EXPERIMENTAL AND NUMERICAL INVESTIGATION OF NACA AIRFOIL WING WITH WINGLETs

by

COURTNEY BACHMANN

(Under the Direction of Mosfequr Rahman)

ABSTRACT

This research was performed in order to study wingtip devices and, in particular, winglets. Winglets are attached to commercial aircraft for the purpose of reducing induced drag caused by wake vortices on the wingtip. A winglet device can save an aircraft anywhere from 3-7% in fuel consumption. Over the course of a year, this can add up to hundreds of thousands of dollars saved. This research consisted of two parts: one part experiment and one part equipment design. The latter phase of this research examined various methods of testing in a subsonic wind tunnel laboratory setting. Experimental results found with each subsequent set-up were examined. The former part consisted of simulation work. Ansys Fluent 2020 was employed to obtain values for pressure, drag, lift, and vortices generated. For the experimental portion, two set-ups were tested: one which consisted of an array of differential pressure sensors, and the second a force balance system employing six load cells. For this research, the force balance system was found to be the more practical of the two. Using the force balance system, two winglet geometries were then compared. One which resembled Boeing’s commonly used “Blended Winglet” and the other a New Design based on the wing tips of soaring type bird wings. With both experiment and simulation, it was found that the New Design created more lift overall. However, the simulation results showed that the “Blended Winglet” outperformed the New Design at angle of attack 11.5° by a small margin. Conversely, experimental results showed that the “Blended Winglet” outperformed only at angle of attack 2.5°. Still, lift generated and drag generated are not the only considerations in the design of a wingtip device. There are factors to take into account when winglet installation is considered such as how much weight and bending moment will be added to the wing, and how much additional cost and maintenance the winglet will require. This research attempted to evaluate different winglet designs using a holistic approach. This research also collected information on how winglet shapes affect fluid flow. More knowledge on fluid flow across a wing, and which geometry can most effectively reduce drag has the potential to create the next generation of efficiency in aircraft design.

INDEX WORDS: Winglet, Sharklet, Boeing, Airbus, Wave drag, Interference drag, Profile drag, Aircraft Efficiency
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by

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EXPERIMENTAL AND NUMERICAL INVESTIGATION OF NACA AIRFOIL WING WITH WINGLETS

by

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DEDICATION

To my dad, Alan Dundas, whose unwavering support made my academic career possible. And to my mom, Deborah Kane, my guide and inspiration.
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CHAPTER 1

INTRODUCTION

1.1 Statement of the Problem

Induced drag is a type of drag created by lift. There is a high amount of induced drag at the tip of an aircraft’s wing because of the vortices created at the end of the wing. The use of wingtip devices, or winglets, in order to reduce drag and thus reduce the overall fuel consumption of the aircraft was first experimented with in the 1970’s by researchers at NASA (Hall, Aircraft Rotations, n.d.). From this research, scientists at Dryden Flight Research Center estimated that an added winglet could reduce fuel consumption on a Boeing 707 by up to 6.5% (Hall, Aircraft Rotations, n.d.).

1.2 Motivation for this Research

Since winglets were first implemented into commercial aircraft design in the 1980’s, companies have been in a competition to design the most efficient winglet type. Despite the other problems faced by the 737 MAX, Boeing still touts its unique winglet shape as being ,“The most efficient winglet on any airplane” (The Most Efficient Winglet on Any Airplane, n.d.). From the Boeing website, this appears to be a major selling point of the aircraft.

In fact the similarity in design of Aviation Partners’ “Blended Winglet” developed for Boeing and Airbus’ “Sharklet” has been the subject of legal mitigation. Both feature a smooth upward transition rather than the sharp upturn of previously used wingtip devices. Airbus had approached Aviation Partners to develop a wingtip device for their airplanes. However, the company did this while simultaneously developing its design for the Sharklet. When Aviation Partners saw the new design and its similarity with their “Blended Winglet”, the company asked
Airbus for royalties. In order to add the Sharklet design to the company’s A320 line, Airbus attempted to have Aviation Partner’s patent for the “Blended Winglet” thrown out in court. Airbus also attempted to take its case to the U.S. Patent and Trademark Office. One argument in Airbus’ favor was that both designs came from publicly available research provided by NASA. Airbus applied for patents for its Sharklet design, which the company claims will reduce the fuel cost by 3.5%. In opposition, Aviation Partners defended its own patent which the company claims decreases fuel costs by 5-7% (Kesmodel 2012). The case was ultimately settled by Airbus’ paying Aviation Partners an undisclosed sum.

1.3 How this Work is Unique

This work is unique in that it will compare not only different geometries of winglet, but it will also trace the development of the winglet from the older models and shapes to the newer models and shapes. This research will specifically trace winglet types used on Boeing’s 737 model. This aircraft was selected as a good example of how winglets across industry have developed over the years. The 737 has employed many different winglet types over the years from the simple upturned, or canted winglet, to the now most commonly used “Blended Winglet”, to the newer split scimitar winglet to the more experimental winglet found on the Boeing 737 Max.

1.4 What this Work will Contribute to the Engineering Body of Knowledge

This work will contribute to the engineering body of knowledge in that it will take a holistic approach when examining the winglet. This work was performed in order to determine which is the most efficient winglet type. There are many factors that contribute to winglet efficiency. The primary goal is to determine which winglet shape is the most effective at
reducing induced drag, and thus reduces fuel efficiency. However, there are other factors that must be considered in winglet selection. Can this winglet be retrofitted to older aircraft? How much weight and bending moment does this winglet add to the aircraft? How expensive is this winglet to manufacture? Winglets are also not beneficial when the aircraft is flying at a low lift coefficient. This occurs when the aircraft is low mass and flying at low altitude with high cruise speeds (Dieter 2018). This means that not every aircraft may be well-suited to winglet installation.

1.5 Research Hypothesis

A New Design of winglets based on the wingtip of a soaring type bird can increase the lift and reduce the weight of an aircraft wing when compared with the industry standard “blended winglet.” However, this type of winglet can also increase drag and may also increase the cost of maintenance and installation.
CHAPTER 2
LITERATURE REVIEW

2.1 Drag Reduction with Winglets

2.1.1 The Function of a Winglet

In his paper “Definition and discussion of the intrinsic efficiency of winglets” Dieter Scholz provides an explanation of drag on a wingtip. “To create... lift, the wing pushes downward on the air it encounters and leaves behind a wake ... forming two large vortices” (Dieter 2018) (Airfoil database search, n.d.). This creates a large amount of vortex drag. The easiest way to reduce vortices created by the airfoil is to extend the length of the airfoil. If the wingspan is increased, a smaller amount of wing can produce the same amount of lift. This leads to less vortices and induced pressure drag acting on the airfoil. An airfoil of longer length can influence the vortices more than a winglet redirecting the airflow upward (Dieter 2018).

![Figure 1: Vortices Generated With and Without Winglet (Zhang 2016)](image)

2.1.2 Types of Drag Caused by a Winglet
Winglets are added to the tip of airfoils to reduce drag. Drag can be categorized as being mostly dependent on lift, induced drag, or mostly independent of lift, zero-lift drag. Zero-lift drag can be categorized as miscellaneous drag, wave drag, interference drag and profile drag. Profile drag can be further divided into skin-friction drag and pressure drag. The purpose of a winglet is to reduce induced drag. However, this comes at some cost. A winglet adds interference drag at the point where different air flows meet at the joining point of the wing and winglet. A winglet also adds zero-lift drag, because it adds to the overall surface area. Winglets are often swept back in shape. This shape was designed because aircraft at speeds of 250 mph, but less than 760 mph, can also experience wave drag from winglets (Dieter 2018).

2.2 Retrofitting

Another important factor to consider when comparing winglets is can this winglet be retrofitted to older models of aircraft? And what are the benefits of retrofitting? Winglets such as Boeing’s “Blended Winglet” and the split scimitar winglet have the advantage of being able to be retrofitted to older models. According to *Aero Magazine*, a Boeing publication, the manufacturer can retrofit an aircraft with a winglet in the span of 2.5 to 14 days. Boeing also makes a variety of claims regarding efficiency of the “Blended Winglet.” Boeing says that there is evidence that its winglets can reduce not only inflight drag, but also drag produced at take-off and landing. Boeing states that the installation of one of its winglets can lead to fuel savings of 2.5-4.4%. This has the advantage of cutting harmful CO2 and NOx emissions. Another selling point of a “Blended Winglet”, according to the company, is a reduction in community noise. This is an important consideration because some airports can be charged landing fees based on noise. The company claims that installation of its winglet can reduce takeoff noise by as much as 6.5%. The
company also states that the payload or range of the aircraft could be increased instead of the amount of fuel consumed (Freitag and Schulze 2009). Another potential selling point of a winglet is its ability to improve second segment climb and diminish takeoff field length (Dieter 2018). According to the Aviation Partners / Boeing website, the base price of adding a blended winglet to the 737 models 700, 800, and 900 is $750,000. For the 757-200 the cost is $850,000. For the 767-300ER/F the cost is $1,800,000. In order to upgrade the 737 models 700, 800, 900 and 900ER to a split scimitar winglet, presumably from a blended winglet, costs $430,000 (Products, n.d.).

