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EXPERIMENTAL INVESTIGATION INTO THE AERODYNAMIC GROUND EFFECT OF A TAILLESS CHEVRON-SHAPED UCAV

THESIS

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Abstract

This experimental study adequately identified the ground effect region of an unmanned combat air vehicle (UCAV). The AFIT 3’ x 3’ low-speed wind tunnel and a ground plane were used to simulate the forces and moments on a UCAV model in ground effect. The chevron planform used in this study was originally tested for stability and control and the following extends the already existing database to include ground effects. The ground plane was a flat plate mounted with cylindrical legs. To expand the capabilities of the AFIT 3’ x 3’ low-speed wind tunnel, hot-wire measurements and flow visualization revealed an adequate testing environment for the use of the ground plane.

Examination of the flow through the test section indicated a significant difference in test section transducer velocity and the hot-wire measured velocity. This disparity, along with the velocity difference due to the ground plane, was accounted for as wind tunnel blockage. In addition, the flow visualization revealed the horseshoe vortices that built up on the front two mounted legs of the ground plane.

The ground effect region for the chevron UCAV was characterized by an increase in lift, drag, and a decrease in lift-to-drag ratio. Previous studies of similar aspect ratio and wing sweep noted these trends as well.
To my parents and sister for their love and support in every endeavor of my life and to my girlfriend for her patience and encouragement throughout this entire project.
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Brett L. Jones
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<td>Y</td>
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<td>Angle of Attack (α = θ)</td>
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<td>γ</td>
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<td>δ*</td>
<td>Displacement Thickness</td>
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<td>Symbol</td>
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<td>Laminar Boundary Layer Thickness</td>
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EXPERIMENTAL INVESTIGATION INTO THE AERODYNAMIC GROUND EFFECT OF A TAILLESS CHEVRON-SHAPED UCAV

I. Introduction

Section 1 – Ground Effect

Ever since the early days of aviation, pilots have experienced a phenomenon while operating an aircraft very close to the ground. Either during take-off or landing, any air vehicle will experience improved efficiency near the ground in the form of increased lift. However, this poses a problem because most aircraft are not designed for this flight condition and therefore can behave very awkwardly.

A typical aircraft is in-ground-effect (IGE) when it is within one wingspan of the ground (1). The amount of ground effect experienced by an aircraft is dependent on the induced drag. When the height of an aircraft is below one wingspan of the ground, the induced drag significantly decreases due to the wingtip vortices interacting with the ground (1). During normal flight, wingtip vortices are cylindrical in shape, but while interfering with the ground, they tend to flatten out which improves the effective wingspan and aspect ratio. Since aspect ratio has a strong inverse effect on induced drag, an aircraft flying very near the ground will experience a reduction in induced drag reducing the total drag of the aircraft (1).

In addition to a reduction in drag, an increase in lift and pitching moment are characteristics of an aircraft in ground effect. The increase in lift along with the reduction of drag significantly increases the lift-to-drag ratio, which intuitively increases
the overall aircraft efficiency. The discovery of this improved efficiency led to the development of Wing-In-Ground vehicles (2).

**Section 2 – Wing-In-Ground Vehicles**

Wing-In-Ground (WIG) vehicles take advantage of all the benefits of ground effect because they are designed to operate at very low altitudes. As knowledge and technology improved during the 20th century, WIG vehicles increased in popularity and many thought they were the future of marine transportation.

In the 1960’s, Russian scientist Rostislav Alexeiev led the development of WIG boats. With his background in hydrofoil ship design, Alexeiev’s research led to the development of ekranoplanes. (‘skimmer' in English) The Soviet Union saw the military potential in these vessels, and so Alexeiev received practically unlimited funding for his then top-secret project (2). Only a few years later, in 1966, Alexeiev unveiled the KM Caspian Sea Monster, a 550-ton WIG vehicle designed heavy loading and fast transportation over water. The KM was far more advanced than the ekranoplans developed earlier by Alexeiev mainly because its weight was 100 times that of the heaviest ekranoplan at that time. Several other crafts were developed and built for the Russian Navy in the decades to follow, but in the late 1980’s, funding was lost due to the fall of the Soviet Union and the end of the Cold War (2).
To meet the growing demands of the U.S. Army Mobility Command, Boeing Phantom Works is evaluating a similar concept with the Pelican project. Like the Russians concept of WIG vehicles, the Pelican would have twice the external dimensions of the world’s largest aircraft and would utilize ground effect to produce the necessary lift-to-drag ratio for flight operations. It would have the cargo capacity to carry an entire Army division of supplies and soldiers or up to 17 M-1 tanks (3). The WIG vehicle concept could revolutionize marine transportation thanks to the beneficial effects of flying low.

Section 3 – Unmanned Air Vehicles

Ever since the beginning of aviation, the concept of unmanned flight has intrigued engineers and scientists. The first unmanned air vehicles (UAV) were built to be used as guided missiles. The Kettering “Bug” and Sperry aerial torpedo were the first two combat UAVs but were never used in operation due to inaccuracy. As technology advanced, researchers investigated the use of radio and eventually television control links to correct the erroneous navigation issues. During the last quarter-century, significant
advances in computing capabilities, electronics miniaturization, communications, guidance, navigation, and control have allowed for successful flight operations of the Global Hawk and Predator UAVs, which are currently being used daily in conflicts around the world (4).

The next development of unmanned flight is the unmanned combat air vehicle (UCAV). Currently, the primary program for UCAV exploration is the joint unmanned air systems (J-UCAS) program, which is a joint Darpa, Air Force, and Navy program. The J-UCAS program is designed to

demonstrate the technical feasibility, military utility and operational value for a networked system of high performance, weaponized unmanned air vehicles to effectively and affordably prosecute 21st century combat missions, including Suppression of Enemy Air Defenses (SEAD), surveillance, and precision strike within the emerging global command and control architecture. (5)

The two leading UCAVs are the Boeing X-45 and the Northrop Grumman X-47. Each one has an unconventional configuration including a blended wing body with swept wings and no tail. Even though today’s advanced control systems allow for such unconventional designs, the ground effect phenomenon still poses problems.

Section 4 – UAVs and Ground Effect

Understanding the location and the extent of the ground effect region is of particular interest for UAVs because of the shear fact that they are unmanned. Pilots use sight and feel when operating a conventional aircraft near the ground. During a landing, a pilot will normally flare the aircraft to ensure that the rear landing gear strikes first. If necessary, the pilot can make small adjustments to the aircraft attitude for the drag reduction and increase in lift while in the ground effect region. The pilot for a UAV
operates the craft from a Ground Control Station (GCS) and uses real time video and sensors. The removed operator or UAV pilot cannot feel the effects of the ground during take off and landing and depends entirely on the automatic control system. Therefore, it is important to identify the ground effect region in order to ensure safe flight. Normally, since the ground effect region is a small portion of time compared to the entire glide slope to land, it is not factored into the landing control system design. However, with sufficient data from flight tests or wind tunnel tests, the control engineer will make gain adjustments to account for the ground effect region (6).

Unmanned flight brought with it numerous mishaps near the ground. One of particular interest was on 22 April 1996, when the Lockheed Martin/Boeing RQ-3A DarkStar’s flight control system did not properly account for ground effect. It ‘porpoised’ during take-off, pitched up, and stalled due to over-correction by ailerons (7).

Section 5 – Boeing AFRL/VAAA UCAV Program

In an effort to expand the database for unconventional aircrafts, Capt. Shad Reed of the Air Vehicles Directorate (VAAA) of the Air Force Research Laboratory (AFRL) conducted a low-speed wind tunnel investigation on three generic UCAV planforms. The test program defined the stability and control characteristics of moderately swept, low aspect ratio, tailless, blended wing body planforms. The three planforms tested were a chevron, lambda, and diamond shape. Their characteristics are found in reference (8). Of the three configurations tested, the chevron-shaped planform had the highest maximum lift coefficient, lift-to-drag ratio, and lowest minimum drag coefficient. However, due to the chevron planform’s lack of fuselage, Reed concluded that subsystem
integration would be difficult since engines, weapons, and other components are normally located in the fuselage (8).

Despite Reed’s conclusions about the possible subsystem integration problems of the chevron-shaped planform, a ground effects test is still of interest because improved technology can solve the apparent subsystem integration problems (8).
II. Literature Review

Section 1 – Ground Effect Theory

Since the beginning of flight, aircraft designers noticed the decrease in landing speed due to an increase in lift while in close proximity to the ground. Engineers conducted numerous wind tunnel and flight test experiments around the world in order to investigate this phenomenon called ground effect.

In 1922, Wieselsberger developed his famous theoretical equation for estimating the induced drag reduction of aircraft near the ground. He used Prandl’s three-dimensional wing theory and the reflection method to establish a relatively simple relationship between height above ground and induced drag (9). His equation became the standard for predicting ground effect and was verified throughout the 1930s and 1940s in references 10-12, among others.

Another theoretical approach to estimating the decrease in induced drag due to the presence of the ground is to apply McCormick’s induced drag factor. In his section on ground roll and takeoff distance, McCormick derived Equation [1] by replacing a rectangular wing with a simple horseshoe vortex modeled with its image so the vertical velocities cancel each other simulating the ground. The height was the distance between the reflection plane to the horseshoe vortices. McCormick then used the Biot-Savart Law to estimate the velocity induced at a point from each horseshoe vortex. This led him to identify a ratio between the induced drag in ground effect and the induced drag out-of-ground effect (13).
As discussed in Chapter I, ground effect is normally experienced at heights above ground less than one wingspan, and the effect is increased exponentially as the aircraft travels below half of a wingspan as demonstrated in references 17, 20, and 21. Equation [1], when multiplied by the induced drag, provides a prediction for ground effect. Figure 2 is a plot of McCormick’s induced drag factor.

![Figure 2: McCormick’s Induced Drag Factor (13)](image)

**Section 2 – Static vs. Dynamic Wind Tunnel Testing**

Experimental methods for ground effects have become more sophisticated during the past several decades. One of the first wind tunnel investigations was Raymond’s
study at the Massachusetts Institute of Technology in 1921 (14). He analyzed ground
effect by testing three different airfoils in a wind tunnel using a flat plate for a ground
plane. He also attempted to create an imaginary ground plane by means of reflection.
Both methods revealed similar results except at high angles of attack. This test
confirmed that when near the ground, an airfoil will increase in lift and decrease in drag
(14).

As testing techniques advanced, Raymond’s flat plate method took the name of
static wind tunnel testing. A static wind tunnel test involves a fixed ground plane height
and model. Moving the model closer to the ground plane is normally how various
heights above ground are tested. In order to validate these tests, test pilots flew ground
effect testing routes, called ‘fly-by’ patterns. To determine the extent and location of the
ground effect region, altitude and angle of attack were held constant. However, in 1967,
William Schweikhard developed a method for measuring the ground effects of an aircraft
as it approached a runway (15). A test pilot would maintain a constant angle of attack
and power setting, but would let the sink rate vary; this ensured that lift, drag, and
pitching moment were constant just before approaching the ground. Once in the ground
effect region, flight test engineers measured any changes in flight path angle, velocity, or
control surface deflection. They found that this flight test technique saved time and data
analysis over standard fly-by or static tests (15).

In an effort to reduce flight test costs, engineers developed methods to
dynamically test for ground effect in a wind tunnel. A dynamic wind tunnel test for
ground effect attempts to better simulate a landing approach or a take off by manually or
mechanically moving the model towards the ground plane. Chang et al. found relevance
in dynamic wind tunnel testing as he noted the disparity between static tests and landing data (16). He tested delta wings of 60, 70, and 75 deg sweep, the XB-70, and the F-104A both statically and dynamically. He, along with Baker et al., concluded that at heights of h/b < 0.4, the static wind tunnel results for the delta wings and XB-70 significantly over predicted the change in lift due to ground effect (17). However, he also pointed out that the amount of difference between static and dynamic results decreased as aspect-ratio increased. See Figure 3.

