

Project S.H.R.E.D.: Surfing Hydrodynamic Research with Engineering Design

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Abstract

Project Surfing Hydrodynamic Research using Engineering Design (S.H.R.E.D.) focused on the design and testing of surfboard fins through the application of aerospace industry practices. Two innovative fins, one with a winglet and the other with a vortex generator, are introduced in this study. Both designs were fabricated using a composite SLS core, coated with 4-ounce carbon fiber cloth and epoxy resin. Wind tunnel tests were then conducted in the Embry-Riddle Aeronautical University Low-Speed Wind Tunnel located at the Micaplex. These tests were performed in flows dynamically similar to surfing conditions. A parametric study of dynamic similarity between saltwater and air was also directed which, combined with data collected, provides insight to the limitations of wind tunnel testing for hydrodynamic objects. Both Project S.H.R.E.D. designs as well as four market fins, were tested at three different flow speeds while completing a full sweep of pre-determined angles of attack. The aerodynamic efficiency, which is the ratio of side force to drag, was compared between each design. Both Project S.H.R.E.D. designs performed comparably to all market fin designs. An exceptional spike in efficiency at angles of attack near zero indicates the “AU” fin (one of the market designs) is the most efficient. Further analysis of the data indicates that the winglet fin performed the most consistently over all angles of attack and flow speeds. Overall, the data concludes that the winglet fin and “AU” fin possess the most promising designs for improved surfing performance.

1. Introduction

1.1 Background

While the origins of surfing are not completely clear, it is known that the sport itself has been around for thousands of years. However, it wasn't until surfing was adopted in the early 1900's by western culture that surfboard design began to improve. In the 1930's, surfboard fins began to emerge out of speedboat-style skegs, and by the 1960s fins became standard equipment for all surfers. Within the past few decades, the surfing community has seen an explosion of development in surfboard fin design. Understandably so, as fins play an integral role in being able to control a surfboard.

There is a lot of monetary investment in the surfing industry. For example, two-time Surfing World Champion John-John Florence, earned around \$6.1 million in 2017 [1]. In 2014, over 6.2 million people watched the World Surf League's online stream of the Billabong Pipeline Masters contest (the Super Bowl of the surfing world). For comparison, this event had more viewers than the final game of the National Hockey League's Stanley Cup that same year [2]. In 2013, Michael Lynch from Marketing Daily found through research via Repucom that there are “120 million [and counting] bona fide fans of the sport” [3].

With so much money on the line, one would think that companies involved with competitive surfing would invest more into research to design surfboards, fins, and other accessories. While in recent years, surfboard and fin

manufacturers have begun to conduct more technical research, there is still a widespread “working out of the garage” attitude towards doing so. This attitude has stifled innovation and is evidenced by how the general shape of surfboards and fins have remained mostly unchanged. By applying technology and processes normally reserved for aerospace applications, Project S.H.R.E.D. aims to delve deeper into the physics of surfing equipment to bring a more innovative culture to the industry.

1.2 Preliminary Results

The preliminary investigations of this project (S.H.R.E.D. Phase I) took place between August 2018 and May 2019 and were led by Noah Ingwerson- an Embry-Riddle Aeronautical University (ERAU) alumnus and local surfer with 8 years of experience. The research was sponsored by IGNITE Undergraduate Research at ERAU with the goal of designing and manufacturing a surfboard fin with higher hydrodynamic efficiency. To begin fin design, an adequate airfoil cross-section was selected to be compared to standard surfboard fin cross-sections. The hydrodynamic performance of the airfoil was considered with a goal of optimizing the efficiency ratio, normally defined as the ratio of lift force (or lift coefficient, C_L) to drag force (or drag coefficient, C_D). To analyze the different airfoil shapes, lifting line theory was performed via XFOIL. The data collected indicated that the NACA 4412 shape proved to be the most efficient at the selected Reynolds number, as shown in Figure 1.