2.3 Development of Boeing Winglets

2.3.1 Early Commercial Winglets

The winglet was introduced to Boeing’s commercial aircraft in 1988 with an update to Boeing’s 747 (Muir 2014). This canted winglet was a simple bent up shape. For the 747-8 models, however, Boeing later replaced the canted winglet with a raked wingtip. A raked wingtip provides similar benefits to the canted winglet and has the added advantage of weighing less than the winglets previously used. However, a raked wingtip cannot be retrofitted to older models; this design must be designed and built with the wing (Muir 2014).
2.3.2 Introduction of the “Blended Winglet”

The next innovation from Boeing came from the development of the Boeing 737 Next Generation. This included models 600, 700, 800, and 900. With the Next Generation, Boeing introduced the “Blended Winglet.” This new wingtip device was a winglet with a smooth curve upward. This was an important innovation not only because of the increased efficiency of the new winglet, but also because it could be retrofitted to older aircraft. This included 737 models introduced before the Next Generation: 300, 400, and 500 (Muir 2014). Boeing has made the claim that the Next Generation 737-900 winglets can reduce fuel consumption by up to 150,000 gallons per year. Depending on the costs of jet fuel, a winglet installation could save the company hundreds of thousands of dollars per year. The cost to retrofit a wing with a winglet, according to the company, is $1,000,000 (Arnot 2019). The “Blended Winglet” style of winglet was retrofitted to older aircraft. 11 feet tall winglets were also added to the larger models: 757 and 767 (Muir 2014). Smaller, 8’2”, “Blended Winglets” were retrofitted to Boeing’s 737s and 757s (Arnot 2019). The “Blended Winglet” style was soon replicated by other manufacturers such as Airbus (Muir 2014).
2.3.3 The Split Scimitar Winglet

Next, the split scimitar was developed. This newer design featured a double winglet with a “Blended Winglet” shape on top (Muir 2014). These winglets were developed for the Boeing 737 Next Generation line. The bottom tail of the winglet is meant to disrupt spanwise flow along the bottom of the wing.

Figure 3: Blended Winglet (Flight Testing the 737 MAX, n.d.)

Figure 4: Split Scimitar Winglet (Muir 2014)
2.4 The Boeing 737

The Boeing 737 was first introduced on January 17, 1967. The first production of the 737 took place on the Thompson Site in Washington state. The 737 was unique to Boeing in that it featured a short-range twin jet. The original 737 featured the 707 and the 727 upper lobe fuselage, however, this would later be updated. The 737 was also unique for the time it was introduced in that it had the engines placed under the wing. This was done in order to accommodate more seating and to decrease noise and vibration. The 737 had the advantage of being smaller and able to land in rustic fields. The first delivery of the Boeing 737 was made to Lufthansa on December 28, 1967. Over the next two decades the popularity of the Boeing 737 increased and according to the company, “..by 1987, the 737 was the most ordered plane in commercial history” (Historical Snapshot, n.d.). In the early nineties the 300, 400 and 500 models were replaced by the Next Generation models, 600, 700, 800 and 900ER. Most models were notable for their higher seat capacity; with the model 800 reaching 162-189 seats (Historical Snapshot, n.d.).
More recently the Boeing 737 line was followed up with the 737 MAX. These models were named the MAX 7, 8, and 9. The Boeing 737 MAX was designed with lower thrust and efficient structural design in mind. The MAX was also designed to reduce noise pollution levels (Historical Snapshot, n.d.).

When the 10,000th 737 was manufactured Boeing took the Guinness World Record title of “highest production large commercial jet” (Historical Snapshot, n.d.). In 2019, the company was scheduled to produce 57 aircraft of the 737 line per month (Historical Snapshot, n.d.). For this experiment, the 737 was modeled at 12% of its actual size. This aircraft was chosen for several reasons. First, because of the aircraft’s extreme popularity. This was thought to make the results of this research applicable in more instances. Second, because Aviation Partners Boeing is thought to be an innovator in the field of winglets. Aviations Partners holding the original “Blended Winglet” patent. Third, because of the similarity in other wingtip devices developed by companies like Airbus, the results of this research should be easily transferable.

2.5 Development of Airbus Wingtip Devices

2.5.1 Older Models

Airbus wingtip devices developed over the years in a way similar to their competitor Boeing. Airbus models A330 and A340 employed a canted winglet shape not unlike the one used on the Boeing 747-400. Both models of aircraft, however, are currently out of production and the simple canted winglet design is not used on newer models (Arnot 2019).

2.5.2 Sharklets

Sharklets are the Airbus’ response to Aviation Partners Boeing’s “Blended Winglet.” The design of Aviation Partner’s “Blended Winglet” and Airbus’ sharklet were so close that it
resulted in a court battle between the two manufacturers. This legal battle was lost by Airbus (Arnot 2019).

### 2.5.3 Wingtip Fence

The wingtip fence is a wingtip device unique to Airbus. The wingtip fence design was originally designed for Airbus jets in the 1980s. This design employs an almost flat wall at the tip of the wing. The wingtip fence design was used for the A310 and the A300-600. Newer models of aircraft, such as the A320 and the A380 also employ this design (Arnot 2019).

![Figure 6: A Wingtip Fence on an Airbus A320 aircraft (Arnot 2019)](image)

### 2.5.4 New Designs by Airbus

Other new designs by Airbus include the Airbus A350 winglet and the A330neo winglet. Both designs are winglets and are made for the reduction of induced drag. Neither design, however, can be retrofitted to older aircraft (Arnot 2019).
2.6 Development Experimental Winglets

2.6.1 Articulated Winglet

A type of experimental wingtip device that is currently being researched by industry is an articulated winglet. An articulated winglet is a winglet which has the ability to move up and down based on preset controls or based on the captain’s command.

One such experiment into the field of articulated winglets was conducted by A. Gatto, of Brunel University, Uxbridge England, P. Bourdin Bombardier Aerospace, Toronto Ontario, and M.I. Friswell of the University of Swansea, Swansea Wales. This experiment was conducted in order to study the surface pressure distribution on articulated winglets. This articulated winglet has a joint from which the winglet can change its position. This design of winglet, one that is able to move, was developed in order to potentially help with the gust load. For this experiment wings and winglets were constructed using a blue foam interior with a bonded carbon and lacquered exterior. This exterior was chosen in order to make the structure solid and more aerodynamic. In order to take the pressure readings along the surface of the craft, Honeywell
CPC 1 psi dynamic pressure sensors, were inserted into the airfoil and winglets at various points. Two digital Hitec HSR-5995TG robot servos, were used in order to control the movement of the winglet. This model was also built so the angle of attack could be adjusted. This device was then placed in front of a wind tunnel set at 30m/s\(^1\). Using pressure sensors placed inside the device at various points the efficiency of the winglet was able to be determined. Although further testing is required in order to determine if the results produced in this experiment will be applicable to commercial use (Gatto, Bourdin and Friswell 2010).

![Figure 8: Articulated Winglet (Gatto, Bourdin and Friswell 2010)](image)

Figure 8: Articulated Winglet (Gatto, Bourdin and Friswell 2010)

Photo Courtesy of Brunel University Permission Pending

2.7 Comparing Winglets to Wing Extensions

In studying the effectiveness of a winglet it is important to compare the height of the winglet with a corresponding extension of the airfoil. In his paper, Dr. Scholz, examines the work of others to find the correct ratio to compare the same amount of drag reduction for length of airfoil extension to the winglet height. He cites George C. Larson from *Air and Space Magazine*, who argues that for every two feet of wing extension, three feet of winglet may be substituted for
the same benefit. The winglet will only create the bending moment equivalent to one foot wingspan increase. “That is: Same drag reduction at half the mass and winglet of ratio 1.5” (Dieter 2018). In the case where there is not an increase in structural weight, maximum induced drag is reduced by the same amount when comparing a winglet and a wing extension. According to NASA’s Robert T. Jones, a winglet must be twice the length of a wing extension. Dr. Scholz states that Jones’ argument is, “That is: Same drag reduction at same mass and winglet of ratio 2.0. As we will see below this last rule of thumb is the one that comes quite close to the truth” (Dieter 2018).