**Figure 3: Incremental $C_L$ vs. AR for static and dynamic ground effect at h/b=0.3** (17)

Additionally, Corda, et al. (18) performed a dynamic ground effect test on the F-15. Their results are mentioned because the chevron UCAV has a similar aspect ratio to that of the F-15. They fit the following equation to the dynamic ground effect tests for the delta wings presented in Figure 4:
\[\% \Delta C_{L, GE} = \left(\frac{0.2}{AR} + 0.04\right) \times 100\]  \[2\]

Equation [2] quantifies the relationship between percent increase in lift due to ground effect and aspect ratio for a wing. Based on this prediction the chevron UCAV should experience a 10.9% increase in lift due to ground effect.

More importantly, this relationship and results presented in Figure 4 suggest that a static ground effect test for the chevron UCAV should produce similar results as a dynamic test.

Figure 4: Percent Increase in \(C_L\) in Ground Effect vs. AR for Various Aircraft (18)

A common tool used to predict and verify ground effect tests is the U.S. Air Force Data Compendium (DATCOM) (19). This analytical program uses equations, charts, and flight data to predict stability and control characteristics of aircraft. Since the static ground effect prediction for the F-15 lies almost directly on the curve based on dynamic
results for wings (Equation [2]), a static ground effect test for the chevron UCAV should produce similar results to that of a dynamic test.

Section 2.1 – Adverse Ground Effect

While ground effect is normally characterized by an increase in lift and a decrease in drag, not all aircraft configurations experience these beneficial traits. Lee, et al. (20) reported an increase in lift along with an increase in drag as height above ground decreased.

They performed dynamic and static wind tunnel tests on models of a 60 deg delta wing, F-106, and XB-70-1. Re was varied from $3 \times 10^5$ to $7.5 \times 10^5$ and height above ground ranged from $h/b=1.6$ to $h/b=0.2$ for all three models. Their focused primarily on the differences between the static and dynamic results, so no emphasis was placed on the increasing lift or drag. The $C_D$ vs. $(h/b)$ plot for the F-106 in Figure 5 represents their results.

![Figure 5: Adverse Ground Effect for the F-106 at an AOA = 14 deg (20)](image)
Although Lee, et al. did not show any L/D results, the static data were extrapolated from their $C_D$ vs. (h/b) plots (similar to Figure 5) and $C_L$ vs. (h/b) for each model to analyze the trends. The 60 deg delta wing experienced a subtle decrease in L/D. The F-106 and XB-70-1 both experienced a decrease and a slight increase in L/D at the lowest height above ground. The downward trend of $C_D$ between h/b=0.3 and 0.2 in Figure 5 was common for the XB-70-1 and explained the increase in L/D.

It is possible that aspect ratio and wing sweep played a role in these results. The 60 deg delta wing, F-106, and XB-70-1 had aspect ratios equal to 2.3, 2.4, and 1.78, respectfully. The F-106 had a wing sweep of 60 deg and the XB-70-1 had wing sweep of 65 deg. Again, these considerations were not discussed in their report, but are mentioned because the chevron UCAV has similar characteristics.

Similarly, the F-16 XL aircraft was flight tested and wind tunnel tested for ground effects by Curry (6). He found an increase in $C_D$ as height above ground decreased and explained that an increase or a decrease in drag is possible for aircraft flying close to the ground. Curry and Owens (21) also discovered an increase in drag when the Tu-144 supersonic transporter flew in close proximity to the ground.

Section 3 – Boundary Layer Removal

One limitation using a ground plane in a wind tunnel to simulate ground effect is the boundary layer build-up across the top surface. Boundary layers form on any surface where a moving fluid has direct contact, so they cause an unrealistic test condition in
wind tunnels when a ground plane is used to simulate the ground. A boundary layer removal system is typically employed to resolve this issue.

One method of removing the boundary layer in a wind tunnel is to use a moving-belt ground plane. A moving-belt would better simulate an aircraft flying over the ground because the belt would spin at the same velocity of the air, which in turn removes the boundary layer.

While it seems that boundary layer removal with a moving-belt ground plane is essential to achieve proper flight dynamics, two different studies were conducted that showed the necessity of a moving-belt ground plane depends on the maximum lift coefficient of the air vehicle. Turner (22) investigated the use of conventional ground planes for ground effect wind tunnel testing. Specifically, he examined the possible use of endless-belt ground planes and determined the conditions under which it would be preferable. He concluded that the use of a moving-belt ground plane depended on spanwise lift coefficient and height above ground (22).
The shaded box in Figure 6 indicates the region tested in the present study, and the $C_L_{\text{max}}$ line indicates the maximum lift coefficient found in Reed’s study (8). Thus, according to Turner, a moving-belt ground plane was not required for this experiment.

Kemmerly and Paulson, Jr. did a similar study comparing the use of a conventional ground plane (23). While Turner studied high-lift, high-aspect-ratio models, Kemmerly and Paulson, Jr.’s study evaluated an F-18 and delta wing models. They concluded that if the condition in Equation [3] was satisfied, then an engineer must use a moving-belt ground plane to study ground effects.

$$\frac{(h/b)}{C_L} < 0.05$$  \hspace{1cm} [3]
According to the heights used in this study and the maximum lift coefficient according to Reed, a conventional flat-plate ground plane without a moving-belt was adequate to properly measure ground effects, Table 1 shows that Equation [3] was not satisfied.

Table 1: Justification for a Flat-plate Ground Plane

<table>
<thead>
<tr>
<th>h/b</th>
<th>C_L max *</th>
<th>(h/b) / C_L max</th>
<th>&lt; 0.05 ?</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>0.9</td>
<td>0.33</td>
<td>No</td>
</tr>
<tr>
<td>0.15</td>
<td>0.9</td>
<td>0.17</td>
<td>No</td>
</tr>
<tr>
<td>0.1</td>
<td>0.9</td>
<td>0.11</td>
<td>No</td>
</tr>
<tr>
<td>0.05</td>
<td>0.9</td>
<td>0.06</td>
<td>No</td>
</tr>
</tbody>
</table>

* as denoted in Reed's study

Section 4 – Goals of the Experimental Effort

Reed concluded that the chevron shaped planform performed the best with respect to aerodynamics and longitudinal/lateral stability. A ground effect analysis will further the investigation of the aerodynamics of an advanced aircraft configuration.

The goal of this effort is to:

- identify the ground effect region of the chevron-shaped planform with respect to height above the ground;
- expand the existing aerodynamic database for moderately swept, low aspect ratio, tailless, blended wing body UAVs;
- analyze the test section flow characteristics of the AFIT 3’ x 3’ wind tunnel with a ground plane;
- verify McCormick’s equation for induced drag factor, and
- compare aerodynamic out-of-ground effect data with Reed’s study.

The following will include an overview of the research considered, a description
of the equipment and procedures used, results and analysis of the experimental data, concluding remarks, and recommendations.
III. Experimental Set-up & Procedures

The following chapter will explain the various resources and materials used to test the chevron-shaped UCAV in ground effect. It will also include an outline of the wind tunnel testing procedures.

Section 1 – UCAV Model

As mentioned previously, the wing planform used in this study was originally tested by Capt. Shad Reed of AFRL/VAAA. The original model was built by Dynamic Engineering, Inc. in 1996 and was tested in the Boeing St. Louis Low Speed Wind Tunnel (LSWT) and in the AFRL Subsonic Aerodynamic Research Laboratory (SARL). It was built out of Ren 450, a woodlike epoxy resin board, and 7075-T6 aluminum. Its dimensions can be found in Table 2.

Table 2: Original and Scaled UCAV Model Properties

<table>
<thead>
<tr>
<th>Chevron UCAV Dimensions</th>
<th>Original Model</th>
<th>Scaled Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Ren 450 &amp; Aluminum</td>
<td>Photopolymer Plastic</td>
</tr>
<tr>
<td>Wing Area, in²</td>
<td>364.87</td>
<td>87.396</td>
</tr>
<tr>
<td>Span, in</td>
<td>32</td>
<td>16</td>
</tr>
<tr>
<td>Root Chord, in</td>
<td>14.85</td>
<td>7.42</td>
</tr>
<tr>
<td>MAC, in</td>
<td>13.35</td>
<td>5.20</td>
</tr>
<tr>
<td>Aspect Ratio</td>
<td>2.806</td>
<td>2.929</td>
</tr>
<tr>
<td>Leading Edge Sweep, deg</td>
<td>45</td>
<td>45</td>
</tr>
</tbody>
</table>
Figure 7: Original Chevron UCAV

The original chevron UCAV model (shown in Figure 7) has a 32-in wingspan, making it just small enough to fit it the AFIT 3’ x 3’ wind tunnel. Because its wingtips would extend too close to the test section walls to produce accurate results, so a scaled down version was created. The original electronic drawings could not be found, a 3-D scanner digitized the original model. The engineers and technicians of AFRL/Human Effectiveness Branch (HECV) allowed the author to use a 3-D digitizer and software to digitize the chevron UCAV model.
The digitizer set up included the FARO Space Arm™ (shown in Figure 8) along with Caliper 3D™ Version 2.43. After probe calibration, the pivoting arm was moved so that the probe touched the surface of the model. The points collected were transposed into an IGES file, which was then read into the drawing program Solid Works®. Only points along the top surface of the right wing were collected. Since the chevron UCAV is perfectly symmetrical, the surfaces were mirrored across the centerline, and then again to form the bottom surface. Once the model was in Solid Works®, the hole for the balance was added so that the model center of gravity (CG) was precisely located 2.5 inches from the back edge of the hole. A scaling factor of $\frac{1}{2}$ was selected, allowing the model to be small enough to fit into the wind tunnel, but large enough to compare and gather aerodynamic data.
The final step in producing the scaled-down version was converting the file into .stl format and then printing it with the AFIT/ENY 3-D rapid prototyping machine. The Stratasys Objet EDEN 333 rapid prototyping machine uses eight small jets that lay down UV plastic (also known as photopolymer plastic) material and a gel-like UV plastic for support material in 0.0006-in layers. The eight jets transverse across the printed region in 2-in strips followed by a UV light which cures the plastic simultaneously (24). The Full Cure 700 series photopolymer plastic model material can be machined, drilled, and chrome-plated; used as a mold; and absorb paint (25). Three images of the scaled down rapid prototyped model are shown in Figure 10 and Figure 11. Refer to Appendix A for more pictures.
Figure 10: $\frac{1}{2}$-Scaled Chevron UCAV Model

Figure 11: $\frac{1}{2}$-Scaled Chevron UCAV in Test Section


**Section 2 – Wind Tunnel**

**Section 2.1 – Equipment**

The AFIT 3’ x 3’ wind tunnel was fabricated by the New York Blower Company. It includes an ACF/PLF Class IV fan with a Toshiba Premium Efficiency (EQP III) fan motor, all controlled by the Siemens (13710) Adjustable Frequency Tunnel Controller. The fan motor and controller specifications can be found in Table 3.