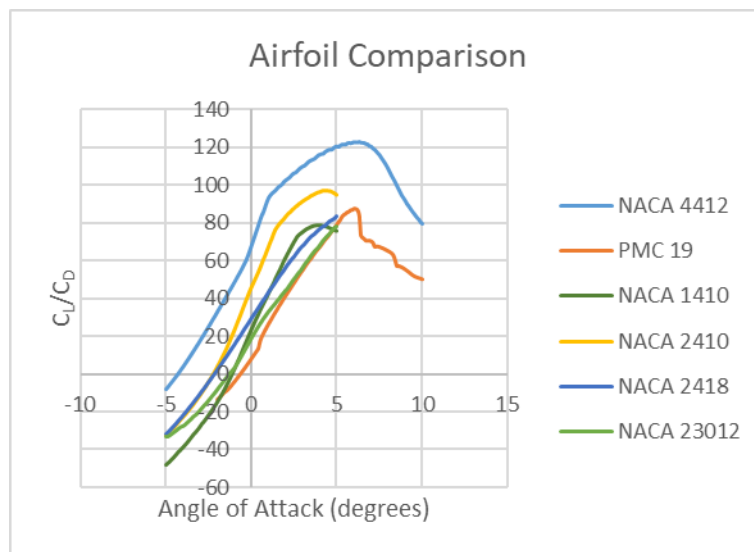


Figure 1: Airfoil Efficiency Performed in XFOIL.

It is important to note that for the specific case of surfing, the “lifting” surface in question is vertical and producing side force. The respective efficiencies mentioned in the remainder of this paper correspond to the ratio of side force generated by the fin to the ratio of drag force generated (or side force coefficient to drag coefficient).

To improve efficiency, a winglet fin design was included in the preliminary designs. The NACA 4412 shape was taken from airfoiltools.com and manipulated using generative shape design (GSD) in CATIA-V5 to create a typical surfboard fin shape with a winglet. The design was then printed using a Prusa i3 and coated in 4-oz fiberglass and polyester resin, shown in Figure 3. The winglet fin (Figure 2) consisted of a 45-degree deflection at three fourths of the total height of the fin (minus tabs when placed vertically). The 45-degree angle was chosen as difficulty arose when 3D printing higher winglet deflection angles.

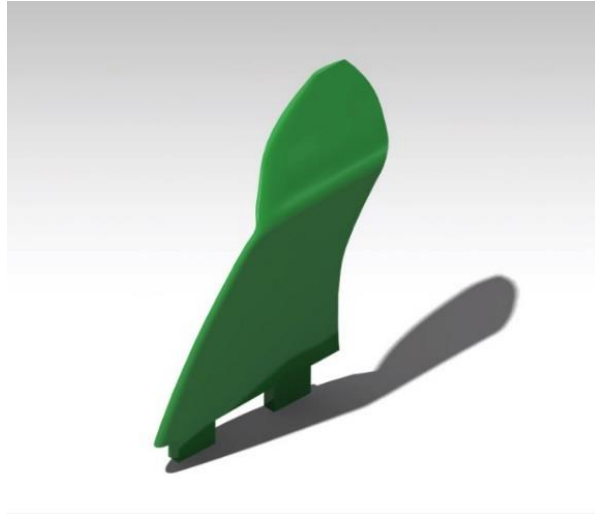


Figure 2: 3D Render of Phase I Winglet Fin.



Figure 3: Coating Fiberglass on 3D Printed Fin which resembles the FCS baseline.

The Project SHRED Phase I winglet fin was tested in the water on various waves deemed similar along with market competitors to collect qualitative and quantitative data. Based on data collected in Phase I, shown in Figure 4, the Phase I winglet fin performance was deemed sufficiently comparable with market competitors when considering maximum velocity reached. In addition, the fin was able to produce more turns on average than two out of three market competitors. Wind tunnel testing was performed on the fins but ultimately discarded upon the lack of similarity to traditional lift curve slopes. It was deemed that the mount used contributed to most of the drag data collected and that the force balance sensor in the wind tunnel was not sensitive enough to properly identify the forces attributed exclusively to the fin.