It is also important to note when comparing a wing extension with a winglet that both add a bending moment to the wing. However, a wing extension also adds shear forces which can make the retrofitting more expensive (Dieter 2018). However, Dr. Scholz argues that in most situations a wingspan extension is more effective at drag reduction than a winglet. But this is only in the case where the wing can be expanded without width limits. In the design of wingspan, commercial aircraft must adhere to limits laid out in the “FAA Airplane Design Group” and the “ICAO Aerodrome Reference Code” (Dieter 2018).

Table 1: ICAO Aerodrome Reference Code (*ICAO Aerodrome Reference Code* 2017)

<table>
<thead>
<tr>
<th>Code Letter</th>
<th>Wingspan</th>
<th>Typical aeroplane</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>&lt; 15 m</td>
<td>PIPER PA-31/CESSNA 404 Titan</td>
</tr>
<tr>
<td>B</td>
<td>15 m but &lt; 24 m</td>
<td>BOMBARDIER Regional Jet CRJ-200/DE HAVILLAND CANADA DHC-6</td>
</tr>
<tr>
<td>C</td>
<td>24 m but &lt; 36 m</td>
<td>BOEING 737-700/AIRBUS A-320/EMBRAER ERJ 190-100</td>
</tr>
<tr>
<td>D</td>
<td>36 m but &lt; 52 m</td>
<td>B767 Series/AIRBUS A-310</td>
</tr>
<tr>
<td>E</td>
<td>52 m but &lt; 65 m</td>
<td>B777 Seies/B787 Series/A330 Family</td>
</tr>
</tbody>
</table>
2.8 Downsides of Winglets

There are, however, some downsides of winglets which should be mentioned. As previously discussed, a winglet adds inference drag and bending moment to the wing. There is also some considerable cost to the installation of a winglet. To retrofit Boeing’s 767-300ER/F, for example, the cost is $1,800,000 (Products, n.d.). Winglets may also lead to other increased costs for maintenance. Winglets can also make cross-wind landings harder. Winglets can also increase the likelihood of oscillation and areoelastic flutter. The newer style of winglets, which have components above and below the wing, such as the split scimitar also are susceptible to being negatively impacted by ground service equipment (Dieter 2018).

2.9 Why is This Research Needed?

As discussed, winglets are made by competing manufacturers. These manufacturers also have competing values for the performance of their winglets. There is often a high discrepancy between the boasts from the manufactures and the values found in scientific literature. There is also a high discrepancy between values found in scientific studies. Another problem faced when winglets are studied is that it is thought by manufacturers that the efficiency of the winglet is dependent on the geometry of the entire airplane. This makes it difficult to compare only the winglet, because it is thought to be more accurate to compare a specific winglet attached to a specific plane. This makes the results of any experiment non transferable to other experiments (Dieter 2018). For this reason, this experiment employs a wing modeled after a highly used aircraft, the Boeing 737. This experiment also tests each winglet on the same wing to be able to
better compare the results. This experiment will also 3-D print the winglet and wing. This process will more accurately reproduce the shape of the wing and winglet than fabricating it in a way similar to the Brunel University study. Also, a similar method of pressure sensor array connecting to the geometry will be used.

2.10 “Featherlike” Winglet

The Aerodynamics Laboratory in Universiti Putra Malaysia conducted research on a bird-feather type winglet on a square wing. In this research article, entitled “Drag Analysis of an Aircraft Wing Model with and without Bird Feather like Winglet” the researchers point out that large amounts of vortices left by aircraft wings can actually be dangerous. If a smaller aircraft gets caught in the vortices of a larger aircraft it can cause the smaller aircraft to crash. Airports have to space aircraft out accordingly. Their stated mission for the design of their winglet was: “By designing wings which force the vortices farther apart and at the same time create vortices with large core radii, one may significantly reduce the amount of the drag the aircraft induces” (McCormic 1967) (Hossain et al.2011). According to the researchers in this study, a major limitation of a slotted wing-like winglet is that it cannot change orientation during flight in order to reduce the most drag. This study employed a NACA 65-218 shape airfoil for the wing and winglet. One wing and two winglets were constructed from wood. This study employed a six component balance system to obtain results. The slotted winglet was then tested at 60° and 0°, the wing without a winglet was also tested. This experimentation found a 10-20% increase in lift coefficient and a 25-30% decrease in drag when tested at angle of attack of 8 degrees (Hossain et al.2011). However, it is interesting to note that in terms of drag coefficient and lift drag ratio, the 0° oriented winglet seemed to outperform the 60° winglet.
2.11 The Wing Grid

![The Wing Grid](image)

Figure 9: The Wing Grid (Bennet and Oliver 2001).

The wing grid was invented by Dr. Ulrich La Roche of the Fluid Mechanics Laboratory at the Brugg-Windisch School of Engineering in Switzerland. The wing grid is a wingtip device built in the shape of a series of smaller wings. The purpose of this design is to encourage vortex shedding; wind will be broken up at the tips of the small wings. The MIT researchers of this experiment hoped that this configuration would increase the lift to drag ratio substantially. They used La Roche’s research as a starting point. According to La Roche, a 50% drag reduction could be expected from the winglet as long as the Reynolds number was over the critical value. During this study, negative results were found for laminar flow over the wing grid (Bennet and Oliver 2001).

In order to begin their experiment, MIT researchers constructed two wing grid devices and one wing extension for a control. A six-component pyramidal force balance was used. The model was adjusted for various angles of attack and wind speeds. One winglet grid designed used had the same angle of attack for each individual mini-wing, matching the AOA of the main wing. The other had varying angles of attack for each mini-wing in order to adjust for the aerodynamic
loading. It was found that the equal angle of attack wing grid displayed less lift-to-drag ratio at higher angles of attack. The wing grid designed for equal loading, however, was more efficient at higher angles of attack and less efficient at lower AOA. The researchers concluded that the wind tunnel had not reached high enough speeds for the wing grid to have a substantial effect on reduced drag (Bennet and Oliver 2001).

2.12 The Force Balance System

2.12.1 Purpose

A force balance system is a device used in a wind tunnel laboratory setting. The function of a force balance system is to divide load produced by the force of the wind into components. Internal balance systems and external balance systems can be used based on the placement of the system. This system must be carefully calibrated and much of the accuracy of this system is based on the equipment used (Samardžić et al. 2014, 40-46).

![Figure 10: Moment Acting on Aircraft](image)

The aerodynamic load on an aircraft can be divided into several moments and directional loads. The forward thrust force, the backward drag force, the upward lift force, and the downward weight force. The moment of an aircraft is defined by which axis the moment occurs.
The moment that occurs on the same axis as the lift force is called yaw motion. Yaw causes the nose of the aircraft to move side to side. The moment created along the axis of drag is called rolling motion; this motion cruises the wings to move up and down. Pitch is the moment acting along the axis of the side force. This moment causes the nose of the aircraft to move up and down (Hall, *Aircraft Rotations*, n.d.).

2.12.2 External Balance Designed by Korea Aerospace Research Institute

The paper “Wind Tunnel Test of MRP Model using External Balance” describes a collaboration project between The Korea Aerospace Research Institute Low Speed Wind Tunnel and the Glenn L. Martin Wing Tunnel of the University of Maryland. In this study, an external 6-component external balance was constructed using strain gauge load cells. The balance system was matched with the center of the wind tunnel. For this experiment, a seaplane model from the University of Maryland was used. The same wind tunnel tests were performed in both laboratories. However, there were some discrepancies in size: the University of Maryland’s wind tunnel was 66% the size of the Korea Aerospace Research Institute’s, and the speed of Maryland’s wind tunnel was slightly slower. Calculations were performed in order to make up for these differences (Chung, Sung, and Cho 2000, 68-74).
Figure 11: External Balance Design (Chung, Sung, and Cho 2000, 68-74)

The figure above shows the experimental set-up used which included two platforms: strut interface platform, model platform interface and support struts. The design was then subjected to a load which would create a displacement in the axial direction of +/- 2mm and a rotation of +/- 0.3 deg. Fairings covered the support struts in order to ensure minimal blockage. The pitch strut has the option of being in the positions 350, 500, 650, and 950 mm from the front of the vertical center of the balance. The pitch strut can be rotated 90, 180, and 270 degrees. The front strut can be placed +/- 240, +/- 480, +/- 960 mm to the side of the vertical center (Chung, Sung, and Cho 2000, 68-74).