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fan Motor</td>
<td></td>
</tr>
<tr>
<td>3 phase induction</td>
<td></td>
</tr>
<tr>
<td>4 Poles</td>
<td></td>
</tr>
<tr>
<td>60 Hz</td>
<td></td>
</tr>
<tr>
<td>230/460 Volts</td>
<td>460 Volts</td>
</tr>
<tr>
<td>444/222 Amps</td>
<td>315 Amps</td>
</tr>
<tr>
<td>200 Brake Horsepower</td>
<td>250 max HP</td>
</tr>
<tr>
<td>1785 RPM Operating Speed</td>
<td></td>
</tr>
<tr>
<td>150 mph - Theoretical Max</td>
<td></td>
</tr>
<tr>
<td>148 mph - Tested Max</td>
<td></td>
</tr>
</tbody>
</table>

The tunnel is an Eiffel-type, open circuit configuration with a closed test section. The tunnel fan draws ambient air through the 122-in wide by 111-in tall by 70-in deep intake plenum, which internally has a quarter-inch aluminum honeycomb flow-straightener and steel mesh anti-turbulence screens. After the flow passes the last anti-turbulence screen it passes through the convergent portion of the tunnel, which is 95.5-in long and has a contraction ratio of 9.5:1.
After the convergent section, the flow passes through the test section. The test section is octagonal in shape to eliminate the corner interference effects and has dimensions of 31.5-in tall, 44-in wide, and 72-in long. The chevron UCAV has a span-to-tunnel width ratio of 0.37, which is well below the recommended value of 0.8 (27). In addition, the ground plane frontal area is 6.7% of the test-section cross-sectional area, which is below the recommended value of 7.5% (27).

The model sting support is positioned in the test section through a slot in the traverse circular plate. This remotely controlled device can vary the angle of attack of the model from -25\(^{\circ}\) to +25\(^{\circ}\). For yaw angle, the traverse circular plate rotates and moves the entire sting mechanism and can be rotated from -20\(^{\circ}\) to +20\(^{\circ}\).
The balance used for this test was the AFIT-1 Balance, an internal six-component balance manufactured by Modern Machine & Tool Co, Inc. See the complete capacity of strain gage rosettes listed in Table 4. Refer to reference 29 for a more thorough description of the AFIT-1 Balance.

<table>
<thead>
<tr>
<th>Component</th>
<th>Maximum Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal Force (N1)</td>
<td>10 lbs</td>
</tr>
<tr>
<td>Pitch Moment (N2)</td>
<td>10 in-lbs</td>
</tr>
<tr>
<td>Side Force (S1)</td>
<td>5 lbs</td>
</tr>
<tr>
<td>Yaw Moment (S2)</td>
<td>5 in-lbs</td>
</tr>
<tr>
<td>Axial Force (A1)</td>
<td>5 lbs</td>
</tr>
<tr>
<td>Roll Moment (L1)</td>
<td>4 in-lbs</td>
</tr>
</tbody>
</table>

After the flow travels through the test section, it enters the 26-ft long divergent section, which includes a model catcher in case of any component failure. Once through
the divergent section, the flow goes through the fan and exits vertically up through the exhaust pipe. See Figure 14 for complete schematic of the wind tunnel.

![Figure 14: Wind Tunnel Schematic (28)](image)

**Section 2.2 – Procedure**

A static weight calibration process was carried out first. Known weights were attached to the balance and the calibration constants were adjusted in the data collection software by manually matching the loads on the balance to the loads registered in the software. Linearity was verified by ensuring that the voltages corresponded linearly to the increases in weights attached. LabView Virtual Instrument© interface was used to control all tunnel parameters including angle of attack, yaw angle, and tunnel speed. While this interface controlled these parameters, analog backups of angle of attack and sideslip angle were also monitored with sting mounted optical encoders. The analog measurement for velocity was a pressure transducer and pitot-static tube and was the main guide for tunnel velocity throughout all the test runs.
The measured data from the balance was stored in the form of two normal force components \((N_1 \text{ & } N_2)\), two side force components \((S_1 \text{ & } S_2)\), an axial force component \((A_1)\), and a roll moment \((\ell_1)\). Voltage was continuously applied to the strain gage rosette, and resistance was measured across the wire filament. The applied load elongated the wire causing an increase in the resistance. Output voltages from the increased resistance were equated to strain and finally force through a series of calibration equations. A conventional coordinate system was used in the tunnel with \(+x\)-direction pointing towards the intake, \(+y\)-direction pointing out towards the access door, and \(+z\)-direction pointing down towards the tunnel floor. See Figure 15 for a better understanding of the coordinate system.

![Figure 15: Test Section Coordinates (26)](image)

After the balance was calibrated, the chevron UCAV was mounted to the balance using two 2-56 screws. Because of the symmetrical wing planform of the UCAV model,
the balance was in line with the longitudinal x-axis and at the y- and z-axis centers of gravity.

The chevron UCAV model was tested in two different flight conditions: Out-of-Ground-Effect (OGE) and In-Ground-Effect (IGE). The OGE tests examined the longitudinal forces and moments on the UCAV away from the ground, whereas the IGE tests explored the same criteria except the ground plane was placed at four different heights. The proposed test conditions called for four different wind tunnel speeds each with angle of attack sweeping from -10 deg to +20 deg. However, these conditions were not met for most of the test runs due to balance capacity limitations and potential model or sting mechanism collision with the ground plane. Table 5 shows the actual test matrix for each test run. A tare or wind-off run was completed to calculate the effect of the UCAV’s static weight on the balance. This effect was necessary to remove the tare effects on the axial sensor, which affects the drag coefficient calculation.

Table 5: Experimental Test Matrix

<table>
<thead>
<tr>
<th>Tunnel Speed: (mph)</th>
<th>Plane 1 h/b = 0.3</th>
<th>Plane 2 h/b = 0.15</th>
<th>Plane 3 h/b = 0.10</th>
<th>Plane 4 h/b = 0.05</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>(-10^\circ &lt; \alpha &lt; +20^\circ)</td>
<td>(-10^\circ &lt; \alpha &lt; +17^\circ)</td>
<td>(-10^\circ &lt; \alpha &lt; +11^\circ)</td>
<td>(-5^\circ &lt; \alpha &lt; +6^\circ)</td>
</tr>
<tr>
<td>60</td>
<td>(-10^\circ &lt; \alpha &lt; +14^\circ)</td>
<td>(-10^\circ &lt; \alpha &lt; +14^\circ)</td>
<td>(-8^\circ &lt; \alpha &lt; +11^\circ)</td>
<td>(-5^\circ &lt; \alpha &lt; +6^\circ)</td>
</tr>
<tr>
<td>80</td>
<td>(-8^\circ &lt; \alpha &lt; +7^\circ)</td>
<td>(-7^\circ &lt; \alpha &lt; +7^\circ)</td>
<td>(-5^\circ &lt; \alpha &lt; +6^\circ)</td>
<td>(-4^\circ &lt; \alpha &lt; +6^\circ)</td>
</tr>
<tr>
<td>100</td>
<td>(-5^\circ &lt; \alpha &lt; +4^\circ)</td>
<td>(-4^\circ &lt; \alpha &lt; +4^\circ)</td>
<td>(-3^\circ &lt; \alpha &lt; +3^\circ)</td>
<td>(-3^\circ &lt; \alpha &lt; +3^\circ)</td>
</tr>
</tbody>
</table>

The test matrix in Table 5 shows that as the height above ground decreased, angle of attack variation declined due to the extra forces and moments on the model as it entered into the ground effect region. To avoid damaging the balance due to these added loads, the alpha sweeps were limited.
Section 2.3 – Data Analysis

A data acquisition program was set up within the control computer to store the data in a tab delimited text file at a rate of two data points per second (2 Hz sampling rate). For the alpha sweeps, the flow velocity was slowly increased until the desired speed was reached. After ensuring that the balance was taking accurate data, the model was dropped to its least negative alpha setting and data were acquired for 30 sec. The angle of attack then increased 2 deg and held for another 30 sec. This was repeated until either the balance reached its capacity or the ground plane interfered with the sting mechanism.

A MATLAB® code, written by Capt. DeLuca (26), Lt. Gebbie (28), and altered for the AFIT-1 balance by Lt. Rivera Parga (29) was used to reduce the acquired force and moment data. The data reduction program received the tare file and one of the experimental test files simultaneously. It then combined the similar measured forces and moments and averaged them to a single test point for each angle of attack. Before this data were exported as aerodynamic coefficients, the physical testing conditions, balance interactions, and blockage correction factors were calculated. For more detail regarding the data reduction program, see references 26, 28, and 29.

After the MATLAB® program reduced the data, an EXCEL® output file was created that consisted of Mach number, Reynolds number, dynamic pressure, velocity, angle of attack, lift, drag, roll moment, pitching moment, yaw moment, and side force coefficients for every angle of attack tested. Standard aerodynamic plots were then created. See Appendix C for a sample calculation of the data reduction.
**Section 3 – Ground Plane Design and Construction**

In order to properly represent the model flying close to the ground, a ground plane was built and mounted in the wind tunnel. The ground plane was composed of two plates and eight cylindrical legs. The plates were hot-rolled steel and the legs were cold-rolled steel. The dimensions are shown in Table 6 and pictures of the ground plane are shown in Figure 16 and Figure 17. Refer to Appendix A for more pictures and to Appendix B for detailed drawings of the ground plane.

![Ground Plane](image-url)
The circular plate is identical to the traverse circular plate on the floor of the test section, which rotates to simulate yaw angle. By mounting the circular ground plane piece on top of the circular floor plate, the model being tested with the ground plane can
also experience the same yaw deflection as a model not tested with the ground plane. The circular piece also has a cut 11-in by 1.5-in in the rear to allow the sting mechanism to rotate to alter the angle of attack of the model. Figure 18 shows the two pieces separated.

![Figure 18: Top View of Ground Plane with Front and Circular Pieces Separated](image)

The front piece of the ground plane provides a straight leading edge that is rounded and beveled cut as shown in Figure 19.
A pair of screws mounted in counter-bored holes was used to attach each cylindrical leg to the flat plate. Sixteen holes were drilled in the test section floor so that the eight legs were mounted securely. A stress analysis was completed to ensure that the maximum dynamic pressure of the wind tunnel’s maximum velocity (150 mph) would not sever the screws and overturn the ground plane. Four quarter-inch screws were used to mount each leg, which resulted in a factor of safety of 18.

**Section 3.1 – Predicting the Leg Heights**

Not having the flexibility of altering the model height with the sting, the ground plane height was changed to vary the height above ground. Various methods were considered including using hollow cylinders with varying rows of holes held together by pins to allow for a changing ground plane height. With the uncertainty of how the
dynamic pressure would affect the ground plane, it was decided to use four different leg heights that were interchanged for each height.

The ground plane heights were selected to ensure the greatest effect from the ground on the model. Based on McCormick’s ground effect prediction for induced drag along with the ground effect regions discovered in references 17, 20, and 21, the four heights were chosen and can be seen in Table 7.

<table>
<thead>
<tr>
<th>GP Designator</th>
<th>height</th>
<th>h / b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plane 1</td>
<td>10.02</td>
<td>0.3</td>
</tr>
<tr>
<td>Plane 2</td>
<td>12.42</td>
<td>0.15</td>
</tr>
<tr>
<td>Plane 3</td>
<td>14.22</td>
<td>0.1</td>
</tr>
<tr>
<td>Plane 4</td>
<td>14.02</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Model height above ground was referenced from the root quarter-chord.

Section 4 – Boundary Layer Calculations

While time constraints did not allow for boundary layer measurements, conventional flat plate boundary layer equations were used to predict the boundary layer height and displacement thickness at the model location.

Typically, boundary layers are divided into two types: laminar and turbulent. Each type has a no slip and solid surface boundary condition, which means that the fluid particles touching the surface have zero velocity and the flow can not travel through the surface.

