Widener University
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Oscillating Foils Testing Apparatus
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Senior Project Team #18

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Executive Summary

The goal of this project was to design and construct a testing apparatus that is capable of measuring the thrust produced through the motion of a pitching airfoil placed in a moving stream of water. The apparatus was designed so the airfoil’s pitching amplitudes and frequencies could be varied, and the resulting thrust could be measured. Additionally, a simplified method of Particle Image Velocimetry (PIV) was conducted for rudimentary flow visualization of the wake downstream of the airfoil. This report provides a brief background on the current research in oscillating foils and simplified PIV methods. Additionally, the design and analysis of the constructed apparatus and PIV setup is outlined. Moreover, the results of the design, construction, and testing of the apparatus are evaluated. Finally, the conclusions from the completion of the project are outlined along with recommendations for furthering this project in the future.
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Introduction

Oscillatory motions of aerodynamics objects have been considered in diverse applications such as energy harvesting configurations and unmanned micro vehicles. The study of these objects undergoing oscillatory motion presents unique fluid dynamics challenges, which warrants further investigation. The present project was aimed at the design and construction of an experimental setup for testing of an airfoil set in oscillatory motion subjected to a moving stream of water. The constructed apparatus utilizes an airfoil which can undergo varying pitching amplitudes and frequencies, and the resulting thrust produced from the motion of the airfoil could be measured and quantified. A simplified Particle Image Velocimetry (PIV) visualization system was also employed to visualize the flow pattern trailing the airfoil to better characterize the forces. Some of the recent research efforts aimed at investigating the oscillating airfoils have greatly influenced the design of the apparatus presented here. Moreover, the PIV flow visualization system developed for this project was constructed based on guidelines provided by several recent articles that focused on inexpensive PIV systems.
Literature Review

Apparatus Design

There has been significant progress and innovation in the design and development of Autonomous Micro Vehicles (AMV) in recent years. To make these vehicles more energy efficient and maneuverable, researchers have focused on the oscillatory motion of natural flyers and swimmers. Therefore, a significant number of studies have focused on the investigation of forces produced by these oscillatory motions. For example, Mackowski and Williamson [1] studied the direct measurement of thrust and efficiency of an airfoil undergoing pure pitching. In their work, the airfoil experienced purely pitching motion at different frequencies and amplitudes in a tank with the uniformly distributed flow. Moreover, a force-torque sensor and PIV were used to measure the forces on the airfoil and visualize the flow field, respectively. The results of this experiment determined a linear upward trend when comparing dimensionless frequency and the coefficient of thrust on an airfoil. This paper provided a detailed experimental setup using oscillating airfoil research and was used as a template for the current research.

PIV Flow Visualization

Particle Image Velocimetry (PIV) is generally utilized to visualize and characterize the flow field downstream of the airfoil. PIV is a non-intrusive measurement technique and an experimental tool used for the investigation of fluid dynamics problems. PIV can provide a significant amount of quantitative information such as estimation of velocity, vorticity, and turbulence intensity of the flow field. PIV measures the flow field velocity by analyzing the motion of the seeded particles in the flow from a series of consecutive images. The movement of light-scattered particles in the flow field can be used to determine the velocity vector field. The particle velocities can represent the local fluid velocities if particles trace the fluid flow. By using PIV, the flow pattern trailing the foil can be observed to get a better understanding of how different factors, such as water velocity or pitching frequency, can alter the wake and hence affect the energy generated by the foil.

Sophisticated PIV systems can range in hundreds of thousands of dollars using powerful lasers and advanced cameras. However, there are several papers, such as the one published by Ryerson and Schwenk [2], that provide a template on how to create a simple and relatively inexpensive PIV test setup. Ryerson and Schwenk provided guidelines for using several individual components to create a system similar to their PIV testing apparatus. Similarly, Howison [3] provided details on how to create a simple PIV setup for undergraduate research use. In the present project, a simple and inexpensive PIV, similar to the two above-mentioned papers, was developed for rudimentary flow visualization.
The thrust coefficient and Garrick reduced frequency are the two primary parameters used in this report for analyzing the airfoil performance. The Garrick reduced frequency, $k$, is helped to non-dimensionalize the airfoil’s oscillation frequency, $f$. Equation 1 presents the equation used to obtain the reduced frequency.

$$k = \frac{2\pi f c}{2U_\infty} \quad \text{Equation 1}$$

where $U_\infty$ is the free stream velocity, $c$ is airfoil chord length. Equation 2 is used to determine the coefficient of thrust, $C_T$, as a function of the average airfoil force, $F_x$, fluid density ($\rho$), free stream velocity, chord length, and the submerged length of the airfoil, $h$.

$$C_T = \frac{F_x}{\rho U_\infty^2 c h} \quad \text{Equation 2}$$

It should be noted that the values of the free stream velocity, chord length, submerged length, and fluid density all remained constant through testing.
Analysis and Design

This project also had to respond to several design constraints. These design constraints included apparatus size, testing at the microscale, and apparatus modularity. Patterned after the previous research by Mackowski and Williamson [1], the general design of the testing apparatus consisted of an airfoil system and a tank. The airfoil system has been designed to put the airfoil in a pitching motion mimicking the undulation of a fish. The pitching motion is accomplished by simply rotating the airfoil about a shaft through one axis.