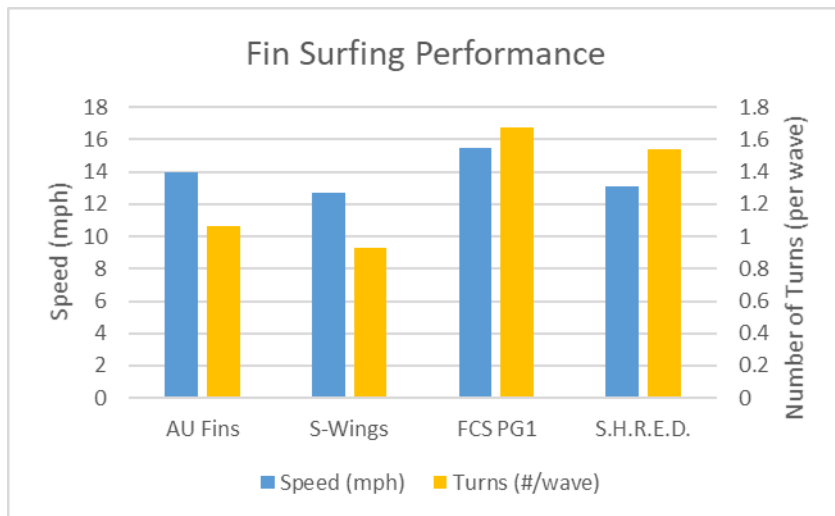


Figure 4: Bar Graph Comparing Speed and Average Number of Turns of Various Fins.

2. Theory of Fin Design

2.1 Winglet Fin

As briefly introduced above, the classic wing theory was used to improve fin design as the fin can be considered analogue to an aircraft wing. Starting from the flow around a 2D airfoil as shown in **Error! Reference source not found.**, the top and bottom sides can be classified as suction and pressure sides, respectively. The suction side is associated with a lower pressure field whereas the bottom pressure side is a high-pressure region. This is the same as how a fin produces the side force in the water flow. When the airfoil is extruded into a 3D body, the finite body experiences mixing at the tip where the suction and pressure surfaces meet. This mix between the pressure fields causes the difference in magnitude between both pressure regions to decrease. This yields a lower lifting force (dependent on pressure differential across the wing) while still producing the same amount of drag force (dependent on airfoil shape); thus, the efficiency is lowered. The mixing can be visualized by the wingtip vortex as a vortex centering around the tip of the finite body, with the concentrated mixing occurring closest to the center point. The aviation industry has found ways to overcome this specific problem. In the late 1890's English engineer Frederick W. Lanchester produced and patented the idea of having a wall that would stop the two pressure fields from mixing. This evolved into the modern wingtip, a common performance enhancing device found on airliners today [4]. Figure 6 visualizes a comparison of vortex development on the wing tip with and without the winglet device. Due to the presence of the winglet, the size of the wingtip vortex was significantly reduced, thus increasing lift.

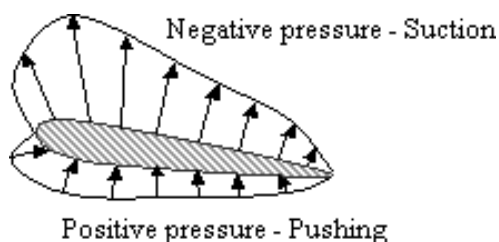


Figure 5: Pressure and Suction Sides of an Airfoil.

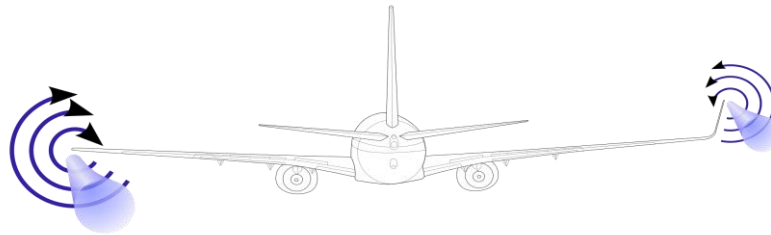


Figure 6: Comparison of Vortices Created with and without Wingtips [1].