The laminar boundary layer calculations utilized the Falkner-Skan method (30). While this method can be used for flows around a wide range of configurations, the simplest form, flow past a flat plate, was used in this study. The laminar boundary layer
thickness was defined as the distance from the flat plate to where the velocity equaled 99% of the free-stream velocity. Assuming an inviscid, incompressible flow, the laminar calculations used the following equation:

\[ \delta_{\text{lam}} = \frac{5.0x}{\sqrt{\text{Re}_x}} \]  \[\text{[4]}\]

As the boundary layer builds up in the streamwise direction, a transition process takes place due to disturbances in the flow. This transition segment can vary widely in length and strength, but normally depends on pressure gradient, surface roughness, compressibility effects, surface temperature, suction or blowing on the surface, and free-stream turbulence (30). For this study, it will be assumed that this process occurs instantaneously.

For incompressible flow past a flat plate, transition is function of Reynolds number. It is customary to use a Reynolds number of 500,000 to locate the transition point (30). For each tunnel velocity used for the experiment, a different transition point was located. The laminar boundary layer thickness was noted at this location, and the turbulent boundary layer was set equal to this thickness.

Exact calculations of the turbulent boundary layer normally involve differential equations of motion for computational fluid dynamic models. For this study, time-averaged (or mean-flow) properties were assumed and the flow velocity was represented by the power law approximation, noted in Equation [5].

\[ \frac{U}{U_\infty} = \left( \frac{y}{\delta} \right)^{\frac{1}{3}} \]  \[\text{[5]}\]
From this estimate, the turbulent boundary layer thickness could be derived based on Blasius’ skin friction coefficient for a turbulent boundary layer on a flat plate. To see the actual derivation, see reference 31.

\[ \delta_{turb} = \frac{0.3747x}{(Re)^{0.2}} \]  \[6\]

As mentioned before, an instantaneous transition was assumed, and so Equation [6] was set equal to Equation [4] at the transition point. Solving this equation for \( x \) and subtracting the result from the transition point gave the pseudo-starting point for the turbulent boundary layer build-up. Figure 20 illustrates the assumptions.

![Figure 20: Schematic of Boundary Layer Build-up](image)

The boundary layer thickness results were most relevant for the streamwise \( x \) locations from the nose of the model to the trailing edge. In order to determine the
distance the external streamlines were shifted due to the presence of the boundary layer, the displacement thickness was calculated using Equation [7].

\[
\delta^* = \int_0^\delta \left( 1 - \frac{U}{U_\infty} \right) dy
\]  

[7]

The displacement thickness is largely dependent on the velocity profile. Substituting Equation [5] into Equation [7] with \( \delta = \) the turbulent boundary layer thickness at the trailing edge of the model, the displacement thickness was estimated.

Section 5 – Hot-wire Anemometry

A hot-wire anemometry experiment was used to determine the difference between the indicated transducer velocity and the actual velocity at the model. Also, it was used to examine the blockage effects due to the ground plane. The following describes the equipment, procedure, and data analysis.

Section 5.1 – Equipment

The AFIT low-speed 3’ x 3’ wind tunnel is equipped with a Dantec-Dynamics Streamline 90N10 Constant Temperature Anemometer (CTA). It is fully motorized and programmable with a 3-axis traversing system. The probe type used was a single wire 55 P11 and was used with the vertical attachment. Figure 21 is a drawing of the probe with the single wire parallel to the y-axis.
The maximum range of the probe is 19.7 inches in the horizontal (y-direction) and vertical (z-direction) direction. It also has the capability to traverse longitudinally in the x-direction approximately 3 ft. The Dantec hot-wire anemometer came with a data acquisition program called Streamware® which was used to collect, process, and format data.

**Section 5.2 – Procedure**

The hot-wire anemometer was calibrated using the Dantec automatic calibrator system. While the hot-wire is outside the tunnel, the automatic calibrator with attaching nozzle blew air across the single wire probe. The velocity was controlled by the Streamware® software in the control room and was increased from 4.5 mph to 161 mph. As the known velocity increased, the anemometer measured the voltage across the single wire. The calibration program within the Streamware® software automatically created
the conversion factor between volts and metric-based velocity, which was manually converted to mph for consistency.

For the hot-wire anemometry experiment, the top Plexiglas window was removed and replaced by one with slotted groves specifically designed for the hot-wire. The slots were plugged according to the longitudinal station of interest. Figure 22 illustrates slot number 1 open for hot-wire velocity measurements.

![Figure 22: Removable Plexiglas Top for Hot-wire Anemometry (26)](image)

Slot number 2 was used for this experiment because it was the closest station to the model CG. Its exact location was 2 inches in front of the model CG. Velocity was measured without the ground plane, at the lowest ground plane height, and the highest ground plane height at speeds of 40, 60, 80, and 100 mph.
The probe started at a position 1-in outside the left wing and 1-in above the top surface. It first descended 2.36-in collecting velocity data every 0.40-in to a location 0.36-in below the bottom surface of the model. It then translated 1.89-in in the positive y-direction, collected data, and then ascended 2.36-in again collecting data every 0.40-in. It continued on this pattern across the entire span of the model stopping at 1-in outside the right wingtip. See Figure 23 for the nominal probe grid test pattern.

![Figure 23: Hot-wire Test Grid](image)

**Section 5.3 – Data Analysis**

The Dantec Streamware® software stored the data files from each test run as a Comma Separated File (.csv). The software converted the raw test data, as voltages into
mean velocities at each test point. The mean velocities were compared to the transducer indicated velocities to illustrate the differences.

Section 6 – Vortex Panel Code

A theoretical 2-D vortex panel code from Kuethe, et al. (32) was used to analyze the data from the wind tunnel investigation. A vortex panel method is one in which the flow around a body is represented by replacing the surface of that body by a “source sheet” (32). The strength of each sheet or panel linearly varies over the surface so that every point on the sheet has a normal velocity equal to the normal component of the free stream velocity. For airfoils, or lifting bodies, the Kutta condition fixes the circulation strength.

Accuracy of the vortex panel method depends on how viscosity, compressibility, and high flow speeds can be incorporated into the computation. The code for this study was strictly inviscid and because of the low speeds tested, compressibility was not a factor. Additionally, the accuracy of the vortex panel method depends on the number of panels used to represent the surface. The more panels used, the more accurate the code. The location of the panel boundaries was based on a circle drawn around the airfoil intersecting through the leading and trailing edges centered at the midchord. Diameter lines were drawn through the midchord point. Another line was drawn from the intersection of the diameter lines with the circle to the airfoil inside, identifying the boundary points for each panel.

Control points were established at the center of each panel. The normal velocity at these points was set to zero to ensure the vortex panel code met the condition of the
airfoil being a streamline. Figure 24 is a picture of the method by which the panel boundaries were determined along with the location of the control points.

![Figure 24: Method for Determining Panel Boundaries (32)](image)

Figure 24 shows how 12 source panels represent an airfoil. The vortex panel code used in this experiment utilized 100 panels and control points.

The vortex panel method used reflection to analyze ground effect. Two airfoils were placed a certain distance from each other, and a region of zero vertical velocity forms halfway between each airfoil, which simulates the ground. The code inputs airfoil chord length, thickness, camber, max camber location, and angle of attack. Also, airspeed, density, and distance from the ground (measured from the quarter-chord) were inputted. The four plots outputted were surface pressure coefficient distribution, pressure...
field, streamlines representing the flow field, and velocity field. Additionally, the code calculated lift coefficient, circulation, lift force, pitching moment.
VI. Results & Analysis

This chapter presents the data gathered from the wind tunnel experiments for the chevron UCAV. The hot-wire anemometry data will be presented first followed by the flow visualization and ground effect results.

Section 1 – Hot-wire Anemometry

The results from the hot-wire anemometry experiment exposed a significant difference in the velocity measured by the pressure transducer and the hot-wire anemometer. Figure 25 shows the transducer measured velocity compared to the hot-wire measured velocity for the open tunnel or OGE test condition.

Figure 25: Open Tunnel Hot-wire and Transducer Velocity Comparison
The first observation from the data in Figure 25 is the averaged 9% difference in the open tunnel hot-wire velocities compared to the transducer velocities at each test condition. Although, there was no blockage in the test section during the open tunnel hot-wire runs, this difference was accounted for in the MATLAB© data reduction code in the form of a blockage correction. It was later discovered that the pressure transducer tube had a leak, which perhaps attributed to this error. The leak was patched, but due to time constraints, re-testing was not done, so the hot-wire measured velocities were considered the reference wind tunnel speeds.

To measure the blockage effect due to the ground plane, the wind tunnel velocity, as indicated by the pressure transducer, was held constant while the hot-wire measured the tunnel velocity with the ground plane in the test section. The ground plane was set at its lowest height (\(h/b = 0.3\)) and its highest height (\(h/b = 0.05\)) for the blockage measurements. Figure 26 are the results of the ground plane hot-wire measurements compared to the open tunnel hot-wire measurements.
The percent difference between the average velocities measured at the two ground plane heights was less than 1%, so the ground plane hot-wire velocities in Figure 26 were averaged.

With the ground plane in the test section, the airflow was forced to speed up to satisfy the conservation of mass. Blockage correction factors consisted of ratios between the open tunnel and ground plane velocities.

The total blockage correction factors between the tunnel velocity with the ground plane and the transducer velocity were computed as follows:

$$\frac{GP}{Tr} = \frac{OT}{Tr} \ast \frac{GP}{OT}$$  \[8\]

where
Table 8 summarizes the correction factors.

### Table 8: Velocity Correction Factors Used for Blockage

<table>
<thead>
<tr>
<th>Correction Factors</th>
<th>40 mph</th>
<th>60 mph</th>
<th>80 mph</th>
<th>100 mph</th>
</tr>
</thead>
<tbody>
<tr>
<td>OT-to-Tr</td>
<td>1.094</td>
<td>1.093</td>
<td>1.084</td>
<td>1.089</td>
</tr>
<tr>
<td>Plane 1-to-OT</td>
<td>1.075</td>
<td>1.052</td>
<td>1.055</td>
<td>1.042</td>
</tr>
<tr>
<td>Plane 2-to-OT</td>
<td>1.077</td>
<td>1.049</td>
<td>1.052</td>
<td>1.040</td>
</tr>
<tr>
<td>Plane 3-to-OT</td>
<td>1.078</td>
<td>1.046</td>
<td>1.050</td>
<td>1.038</td>
</tr>
<tr>
<td>Plane 4-to-OT</td>
<td>1.080</td>
<td>1.043</td>
<td>1.047</td>
<td>1.036</td>
</tr>
</tbody>
</table>

Section 2 – Wind Tunnel Ground Effect Tests

The following is the wind tunnel data collected during this test on the chevron UCAV. The ground effect region was examined and identified from the lift and drag coefficient with respect to the longitudinal axis. Table 9 presents the flight parameters at the various test speeds. It should be noted that the wind tunnel velocities labeled on figures in this section and in the Appendix E are 40, 60, 80, and 100 mph, but the corrected velocities accounting for the blockage and measurement error are in Table 8.

### Table 9: Summary of Flight Conditions

<table>
<thead>
<tr>
<th>Uₜ* (mph)</th>
<th>Mach No.</th>
<th>qₑ (lb / ft²)</th>
<th>Reₑ</th>
</tr>
</thead>
<tbody>
<tr>
<td>OGE</td>
<td>IGE</td>
<td>OGE</td>
<td>IGE</td>
</tr>
<tr>
<td>43.65</td>
<td>46.20</td>
<td>0.056</td>
<td>0.060</td>
</tr>
<tr>
<td>66.00</td>
<td>68.05</td>
<td>0.085</td>
<td>0.088</td>
</tr>
<tr>
<td>87.88</td>
<td>91.60</td>
<td>0.114</td>
<td>0.119</td>
</tr>
<tr>
<td>109.30</td>
<td>113.29</td>
<td>0.141</td>
<td>0.147</td>
</tr>
</tbody>
</table>

* = corrected velocity
Section 2.1 – Model Only Runs

The purpose of the tunnel tests without the ground plane was to establish OGE data and also to verify the results with the longitudinal characteristics Reed (8) identified. Figure 27 shows similarities between the lift coefficients measured with the original chevron UCAV and the scaled down version.

