the mean coefficient of lift at a $H/c = 3.3$ is that by inducing more ground effect through down biasing the foil, $\alpha_{max}=20^\circ$ with down biasing produces slightly more lift than $\alpha_{max}=35^\circ$ without down biasing. This confirms the positive increase in lift due to down biasing within the ground effect region.

5. Sources of Error and Future Work

5.1 Sources of Error

5.1.1 Timing

The LDM readings, DAQ card force signal readings, and the Galil motor control card were not synchronized in time. Each operated at its maximum capability. The LDM communicates its distance measurement via RS-232 serial communications. This send receive process for getting the distance measurement, the motion control card's ability to send its messaging via Ethernet and the DAQ card with its onboard timing makes it nearly impossible to synchronize the three signals in time without complex external triggering which would inevitably affect sampling rate. Additionally the operational speed of the LDM is nowhere near that of the DAQ card. The data resulted in three different signals with individual time vectors for their samples. The timing issues were adjusted in post processing by aligning time vectors, however if synchronization could be performed up front less interpolation would have been performed in processing. The timing inconsistency no doubt contributed to the alignment of position data with force data for phase averaging.

5.1.2 GUI

While the GUI built in this work is a very nice interface for operation of the experiment, the author was not the most proficient in coding LabVIEW virtual instruments and stumbled his way through most of the process. The GUI is functional but with bugs that still need to be tracked down and worked out. The program contains

many event functions and dependencies which could certainly be optimized for better performance. A substantial amount of time was spent trying to debug the system, and efficiently write data to file in a repeatable manner without error.

5.1.3 Mechanical Backlash

It may be next to impossible to remove 100% of the mechanical play or backlash in the physical system however, future redesign could use better drive train components and foil attachment methods to reduce it. Previous authors also cited this. A concise decision was made to focus on the new installation of the force sensor rather than spend time upgrading mechanical components. The motors and gearing within, are nearing 10 years old and upgrading these components would be beneficial to the study of less aggressive flapping regimes where the signal to noise ratio may be much lower.

5.1.4 Dual canister turbulence

There is undoubtedly some turbulence created from the dual canister as it translates the tow tank. The cylindrical canister equates to a bluff body being dragged through the water. The creation of vortices and turbulence from the cylinder certainly has some effect on the forces on the foil. These have yet to be studied quantified. A nose cone mounted to the front of the dual canister system could easily streamline flow around it creating less turbulence. The current author was in the process of constructing this however time did not permit completion.

5.1.5 Tow Tank Carriage

The carriage drive train is very old and antiquated. While it worked, it generated much vibration and introduces more unwanted mechanical noise into the system. Currently there is no work around for this other than upgrading the entire testing tank. There are no limit switch systems or capability to set limits on the system currently. This makes testing dangerous. The ability to control the carriage at a precise speed is very difficult. The carriage has to be “dialed in” using the speed potentiometer on the control box while watching the LDM readings calculated into velocity. Programmatic upgrades could be made to enhance automation of carriage movement. An integrated system with software controls, limit switches, and use of the LDM would greatly enhance the safety, reliability, and usability of the tow system. This could certainly be achieved without a major rebuild of the tow tank.

5.2 Future Work

5.2.1 Different Boundary Conditions

This current effort originally intended to investigate different ground effects due to different types of solid boundary conditions such as a corner, under the free surface, or just the foil tip within close proximity from the system vertically oriented. All of these different boundary conditions have yet to be studied for a 3D flapping foil and could be interesting investigations. These different solid boundary conditions could certainly relate to real world operational spaces for AUVs.

5.2.2 Broader parameter space

In this work, the anticipated forces used to calculate a sensible sensing range were underestimated. This was in part due to the new foil that was used. Modifying the aspect ratio of the foil, using another foil, or simply swapping the sensor for a larger calibration range would enable a more expansive test matrix. A likely combination of the changes would be ideal since a larger calibration range sensor is already available and it would be easy to modify the existing foil. Time did not permit the ability to this in the current work.

Another interesting investigation under this topic would be the study of an asymmetric flapping cycle. The current work utilized a symmetric roll amplitude. Animals in nature are known to modulate their flapping near solid boundaries minimize the downstroke amplitude and increasing the upstroke amplitude. (Rayner, 1991). The study of this type of exploitation of ground effect through active modulation has only been based upon observation rather than, experimentation. This would be a nice addition to the varying height tests with down biasing once a larger parameter space is evaluated.