2.2 Vortex Generator Fin

Another common device to improve the efficiency of finite span wings are vortex generators. Flow across a surface can be classified as laminar and turbulent flow. Low kinetic energy in the flow close to the surface and high risk of separation downstream are characteristics of laminar flow. Conversely, turbulent flow has more energy closer to the surface which can cause higher skin friction but suppresses separation downstream as visualized in **Error! Reference source not found.**

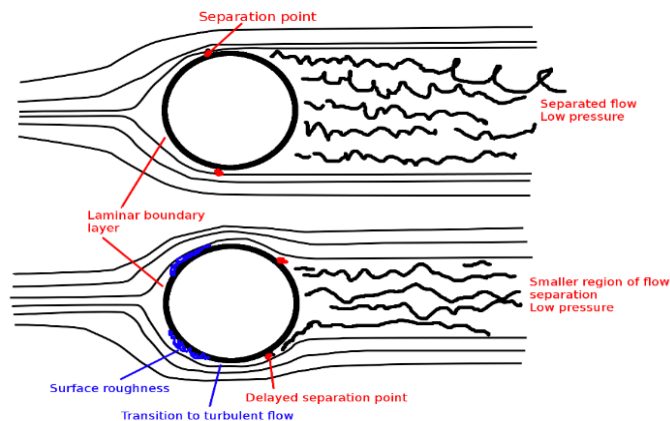


Figure 7: Flow separation after a 2D cylinder with laminar flow (top) and turbulent flow (bottom) [13].

Flow separation from the surface results in higher drag, which is avoided by aerodynamicists and surfers. The vortex generators on leading edges of a lifting surface, such as aircraft wings, force the transition from laminar boundary layer flow into a turbulence. Vortex generators are small, vertical bodies (**Error! Reference source not found.**) placed linearly along the leading edge of wings to create a turbulent boundary layer along the span and prevent flow separation, particularly at low airspeeds. For this reason, vortex generators are often implemented on aircraft to prevent stalls (which result from flow separation). The delayed flow separation also decreases the amount of total drag experienced by a wing and therefore increases its efficiency. The same concept was applied to Project S.H.R.E.D.'s Vortex Generator surfboard fin. Vortex generator size is optimized to create a turbulent boundary layer without being too tall as to increase parasitic drag. Therefore, they typically are only very slightly taller than the boundary layer itself. XFOIL was used to determine the ideal height of the vortex generators on the Project S.H.R.E.D. fin (Figure 8), which corresponded to 0.5 mm for a Reynolds number of 1.6×10^6 . This Reynolds number was chosen via the dynamic similarity calculations described in Section 4.1.

2. Production of Fins

In Phase I, a composite production method was used where the fin models were 3D printed in polylactic acid (PLA), the most common plastic filament used, before being covered with a layer of fiberglass and coated with polyester resin. This composite “sandwich” method is commonly used in the surfing industry to create a strong yet flexible composite. Issues arose in Phase I during the application of the fiberglass layer. Due to the change in shape, carbon fiber cloth could not be applied over the fin tabs (visible compared to the fin surface in **Error! Reference source not found.**) and pooling for epoxy resin occurred (white patches at fin base). The design of the fin attachment tabs also reduced the ability of the fiberglass to provide significant structural reinforcement at the attachment points. However, due to the experience gained from producing fins in this manner during Phase I, it was determined that the composite method would be the most efficient method of production for Phase II. A resin injection method, which is popular in the surf industry for mass producing fins [5] was determined to be a more viable option after the proof of concept in wind tunnel testing was completed. This method would make it easier to produce multiple fins to conduct water and load testing but was determined to be too expensive and time consuming to be used for current investigation.



Figure 8: Image of inconsistencies on the Vortex Generator fin arising from the change in shape of the base of the fins at the fin tab attachment points.