![Graph of C_L vs. alpha](image_url)

**Figure 27: Aerodynamic Comparison - C_L vs. alpha**

The lift curve slope, C_{La}, as approximated from Figure 27, is 0.044 per deg, and is relatively the same for both tests. Another comparison from Figure 27 is the lower C_L max for the scaled chevron UCAV. Reed’s data indicates a C_L max of 0.917 which is 0.1 higher than the inferred C_L max of the scaled model at 40 mph (8). This difference agrees with the convention that higher Re, the higher C_L max for similar planform shapes (27). Reed conducted his experiments at a Reynolds number based on the root chord of
$1.30 \times 10^6$ which makes it reasonable to suggest that the $C_L$ max values for the chevron UCAV of this study would be less than 0.917.

In the same fashion, the drag coefficient of Reed’s study (8) and the one measured on the scaled UCAV differ, but again it is most likely because the models were tested at different Reynolds numbers. Figure 28 and Figure 29 are the drag polars of the original chevron UCAV and the scaled version at each test speed.

![Figure 28: Aerodynamic Comparison - $C_L$ vs. $C_D$](image_url)
As can better be seen from the reduced range plot of Figure 29, as $Re$ decreases, $C_D$ increases. This is consistent with convention that at lower $Re$, more flow separation occurs causing more drag (27).

On another note, the balances used for each respective test were stressed close to their full capacity. The previous study used a 200-lb balance whereas the AFIT-I balance had a capacity of 10-lbs, but due to the significant weight difference between the two models, each balance was stretched to its full capacity, which decreases the uncertainties of the data (8).
Section 2.2 – Varying Ground Plane Heights

The following plots illustrate the effects of the decreasing height above ground with respect to lift and drag. The height above ground was measured from the root quarter-chord. The data presented is only for the two lowest speeds, 40 and 60 mph, because the balance limitations were exceeded at the two faster speeds. Refer to Appendix E for plots of the data collected at the two faster speeds.

Section 2.2.1 – Lift Coefficient Variation

The OGE data is shown in the following plots as the far right point or the point where \( h/b = 0.93 \). Figure 30 and Figure 31 show the variation in lift at four different angles of attack as a function of height above ground at 40 and 60 mph, respectfully.

![Figure 30: Ground Effect - \( C_L \) vs. (h/b) 40 mph](image-url)

Figure 30: Ground Effect - \( C_L \) vs. (h/b) 40 mph
Since the OGE or model-only test runs were at a slightly slower velocity than the runs with the ground plane, as shown in Figure 25, the points corresponding to OGE were omitted from the analysis of the ground effect region.

The overall trend in $C_L$ as height above ground decreases is consistent in Figure 30 and Figure 31. At 6 and 8 deg angle of attack (AOA) $C_L$ increases steadily below h/b of 0.3. This increase is typical and expected for most aircraft flying in ground effect. Also, rate of change in $C_L$ increases from 0.095 to 0.11 per h/b at 40 mph and from 0.13 per to 0.22 per h/b at 60 mph. At an AOA of 4 deg the lift coefficient does not change much as the height above ground is decreased, but at 2 deg AOA $C_L$ clearly drops.

The behavior of the lift coefficient as height above ground decreases suggests that the influence of the ground on the chevron UCAV wing planform can be explained using
a 2-D theoretical prediction. The model’s airfoil, the NACA 0015, was inserted into the vortex panel code described in Chapter III. Figure 32 shows the section lift coefficient as a function of height above ground for 40 mph.

The values of lift coefficient in Figure 32 do not match up to those in Figure 30 and Figure 31 because section lift coefficient is generally higher compared to a wing of finite span with the same airfoil (27). Nevertheless, the trends of the curves are similar. The increase in lift at AOA of 8 deg suggests that the airfoil is behaving like a standard airfoil with flow traveling faster across the top surface compared to the lower surface producing a positive pressure differential. A pressure coefficient, $C_p$, contour plot is shown in Figure 33, which was calculated with the vortex panel code.
Figure 33 shows that the 2-D vortex panel code predicts the $C_p$ distribution similar to that using thin-airfoil theory, which for a symmetric airfoil states that section lift coefficient is directly proportional to circulation and AOA. However, at lower angles of attack, the vortex panel predicted the opposite distribution as shown in Figure 34.
At the same height above ground as in Figure 33, Figure 34 shows a negative pressure coefficient beneath the airfoil. This $C_p$ distribution suggests that airflow was traveling faster across the lower surface of the airfoil compared to the upper surface, which produces negative circulation and negative lift. Whereas the 8 deg AOA $C_p$ distribution was due to the airfoil producing lift agreeing with thin airfoil theory, the $C_p$ distribution in Figure 31 suggests that the thickness of the airfoil was the reason for the negative lift.

As the air attempted to travel between the airfoil and the ground, or streamline of zero vertical velocity, the air speed increased. This is called the Venturi effect, which
states that as a fluid travels through a decreasing cross-sectional area, conservation of mass forces the fluid’s velocity to increase for incompressible flow.

The percent increase in lift coefficient is another valuable reason for studying the ground effect. The magnitude of the increase in lift can be used to classify certain types of aircraft configurations. For example, it has been shown that the amount of ground effect experienced is a function of aspect ratio and wing sweep. Figure 4 shows that aircraft with aspect ratios near 3 can expect a change in lift coefficient around 10% when at a height above ground of \( h/b = 0.3 \) (18). Since the OGE data \( (h/b = 0.93) \) was measured at a different Re due to the velocity measurement error and ground plane blockage, the data from this study can not be compared directly to Figure 4. The only reasonable increase in lift occurred below \( h/b = 0.3 \). The 40 mph test runs showed an increase in lift from \( h/b = 0.3 \) to \( h/b = 0.05 \) of 8.6% while the 60 mph test runs increased 14.0% both at an AOA of 6 and 8 deg.

### Section 2.2.2 – Drag Coefficient Variation

Unlike the lift coefficient, the drag coefficient generally increased for all four angles of attack measured. Figures Figure 35 and Figure 36 show the effect of the ground plane on the \( C_D \) of the chevron UCAV model.
Figure 35: Ground Effect - $C_D$ vs. (h/b) 40 mph

Figure 36: Ground Effect - $C_D$ vs. (h/b) 60 mph
The $C_D$ at all four angles of attack steadily increased roughly at the same rate as height above ground decreased. For the AOA of 6 and 8 deg, this result was expected after noticing the behavior of the lift. The induced drag component of $C_D$ is a function of $C_L^2$, so when the lift increases as the UCAV enters ground effect, the drag should also increase. However, this relationship was not consistent at all heights above ground. At $h/b = 0.05$, $C_D$ drops slightly at an AOA of 6 deg and possibly at 8 deg, balance limitations prevented the full range of testing at an AOA of 8 deg.

The $C_D$ data shown in Figure 35, specifically for AOA of 6 deg, was applied to the following equation from Bertin (30) in order to analyze the various components of the drag.

$$C_D = C_{D0} + kC_L^2$$  \[9\]

Equation [9] assumes a linear relationship between $C_D$ and $C_L^2$, but the experimental data revealed more of a weak quadratic relationship for all the data gathered. Figure 37 shows this non-linear relationship.
The factor $k$, in Equation [9] typically equals the slope of the $C_D$ vs. $C_L^2$ curve (27), but because of the non-linear relationship in Figure 37, $k$ was approximated to be 0.115 from the nearly linear curves in the lower $C_D$ and $C_L^2$ region (see arrow in Figure 37).

After $k$ was determined, and the minimum measured $C_D$ was inserted for $C_D0$, the total drag coefficient was calculated. Additionally, McCormick’s induced drag factor, Equation [1], was multiplied by the induced drag term of Equation [9] to evaluate the accuracy of its prediction as shown in Equation [10].

$$C_D = C_D0 + \phi kC_L^2$$  \[10\]
Figure 38 shows the total $C_D$ calculated from Equations [9] and [10] plotted adjacent to the $C_D$ measured at an AOA of 6 deg.

![Figure 38: Ground Effect - Induced Drag Factor Comparison, 40 mph](image)

The curves in Figure 38 suggested that McCormick’s induced drag factor over predicted the reduction in total drag for the chevron UCAV at 6 deg AOA. This overprediction was because McCormick developed his factor assuming a rectangular wing and inviscid flow conditions.

Without analyzing the viscous forces on the model to quantify the friction drag, it is reasonable to suggest that further investigation be conducted on the wing tip vortices induced by the chevron UCAV. This would provide a better explanation for $C_D$ behavior in the ground effect region.
The percent increase in $C_D$ of the chevron UCAV was on the order of 30% which is comparable to the F-106 model tested by Lee, et al. (20). Curry (6), Curry and Owens (21) found that the Tu-144 and F-16 XL aircraft experienced an increase in drag on the order of 5-15%. This is mentioned to illustrate that other aircraft of similar aspect ratio and wing sweep can experience an increase in $C_D$ while in the ground effect region.

**Section 2.2.3 – Lift-to-Drag Ratio Variation**

In an effort to draw some conclusions to the above analysis and further understand the complexities of the ground effect region for the chevron UCAV, lift-to-drag ratios (L/D) were calculated. Typically, L/D is directly correlated to aircraft efficiency, and is normally analyzed in ground effect studies to illustrate the improved, or in this case, unimproved efficiency of the ground effect region. Figure 39 and Figure 40 illustrate the negative trend of L/D for the chevron UCAV while in the ground effect region.
Figure 39: L/D vs. (h/b) 40 mph

Figure 40: L/D vs. (h/b) 60 mph
The only positive slope was at an AOA of 6 deg while at the lowest height above ground. Not only did the AOA of 6 deg have the maximum value for L/D, as seen in Figure 41, it also was the only AOA that experienced a reduction in drag while in close proximity to the ground.

![Figure 41: Ground Effect - L/D vs. alpha, 40 mph](image)

Refering to Figures Figure 39 and Figure 40 L/D increased 3.3% at 40 mph and 5.9% at 60 mph at h/b = 0.05. This increase is consistent with the slight decrease in $C_D$ at the same height.

The L/D variation for the chevron UCAV illustrated that the increase in lift at AOA of 6 and 8 deg was not enough to overcome the increase in drag. However, the slight L/D increase at AOA of 6 deg at h/b = 0.05 suggests that possible reduction in
induced drag caused an increased L/D. At AOA of 2 and 4 deg, the decreasing L/D suggests that the significant loss of lift from the Venturi effect as shown in Figure 30 and Figure 31 played a role in the L/D variation of the UCAV while in the ground effect region.

In addition, the increase in $C_D$ played a significant role in the behavior of the L/D variation for the chevron UCAV and comparisons were drawn from previous studies. The resulting L/D for the F-106 model decreased (20), and the L/D for the Tu-144 (21) and F-16 XL (6) increased which can be attributed to differences in percent increase of $C_D$ as mentioned before.

**Section 3 – Test Section Flow Analysis**

**Section 3.1 – Flow Visualization**

To ensure the air flow over the ground plane was uniform, a flow visualization experiment was conducted. Small tufts were attached on the top surface of the ground plane covering the leading edge, side edges, across the circular gap, and uniformly across the remainder of the surface. To see how the tufts were placed on the ground plane refer to Figure 42 - Figure 44.
When the ground plane was mounted in the tunnel test section, the circular piece and the front piece did not exactly fit perfectly together. This imperfection needed to be analyzed, so tufts were placed just before and over the small gap as shown in Figure 42. Since the circular piece was slightly lower than the front piece, the flow beneath the ground plane contacted the front edge and traveled up through the gap. The tufts across the gap illustrated this effect and the tufts downstream of the gap showed that the flow remained uniform not having any apparent effect on the balance data.