A future goal for this project is to create and test a robotic fish that uses propulsive forces for forward motion. Therefore, the testing apparatus was designed and constructed for data to be gathered in a moving stream of water. Moreover, the moving water into the tank was required to be uniformly distributed to create a more stable testing environment for more accurate analysis. The previous studies, focusing on the oscillatory motion of airfoils, generally used tanks with a longer span allowing for more uniformly distributed freestream. However, the tank for this project was scaled down to meet the budget and allow for the portability of the testing apparatus. However, the smaller tank created would not allow for the flow to become uniform naturally and required modifications in the flow delivery system to induce a uniformly distributed flow in a short distance.

A major task in the testing and analysis was the measurement of forces generated due to oscillation. More specifically, the airfoil was required to have variable oscillation amplitudes and frequencies to investigate the effects of oscillation on thrust and drag forces. The thrust and drag coefficients are calculated by measuring small forces found between the reaction of the airfoil and the shaft. However, the magnitude of these forces were affected by the smaller sizing of the tank as well. Due to the reduction in scales, the forces were then measured on a micro-scaled airfoil (measured in centimeters), resulting in smaller magnitude forces, which typically require more expensive sensors. Therefore, it was important that this project found affordable alternatives for accurate measurements of these small forces.

Finally, the apparatus needed to be modular, so it was capable of accommodating different geometries, obstructions placed in front of the airfoil, or changes to fluid flow. A simplistic design with few permanently fixed features allows the present apparatus to meet the need for a modular tank and allow for future testing to be conducted more easily.
Final Design and Rationale

Flow Uniformity in Tank

The selected option to create a uniform flow stream in the tank was a honeycomb baffle. The honeycomb baffle was constructed by drilling holes into a basket and placing the discharge hose from the pump into the basket. The honeycomb baffle would then disperse the water through the holes, allowing for a better distribution of the flow within the tank.

Measuring Flow Rate

A propeller based device was selected from the various flow rate measuring methods considered. In this method, the free stream velocity of the fluid can be directly measured. This method is a relatively low cost, especially when compared to either inline flow meters or ultrasonic flow meters. This device could also easily be used during the initial setup for a testing session, which allows for more accurate data. Measuring the free stream velocity at multiple points was also possible with this device, which helps to visualize the uniformity of the fluid flow.

Motor for Pitching Motion

A stepper motor was selected for the final construction. The stepper motor can handle larger torque applications, and a driver shield is used to protect the controller while operating the stepper motor at higher voltage and torque. Additionally, a stepper motor has higher precision in comparison to a servo, which makes a stronger case for the results produced in the experiment. The servo has a larger range of rotation, which may be more useful in future research.

Airfoil Orientation

The vertical and horizontal airfoil orientations were compared regarding ease of construction and applicability to the testing and future use. For this apparatus, the vertical orientation was selected since it allows for the installation of a larger foil. Since the width of the tank is larger than its height, the vertical foil will also help reduce the end effects by allowing for more buffer room to the sides of the foil to reduce interference. The vertical orientation also allows for complete freedom of positioning throughout the tank, as the mount can be made mobile for forward/backward and side to side changes as opposed to the fixed position of a drill mount on the side of the tank.

Pitching Motion Configuration

A gear train was the selected option to transfer the motion for the final assembly. Comparison of a gear train and a belt and pulley system pointed to the gear train as the best option for this project. The belt and pulley system can pose issues because the proper tension between the pulleys must be maintained and the belt can wear overtime of extended use. On the other hand, the gear train was determined to be a better option for extended use and was within our budgetary requirements.