To improve upon and combat the issues faced by the composite method in Phase I, varied materials were employed to improve the strength, flexibility, and workability of the composite. Instead of printing the fins in PLA, Phase II employed the use of a Markforged Mark Two 3D printer to print the fin models in SLS (a carbon fiber composite filament). In addition, the airfoil shape was changed to a flat foil as it was determined it would be too difficult to use the composite method with a NACA 4412 airfoil. To compromise, the pressure side of the airfoil was flattened so that production could continue. The advantage was that the SLS cores were more flexible than their PLA predecessors. To maintain this flexibility while obtaining adequate fin strength, a carbon fiber cloth was sealed to the fin cores using an epoxy sanding resin. The use of carbon fiber cloth and epoxy resin as opposed to fiberglass and polyester resin reduced the difficulty related to supporting the fin tabs. The carbon fiber cloth did not fray when cut as much as the fiberglass, and the epoxy resin sanded much more cleanly than the polyester resin. As a result, the Phase II fins were stronger and more flexible than the Phase I fins (particularly at the fin tab attachment points).

3. Wind Tunnel Testing

3.1 Wind Tunnel Facility

In many engineering industries, a controlled experiment of how a product will work for its intended use is performed to collect quantitative data for analysis. For vehicles, the controlled environment is simulated in a wind tunnel, where the air flowing around the object correlates directly to an object in motion, this is explained by the wind tunnel theorem [6]. Like air, water is a fluid and can be simulated in a wind tunnel under certain conditions. Project S.H.R.E.D. conducted wind tunnel testing on the Phase II Winglet Fin and Vortex Generator fins, as well as the Moonraker, FCS G-3000x and the AU fins in Embry-Riddle Aeronautical University's Low-Speed Wind Tunnel located in the John Mica Engineering and Aerospace Innovation Complex (Micaplex) and became the first undergraduate led group to use the facility. The wind tunnel facility is a closed-return, closed-test section low-speed wind tunnel. The maximum speed in the test section is 0.38 Mach. The test section of the wind tunnel is 6ft wide, 4ft tall and 12ft long. The turbulence intensity was measured as low as 0.1% of the free-stream speed. The fins were swept for a sweep of angles (β) from -6° to 25° with increments of 1° , at speeds of 50 and 75 m/s. The forces on the fins are measured by a six component, pyramidal external force balance, which is mounted on a seismically isolated concrete foundation below the test section. The isolated foundation reduced the vibration from the wind tunnel transmitted to the balance, thus reducing the possibility of affecting the readings made on the fins. The load cells on the force balance have the capability of measuring lift and side forces of up to 500 lbf for the fin tested.



Figure 9: Fins from top left to bottom right: AU, FCS G-3000x (baseline), Phase II Winglet, Phase II Vortex Generator, Moonraker

3.2 Dynamic Similarity

Dynamic similarity is the bridge between comparing surfing in saltwater and running experiments in a wind tunnel. By matching the Reynolds number, two differing scenarios can be equated in terms of fluid dynamics [2]. The parameters that affect Reynolds Number are given by Equation 1:

$$Re = \frac{\rho v l}{\mu} \quad (1)$$

where the characteristic length l is consistent for both scenarios since the same object is used. The density, ρ , is 1025 kg/m^3 for saltwater and 1.184 kg/m^3 for air. The kinematic viscosity, μ , is $1.09\text{e-}3 \text{ Pa} \cdot \text{s}$ and $1.867\text{e-}5 \text{ Pa} \cdot \text{s}$ for saltwater and air, respectively. Per *Surfing Everyday*, the average speed of surfers in saltwater is between 10-15 miles per hour (4.5-6.7 m/s) [3]. By using the similarity of Reynolds numbers ($Re_{\text{saltwater}} = Re_{\text{air}}$) and manipulating the equation, the velocity necessary in air can be determined to produce a condition where the aerodynamic forces measured in the wind tunnel would be the same as the forces felt by the fin in salt water. To satisfy dynamic similarity for normal surfing conditions in a wind tunnel, the airspeed must be 14.59 times the speed

in saltwater. This corresponds to a range between 65 m/s to 98 m/s under standard atmosphere conditions at sea level.