6. Conclusion

The data presented in this work using enhanced force sensing is just the beginning for use of this redesigned system. Comparatively speaking, the results of the data provided, indicate all similar trends to what is expected for flapping foil dynamics in ground effect. There is a notable increase in the generation of lift force for flapping within close proximity to a solid boundary. Varying the height above ground creates the ability to better quantify ground effect and down biasing creates a potential opportunity to capitalize on ground effect force sensing. For the prospect of seeking real time information through force sensing the presented preliminary experiments show promise that change in lift force could be indicative of near boundary proximity. For an AUV employing flapping foil propulsion and using force sensing as a metric for altitude when near bottom operation is desired, corresponding differences in lift could provide greater information to that near boundary proximity given its current operating kinematics. This could prove to be a useful tool for vehicle altitude control in such benthic operation where traditional instrumentation has proven unsuccessful. The next logical step is to evaluate other kinematic motions and their instantaneous force profiles in an attempt to understand a greater parameter space. As noted by (Mivehchi et al, 2016) the instantaneous force profile is seen to alter greatly between different kinematics and that the time average mean force may not be significant enough for close proximity detection. Future work should pursue more kinematic profiles to observe the change in lift force using this test system. Down biasing effectively enhances sensing of ground effect to a greater extent which could allow for greater heave amplitude to be performed in the flapping motion while still maintaining relative body altitude. Additional effort is

needed to further explore the varying height and down biasing experiments however, these preliminary results prove promising in being able to expand the study of ground effect force sensing for flapping foil AUVs.

Appendices

Appendix 1. Static pitch bias lift plots used to find the zero foil pitch bias.

Bias of 4 degrees

Bias of 3 degrees

Appendix 2.

Once the foil was constructed, the assembled part weighed 462.18 g. A Solidworks model was constructed based off the final cast foil dimensions and the internal geometry of the titanium skeleton. An origin was created at a point in space on the 3D model relative to the actual origin of the sensor in the pitch canister. The material properties were selected within the model accordingly and the assembly was evaluated for its mass properties about the origin. The evaluated mass based off SolidWorks came in at 461.57 g. The below equations of motion, mass moments of inertia, and distances to the center of gravity are used to calculate the reaction forces at the body origin and are denoted as r_f .

<u>Equations of motion:</u>	<u>COG location from Body</u>	<u>Mass Moments of Inertia:</u>
$p = \phi_o \omega \sin(\omega t)$	<u>Origin:</u>	$I_{xx} = 0.0504 \text{ kg} - m^2$
$\dot{p} = \phi_o \omega^2 \cos(\omega t)$	$x_g = 14.3 \text{ mm}$	$I_{xy}, I_{yx} = 0.0023 \text{ kg} - m^2$
$q = \theta_o \omega \sin(\omega t + \psi)$	$y_g = 322.2 \text{ mm}$	$I_{xz}, I_{zx} = -0.0000 \text{ kg}$
$\dot{q} = \theta_o \omega^2 \cos(\omega t + \psi)$	$z_g = 0 \text{ mm}$	$- m^2$
$u = U \cos(\theta(t))$	$m = 461.57 \text{ g}$	$I_{yy} = 0.0002 \text{ kg} - m^2$
$\dot{u} = -U^2 \sin(\theta(t))$	$r_o = 164 \text{ mm}$	$I_{yz}, I_{zy} = -0.0000 \text{ kg}$
$w = U \sin(\theta(t))$		$- m^2$
$\dot{w} = U^2 \cos(\theta(t))$		$I_{zz} = 0.0506 \text{ kg} - m^2$
$\psi = \pi/2$		

$$Xr_f = m \left[\frac{\partial u}{\partial t} + qw - rv + \dot{q}z_g - \dot{r}y_g + p(qy_g + rz_g) - x_g(q^2 + r^2) \right]$$

$$Xr_f = m \left[\frac{\partial u}{\partial t} + qw + qy_g p - x_g q^2 \right]$$

$$Yr_f = m \left[\frac{\partial v}{\partial t} + ru - pw + \dot{r}x_g - \dot{p}z_g + q(rz_g + px_g) - y_g(p^2 + r^2) \right]$$

$$Yr_f = m[-pw + px_g q - y_g p^2]$$

$$Zr_f = m \left[\frac{\partial w}{\partial t} + pv - qu + \dot{p}y_g - \dot{q}x_g + r(px_g + qy_g) - z_g(q^2 + p^2) \right]$$

$$Zr_f = m \left[\frac{\partial w}{\partial t} - qu + \dot{p}y_g - \dot{q}x_g \right]$$

$$Kr_f = I_{xx}\dot{p} + I_{xy}\dot{q} + I_{xz}\dot{r} + rq(I_{zz} - I_{yy}) + I_{yz}(q^2 - r^2) + I_{xz}pq - I_{xy}pr \\ + m \left[y_g \left(\frac{dw}{dt} + pv - qu \right) - z_g \left(\frac{dv}{dt} + ru - pw \right) \right]$$

$$Kr_f = I_{xx}\dot{p} + I_{yz}q^2 + I_{xz}pq + m \left[y_g \left(\frac{dw}{dt} - qu \right) \right]$$