Figure 43 is a top view of the model and ground plane during testing.
As one can see, the flow was straight and uniform beneath the model which confirmed that no obvious irregularities existed where the balance gathered data.

Another important aspect to analyze was the effect of the cylindrical mounting legs on the flow across the ground plane. Figure 44 illustrates how the flow traveled along the side edges and at the leading edge.
Tufts were placed along each side in order to determine if the flow beneath the ground plane rolled around the side edges. The near tufts in Figure 44 are a good representation of the uniform flow that resulted along the edges of the ground plane, which suggests that the flow beneath the ground plane did not roll over the side edges.

Also shown in Figure 44 is the only unusual outcome from the flow visualization. The second tuft from the side at the leading edge was 90 deg inward and the third tuft from the side edge was 90 deg outward compared to the remainder of the tufts. Although not shown in Figure 44, the tufts above the opposite front leg acted identical to the ones shown. This can best be explained by discussing the horseshoe vortex system that results from the boundary layer on the underside of the flat plate interacting with a circular cylinder (33). In subsonic flow, any disturbance downstream is experienced to some degree upstream as well, which strongly suggests that the effects of the counter-rotating
horseshoe vortices caused the two tufts in Figure 44 to turn towards each other. Although not shown in Figure 44, the tufts further downstream indicate that the horseshoe vortices diminished or dampened out prior to the model location, which reduced the likelihood of this phenomenon affecting the balance data.

Section 3.2 – Boundary Layer Thickness

In order to qualify the data gathered at the low heights above ground, the boundary layer growth on the ground plane was estimated. Using the incompressible laminar and turbulent boundary layer equations for a flat plate outlined in Chapter III, the following results were obtained:

Table 10: Boundary Layer Growth on the Ground Plane

<table>
<thead>
<tr>
<th>$U_\infty$ (mph)</th>
<th>$x_t$ (ft)</th>
<th>$d_{t.e.}$ (in)</th>
<th>$d_*$ (in)</th>
<th>$d^*$ (ft)</th>
<th>$% \text{ disp.}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>47.2</td>
<td>1.1366</td>
<td>0.2148</td>
<td>0.4809</td>
<td>0.0601</td>
<td>12.4974</td>
</tr>
<tr>
<td>68.7</td>
<td>0.7806</td>
<td>0.2760</td>
<td>0.5105</td>
<td>0.0638</td>
<td>12.4976</td>
</tr>
<tr>
<td>91.2</td>
<td>0.5880</td>
<td>0.2980</td>
<td>0.5146</td>
<td>0.0643</td>
<td>12.4951</td>
</tr>
<tr>
<td>113.1</td>
<td>0.4739</td>
<td>0.3061</td>
<td>0.5109</td>
<td>0.0639</td>
<td>12.5073</td>
</tr>
</tbody>
</table>

Table 10 indicates a relatively consistent turbulent boundary layer and displacement thickness for the various test speeds. This consistency is attributable to the transition location moving closer to the leading edge of the ground plane as the velocity increased. The far right column is the percent of $\delta_{t.e.}$ that $\delta^*$ displaces. Since the boundary layer was not measured, the estimated thicknesses in Table 10 were not validated, but the hot-wire results suggested a thicker boundary layer than estimated.

While the hot-wire anemometry experiment was not intended to identify the boundary layer on the ground plane, the results clearly offer a boundary layer thickness result. During the hot-wire runs with tallest ground plane ($h/b = 0.05$), there was an
averaged 7% difference in measurements when the probe was at its lowest position \( z = 2.36 \text{ in} \) compared to the higher readings \( 0 \leq z \leq 1.97 \text{ in} \). Figure 45 illustrates the probe location relative to the model and the highest ground plane setting.

As stated in Chapter III, the 2.36-in location of the probe corresponded to a distance below the model CG of 0.36-in, which means that if the 7% difference is due to the boundary layer, then the boundary layer thickness could be larger than 0.44-in at the model CG. Comparing this to the calculated values in Table 10, one can clearly see that the calculated thicknesses are slightly lower than the hot-wire results which may indicate that further investigation is necessary in order to accurately identify the boundary layer build up on the ground plane.
Section 1 – Conclusions

Investigating the ground effect region for the chevron UCAV took a lot of coordination, but in the end, all the established goals were achieved. The goals, as explained in Chapter I, will be re-iterated below followed by a discussion of how each goal was met.

The first goal was to expand the test capabilities of the AFIT 3’ x 3’ wind tunnel by analyzing the flow characteristics through the test section with the ground plane. This was accomplished primarily by three different methods, hot-wire measurements, flow visualization, and boundary layer calculations. The hot-wire results indicated a significant disparity between the indicated transducer speed and the hot-wire measured speed. An average correction factor of 9% was applied to the data reduction program for the test runs without the ground plane. Adding the ground plane revealed more of a difference between indicated transducer speed and the actual speed at the model location in the wind tunnel. Additional correction factors ranging from 3.5 to 7.9% were multiplied by the 9% correction factor to form the complete blockage correction.

The flow visualization results revealed a uniform flow over the top of the ground plane, especially beneath the model. The circular gap where the two pieces of the ground plane came together caused a small updraft of air, but the effect seemed negligible. The only unusual occurrence was at the leading edge directly above the front two cylindrical
legs, which was believed to be the result of the horseshoe vortices that developed at the
junction of a cylinder and a flat plate.

The boundary layer build-up across the ground plane was modeled using
conventional flat-plate laminar and turbulent boundary layer equations. Beneath the
model, which was the area of most concern, the boundary layer was turbulent with an
instantaneous transition point well in front of the model. The boundary layer thickness
was on the order of 0.5-in, which corresponded to a displacement thickness on the order
of 0.06-in. An interesting result from the hot-wire experiments indicated that the
boundary layer at the model CG was approximately 0.44-in thick based on an obvious
drop in mean velocity.

Since the idea for this project originated with Reed’s thesis (8), another goal was
to compare his data with the OGE data collected in this study. Although, not all test
conditions could be matched due to the constraints of the balance limitations, the data
still compared to a reasonable degree of accuracy. Reynolds number differences were the
likely reason for the slight variations.

During the experiment, the ground plane had no major installation or testing
issues. The airflow traveled across the ground plane with uniform flow, but blockage
corrections for wind tunnel speed were necessary. Boundary layer build-up on the
ground plane was a concern, but it appeared as though it did not affect the aerodynamic
test results.

Identifying the ground effect region for the chevron UCAV planform with respect
to height above ground will be the next goal discussed. Force and moment data was
collected and reduced to calculate the aerodynamic coefficients while the UCAV was in
close proximity to the ground plane. The data was presented by analyzing the change in $C_L$ and $C_D$ near the ground.

The $C_L$ variation with height above ground for AOA of 6 and 8 deg suggested that the chevron UCAV performed as a typical aircraft would according to standard convention. At lower AOA of 2 and 4 deg, the lift responded in the opposite fashion and decreased with the 2 deg case decreasing at a greater rate. This behavior was explained by analyzing the $C_P$ contour plot of the 2-D airfoils in reflection. The negative $C_P$ beneath airfoil suggested that the flow was traveling faster due to the Ventri effect. This higher velocity caused lift to decrease. The trends from a 2-D vortex panel program agreed with the experimental results.

$C_D$ variation with height above ground for AOA equal to 6 deg showed that the drag increased and then decreased as the UCAV got closer to the ground plane. The increase in $C_D$ most likely came from the increase in $C_L$ and the slight decrease at $h/b = 0.05$ was probably because of the flattening out of the wingtip vortices. At lower AOA, $C_D$ increased as height above ground decreased, which was not the expected result since the lift decreased.

Another goal was to verify McCormick’s induced drag factor with the experimental results. It was concluded after analyzing the variation in $C_D$ with height above ground that at AOA equal to 6 deg that McCormick’s induced drag factor over predicted the decrease in induced drag for the chevron UCAV.

Finally, the last goal of this experiment was to expand the existing aerodynamic database for moderately swept, low aspect ratio, tailless, blended wing body UAVs. This
was accomplished for small angles of attack and low speeds. Further analysis is required to complete the ground effect data for higher angles of attack.

Section 2 - Recommendations

While this thesis only provided a first-cut analysis in many of the aspects studied, it should lay the foundation for further experiments with the chevron UCAV and the ground plane in the AFIT 3’ x 3’ wind tunnel. Based on the findings of this study, the following are recommendations for further experiments and analysis:

- use a 100-lb balance to expand the test results. Higher angles of attack could be analyzed which would allow for more of a comparison to previous studies;

- take measurements of the boundary layer on the ground plane to better analyze possible effects. Also, measurements or better predictions of the boundary layer transition will further the analysis significantly;

- ensure that the test speed is adjusted properly when testing in the OGE region. The tunnel should be sped up according to the factors calculated in Table 8 for each ground plane height;

- measure the wake and/or vortices shed by the UCAV at all ground plane heights in order to better analyze the reduction in induced drag;

- use another flow visualization technique to verify the findings found in this study;

- set up a boundary layer removal system, such as blowing or sucking air along the top surface of the ground plane, to better simulate an actual aircraft flying over the ground;

- analyze the effects of sideslip and lateral stability of the chevron UCAV in ground effect;

- compare the results found in this study with a dynamic ground effect experiment.
Appendix A: Chevron UCAV & Ground Plane Pictures

Figure 46: Model & Ground Plane at h/b = 0.3

Figure 47: Ground Plane - Top View & Separated View
Figure 48: Original Chevron UCAV - Top View

Figure 49: 1/2 Scaled Chevron UCAV
Appendix B: Ground Plane Drawings

Below are the drawings with dimensions of the circular plate, front plate, and the mounting legs for the ground plane.
8 pieces of each
DIM 'A' to be:
9.77
12.17
12.97
13.77

4x 1/4-20 ∅ 1.500

DIM 'A' (inches)

∅ 1.500

DETAIL A
SCALE 1 : 1
(2X)

750
Appendix C: Data Reduction Sample Calculation

The following is a sample calculation for the MATLAB© data reduction program used for this experiment for the following test condition:

\[ U_\infty = 40 \text{ mph} \]
\[ \frac{h}{b} = 0.15 \]
\[ \alpha = 6 \text{ deg} \]

Test room conditions and model specifics:

\[ T = 533.7 \text{ °R} \]
\[ P = 14.066 \text{ psia} \]
\[ R = 1716 \text{ \frac{ft-lb}{slug-R}} \]
\[ \mu = 0.372 \times 10^{-6} \text{ \frac{slug}{ft-sec}} \]
\[ c_r = 0.6183 \text{ ft} \]
\[ S = 0.607 \text{ ft}^2 \]
\[ b = 1.333 \text{ ft} \]
\[ AR = \frac{b^2}{S} = 2.93 \]
\[ \gamma = 1.4 \]
\[ \rho = \frac{P}{R*T} = 0.0022 \text{ \frac{slug}{ft^3}} \]
\[ q_\infty = \frac{1}{2} \rho * U_\infty^2 = 3.633 \text{ \frac{lb}{ft^2}} \]
\[ a = \sqrt{\gamma * R * T} = 1132.3 \text{ \frac{ft}{sec}} \]
Blockage / Velocity Corrections:

\[ \varepsilon = \text{blockage correction term} \]
\[ sb = \text{solid blockage} \]
\[ gp = \text{ground plane} \]
\[ tc = \text{transducer correction} \]
\[ K_i = \text{body shape factor} = 1.04 \]
\[ \tau_1 = f(\text{test section shape} \& \frac{2b}{B}) = 0.86 \]