3.3 Force Balance Mount

To mount the test articles to the force balance in the Micaplex wind tunnel, a specific mount was designed. The new testing mount (Figure 10) needed to be compatible with the force balance in such a way that no inessential attachment hardware was required, minimizing drag caused by the mount, and allowing for the fin to be changed without disassembling the mount or removing it from the test section.

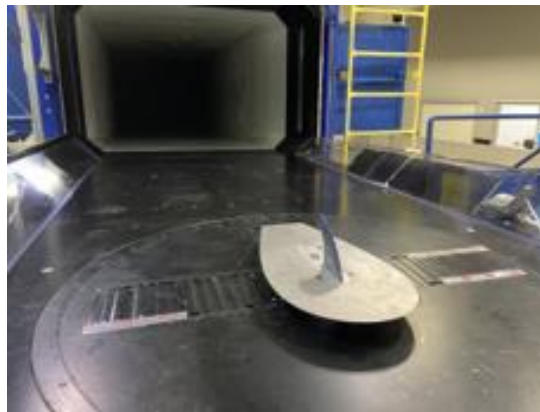


Figure 10: The testing mount and splitter plate after installation into the test section with the Moonraker Fin installed.

The wind tunnel testing mount was machined from a steel block. A drill press was used to mill the fin slots as well as drill the fin screw holes. The fin screw holes were countersunk and threaded to support the cup-point set screws securing the fins. The total time required to install the testing mount was roughly 20 minutes. The installation and fin changing times were dramatically reduced from Phase I. This is due in part to the design of the Micaplex wind tunnel, as well as the much more efficient design of the Phase II testing mount. The data shows that the testing mount performed well with effects from the mount on the test article. Uncertainty in the data was also mitigated by the simplified design of the Phase II testing mount. Any lingering uncertainty can be attributed to spillage points created by clearance as demonstrated in **Error! Reference source not found..**



Figure 11: Potential spillage point between mounting block and panel.

Future improvements to the mount design could include the ability to test fins that use different attachment mechanisms. Phase II exclusively analyzed fins that utilized the FCS II fin attachment system. Two other attachment systems are commonly used in the surfing industry and having the ability to test fins utilizing them would expand the types of fins that could be tested.

4. Results and Discussion

The data collected by the experiment is nondimensionalized by the dynamic pressure and length. This is done to compare the fins regardless of differing sizes. The general trends of the side force coefficient and the drag coefficient plots resemble traditional fluid dynamic force coefficient charts, as shown in Figure 12 and Figure 13. For the comparison, the 75 m/s trial was used as this was deemed the most dynamically similar to surfing conditions. The baseline fin produced the largest side force at coefficient of side force of 0.1671, with the vortex generator coming second followed by the winglet fin, the AU fin and finally the Moonraker fin. The maximum forces recorded were found just before stall, as is the norm. Additionally, the stall has been noticed for the baseline and Moonraker fins, at 22° and 19°, respectively. For the other fins, the stall has not been observed in the tested angle range.

Figure 13 is the drag coefficient chart for all the fins tested. The AU fin (orange) shows the lowest drag coefficient at all angles compared to the other fins. The baseline fin (blue) has significantly higher drag coefficients, especially at higher angles. A similar trend to the baseline fin is found for the Moonraker fin (yellow), however, the drag coefficients are slightly lower than the baseline when the fin enters the stall region.

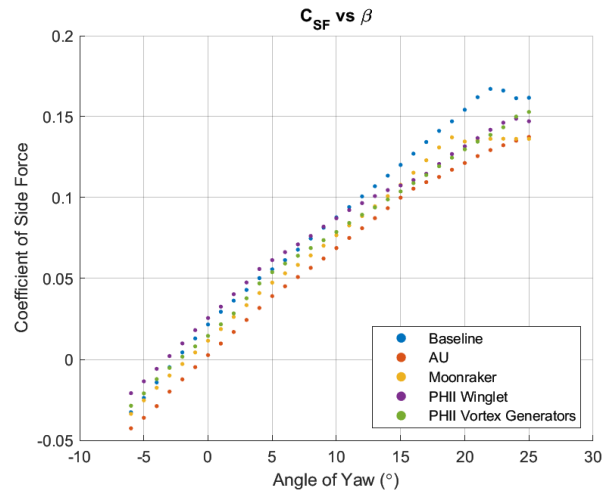


Figure 12: Side force coefficient vs. angle of yaw.