In this case, using the Pyramidal type of force balance system, an airplane model is matched at the vertical center of the system and the resulting moments are resolved around that point. The height of the balance system can be adjusted as needed. The resolution of the load is 0.02%; lift force can be measured to 400 g and drag to 120 g. Precautions were taken not to expose the balance to humidity or changes in temperature in order to produce the most accurate results possible. Care was taken to eliminate the effect of the supports and fairings. The supports were moved to several positions and calculations were made in order to subtract the effect of the
supports. This was done with the calculations below. The second and third formula were subtracted from one another in order to determine the actual drag. The effects of the supports and fairings were found by subtracting the second equation from the third. When the two research facilities compared their final results they found that the resulting moments, side force and lift were very close. However, the drag and tare drag due to the mount were found to be significantly different between the two laboratories (Chung, Sung, and Cho 2000, 68-74).

\[ D_N = D_{nM} + D_{bB} + I_{bBM} + I_{bfM} \]  \hspace{1cm} (1)

\[ D_I = D_{iM} + D_{tB} + I_{tBM} + I_{tFM} + D_{bB} + I_{bBM} + I_{bfM} \]  \hspace{1cm} (2)

\[ D_{Ii} = D_{iM} + D_{tB} + I_{tBM} + I_{tFM} + D_{bB} + I_{bBM} + I_{bfM} \]  \hspace{1cm} (3)

- \( D_N \): measured drag in normal position
- \( D_I \): measured drag in inverted position
- \( D_{Ii} \): measured drag in inverted position with image
- \( D_{nM} \): drag of model in normal position
- \( D_{iM} \): drag of model in inverted position
- \( D_{bB} \): drag of bottom bayonet attached
- \( D_{tB} \): drag of top bayonet attached
- \( I_{bBM} \): Interference of bottom bayonet on model
- \( I_{tBM} \): interference of top bayonet on model
- \( I_{bfM} \): interface of bottom fairings on model
- \( I_{tFM} \): interface of top fairings on model
Figure 12: Balance Configurations (Chung, Sung, and Cho 2000, 68-74)
2.12.3 Inspiration

![Image of a six-component external balance system]

Figure 13: “Six-Component External Balance” (Samardžić et al. 2014, 40-46)

The force balance system presented in this thesis was heavily influenced by the system presented in the paper “External Six-Component Strain Gauge Balance for Low Speed Wind Tunnels” (Samardžić et al. 2014, 40-46). In this paper, researchers constructed a balance system for a wind tunnel with dimensions of 0.4-0.6 m x 0.4-0.6 m. For this experimental set-up, the researchers recommend a maximum speed of 50 m/s. This force balance connects directly to the wind tunnel via two support struts connected to the triangle piece. This set-up can be rotated along the yaw and pitch axis by use of two-step motors in the base. With this set-up, the test subject can reach a yaw of range -180° to 180° and a pitch between -20° to 30°. For this system, three vertical load cells are used as well as three horizontal. These load cells were made from ARMCO PH 13.8-Mo steel for the strain gauges TK-06-S082R-350 were used. The load range
for the horizontal load cells was 100 N and the vertical 200 N. These load cells were fed to one data acquisition system. The load cells for this experiment were made with four strain gauges which measure branding moment. These load cells were then connected to a full-wheatstone bridge. This was done in order to produce the highest signal possible while curtailing thermal effects. In order to select strain gauges, a balance had to be made between high and low excitation. The highest output possible was desired while not making it so high that the gauges produced errors due to heat. In order to find this balance, a 6 V excitation voltage was used. With calibration, the load cells were able to achieve an accuracy of 0.25%. A number obtained from three standard deviations (Samardžić et al. 2014, 40-46).

2.12.4 Associated Calculations

![Diagram of force balance calculations](image)

Figure 14: Force Balance Calculations (Samardžić et al. 2014, 40-46)

In order to use this system and find values for lift, drag, and moment the researchers of this paper used the following equations (Samardžić et al. 2014, 40-46).

\[ X = XD + XL \]  \hspace{1cm} (1)

\[ Y = YY \]  \hspace{1cm} (2)
\[ Z = ZPD + ZPL + ZZ \]  
\[ L = c_2 \cdot YY + l \cdot ZPD - l \cdot ZPL \]  
\[ M = -c_1 \cdot XD - c_1 \cdot XL + f \cdot ZPD + f \cdot ZPL - 2f \cdot ZZ \]  
\[ N = -n \cdot XD + n \cdot XL \]

2.13 Nature and Winglets

2.13.1 Types of Wings

Nature has long inspired the design of aircraft, and winglets are no exception. In order to find the correct inspiration, however, it is important to understand some intricacies of bird flight. Wing shapes can first be categorized by the type of flight they provide: gliding, soaring, rapid take off, high speed, and hovering. They can also be classified according to their aspect ratio from width of wing to length of wing (Ritchison, n.d.).
The gliding wing, such as those of an albatross, has a high aspect ratio. These wings are long and thin and designed to glide over long stretches of ocean over long stretches of time. This type of flight requires minimal movement from the bird and the wing is able to capture 90% of energy needed from the surrounding air. This wing design, however, lacks efficiency in turning, taking off, and landing. Lower aspect ratio wings are better suited for more movement. In the world of aeronautical design, this wing-type is mimicked by glider aircraft (Bush 2018), (Ritchison, n.d.).

The soaring wing has a lower aspect ratio. This wing is found in birds such as hawks, storks and eagles. Birds that need efficient wings for long periods of flight, but also require maneuverable wings for the rapid descents and accents required for hunting. This wing is a balance between the high aspect ratio - high lift gliding wing and the lower lift - lower aspect ratio rapid takeoff wing (Bush 2018) , (Ritchison, n.d.). This combination of soaring flight and maneuverability is mimicked in the design of commercial aircraft. What is of particular interest to this study is the slots found on the tips of these wings. One purpose of these slots is to aid in the quick takeoff of a bird when it is lifting its prey (Bush 2018) . The slots also aid in the reduction of induced drag at the wingtip (Ritchison, n.d.). In this way, the slots function as
winglets. The soaring wing serves as the inspiration for the wingtip design presented later in this study.

![Figure 17: Fighter Jet (Mizokami, n.d.)](image)

The rapid takeoff and high speed wings are about maneuverability. These wings require rapid flapping in order to generate the speed required for hunting prey. Here, long distance flight is not the priority. A peregrine falcon, for example, can use its wings to rapidly ascend and then fold them into an inverted v-shape to make a high speed dive of up to 386 kph for hunting. The maneuverability and rapid movements is mimicked by the design of fighter jets (Bush 2018), (Ritchison, n.d.).

2.14 Summation

This work is unique in that it focused on modeling a winglet from the soaring bird type wing. The slotted tips of that wing-type were studied and replicated. This wingtip was then compared to wingtips commonly used in industry. For this purpose, a wingtip device modeled after the Airbus “Sharklet” or Boeing “Blended Winglet” was modeled. A force balance system was constructed. This system is similar to the force balance systems discussed in this chapter. The system in this research, however, has some key differences. First, the system used in this research was made out of mixed materials; 3-D print, MDF and hardwood were used as opposed
to all metal parts. Second, the system in this research was constructed on a larger scale than those discussed in this chapter. It also is a free standing structure, as opposed to one attached to the wind tunnel. Lastly, the “Six-Component External Balance” employed strain gauges attached to handmade load cells. This research employs 10 kg s-shaped load cells. This size was deemed to be sufficient after calculations regarding wind force and total force applied were estimated for the system.
CHAPTER 3
EXPERIMENTAL MYTHOLOGY

3.1 Introduction

In this chapter will be discussed the construction and implementation of a differential pressure sensor array. This array will take reading to mimic ANSYS nodal analysis. Next, this chapter will discuss the experimental set-up for a followup experiment: the force balance system. This system consists of a set of 10 kg s-shaped load cells and is able to produce results for lift, drag, and moment for each winglet testes.

3.2 Experimental Setup: Pressure Sensor Array

3.2.1 Wind Tunnel and Winglet

For the experimental portion of this experiment, Georgia Southern University’s wind tunnel was used.

Figure 18: Georgia Southern University’s Wind Tunnel
The wind tunnel velocity was set to half of its maximum speed at 7 m/s. The speed of the wind was adjusted using the control panel which is placed on the far side of the wind tunnel than the side pictured. The control panel adjusts the hertz at which the wind tunnel operates, the speed is then adjusted with a wind gauge.

![Control Panel](image)

**Figure 19: Control Panel for Georgia Southern University’s Wind Tunnel**

In order to construct the stand holding the wing and winglet in front of the tunnel, a 23/32” T x 4’L x 4’W plywood board which was cut down to around 16” x 16” and wood supports were added for balance. Next a ¾” silver galvanized steel structural pipe fitting rail support was attached to the center of the stand and a LDR ¾” x 120” galvanized steel pipe was inserted into the mount to support the wing and winglet. A 3-D printed part was made to attach the wing to the steel pipe.
The wing and winglet were printed using PLA at 100% infill. The wing was printed in six pieces and the winglet was printed in two. The wing and winglet together measured about one meter in length. These pieces were superglued together and the seam gaps were filled with Loctite All Purpose Repair Putty. A smooth surface was given to the 3-D print using automotive filler primer spray and 2500 grit wet dry sandpaper for sanding. The winglet was left hollow on the inside and channels were printed into the wing so that the tubes connecting to the pressure sensors could feed through to the winglet.