Wing volume = Body volume = 0.03668 ft\(^3\)
C = tunnel cross section area = 9.4722 ft\(^2\)
\[ \varepsilon_{sb,wing} = \frac{K_i \cdot \tau_1 \cdot \text{Wing volume}}{C^{3/2}} = 0.001125 \]
\[ \varepsilon_{gp} = 1.077 \text{ (calculated from hot-wire results)} \]
\[ \varepsilon_{tc} = 1.090 \text{ (calculated from hot-wire results)} \]
\[ \varepsilon_{Total} = \varepsilon_{sb} + \left( \varepsilon_{gp} \cdot \varepsilon_{tc} - 1 \right) = 0.17476 \]

Note: solid blockage correction equations taken from Barlow, et al. (27)

Calculating the flight parameters with corrections applied:

\[ U_{w,corr} = U_\infty \cdot (1 + \varepsilon_{Total}) = 67.4286 \frac{\text{ft}}{\text{sec}} = 45.9740 \text{ mph} \]
\[ q_{w,corr} = q_\infty \cdot (1 + \varepsilon_{Total})^2 = 5.0279 \frac{\text{lb}}{\text{ft}^2} \]
\[ M = \frac{U_{w,corr}}{a} = 0.0593 \]
\[ \text{Re} = \frac{\rho \cdot U_{w,corr} \cdot c_r}{\mu} = 2.468 \times 10^5 \]

The raw data from the control computer contained the following measurements:

\[ [N_1, N_2, S_1, S_2, A_1, \ell] \]. These force and moment measurements were subtracted from the
tare effects and corrected for the balance interactions. Refer to DeLuca (26) or Rivera
(29) see a complete procedure of data reduction program. The remainder of the sample

80
calculation will carry on after the balance and tare effects were removed from the inputted data.

The corrected data was originally in the UCAV’s body axis frame. The following equations converted the drag, side, and lift forces $[D, S^*, L]$; and roll, pitch, and yaw moments $[\ell, m, n]$ into the wind axis frame:

$$
\begin{bmatrix}
D \\
S^* \\
L_{\text{wind}}
\end{bmatrix}
= 
\begin{bmatrix}
A^* \cos \theta \cos \psi + Y^* \sin \psi + N^* \sin \theta \cos \psi \\
- A^* \sin \psi \cos \theta + Y^* \cos \psi - N^* \sin \theta \sin \psi \\
- A^* \sin \theta + N^* \cos \theta
\end{bmatrix}
$$

$$
\begin{bmatrix}
\ell \\
m \\
n_{\text{wind,bc}}
\end{bmatrix}
= 
\begin{bmatrix}
\ell^* \cos \theta \cos \psi - m^* \sin \psi + n^* \sin \theta \cos \psi \\
\ell^* \sin \psi \cos \theta + m^* \cos \psi + n^* \sin \theta \sin \psi \\
- \ell^* \sin \theta + n^* \cos \theta
\end{bmatrix}
$$

where:

$A = A_1$ corrected = -0.02698 lb

$Y = S_1$ corrected = 0.00122 lb

$N = N_1$ corrected = 0.93839 lb

$\ell = \ell_1$ corrected = 0.02889 lb-in

$m = N_2$ corrected = 2.28160 lb-in

$n = S_2$ corrected = 0.03048 lb-in

$\theta$ = pitch angle (AOA) = 0.1078 rads = 6.17 deg

$\psi$ = yaw angle = -0.7330x10^{-3} rads = -0.042 deg (negligible)

Carrying out the above force equations for drag and lift: (side force was treated as negligible and not used in the analysis)

$D = 0.07409$ lb

$L = 0.93585$ lb

Before the moments were calculated, the reference point was adjusted from the balance CG to the model CG. The chevron UCAV’s CG was found in the Solid Works© program and verified by hanging it with a small string through the drilled balance holes.
Since the model CG was located along the x-axis, the \( y \) and \( z \) locations were zero. The following were the equations used to correct the pitching moment: (roll and yaw moment were negligible and not used in the analysis).

\[
m_{\text{wind,\,bc}} = 2.28156 \, \text{lb}_t - \text{in}
\]
\[
X_{cg,\text{dist}} = \text{dist. between model CG and balance CG} = 1.3725 \, \text{in}
\]
\[
X_{cm} = X_{cg,\text{dist}} \times \left[ \cos(\theta + \psi^0) + \tan \psi \right] = 1.3645 \, \text{in}
\]

where:

\( w = \text{angle between } X_{cg} \text{ and } x\)-axis at \( \alpha = 0 \)

\[
m_{cg} = m_{\text{wind,\,bc}} - L \times X_{cm} + D \times Z_{cm}^0 = 1.02632 \, \text{lb}_t - \text{in}
\]

Non-dimensionalizing the lift and pitching moment yields:

\[
C_{L_w} = \frac{L}{q_{\infty,\text{corr}} \times S} = 0.3067
\]
\[
C_{m_{cg}} = \frac{m_{cg}}{q_{\infty,\text{corr}} \times S \times c} = 0.06467
\]

These values for lift and moment coefficient agree to those in Table 13 to 0.02%.

The drag coefficient was corrected for test section geometry and flow field interference as such:

\[
\delta = \frac{b}{\text{Tunnel span (B)}} = 0.3636
\]
\[
\Delta C_{D_w} = \frac{\delta \times S}{C} \left( C_{L_w} \right)^2 = 0.00219
\]

The final drag coefficient is as follows:

\[
C_{D_w} = \frac{D}{q_{\infty,\text{corr}} \times S}
\]
\[
C_{D,\text{corr}} = C_{D_w} + \Delta C_{D_w} = 0.02647
\]
The corrected drag coefficient disagrees with the value in Table 13 by 6.07%. This was due to an incorrect model span-to-test section width ratio, δ. The δ used for the $C_D$ in Table 13 was 0.1125, which was from a previous experiment.
Appendix D: Additional Ground Effect Plots

Figure 50: $C_m$ vs. $(h/b)$ 40 mph

Figure 51: $L/D$ vs. $(h/b)$ 40 mph
Figure 52: $C_m$ vs. $(h/b)$ 60 mph

Figure 53: $L/D$ vs. $(h/b)$ 60 mph
Figure 54: $C_L$ vs. $(h/b)$  80 mph

Figure 55: $C_D$ vs. $(h/b)$  80 mph
Figure 56: $C_m$ vs. $(h/b)$ 80 mph

Figure 57: $L/D$ vs. $(h/b)$ 80 mph
Figure 58: $C_L$ vs. $(h/b)$ 100 mph

Figure 59: $C_D$ vs. $(h/b)$ 100 mph
Figure 60: $C_m$ vs. (h/b) 100 mph

Figure 61: L/D vs. (h/b) 100 mph
## Appendix E: Data Tables

The following tables were outputted from the data reduction program and used in the various plots.

**Table 11: U=40mph, h/b=0.93 (OGE)**

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<tr>
<th>Mach No.</th>
<th>Re No.</th>
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<th>Uoo</th>
<th>alpha_c</th>
<th>C_L</th>
<th>C_D_c</th>
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**Table 12: U=40mph, h/b=0.3**

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### Table 14: U=40 mph, h/b=0.10

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<th>C_L</th>
<th>C_D_c</th>
<th>Cm_cg_c_w</th>
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### Table 15: U=40 mph, h/b=0.05

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<th>C_L</th>
<th>C_D_c</th>
<th>Cm_cg_c_w</th>
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### Table 16: U=60 mph, h/b=0.93 (OGE)

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<th>C_L</th>
<th>C_D_c</th>
<th>Cm_cg_c_w</th>
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### Table 17: U=60 mph, h/b=0.3

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### Table 19: U=60 mph, h/b=0.10

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<th>C_D_c</th>
<th>Cm_cg_c_w</th>
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### Table 20: U=60 mph, h/b=0.05

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### Table 21: U=80 mph, h/b=0.93 (OGE)

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<th>C_L</th>
<th>C_D_c</th>
<th>Cm_cg_c_w</th>
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<td>87.762467</td>
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### Table 22: U=80 mph, h/b=0.3

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<th>C_L</th>
<th>C_D_c</th>
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<th>C_D_c</th>
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### Table 25: U=80, h/b=0.05

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### Table 26: U=100 mph, h/b=0.93 (OGE)

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<th>C_D_c</th>
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Table 27: U=100 mph, h/b=0.3

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<th>Uoo</th>
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<th>C_D_c</th>
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<td>0.023892663</td>
</tr>
<tr>
<td>0.147885749</td>
<td>621386.5533</td>
<td>31.35636949</td>
<td>114.3789104</td>
<td>3.200124827</td>
<td>0.169780757</td>
<td>0.011616261</td>
<td>0.035251169</td>
</tr>
</tbody>
</table>

Table 28: U=100 mph, h/b=0.15

<table>
<thead>
<tr>
<th>Mach No.</th>
<th>Re No.</th>
<th>q_c</th>
<th>Uoo</th>
<th>alpha_c</th>
<th>C_L</th>
<th>C_D_c</th>
<th>Cm_cg_c_w</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.146818981</td>
<td>611345.3488</td>
<td>30.57255403</td>
<td>113.3504901</td>
<td>-3.21084875</td>
<td>-0.19574467</td>
<td>0.016916351</td>
<td>-0.03966358</td>
</tr>
<tr>
<td>0.146860937</td>
<td>611520.0503</td>
<td>30.5900297</td>
<td>113.3828817</td>
<td>-2.14228444</td>
<td>-0.13385038</td>
<td>0.015018615</td>
<td>-0.02626131</td>
</tr>
<tr>
<td>0.146899832</td>
<td>611682.006</td>
<td>30.60623485</td>
<td>113.4129102</td>
<td>-1.07392477</td>
<td>-0.07487263</td>
<td>0.013648389</td>
<td>-0.01234084</td>
</tr>
<tr>
<td>0.146830287</td>
<td>611392.423</td>
<td>30.57726245</td>
<td>113.3592182</td>
<td>-0.00650675</td>
<td>-0.01575363</td>
<td>0.012884893</td>
<td>0.001473495</td>
</tr>
<tr>
<td>0.146826409</td>
<td>611376.2784</td>
<td>30.57654671</td>
<td>113.3562248</td>
<td>1.061904483</td>
<td>0.045770059</td>
<td>0.012786065</td>
<td>0.016171272</td>
</tr>
<tr>
<td>0.146911178</td>
<td>611729.2502</td>
<td>30.61069287</td>
<td>113.4216698</td>
<td>2.130658903</td>
<td>0.105703527</td>
<td>0.01348142</td>
<td>0.029515747</td>
</tr>
<tr>
<td>0.146831176</td>
<td>611396.1278</td>
<td>30.57763302</td>
<td>113.3599051</td>
<td>3.110482643</td>
<td>0.163383707</td>
<td>0.014768572</td>
<td>0.041690309</td>
</tr>
</tbody>
</table>