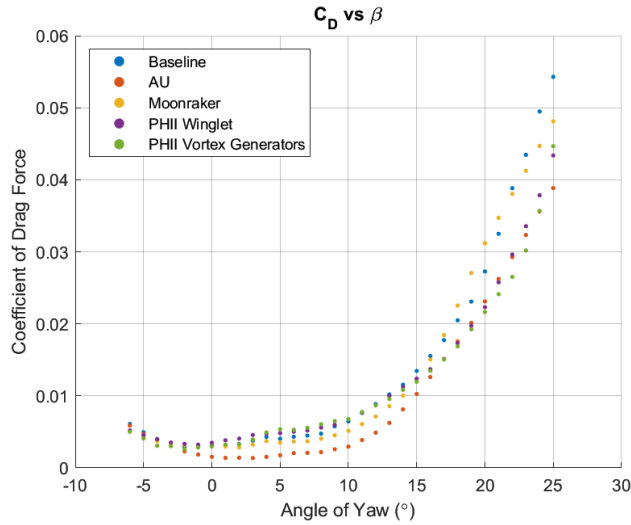


Figure 13: Coefficient of drag vs. angle of yaw.

The efficiency was plotted against the angle of yaw as seen in Figure 14. Efficiency can be defined as side force over drag coefficients, or side force over drag force as the surface areas of the fins and the testing dynamic pressure are nonconsequential so long as the test conditions are consistent. The optimal angle is defined as the angle for which each fin was the most efficient. All three fins currently on the market had an optimal angle of 8° , while the winglet and vortex generator fins had optimal angles of 9° and 10° , respectively. It becomes evident that the AU was the most efficient at nearly all angles of yaw. This was surprising given the nontraditional shape of the fin which vaguely resembles a “U shape” when observed straight on from the leading edge in the direction of the flow. The Phase II Winglet Fin proves to be up to par with most of the market competition and seems promising to revisit in future redesigns. The Phase II Vortex Generator fins performed worse than anticipated. This can be attributed to the manufacturing process as the vortex generators are too short to transition the laminar flow. Given the difficulty in printing something as small as half a millimeter with precision, it was decided that slots would be placed instead of extrusions where the vortex generators would have gone. Clumps of fiberglass would then be placed in the slots to give the vortex generator shape, however, when coated with the resin, the precision of the shape and size of the vortex generators decreased visibly. This robust and smooth shape increases drag, nullifying the positive effects of creating a turbulent boundary layer in the low angle range. The effects of the vortex generators would be more pronounced at higher angles. All important parameters collected during the wind tunnel testing are summarized in Table 1.

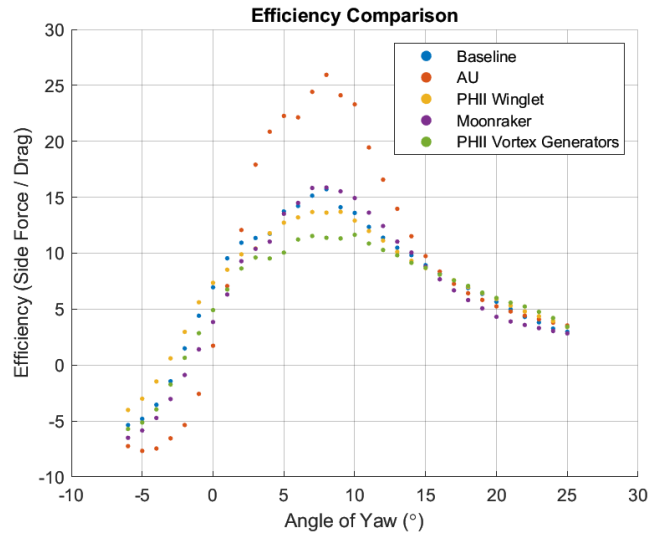


Figure 14: Efficiency comparison of five fins testing in the ERAU Micaplex Low-speed Wind Tunnel.