The pressure sensory array was designed to mimic FEA nodal analysis. Pressure sensors were installed into the 3-D printed winglet at random points. This created “nodes” or points
where the pressure readings are taken and known. The major advantage of this approach is that from the information gathered by these sensors at these locations can produce a color gradient chart of pressure points that can be compared to FEA results. A major disadvantage of this design was that it limits what may be tested. Only winglet shapes that could be made hollow and have the tubes fed through them could be tested. So more complicated winglet geometries could not be used. In order to accommodate the tubes, the overall size of wing and winglet had to be substantially increased - the wing and winglet mentioned in this paper measured about one meter in wingspan.

Figure 22: Pressure Sensor Array Designed to Imitate Nodal Analysis

3.2.3 Data Acquisition System

A pressure sensor array was fed into the wing in order to take readings at multiple points in the winglet. These pressure sensors were fed into the winglet using polyurethane plastic tubing, ⅛”. This pressure sensor array was constructed from two pieces of MDF and 24 Diymore Breakout Board MPXV7002DP Transducer APM 2.5 APM2.52 Differential Pressure Sensors. The circuit was constructed from 24, 10k ohm resistors, and 24 2N3906 B 331
transistors. These were then soldered onto a 15x20 cm proto board. This was connected to an Arduino and linked to a Dell desktop.

Figure 23: Circuit Set-up

Figure 24: Circuit Set-up with 24 Inputs
For the data acquisition, the C++ program in Figure A2 was written for the Arduino and uploaded to the hardware using Arduino IDE 1.8.13 software. This code was written to upload the pressure readings from each sensor and export that data into an Excel spreadsheet.

The following sketch depicts the completed experimental set-up. GrabCAD drawings were used for a portion of this sketch (Design Community, Cad Library, 3d Printing Software, n.d.).
3.2.3 Experimental Procedure

For the experimental procedure a file was generated in Solidworks 2020. This was made to be a replica of a Boeing 737 wing with a separate part file for a “Blended Winglet”. These parts were scaled down to be 12% of the original size. This scale was chosen in order that the winglet be a height to fit the entrance of the wind tunnel. The parts for the winglets were made hollow in order to accommodate the tubes for the pressure sensors to be fed through them. Also, because of the limitations in the size of the 3-D printer, part of the wing was removed for printing. The wing, at 12% scale, was about one meter long. About ⅔ of this wing was removed for printing. The following picture is of the CAD model used for 3-D printing.

On the subject of scaling the Reynolds number should also be addressed. In this case the scaling for this model would be represented in the following way. In this case the left hand side represents the Reynolds number of the full scale plane and the right hand side represents the scaled down model.
\[
(0.12) \frac{\rho_{\text{plane}} V_{\text{plane}} l_{\text{plane}}}{\mu_{\text{plane}}} = \frac{\rho_{\text{experimental}} V_{\text{experimental}} l_{\text{experimental}}}{\mu_{\text{experimental}}}
\]

There is, however, difficulty presented in scaling down a model in this way. This case makes the assumption that in both cases the dynamic viscosity and density is the same. Algebraically, in order to scale down the size of the model 12%, \( \frac{12}{100} \) must be multiplied by \( l_{\text{experimental}} \). Next, in order to keep both sides balanced \( v_{\text{experimental}} \) must be multiplied by \( \frac{100}{12} \). The problem this presents is that this increase the velocity of \( v_{\text{experimental}} \) to a point that is not practical for the wind tunnel. This obstacle is oftentimes overcome by placing the experimental model into another fluid thereby changing the values for \( \rho_{\text{experimental}} \) and \( \mu_{\text{experimental}} \) (Brainstorms 2015).

Figure 27: Airfoil and Winglet File used for Printing
The 3-D printing and piecing together produced a winglet approximately 0.27 m in height. The winglet and wing was primed and sanded in order to produce more aerodynamic properties. One winglet at a time was attached to the wing for testing. When finished, the winglet was removed and another winglet was attached and tested. The winglets were attached and removed using tape. This procedure may have added to the interference drag of the wing and winglet, but the levels were deemed to be insignificant. Holes were drilled into the winglet part of the 3-D print and tubes were fed through the wing connecting to an array of pressure sensors. This array of pressure sensors was attached to an Arduino and a data acquisition system. The wing and winglet was then placed in front of the wind tunnel and readings for each point were recorded through the DAQ. The pressure distribution generated by the simulation was then compared to the pressure distribution generated in the lab. In the following picture the pressure sensor tubes, which were fed through the wing, can be seen on the top left of the wing.

Figure 28: 3-D Print of Wing and Winglet
3.3 The Force Balance System

3.3.1 Preparation to Build the Force Balance System

The data acquisition system involving the pressure sensor array system was considered a success. With this system pressure could be taken at different points on a geometry in a way similar to the nodes on a FEA simulation. There is a definite advantage to this while comparing lab results with FEA simulation results. However, this experimental set-up also has major limitations. The size of the 3-D prints used in this experimental set-up was very large: one wing and winglet that was printed for use with the pressure sensor array measured just over one meter long. In order to be able to print the winglet the correct size, part of the geometry of the wing had to be cut off in order to be able to print the winglet and maintain the proportions of the wing and winglet. This was because prints had to be large enough that the tubes for the pressure sensors could be fed through them. This system also limited the geometry which could be tested. In order to feed the pressure sensor tubes through the geometry, the geometry had to be made hollow. This limited the kind of shapes which could be used because many geometries had points which were too narrow to be made hollow.

For these reasons a new system was adopted. Using the force balance system any geometry may be tested. The geometry used can also be smaller. For this experimentation, the geometry used was around 457.2 mm and included the entire wing and winglet. In order to manufacture the force balance system a CAD model was first made using SolidWorks, Figure 29. In this drawing, the pentagon shapes represent 10 kg s-shaped load cells. The base of this piece were constructed from a 25.4 mm x 609.6 mm piece of spruce pine fir, the bottom and top supports were 3-D printed using PLA with 100% infill, the triangle base was cut from a piece of
16 mm MDF board. The wing and winglet were attached to the force balance system using neodymium magnets.

Figure 29: CAD Drawing of Force Balance System

A wiptip was modeled which was designed to replicate the geometry of Boeing’s Blended Winglet or Airbus’ Sharklet. This design was used in order to replicate a winglet commonly used in industry.
Figure 30: CAD Drawing of “Blended Winglet”

For this CAD model, the wing of the Boeing 737 was modeled. As the aircraft is one of the most popular planes ever built, it was taken as an industry standard. A wing of a Boeing 737 NG 800 airplane wing was recreated in Solidworks 2020. This wing and the corresponding winglets were scaled down. The cross-sectional geometry for the root, midspan, and outboard airfoil were determined using AirFoilTools.com. The three NACA airfoils used for this model were BAC449 for the root airfoil, BAC450 and BAC451 for the midspan airfoils and BAC442 for the outboard airfoil (Airfoil database search, n.d.).
Next, a new wingtip device design was modeled. This design was created using the basic geometry of the “Blended Winglet” as its inspiration. The MIT study “The Wing Grid” was also used as inspiration for this design (Bennet and Oliver 2001). Like The “Wing Grid” This design features several small wing shapes in order to reduce drag at the end of the wing. The last inspiration for this New Design was the slotted wingtips of the soaring wing type birds discussed earlier in this paper. Figure 32 was one of the reference images used in modeling a soaring bird type with slotted wingtips. Figures 33 and 34 are the resultant CAD models.
3.3.2 Electrical Set-up

For the electronic components of the force balance system a collection of Phidget devices were used. The first four of the load cells were fed into a Phidgets PhidgetBridge Wheatstone Bridge Sensor Interface. This was connected to a mini-usb connection which fed into the computer.
The last two load cells were fed into a two port Phidget VINT Wheatstone Bridge Sensor Interface. This then fed into a VINT Hub Phidget using a Phidgets Sensor Cable, a mini-usb cable then fed into the computer.
3.3.3 Calibration

Figure 37: Load Cell Calibration Process

The force balance system employed six s-shaped load cells. Weights were used for the calibration of these load cells. In increments of 10g, weights were placed on each load cell with a range of 10 - 110g. For this process, first the pre-load voltage was noted, the weight was added to the load cell and the corresponding voltage was noted, the pre-load voltage was then subtracted from the total voltage found with the weight. This process was repeated 11 times for each of the 6 load cells. A calibration curve was then found for each load cell. For the calibration curve the mass, g, was converted to force, N.
The completed system can be found in the figure below. This includes: wind tunnel, force balance system, and computer. In order to change the angle of attack, the force balance system was mounted on a 50.8 mm diameter PVC pipe. The angle was then adjusted and determined using an inclinometer.
3.5 Conclusion

For this experiment a dynamic pressure sensor array was constructed. This sensor array was designed to mimic nodal analysis. This sensor array posed major limitations, however. The wing and winglet had to be printed at large and cumbersome size, and the shape of the winglet that could be tested was limited to the shapes that could fit the pressure sensor tubes. For this reason, the force balance system was constructed. With this system the size and shape of the wing and winglet were not constrained. This system was also able to provide more data including moment, lift and drag results.
CHAPTER 4

SIMULATION METHODOLOGY

4.1 Introduction

In this chapter the set-up and boundary conditions for two separate simulations will be discussed. The first simulation was performed using Ansys Fluent. This simulation was linked to the study employing the pressure sensor array. The second simulation was performed using Ansys CFX. This numerical study consisted of eight separate simulations: one for each of the four angles of attack studied for the two separate geometries.