Force Measurements

An off-the-shelf force sensor was selected for measuring the force on the foil. The force sensor that was selected is capable of measuring forces in a single direction along the shaft. The force sensor would allow for force measurements to be taken continuously during the airfoil’s oscillation. The force
measured corresponded to the thrust or drag that was experienced on the pitching airfoil placed in a steady stream of water.
Testing Apparatus Setup

Flow Delivery System

The flow delivery system consisted of two key components: the piping from the pump into the tank and the honeycomb baffle. The baffle was installed to create uniform flow from the discharge of the pump, as shown in Figure 1. Clear PVC tubing with polyester braiding, with 1-1/2 inch inner diameter and 2-inch outer diameter, was used for the discharge and suction from the pump into the tank. On the suction side, a check valve was submerged approximately half the height of the water level within the tank. Additionally, multiple 1-1/2 inch barbed 90-degree elbows were used to run the suction out of the tank and back into the centrifugal pump. On the pump discharge, the tubing was approximately half the height of the water level. The same size elbows and tubing were also used on the discharge side of the pump feeding directly into the honeycomb baffle, as shown in Figure 2.

Figure 1: Side View of Flow Delivery System Setup with Pump Behind the Tank

Figure 2: Top View of Pipe Discharging Into the Honeycomb Baffle
The honeycomb baffle was constructed using an inexpensive 8-gallon basket. Several holes of equal diameter were drilled throughout the side of the container closest to the airfoil, so the discharge from the pump would flow uniformly towards the airfoil through the holes. The holes were positioned to provide more room for the flow to even out. The container was held down to the surface of the tank using a wood frame to provide consistency in the placement of the container during testing. Figure 3 shows the overall tank setup with all various components in place.

Figure 3: Overall Tank Setup

Airfoil Assembly

The airfoil assembly would allow for relative ease in adjustment and modification of the assembly itself without disruption of the rest of the setup. The base of the assembly consisted of a cross-sectional H-bracket consisting of 2”x1/4” aluminum strips to provide mounting points for the electrical and foil assemblies. The rear strip would provide torsional resistance and additional loading stability due to the offset position of the airfoil and measurement apparatus. The strips would span the width of the tank, as seen in Figure 3, sitting firmly along the sides of the tank after being shimmed into a tight fit to eliminate movement of the base.

The force sensor was affixed to the cross member of the bracket with cable ties to provide sufficient mounting as well as a quick method of detachment for adjustments, takedown, and troubleshooting. The force sensor was affixed to the cross member while preloaded on the shaft slightly, placing a negative force on the sensor to account for the thrust expected to be experienced by the foil.

An additional aluminum plate, which contained the lower bearing for the foil shaft, was placed against the force sensor. The plate would move in congruence with the foil shaft, allowing for a larger point of contact with the force sensor and providing the bearing mount point without reducing movement of the shaft itself. A larger hole was drilled in the cross member below the mobile plate to allow the shaft to pass through the cross member while retaining free horizontal movement without any contact between the two. The base would also provide a mounting point for the wood assembly described below. The mounting point would hold the motor and foil shafts in places for optimal gear power transmission for foil oscillation. The fixation of the motor and upper foil bearing allowed for movement only by the foil and force sensor’s plunger to ensure proper force read by the sensor.
Controls

The airfoil’s oscillation was controlled by a stepper motor connected to an Arduino. A circuit was
designed with a motor driver to control and protect the motor. A schematic of the circuit can be seen in
Figure 4.

![Motor Driver Circuit Schematic](image)

After the motor was connected to the microcontroller, Arduino code was written to oscillate the
airfoil for a certain amplitude ($\theta$) and at a certain frequency ($\nu$). These variables are setup as a step
count and a time in the Arduino and can be found using the following equations where “ang” is the
input for the steps required for the desired angle and “mSpeed” is the time inputted to obtain the
desired frequency.

\[ \theta^\circ \times \frac{1 \text{ rev}}{360^\circ} \times \frac{800 \text{ steps}}{\text{rev}} = \text{ang} \]  

Equation 3

\[ \frac{1 \text{ rev}}{s} \times 800 \text{ steps} = \text{mspeed} \]  

Equation 4

Wood Assemblies

It became apparent in the initial testing that the airfoil shafts and the motor would be forced
away when the motor was on due to the lack of upper support for the shafts. However, the motor and
two shafts were required to be held rigidly in place to allow for the accurate collection of the force
experienced by the airfoil. Therefore, an upper bearing retainer was designed and constructed to ensure
that the two gears would stay meshed for the duration of the testing. The retainer is labeled as A in
Figure 5. The motor mount was designed to allow the motor to be as isolated from the stage assembly
as possible to reduce the effect of motor vibrations on the force measurements. This was done by
ensuring that the motor had clearance around all faces except the mounting face, shown as B in Figure
5. Following the construction of the mount, the bracketing for the upper shaft bearing plate was
designed with both rigidity and modularity in mind. The choice of mounting these brackets to the side of
the motor mount with screws will allow for easy modifications in the future while still remaining more
than rigid enough for the present setup. Figure 5 shows the bracketing in use, labeled as C.
A high-powered laser with a wavelength of 532 nm was used with a lens with a focal length of 25 mm to reflect a plane of light into the tank of water parallel to the imaging surface. The distance between the laser, lens, and tank was primarily determined through trial and error. The laser and lens setup, similar to the PIV setup in Figure 6 was positioned about 20 ft from the tank to produce a large enough viewing plane for stronger imaging results.