Table 1: Table of results for 75 m/s.

	Highest Efficiency	Optimal Angle	$C_{SF, Max}$	β_{CSFMAX}
FCS (Baseline)	15.71	8°	0.1671	22°
AU Fin	25.94	8°	0.1375	25°
Moonraker	15.87	8°	0.1372	19°
Phase II Winglet	13.70	9°	0.1487	24°
Phase II Vortex Generator	11.64	10°	0.1529	25°

The most prominent uncertainty in the data can be attributed to compressible effects. This phenomenon highlights one of the difficulties of running dynamically similar tests in a different fluid. The speed of sound for air is 343 m/s at Sea Level Standard. So, while compressible flow speeds in the flow is impossible to reach while surfing due to water being incompressible under normal circumstances, compressibility effects become a problem for wind tunnel tests when higher angles of yaw yield an increased velocity at the maximum camber [2]. Compressibility effects thus rule out the validity of data collected for the 100 m/s.

5. Future Plans

The progress of Project S.H.R.E.D. was affected by COVID-19 greatly. All wind tunnel testing has been completed prior to the university's closure. However, several important facets of the research had to be postponed until the university reopens. These include the production of more copies of the fins and performing in-water and load testing of them. Being unable to perform water testing, Project S.H.R.E.D. was unable to obtain qualitative feedback from surfers on how the fins performed under real conditions, as well as the quantitative data that was hoped to be collected through a proprietary integrated surfboard telemetry device. By being unable to complete load testing, Project S.H.R.E.D. failed to obtain comparative data of the Phase II and Phase I strength and flexibility in addition to confirming the threshold strength required by the fins to be viable in the water. Project S.H.R.E.D. was also prevented from presenting at the 2020 National Conference of Undergraduate Research taking place in Bozeman, Montana.

Moving forward, it is the goal of Project S.H.R.E.D. to complete the in-water and load testing as previously planned. To perform the in-water testing, a surfboard equipped with proprietary telemetry software will be utilized. As of the writing of this report, this surfboard is currently in development. Regarding load testing, a mount and testing procedure was previously designed, but lab access was lost upon the University closure. Project S.H.R.E.D. hopes to complete this testing when the testing equipment becomes available again. Project S.H.R.E.D. also plans to

attend future conferences as they become a possibility, in addition to submitting to peer reviewed publications. Finally, once in-water testing is complete, Project S.H.R.E.D. hopes to receive qualitative feedback from local professional surfers with the aim to further improve the fin designs.

6. Conclusion

This study utilizes the flow control devices in the aerospace engineering field to improve the hydrodynamic performance of the fins. Two fins are designed, fabricated, and tested in ERAU's Low-Speed Wind Tunnel located at the Micaplex. The results proved to be promising, however it is evident that further enhancements can be made on the fins produced during Phase II of Project S.H.R.E.D., particularly the winglet fin which showed promise when compared to the competitors. Although lacking qualitative testing in salt water due to the circumstances surrounding the COVID-19 pandemic, the quantitative data is sufficient to derive conclusions on each fin's hydrodynamic efficiencies. The AU fin was deemed to be most efficient with a maximum efficiency of 25.94 at 8° of yaw. The baseline, Moonraker, winglet, and vortex generator fins yielded maximum efficiencies of 15.71, 15.87, 13.70 and 11.64, respectively. The AU fins' exceptional efficiency is attributed to the unusual "U shape" of the fin when seen from the leading edge in the direction of the flow. In addition, the baseline fin, AU, Moonraker, winglet, and vortex generator fins produced side force coefficients of 0.1671, 0.1375, 0.1372, 0.1487, and 0.1529. The planned effort to use telemetric software will aid in understanding the underlying physics behind the sport of surfing and will shed some light as to which aspects of a surfboard fin's design are most important.

7. Acknowledgments

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