4.2 Numerical Simulation Linked to Pressure Sensor Array Study

4.2.1 Generation of Model in SolidWorks

In order to generate a model for Ansys simulation a wing and winglet were drawn in Solidworks 2020. The cross-sectional geometry for the root and outboard airfoil was determined using AirFoilTools.com (Airfoil database search, n.d.). For this model the same airfoil shape was repeated at the wing root and the winglet tip. In this model, the winglet was straight, with no curve, and bent at an angle in a way similar to Boeing’s canted winglet design.

Figure 40: SolidWorks of Wing and Winglet
4.2.2 Ansys Simulation

These Solidworks files were then imported into Ansys. For the simulation, a cube was generated around the geometry of the wing and winglet, the wing and winglet were then extracted from this geometry using a boolean cutout. For the meshing, a fine mesh was used. In Ansys Fluent, an inlet wind velocity was added. This inlet velocity was added to the side of the cube corresponding to the leading edge of the wing and winglet. The simulation was run for approximately 350 iterations. Results were then generated for the coefficients of lift and drag, for wall surrounding flow channel pressure, and interior surrounding flow channel.

In order to prepare the files for Ansys simulation, the geometry of the wing and winglet had to be slightly modified. It was determined that the file as it was originally created for 3-D printing would not mesh correctly in Ansys. In order to overcome this difficulty the file was changed to incorporate a more round geometry at the trailing edge of the airfoil. This changed the geometry slightly and may have impacted the results.
Another major difficulty presented by this simulation was the difficulty in changing the angle of attack. In Ansys Fluent if the geometry is changed, in order to do something like change the angle of the wing and winglet, all of the boundary conditions are lost and must be reentered. It was therefore deemed impractical to do multiple simulations with multiple angles of attack. This problem was solved by doing future simulations in Ansys CFX. CFX upstreams any changes in geometry into the already set boundary conditions.

4.3 Simulation Linked to Force Balance System Experiment

4.3.1 Model Preparation

For the simulation linked to the force balance system CAD models for the “Blended Winglet” and the New Design were made in SolidWorks. The geometries were then imported into Ansys. In Design Modeler an enclosure was formed around the geometry. The geometry was then extracted from the cube using a boolean cutout. In order to replicate the effect of the fuselage, the wing root was placed against the wall of the cube.

FIGURE 42: Geometry in Ansys Design Modeler
For the meshing for both models the element size was set to 0.03. For the “Blended Winglet” the resolution was set to 7. The New Design, however, was not able to be meshed with these settings due to its more complicated geometry. For this meshing, the resolution was reduced to 3 and a defeature of 0.002 m was added. The above figure is a picture of the mesh used for the New Design.

It was determined that for this simulation CFX-Pre instead of Fluent should be used. This was due to CFX-Pre providing a simpler interface. The boundary conditions were applied in CFX-Pre Setup. An inlet velocity of 7 m/s was added at the leading edge of the cube and an outlet velocity was added to the trailing edge side of the cube. This velocity was chosen in order to replicate the conditions of the wind tunnel in the lab. A symmetry was then added to all other surfaces of the cube.
In order that the simulation provide results for lift and drag coefficient, following values were entered as variables into Ansys.

\[
\text{lift coefficient} = \frac{F_y}{1.25 \frac{kg}{m^2} \cdot \left(7 \frac{m^2}{s^2}\right) \cdot 1m^2 \cdot 0.5} \tag{1}
\]

\[
\text{drag coefficient} = \frac{F_x}{1.25 \frac{kg}{m^2} \cdot \left(7 \frac{m^2}{s^2}\right) \cdot 1m^2 \cdot 0.5} \tag{2}
\]

4.4 Summation

For this research two simulations were performed. One simulation was performed linked to the pressure sensor array experiment, and the other was performed with its results linked to the force balance system experiment. It was determined that the CFX simulation met the needs of this research better. This was because of CFX’s ability to upstream data. The angle of attack of the simulation could be easily changed without repeating the boundary conditions of the experiment.
CHAPTER 5
EXPERIMENTAL AND SIMULATION RESULTS

5.1 Introduction

This chapter will discuss the experimental results from both the pressure sensor array experiment and the force balance system experiment. The results from simulations linked to both of those experiments will also be discussed.

5.2 Experimental Results from Pressure Sensor Array Experiment

As the pressure sensor array was never fully implemented experimentally it is necessary to look at preliminary experimental results. A PLA 3-D print of the canted winglet geometry was used for this purpose. This print was then quickly taped together. For the preliminary results, the sanded and smoothed “blended” winglet shape was not used. In this case, experimental results came from the canted winglet shape.

The pressure was measured at multiple points along the wing and winglet using a rod with a pressure sensor attached. This may have decreased the accuracy of the readings because the stick may have interrupted the flow. The rod also made repeatability of the experiment difficult, as it was difficult to again find the exact point to take pressure readings. Below are pressure readings taken at the leading edge of the wing and winglet.
Figure 45: Dynamic Pressure Points, Upper Side of Wing and Winglet

Figure 46: Lower: Dynamic Pressure Points, Lower Side of Wing and Winglet

The following pressure in, pascal, the following pressure points were generated from the trailing edge of the wing and winglet.
5.3 Experimental Results Linked to the Force Balance System

Results from the force balance system were taken from the load cells using the Phidget Control Panel software. In order to process experimental results from the force balance system, a program was written for Excel VBA which would translate data from voltage to force using the calibration curves found in the experimental set-up. This VBA code can be found in Appendix A, Figure A1. This code used formulas similar to the “Six-Component External Balance” (Samardžić et al. 2014, 40-46) discussed earlier in this paper in order to produce results for lift, drag, and moment.

For each run, 300 readings were taken from each load cell, these readings were taken in about 60 seconds. The lift force, drag force, and moment were determined by finding the average of these readings. From these numbers the standard deviation was also calculated. The chart below represents the experimental findings of the “Blended Winglet” and New Design geometries. The error bars represent the standard deviation.

![Experimental Results for “Blended Winglet”](image-url)
For the purpose of this study we will say that the most effective winglet is the winglet with the highest lift to drag ratio. The chart below depicts the ratio of both winglets for each angle of attack tested. It is interesting to note that the New Design produces more lift relative to how much drag is produced in every case except for at angle of attack 2.5°.
5.4 Simulation Results Linked to the Pressure Sensor Array System

The simulation provided ample information to meet the required criteria for success in this research. That is, to determine the winglet with the highest efficiency. This simulation also provided knowledge on the direction of the fluid flow across the wing. To further understand these results the limitations of this study must also be addressed. This study simulated one winglet geometry. A generic airplane wing was constructed and a winglet shape was constructed without any regard to creating a specific winglet made by a specific manufacturer. Although not specifically made to replicate this geometry, this winglet shape was similar to that of a Boeing canted winglet.

This simulation work only took into consideration one winglet shape. The following figure represents the SolidWorks file constructed of a wing and winglet. Despite only one geometry being studied with this simulation, the results of this simulation do present some interest in the study of the effect of flow around a wing and winglet geometry.

![Solidworks file of Wing and Winglet](image)

**Figure 51: Solidworks file of Wing and Winglet**

The following results were found for the wall surrounding flow channel pressure. This simulation was adjusted to a higher velocity in order to produce more distinguishable results. It is likely that the actual values for pressure will be much lower than the previous values due to the
lesser velocity. However, the color gradient will likely be similar. This pressure gradient can be compared with lab results gathered from the pressure sensors and the 3-D printed wing and winglet parts.

Figure 52: Wall Surrounding Flow Channel Pressure

Figure 53: Wall Surrounding Flow Channel Pressure (200 Color Variations)

The next simulation result will help in the comparison of different geometries. This simulation result is the interior surrounding flow channel. When, in the future, different shapes of geometries are analyzed and compared, the effect of the different shapes of winglet on the
surrounding flow should be clearly seen from these results. The split scimitar winglet, for example, might have a great effect on the shape of the interior surrounding flow channel.