$$Mr_f = I_{yy}\dot{q} + I_{yz}\dot{r} + I_{yx}\dot{p} + rp(I_{xx} - I_{zz}) + I_{zx}(r^2 - p^2) + I_{yx}qr - I_{yz}qp \\ + m \left[z_g \left(\frac{dw}{dt} + qw - rv \right) - x_g \left(\frac{dw}{dt} + pv - qu \right) \right]$$

$$Mr_f = I_{yy}\dot{q} + I_{yx}\dot{p} + I_{zx}p^2 - I_{yz}qp - m \left[x_g \left(\frac{dw}{dt} - qu \right) \right]$$

$$Nr_f = I_{zz}\dot{r} + I_{zx}\dot{p} + I_{zy}\dot{q} + qp(I_{yy} - I_{xx}) + I_{xy}(p^2 - q^2) + I_{zy}rp - I_{zx}rq \\ + m \left[x_g \left(\frac{dv}{dt} + ru - pw \right) - y_g \left(\frac{du}{dt} + qu - rv \right) \right]$$

$$Nr_f = I_{zx}\dot{p} + I_{zy}\dot{q} + qp(I_{yy} - I_{xx}) + I_{xy}(p^2 - q^2) + m \left[-x_g pw - y_g \left(\frac{du}{dt} + qu \right) \right]$$

In addition to the foil, a Solidworks model was constructed for the components of the pitch actuation drive train. The same origin that was used for the foil was created at a point in space on the 3D model relative to the actual origin of the sensor in the pitch canister. The material properties were again selected within the model. The assembly was evaluated for its mass properties about the origin. The evaluated mass based off SolidWorks came in at 1064.98 g. The reaction forces for the drive train were then computed in the same manner as the foil and are denoted by r_d .

COG location from Body Origin:	Mass Moments of Inertia:
$x_g = -53.43 \text{ mm}$	$I_{xx} = 0.0026 \text{ kg} - \text{m}^2$
$y_g = -4.12 \text{ mm}$	$I_{xy}, I_{yx} = 0.0002 \text{ kg} - \text{m}^2$
$z_g = -9.00 \text{ mm}$	$I_{xz}, I_{zx} = 0.0009 \text{ kg} - \text{m}^2$
$m = 1064.9857 \text{ g}$	$I_{yy} = 0.0048 \text{ kg} - \text{m}^2$
$r_o = 164 \text{ mm}$	$I_{yz}, I_{zy} = -0.0002 \text{ kg} - \text{m}^2$
	$I_{zz} = 0.0066 \text{ kg} - \text{m}^2$

$$Xr_d = m \left[\frac{\partial u}{\partial t} + qw - rv + \dot{q}z_g - \dot{r}y_g + p(qy_g + rz_g) - x_g(q^2 + r^2) \right]$$

$$Xr_d = 0$$

$$Yr_d = m \left[\frac{\partial v}{\partial t} + ru - pw + \dot{r}x_g - \dot{p}z_g + q(rz_g + px_g) - y_g(p^2 + r^2) \right]$$

$$Yr_d = m[-\dot{p}z_g - y_g p^2]$$

$$Zr_d = m \left[\frac{\partial w}{\partial t} + pv - qu + \dot{p}y_g - \dot{q}x_g + r(px_g + qy_g) - z_g(q^2 + p^2) \right]$$

$$Zr_d = m[\dot{p}y_g - z_g p^2]$$

$$Kr_d = I_{xx}\dot{p} + I_{xy}\dot{q} + I_{xz}\dot{r} + rq(I_{zz} - I_{yy}) + I_{yz}(q^2 - r^2) + I_{xz}pq - I_{xy}pr \\ + m \left[y_g \left(\frac{dw}{dt} + pv - qu \right) - z_g \left(\frac{dv}{dt} + ru - pw \right) \right]$$

$$Kr_d = I_{xx}\dot{p}$$

$$Mr_d = I_{yy}\dot{q} + I_{yz}\dot{r} + I_{yx}\dot{p} + rp(I_{xx} - I_{zz}) + I_{zx}(r^2 - p^2) + I_{yx}qr - I_{yz}qp \\ + m \left[z_g \left(\frac{du}{dt} + qw - rv \right) - x_g \left(\frac{dw}{dt} + pv - qu \right) \right]$$

$$Mr_d = I_{yx}\dot{p} - I_{zx}p^2$$

$$Nr_d = I_{zz}\dot{r} + I_{zx}\dot{p} + I_{zy}\dot{q} + qp(I_{yy} - I_{xx}) + I_{xy}(p^2 - q^2) + I_{zy}rp - I_{zx}rq \\ + m \left[x_g \left(\frac{dv}{dt} + ru - pw \right) - y_g \left(\frac{du}{dt} + qu - rv \right) \right]$$

$$Nr_d = I_{zx}\dot{p} + I_{xy}p^2$$

After the reaction force equations were found for both the effects of the drive train mass and the foil mass they were summed and component forces were accounted for as the pitch and roll motion occurred. The final component forces were then added or subtracted as necessary from the force measurements obtained from the sensor. A gravity correction was also subtracted from the force measurements to account for the transition of force to other axes for motion after tarring of the sensor.