To visualize the flow, fluorescent red polyethylene microspheres were dispersed into the tank. A camera with a shutter speed of 60 frames per second was then aligned with the plane of interest, and photos were taken of the flow. These photos can be processed using a MATLAB toolbox called PIVLab, which produces vector maps and vorticity fields.
Results

Force Measurements

The comparisons of forces measured at various conditions are presented in this section. It is important to note that the following data analysis can be used to compare the trends at various conditions. However, one cannot make any interpretations of the maximum and minimum values of the forces from these plots due to the inadequate number of recordings per second. Unfortunately, due to the circumstances, the team was not able to redo these tests to rectify the situation.

Figure 7 shows the thrust coefficient over non-dimensionalized time for the oscillation amplitude of $4^\circ$ and frequency of 3.67 rad/sec. This graph shows that the designed apparatus was capable of measuring the force over the period in which the airfoil was oscillating. However, it is recommended that the number of samples per second taken from the force sensor be increased to capture all true maximum and minimum values of the coefficient of thrust. Additionally, it is recommended to use multiple rounds of testing so that an average from several trials can be taken for each amplitude and frequency tested. To allow for the average to be taken from multiple trials, it is also recommended to get the exact position of the airfoil during its oscillation so the data can be compared across several trials.

Figure 7: Thrust Coefficient Time History for Oscillating Airfoil

Figure 8 shows the axial force measured from the force sensor over non-dimensionalized time at a constant frequency of 1.88 rad/s and varying amplitudes. Figure 9 shows the calculated coefficient of thrust over non-dimensionalized time at the same frequency and varying amplitudes as Figure 8. It is shown in both figures that the $8^\circ$ and $16^\circ$ amplitudes showed similar oscillation trends, whereas the $4^\circ$ oscillation looked significantly different. It is recommended to take and average of multiple trials to validate that these trends are consistent at each amplitude. However, the figures do demonstrate that varying pitch amplitude does affect the resulting forces at the airfoil.
Figure 8: Force versus Non-dimensionalized Time for 1.88 rad/s Frequency and 4°, 8°, and 16° Amplitudes

Figure 9: Coefficient of Thrust versus Non-dimensionalized Time for 1.88 rad/s Frequency and 4°, 8°, and 16° Amplitudes

*PIV*

A simple and inexpensive PIV system was assembled for this project, and the results presented show that the system can capture the turbulent flow caused by the airfoil oscillation. Figure 10 shows the instantaneous vorticity field in the wake of the airfoil, where the flow is moving from right to left. The white streamlines show the formation of vortices by the pitching motion. Figure 11, which shows
the variation of the vorticity field with time, indicating the development of the vortices in the wake region. In the right corner of the figure, a strong vortex (marked with red lines) forms from the flow created in this tank. Further PIV results have been omitted for brevity of this report.

Figure 10: Vorticity in Tank, Top View

Figure 11: Changing Vorticity in Tank [t₁, t₃], Top View
Conclusions

This project accomplished the goal of designing and constructing a testing apparatus that is capable of measuring the thrust produced through the motion of a pitching airfoil placed in a moving stream of water. The objectives set out for this project were also successfully met. The constructed apparatus is portable with a modular design that allows for additional upgrades and modifications in the future. Additionally, the apparatus is capable of variable oscillation frequency and amplitude, allowing to investigate the performance of airfoil at varying conditions. Moreover, a simple and inexpensive PIV system was constructed for detailed flow visualization. The images were produced using the PIV system have been valuable in the analysis of the complex flow field generated by the oscillating airfoil. This system can be expanded upon for future flow testing applications, including visualization of flows about unmanned underwater systems.
ASTM Standards

Various ASTM standards have been investigated and considered in this project. The overall standard and its scope have been summarized and presented below. Moreover, cases in which the standards have been used have been outlined, and the relation between the standard and the current project has been detailed.