![Contour plot of interior surrounding flow channel](image)

**Figure 54: Interior Surrounding Flow Channel**

This study also produced results for total lift force generated and total drag force. This information is helpful in determining the efficiency of the winglet geometry. The following tables produced results for total lift and drag generated.

**Table 2: Total Lift Force**

<table>
<thead>
<tr>
<th>Zone</th>
<th>Forces (n)</th>
<th>Viscous</th>
<th>Total</th>
<th>Coefficients</th>
<th>Pressure</th>
<th>Viscous</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>wall-air</td>
<td>7.6896682</td>
<td>-0.0029026929</td>
<td>7.6867655</td>
<td>12.85456</td>
<td>-0.0047350904</td>
<td>12.85456</td>
<td></td>
</tr>
<tr>
<td>Net</td>
<td>7.6896682</td>
<td>-0.0029026929</td>
<td>7.6867655</td>
<td>12.85456</td>
<td>-0.0047350904</td>
<td>12.85456</td>
<td></td>
</tr>
</tbody>
</table>

**Table 3: Total Drag Force**

<table>
<thead>
<tr>
<th>Zone</th>
<th>Forces (n)</th>
<th>Viscous</th>
<th>Total</th>
<th>Coefficients</th>
<th>Pressure</th>
<th>Viscous</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>wall-air</td>
<td>1.51377389</td>
<td>26.240845</td>
<td>27.754324</td>
<td>2.4714759</td>
<td>42.841707</td>
<td>45.313182</td>
<td></td>
</tr>
<tr>
<td>Net</td>
<td>1.51377389</td>
<td>26.240845</td>
<td>27.754324</td>
<td>2.4714759</td>
<td>42.841707</td>
<td>45.313182</td>
<td></td>
</tr>
</tbody>
</table>

The most helpful results from the simulation were the results produced from the charts generated from the lift and drag force and coefficient charts. These charts provided helpful
information in determining which winglet geometry. For this simulation, around 350 interactions were used.

Figure 55: Lift Coefficient Chart

Figure 56: Drag Force Chart

The effect of the different shapes of winglet on the velocity in each direction can also be compared with the following chart produced by Ansys of the velocities in multiple directions.
5.5 Simulation Results Linked to the Force Balance System

5.5.1 Simulation Results: Drag and Lift

For the simulation results linked to the force balance system the first thing that was studied was the lift and drag coefficients generated. For every angle of attack tested the New Design experiences an increase of both lift and drag coefficient over the “Blended Winglet,” Figures 58-59.

Figure 57: Velocities in Multiple Direction, m/s

Figure 58: Lift Coefficient vs Angle of Attack
Figure 59: Drag Coefficient vs Angle of Attack

The difference between the increase in drag and lift coefficient is smaller at smaller angles of attack. At 2.5° angle of attack, for example, there is an increase in lift coefficient for the New Design of 37.5% when compared to the “Blended Winglet.” When the drag coefficients are compared, the New Design experiences an increase of only 17.1%

Figure 60: Percent Increase of Lift and Drag Coefficient of New Design when Compared to “Blended Winglet”
The greatest change in lift and drag coefficient comes at higher angles of attack. For most angles of attack the percent increase of lift coefficient is higher than the increase in the drag coefficient. For angle of attack 10° the lift coefficient experiences a 157.8% increase when compared to the “Blended Winglet” and the drag coefficient experiences a 111.5% increase. This trend changes, however, when the angle of attack is increased to 11.5°. When the angle of attack is increased to 11.5°. The lift coefficient experiences a substantial increase with the New Design of 105.3%. The drag coefficient experiences an increase of 137.9%. This is the point where the percent increase of drag coefficient begins to overtake the percent increase of the lift coefficient.

It is interesting to note that this simulation produced similar results as found in MIT’s “The Wing Grid” study. In that study, it was found that the wingtip design which had all of the mini wings attached at the same angle of attack as the main wing performed better at lower angles of attack than at higher angle of attack. (Bennet and Oliver 2001) The New Design discussed in this paper had all the small wings attached to the main wing at the same angle as the wing and the Design seemed to follow the same pattern as the MIT study in performing better when exposed to wind at lower angles of attack.

The trend of increased pressure acting on the winglet can be seen in the following figure. It can be seen the condition with the highest pressure is the New Design at 10° angle of attack.
<table>
<thead>
<tr>
<th>AoA</th>
<th>“Blended Winglet”</th>
<th>New Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5°</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>2.5°</td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td>10°</td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
</tbody>
</table>
Another major consideration of wingtip devices is weight and bending moment added to the wing. In the case of the comparison of these two designs no significant differences were found. When the weight of the wing and “Blended Winglet” was checked using SolidWorks with the default material set, the weight was found to be 82.08 kg. When the same measurement was performed with the New Design, the weight was found to be 81.62 kg.

5.5.2 Simulation Results: Vorticity

It can be seen in Appendix B, Figure B1, that the vorticity values for the “Blended Winglet” geometry do not vary significantly as the angle of attack is changed. From these images it can also be noted that the position of the vorticity does not change as the angle of attack is changed. For angles of attack 1.5°, 2.5°, 10°, and 11.5° the point of highest vorticity occurs near the root of the wing. The vorticity on the winglet is only slightly elevated. For all four angles, the vorticity is approximately 200s⁻¹.

The simulation results for vorticity for the New Design are very different. The vorticity fluctuates widely as the angle of attack is changed; from 1.5° to 11.5°. When the angle of attack is at 1.5° the vorticity is the highest at the tip of the mini-wings. At 11.5° the vorticity is at the
forward root of the mini-wings. Interestingly, the vorticity is at the same location for angles 2.5° and 10°. These are also the angles where the most amount of drag was generated and the most amount of lift was created. This trend can be seen in the figure above. This would seem to indicate that this is the optimal location for the vorticity.

For the New Design there is much fluctuation in peak values of vorticity. The highest value for vorticity for the New Design is 1679s⁻¹, while for all four values of angle of attack tested the “Blended Winglet” maximum vorticity stays in the range of 200s⁻¹. Below is a table which compares the maximum vorticity results for both designs under each angle of attack tested.

![Figure 62: Comparison of Vorticity Results of New Design and “Blended Winglet”](image)

Chapter one Figure 1, demonstrated air acting on a wing without a winglet. The flow curves from the bottom of the wing around the edge of the wingtip and creates a downward force acting on the wing. This trend can also be seen in Figure B3 of Appendix B which depicts the airflow behind the trailing edge of the wing. The “Blended Winglet” design successfully pushes
some of the airflow upward, but much of the airflow turns downward again and puts pressure on the wing. For the New Design results in Figure B4, however, the airflow is for the most part successfully pushed away from the wing. This is particularly true for angles of attack 1.5° and 2.5° where the flow seems to scatter in every direction. For 11.5°, however, some of the flow seems to make it back to the top edge of the wing, though more of the flow seems to be redirected still than that of the “Blended Winglet” design.

5.6 Conclusion and Comparison

The pressure sensor array system was never fully tested. Initial information gathered from this system was taken using one sensor rather than the full 24 sensor array. The preliminary results presented above, however, do seem to match the trend presented in the simulation as far as pressure distribution points. The pressure on the leading edge of the wing and winglet stays relatively constant until the measurement is taken at the top edge of the winglet. This can be explained by the vortices generated. Interestingly, in both simulation and experiment, a lower pressure point can be found at the root of the winglet.

The simulation successfully produced results for drag and lift coefficient, drag force and lift force. The simulation also depicted flow channel pressure, gave values for velocity in each direction, and provided images of interior surrounding flow channel. However, Fluent was deemed inefficient for the work being performed. CFX provided an easier way to change the angle of attack for multiple simulations without resetting the boundary conditions. Formulas were easily entered into later CFX simulations, which made exact numerical results easy to achieve.
For the force balance system the simulation and experimental results seem to differ slightly. For this study efficiency is measured by which design produces a higher lift to drag ratio. For the experimental results the New Design out performed the “Blended Winglet” design at every angle of attack except for 2.5°, see Figure 50. However, when the same ratio is measured with the simulation results, the New Design outperformed the “Blended Winglet” for every angle of attack except angle 11.5°, Figure C1. The difference is likely due to sensitivity of the equipment. It is also possible that this error would not occur if testing were performed at higher velocities.

Another major consideration of wingtip devices is weight and bending moment added to the wing. In the case of the comparison of these two designs no significant differences were found. When the weight of the wing and “Blended Winglet” was checked using SolidWorks with the default material set, the weight was found to be 82.08 kg. When the same measurement was performed with the New Design, the weight was found to be 81.62 kg. Since the 3-D prints used in the experiment were from these same files, it will be assumed that in both cases the “Blended Winglet” was the heavier geometry.