First the z and y components are found for the gravity correction, where m_T is the total summed mass of the foil and drive train and g is the gravitational constant.

$$Zgc = m_T g - m_T g \cos(\phi(t))$$

$$Ygc = m_T g \sin(\phi(t))$$

Then the reaction forces and gravity corrections are applied to the force measurements (Fz_m, Fx_m, Fy_m) for the z and x axes.

$$Corrected Lift Force = Fz_m - (Zr_f \cos(\theta(t)) + Xr_f \sin(\theta(t)) + Zr_d) - Zgc$$

$$Corrected Thrust Force = Fx_m - (Xr_f \cos(\theta(t)) - Zr_f \sin(\theta(t)) + Xr_d)$$

$$Corrected Y Force = Fy_m - Ygc - (Yr_f + Yr_d)$$

Finally to translated the lift force into the fixed body reference frame of the dual canister system each component of the corrected lift force and corrected Y force are account for as a function of roll position with time.

Body Referenced Lift Force

$$= \text{Corrected Lift Force} \left(\cos(\phi(t)) \right) - \text{Corrected Y Force} \left(\sin(\phi(t)) \right)$$

Appendix 3. Experimental results of Table 2:

It is important to note up front that the data collected from test matrix Table 2 contains significant error in its force and torque readings. Any discussion in relation to data collected from these tests is purely speculative and looking at overall trends rather than definitive conclusions. For tests 9-16 it was observed that the torque readings were outside the calibrated range of the sensor. The amplitudes and frequencies in combination with the new foil proved too aggressive in force production for the linear range of the sensor. Due to the construction of the sensor, any one force or torque reading on a particular axis that is over its calibrated range invalidates all readings from other axes. Additionally, at the conclusion of performing all tests it was found that the attachment screws that mount the foil and pitch drive train to the face of the sensor had come loose. Two of the four screws had come out and the other two remaining permitted significant movement between the plate and sensor face. As this is the primary mechanism for the transmission of force into the sensor any play permitted will disrupt the force and torque readings providing inaccurate data. Contour plots displaying the results of mean lift and mean thrust coefficients for Strouhal numbers 0.3 to 0.6 and varying angles of attack from 20° to 35° are provided below. The shaded region represents the data within the calibration range but still suspect due to the attachment screws. Comparison to the previous efforts of which this test matrix was based upon are very difficult and in order to accurately do so the experiment would need to be run again.

The attachment screw malfunction was found prior to the varying height tests, so to ensure adequate mating Loctite was used on the screws. Time did not permit retesting of Table 2.

Figure 1: Mean lift coefficient in freestream contour plot

Figure 2: Mean lift coefficient in ground effect contour plot

Figure 3: Mean thrust coefficient in ground effect contour plot

Figure 4: Mean thrust coefficient in freestream contour plot

The first contour plot (Figure 1) predominantly displays negative mean lift coefficients generated for the freestream. Positive lift isn't generated until higher Strouhal numbers and smaller maximum angles of attack. The overall trends in this figure indicate similarities to the results of (Chierico, 2014) and other work for a foil flapping in freestream, despite being outside the calibration range. Comparing freestream mean lift coefficients (Figure 1) to the ground effect mean lift coefficients (Figure 2), it is apparent that ground effect has a positive lift influence as all lift coefficient values are positive. There is little difference in the thrust generation within the freestream zone compared to that of the ground effect zone and certainly not as prominent as lift force. Figures 3 and 4 indicate a negative thrust coefficient or excess of drag at high Strouhal numbers and low angles of attack. The excess feathering of the foil results in less thrust production where drag force on the foil then becomes more predominant. The results indicate that the drag force on the foil is larger than the thrust it is producing at those operating points. This is seen in both the freestream and ground effect cases. (Blevins and Lauder, 2013) observed that undulating fins near a solid boundary generally incur locomotor costs. To better observe this, in the current work, we would anticipate more negative thrust coefficient values when looking at the difference between the freestream to the ground effect values. While trends display some similarities to other 3 dimensional flapping foil work, too much error surrounds the data to make accurate conclusions.

Appendix 4.
Additional phase averaged lift and thrust plots for varying height tests without down biasing.

Appendix 5.
Additional phase averaged lift and thrust plots for varying height tests with down biasing.

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