The ASTM D3858-95 standard provides a testing method for measuring volumetric flow rate or stream discharge for open-channel flow. This standard is directly related to the present project since the project is involved with oscillating an airfoil in a moving stream of water with a known velocity. The velocity-area method utilizes the water flow velocity and cross-sectional area of the flow to determine the volumetric flow rate of the water. The D3858-95 standard outlines that the test method is based on the current meters, which are used to measure flow velocities. Additionally, the test method described in the standard covers flow velocities that are taken as single values or flow velocities that are taken as a set of data. Therefore, the same methodology can be used if the flow velocities are taken at varying water-level elevations or stages. Subsequently, the methodology can be applied to developing stage-discharge relations in which the changing stage of a stream can be correlated to the streamflow or volumetric flow rate.

The ASTM D3858-95(2014) Standard is widely used by entities that are responsible for collecting streamflow data. For example, Foth Infrastructure and Environment LLC [5] utilized this ASTM standard when outlining their Standard Operating Procedure (SOP) for open-channel and streamflow measurements with the volume-area method. Specifically, the Foth SOP utilizes the two-point velocity measurement method outlined in section 10.9.2 of D3858-95. However, if a site that is being analyzed for streamflow has conditions where it is not able to use the two-point method, then an alternative method can be chosen from the ASTM standard. The SOP also utilizes the D3858-95 standard to describe procedures for collecting velocity measurements at lower depths by wading.

The ASTM D3858-95 standard relates to the current project since the findings collected through the constructed apparatus could be used in a variety of applications that involve open-channel flow. The apparatus can be used to characterize and quantify the unsteady thrust acting on an oscillating geometry under a moving stream of water. These findings can be used in cases such as energy harvesting and autonomous fish robots. The thrust results could be used for harvesting the energy from unsteady tidal streams with airfoil blades set in oscillatory motion to generate power by the turbine. For these applications, the open-channel volumetric flow rate of the unsteady tidal stream would need to be measured, as detailed in this standard, to find the forces acting on the airfoil. Similarly, the apparatus can be used in the investigation of autonomous fish robots that can propel themselves through water given an initial power input using undulating body motions similar to natural swimmers. Therefore the water stream velocity must be known and can be measured as outlined through the velocity measurement methodologies provided in the ASTM D3858-95 standard.


The ASTM E2206-11 standard describes the calibration or performance confirmation of electronically applied force signals for thermomechanical analyzers. This standard does not address the safety concerns associated with the use of a thermomechanical analyzer and is up to the user to take appropriate safety precautions. The forces considered in this standard must be in a range of 0 to 1N. It
should be noted the magnitude of force should be stated in SI units, which are the standards and no other units of measurement are used within this standard. Also, there is no ISO (International Organization for Standardization) method equivalent to this testing method.

The ASTM E2206-11 Standard Test Method is used to calibrate thermomechanical analyzers used for research and development, quality control, manufacturing, or regulatory applications. This standard is used to confirm or calibrate thermomechanical analyzers. Hence, it is mostly used by companies that produce or calibrate thermomechanical analyzers. One of those companies is TA Instruments, which produces a condensed calibration process based on the ASTM test method [7]. They use the test method to ensure that their thermomechanical analyzers are calibrated before use and allow for their calibration instructions to be easily accessed by those who use their machines.

Our project did not require a thermomechanical analyzer to measure the force produced by the airfoil. While the thermomechanical analyzer details calibration for force measurements within the experimental range, the instrument would not be able to contain the aspects of our apparatus that produce force.


ASTM D7512-09 Standard Guide describes the general structure to be followed for optical instrumentation used to measure sediment concentration in water. This standard can have ramifications on the PIV aspect of the present project, where laser light illuminates suspended polyethylene microspheres in water. The standard stipulated that all equipment should be properly calibrated and scaled for the application, and only one manufacturer type of meter should be used at the site. Additionally, this guide explains how to interpret the data collected for these concentrations and assumes that modifications to procedures given should be at the discretion of the operator.

This standard was mentioned by several papers aiming for accurate measurement of sediment concentrations in their respective applications. Rai and Kumar [9] cite this standard in their paper to collect data on sediment concentration, specifically using several types of meters mentioned in the standard. Their research intended to continuously monitor and measure the concentration of sediment in a given location. Ban, Chen, Yan, and Lei [10] discussed the measurement of sediment concentration in regards to erosion. Their paper examined the concentrations in constant volume situations and aimed to find a new measurement method to replace traditional drying methods.

PIV setup used in this study employs a laser to illuminate the suspend polyethylene microspheres in water to capture flow movement through image processing. The concentration of these particles in the water will affect the accuracy of the results. Too many particles and the images become unclear, and processing errors can increase. Too few particles and important flow patterns can be missed. Having an accurate way to reliably measure the concentration of the particles, such as what was mentioned in the ASTM D7512-09 Standard could be a reliable way to improve PIV results.
References


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