Lastly there is the consideration of cost and ability to retrofit. It can be assumed that since airplanes can be retrofitted with “Blended Winglets” that they may also be able to be retrofitted with the New Design. However, the substantially more elaborate design may add to both cost of installation and to maintenance costs.
6.1 Conclusion

A New Design of winglet based on the wingtip of a soaring type bird can increase the lift and reduce the weight of an aircraft wing when compared with the industry standard “Blended Winglet” design. However, this New Design of winglet can also increase drag in some instances and may also increase the cost of maintenance and installation.

During the course of this experiment, it was concluded that the force balance system should be used over the pressure sensor array system. This was for two reasons. First the pressure sensor array required that the wing and winglet be printed at such a large scale as to make the prints cumbersome. For the “Blended Winglet” geometry the length of both wing and winglet was one meter. This was in order to accommodate the pressure sensor tubes being fed inside the geometry. Secondly, because the pressure sensor tubes had to be fed inside the geometry, it greatly limited the shape which could be tested. Geometries like the New Design, for example, would not be able to be tested as the tubes would not fit.

This research was conducted in order to determine which winglet shape can increase the lift and decrease the drag with the greatest efficiency. Efficiency in this case was measured by which geometry has the highest lift to drag ratio. When the results of the force balance system and the CFX simulation were compared it was found that for the simulation the New Design outperformed the “Blended Winglet” at every angle of attack except 11.5°. Conversely, when the same geometries were compared using the force balance system the “Blended Winglet” ratio was higher only at angle of attack 2.5°. The differences between the two data sets are small and the
error is likely due to sensitivity of the equipment. The force balance system generated a large amount of pitching moment Figures C3-C5. And it is recommended that some of the 3-D printed parts be replaced to correct this.

Despite the New Design for the most part out performing the “Blended Winglet” in lift to drag ratio, it fell short in other areas. Most notably the installation and maintenance cost for such an elaborate design would be significantly higher. However, when the bending moment is considered, the New Design weighs less than the “Blended Winglet.” It thus generates less moment force on the wing.

It is recommended that the vorticity results used in this study be used to improve the design of the winglet. The vorticity for the “Blended Winglet” stays fixed, Figure B1, however, for the New Design, the vorticity moves to the root of the mini-winglets used in the design, Figure B2. In order to correct this, the angle of the back two mini-winglets may be changed. It may also be beneficial to add ribbing between the mini-winglets in order that the winglet may perform better at higher angles of attack.

This study focused specifically on the wing and winglet of a Boeing 737 because of its being one of the most popular aircraft ever built. The results of this study will be transferable to other winglet types such as Airbus’ sharklets. This is because of the similarity of wingtip devices developed in industry through the years. Winglets were first put into use for commercial aircraft in the 1980’s and since that time companies like Boeing and Airbus have been competitive in their designs of wingtip devices. This is what led to the legal battle between Aviation Partners and Airbus over the similarities of the “Blended Winglet” vs the “Sharklet.” A large sum of money is on the line in such cases because Aviation Partners’ original patent claims it can
decrease fuel use by 5-7% (Kesmodel 2012). This case ended with a payment by Airbus to Aviation Partners of an undisclosed amount.

The purpose of a winglet is to reduce induced drag. Induced drag is directly related to lift. Induced drag is a problem at the tip of the wing because of the vortices created at the end of the wing. The use of a winglet for drag reduction on commercial aircraft was first experimented with at NASA’s Dryden Flight Research Center during the fuel crisis of the 1970’s (Hall, Aircraft Rotations, n.d.). Drag reduction is directly proportional to fuel reduction which made the research of a high priority during the fuel crisis faced during this time period. This factor is also what makes this research a high priority in the current day.
REFERENCES


Biology. Department of Biological Sciences Eastern Kentucky University. Accessed


Ritchison, Gary. “BIO 554/754 Ornithology Lecture Notes 2 - Bird Flight I.” Avian


APPENDIX A
PROGRAMS AND CODING

The following six programs will translate voltage from each load cell into force based on the calibration curves provided.

Function forceLCA0(voltage)
forceLCA0 = (49724 * Abs(voltage)) + 0.0017
End Function

Function forceLCA1(voltage)
forceLCA1 = (49237 * Abs(voltage)) - 0.0027
End Function

Function forceLCA2(voltage)
forceLCA2 = (49160 * Abs(voltage)) - 0.002
End Function

Function forceLCA3(voltage)
forceLCA3 = (49690 * Abs(voltage)) + 0.0051
End Function

Function forceLCA4(voltage)
forceLCA4 = (49104 * Abs(voltage)) + 0.0008
End Function

Function forceLCA5(voltage)
forceLCA5 = (49202 * Abs(voltage)) - 0.0016
End Function

Function drag(LCA1, LCA2)
' This program will calculate drag based on the readings from the horizontal load cells
drag = LCA1 + LCA2
End Function

Function lift(LCA1, LCA2, LCA3)
' This program will calculate lift based on the readings from the three vertical load cells
lift = LCA1 + LCA2 + LCA3
End Function

Function rollingmoment(c1, LCA0, LCA1, LCA2, LCB1)
' This program will measure rolling moment
rollingmoment = c1 * LCA0 + c1 * LCA1 + (c1 * LCA2) + (c1 * LCB1 - 1 * LCB3)
End Function

Function pitchingmoment(-c1, LCA0, LCA1, f, LCB2, LCB3, LCB1)
' This program will measure pitching moment
pitchingmoment = -(c1 * LCA0) - (c1 * LCA1) + (f * LCB2) + (f * LCB3) - (2 * f * LCB1)
End Function

Function yawingmoment(n1, LCA0, n2, LCA1)
' This function will calculate the yawing moment
yawingmoment = -(n1 * LCA0) + (n2 * LCA1)
End Function

Figure A1: VBA Code used to Process Data Collected from Load Cells
#define Signal A0

int Sensor_Enable(Dieter 2018) = {23, 25, 27, 29};
float Value(Dieter 2018);

//float Value[24] = {0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0};
void setup()
{
    for (int i = 0; i < 24; i++) {
        pinMode(Sensor_Enable[i], OUTPUT);
        Serial.begin(9600);
        for (int i = 0; i < 24; i++) {
            digitalWrite(Sensor_Enable[i], LOW);
        }
    }
}

void loop()
{
    for (int i = 0; i < 4; i++) {
        digitalWrite(Sensor_Enable[i], HIGH);
        delay(10);
        Value[i] = map(analogRead(Signal), 0, 1028, 0, 100);
        digitalWrite(Sensor_Enable[i], LOW);
        delay(10);
        Serial.print(Value[i]); Serial.print(" ");
    }
    Serial.println(" ");
    Serial.println(" ");
    delay(1000);
}
APPENDIX B

SIMULATION RESULTS

<table>
<thead>
<tr>
<th>Angle of Attack</th>
<th>Blended Winglet</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td><img src="image" alt="Diagram" /></td>
</tr>
</tbody>
</table>

Velocity, Curl vorticity

- 2.046e+02
- 1.535e+02
- 1.023e+02
- 5.116e+01
- 7.655e-07 [s^-1]
Figure B1: Vorticy results for “Blended Winglet”

<table>
<thead>
<tr>
<th>Angle of Attack</th>
<th>Blended Winglet</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5°</td>
<td></td>
</tr>
</tbody>
</table>

![Figure B1: Vorticy results for “Blended Winglet”](image-url)
Figure B2: Vorticity results for New Design

<table>
<thead>
<tr>
<th>Angle of Attack</th>
<th>“Blended Winglet”</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.5°</td>
<td>1.024e+03</td>
</tr>
<tr>
<td>5.141e-07</td>
<td>[s^-1]</td>
</tr>
<tr>
<td>2.560e+02</td>
<td></td>
</tr>
<tr>
<td>5.119e+02</td>
<td></td>
</tr>
<tr>
<td>7.679e+02</td>
<td></td>
</tr>
<tr>
<td>1.024e+03</td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>Angle of Attack</th>
<th>“Blended Winglet”</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>9.636e+00</td>
</tr>
<tr>
<td>2.409e+00</td>
<td>[m s^-1]</td>
</tr>
<tr>
<td>4.818e+00</td>
<td></td>
</tr>
<tr>
<td>7.227e+00</td>
<td></td>
</tr>
<tr>
<td>9.636e+00</td>
<td></td>
</tr>
</tbody>
</table>
Figure B3: Trailing Edge Velocity Airflow for “Blended Winglet”
Figure B4: Trailing Edge Velocity Airflow for New Design
APPENDIX C

EXPERIMENTAL RESULTS

Figure C1: Simulation Results Lift to Drag Coefficient Ratio for Both Designs

FIGURE C2: Experimental Results Percent increase of lift and drag coefficient of New Design when compared to “Blended Winglet”
Figure C3: Percent increase of Force from “Blended Design” to New Design

Figure C4: “Blended Winglet” Moment Values
Figure C5: New Design Moment Values