Table 29: U=100 mph, h/b=0.10

<table>
<thead>
<tr>
<th>Mach No.</th>
<th>Re No.</th>
<th>q_c</th>
<th>Uoo</th>
<th>alpha_c</th>
<th>C_L</th>
<th>C_D_c</th>
<th>Cm_cg_c_w</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.146520132</td>
<td>610144.1688</td>
<td>30.44657276</td>
<td>113.1056347</td>
<td>-3.1414843</td>
<td>-0.23844251</td>
<td>0.018372928</td>
<td>-0.04301614</td>
</tr>
<tr>
<td>0.146433566</td>
<td>609783.688</td>
<td>30.41060969</td>
<td>113.0388105</td>
<td>-2.15700624</td>
<td>-0.16949364</td>
<td>0.016523885</td>
<td>-0.02856014</td>
</tr>
<tr>
<td>0.146529868</td>
<td>610184.7122</td>
<td>30.45639018</td>
<td>113.1131505</td>
<td>-1.08419422</td>
<td>-0.09973624</td>
<td>0.014905483</td>
<td>-0.01274157</td>
</tr>
<tr>
<td>0.146457637</td>
<td>609883.9247</td>
<td>30.42606591</td>
<td>113.0579199</td>
<td>-0.01253696</td>
<td>-0.03035352</td>
<td>0.013946574</td>
<td>0.00306746</td>
</tr>
<tr>
<td>0.146454673</td>
<td>609871.5834</td>
<td>30.41937448</td>
<td>113.0551041</td>
<td>0.973601318</td>
<td>0.040339083</td>
<td>0.013925471</td>
<td>0.019069941</td>
</tr>
<tr>
<td>0.146520782</td>
<td>610146.8733</td>
<td>30.44684267</td>
<td>113.1063161</td>
<td>2.131578385</td>
<td>0.107929705</td>
<td>0.01444742</td>
<td>0.033480456</td>
</tr>
<tr>
<td>0.146405417</td>
<td>609666.4681</td>
<td>30.3989163</td>
<td>113.0170808</td>
<td>3.113643483</td>
<td>0.171036488</td>
<td>0.015559293</td>
<td>0.046464367</td>
</tr>
</tbody>
</table>

Table 30: U=100 mph, h/b=0.05

<table>
<thead>
<tr>
<th>Mach No.</th>
<th>Re No.</th>
<th>q_c</th>
<th>Uoo</th>
<th>alpha_c</th>
<th>C_L</th>
<th>C_D_c</th>
<th>Cm_cg_c_w</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.145747349</td>
<td>606926.117</td>
<td>30.12625415</td>
<td>112.5090875</td>
<td>-1.11609281</td>
<td>-0.17696661</td>
<td>0.017819193</td>
<td>-0.01799912</td>
</tr>
<tr>
<td>0.145673662</td>
<td>606619.269</td>
<td>30.09579956</td>
<td>112.4522055</td>
<td>-0.0340163</td>
<td>-0.08241894</td>
<td>0.016082691</td>
<td>0.003630719</td>
</tr>
<tr>
<td>0.145695435</td>
<td>606709.9367</td>
<td>30.1047967</td>
<td>112.4690131</td>
<td>0.961528214</td>
<td>0.010963359</td>
<td>0.015509789</td>
<td>0.02350601</td>
</tr>
<tr>
<td>0.145713014</td>
<td>606731.1381</td>
<td>30.11260161</td>
<td>112.4825828</td>
<td>1.047710958</td>
<td>0.011405805</td>
<td>0.01532111</td>
<td>0.023594311</td>
</tr>
<tr>
<td>0.145701497</td>
<td>606735.1795</td>
<td>30.10730184</td>
<td>112.4736925</td>
<td>2.126305179</td>
<td>0.095162632</td>
<td>0.01546496</td>
<td>0.040489099</td>
</tr>
<tr>
<td>0.145604011</td>
<td>606329.222</td>
<td>30.06702662</td>
<td>112.398438</td>
<td>3.11445585</td>
<td>0.173003327</td>
<td>0.016334041</td>
<td>0.05478849</td>
</tr>
</tbody>
</table>
Appendix F: MATLAB® Data Reduction Program

%**************************************************************************
%**************************************************************************
%**********        Lt. Gebbie & Capt Anthony DeLuca **********
%******       Adapted for the Balance AFIT 1 by Lt. Rivera Parga  
%**********  re-adapted by Troy Leveron, ENS, USNR   
%**********  re-adapted by Brett Jones, ENS, USNR for UCAV Ground Effects Test  
%**********    Calculation of Lift, Drag, Moments     
%**************************************************************************
%**************************************************************************
%This Code will transfer measured Forces and Moments on the AFIT-1 balance to Wind  
%interactions, and wind tunnel irregularities, then gives a file with all the  
%corrected data

clear;
cle;
close all;
format long

%**************************************************************************
%                               INPUT DECK
%FIRST FILL THE FOLLOWING INFORMATION

Masskg=1.235;                                               % Mass of the UCAV in KGS (~3lbs for now until I weigh it)
T_room = mean([73.4 74 74.7]) + 459.67        %deg R  ****Changed for each day of testing****
P_barro = mean([28.6823 28.6130 28.6228]) * 0.4911541   %Psi   ****Changed for each day of  
testing****

% INPUT DATA FILE AND INPUT DATA TARE FILE
load tarefile.txt;                                   %tarefile GP42005tearA-10to+20B0model
TareFile = tarefile(:,1:9);
load datafile.txt;                                    %datafile (Raw Data file name here)
DataFile = datafile(:,1:9);

%Offset distances from the Mounting Block to the Model C.G. (inches)
Y_cmb = 0;
X_cmb = 1.3725;                                       %inches (from origin @ balance center w/ + right)
Z_cmb = 0;

% Required for the Solid body blockage corrections due to wing  
% and fuselage
Body_Volume = 63.39038 / 12^3 ;                      %ft^3: From Solid Works "Mass Properties"
Wing_Area = 87.3958 / 12^2                           %ft^2

%**************************************************************************
%I.-      Room Conditions and Model Specifics :  
%UNITS are in Ft, Sec, Ibm, Psf, Rankine, fps  

97
Mass = (Masskg * 1000) * 0.0022046;                           %lbm (UCAV)
Gas_Const = 1716;                                                          %ft-lbf/Slug-R
Density = (P_barro * 144)/(1716 * T_room);                 %lbm/ft^3 or lbf-s^2/ft^4
Root_Chord = 7.42/12;                                                    %ft
Span = 16 / 12;                                                                 %ft
Aspect_Ratio = Span^2 / Wing_Area;
Kinematic_Viscosity = .372e-6;                                      %slug/ft-s
Speed_of_Sound = sqrt(1.4 * T_room * Gas_Const);     %fps

%II.-     Solid body blockage corrections due to wing and fuselage (Pope
%pg 369
K_1 = 1.04;                                                 % t/c=.15, 4 digit airfoil
delta = 0.3636;                                            %boundary correction factor (b/B) (Ch. 10)
Tau_1 = 0.86;                                             %factor from pg 369, fun. of tunnel shape and b/B
X_Section = (31/12)*(44/12);                    %ft^2
Wing_Volume = Body_Volume;               %ft^3   Flying Wing UCAV
Epsilon_sb_w = (K_1*Tau_1*Wing_Volume) / X_Section^(3/2)
Epsilon_tunnel_correction = 1.090034;    %from Hot-wire data... ratio between hotwire and transducer vel
Epsilon_sb_gp = 1.076696;                       %Plane # Vel / Open Tunnel Vel as measured by the hot-wire
Epsilon_tot = Epsilon_sb_w+ (Epsilon_sb_gp*Epsilon_tunnel_correction-1)

% III.-  Load the static tare data for the alpha sweep w/o the wind ,
% separate each force from the file, and fit a 4th order poly
% as an x-y plot (AoA vs.Force) for each of the 6 force sensors.
%load tare1.txt;                              %Raw tare data file to be read in.
FILE=TareFile(:,1:9);                    %GP42005tearA-10to+20B0model
j=1;
k=1;
L=length(FILE);
for i=1:L                                         %Run for all data points # of rows
    if i==L                                        %if current row is not last row, go to next
        NEXT=i+1;                             %set next equal to the value of the next row
        VALUE2=FILE(NEXT,1);     %set value2 as next row column 1
    else if i==L                  %unless the it is the last value
        VALUE2=50;                          %value2 set to 50 to end the sequence
    end
end
A(j,:)=FILE(i,:);                          %set row j of A equal to row i of FILE
VALUE1=FILE(i,1);                  %set value1 equal to row i column 1 of FILE
if VALUE1==VALUE2
    j=j+1;
else if VALUE1~=VALUE2      %if value1 equals value2, go to next row
    if length(A(:,1))<5
        j=1;
        clear A;
    else if length(A(:,1))>5
        %if more than 20 values
    end
end
C=length(A(:,1));                   %find length of A
for m=1:9                               %Average all rows of the like values in A
    B(k,m)=mean(A(4:C,m));  %disregarding first 10 for vibrations
end
j=1;
k=k+1;
clear A
end
end
end
end
end
for m=1:9                               %Average all rows of the like values in A
    B(k,m)=mean(A(4:C,m));  %disregarding first 10 for vibrations
end
j=1;
k=k+1;
clear A
end
end
end
end
end
if B(k-1,1)<B((k-2),1)
    B=B(1:(k-2),:)
end
tare=[B];
%_________________________________End of inserted code
[row,col] = size(tare);

for k = 1:row;
    theta_tare(k,:,:) = tare(k,1).* (pi/180);
    NF_tare(k,:,:)    = tare(k,4);
    PM_tare(k,:,:)    = tare(k,5);
    SF_tare(k,:,:)    = tare(k,7);
    YM_tare(k,:,:)    = tare(k,8);
    AF_tare(k,:,:)    = tare(k,6);
    RM_tare(k,:,:)    = tare(k,9);
end
NF_poly = polyfit(theta_tare,NF_tare,4);
PM_poly = polyfit(theta_tare,PM_tare,4);
SF_poly = polyfit(theta_tare,SF_tare,4);
YM_poly = polyfit(theta_tare,YM_tare,4);
AF_poly  = polyfit(theta_tare,AF_tare,4);
RM_poly  = polyfit(theta_tare,RM_tare,4);
%#######################################################################
%IV.- Load the specific test run files,
%#######################################################################
clear ('AA','B','C','L')
%load data1.txt;                         %Raw data file to be read in:
FILE=DataFile(:,:);                    %Same as above
j=1;
k=1;
L=length(FILE);

for i=1:L                                        %Run for all data points # of rows
    if i~=L                                       %if current row is not last row, go to next
        NEXT=i+1;                           %set next equal to the value of the next row
        VALUE2=FILE(NEXT,1);   %set value2 as next row column 1
    else if i==L                                %unless the it is the last value
        VALUE2=50;                        %value2 set to 50 to end the sequence
    end
end

A(j,:)=FILE(i,:);                        %set row j of A equal to row i of FILE
VALUE1=FILE(i,1);                 %set value1 equal to row i column 1 of FILE
if VALUE1==VALUE2            %if value1 equals value2, go to next row
    j=j+1;
else if VALUE1~=VALUE2     %if value1 and value2 are different check
    if length(A(:,1))<5                 %if less than 20 values, ignored due to angle change
        j=1;
        clear A;
    else if length(A(:,1))>5                     %if more than 20 values
        C=length(A(:,1));                      %find length of A
        for m=1:9                                  %Average all rows of the like values in A
            B(k,m)=mean(A(4:C,m));    %disregarding first 10 for vibrations
        end
        j=1;
        k=k+1;
        clear A
    end
end
end
end
if B(k-1,1)<B((k-2),1)
    B=B(1:(k-2),:)
end

sample_data=[B];

%_________________________________End of inserted code
[row2,col2] = size(sample_data);

for i = 1:row2;

    %Angles of the model during test runs (Roll, Pitch {AoA}, Yaw {Beta}):
    
    phi                 = 0;
    theta(i,:)        = sample_data(i,1) .* (pi/180);                  %radians
    si(i,:)           = sample_data(i,2) .* (pi/180);                    %radians
    Wind_Speed(i,:)   = sample_data(i,3) .* (5280/3600);   %fps

    %Flight Parameters (Re#, Ma#, Dynamic Pressure):
    
    q = (.5 * Density) .* Wind_Speed.^2;                                     %lb/ft^2
\( q_{\text{Corrected}} = q \cdot (1 + \text{Epsilon}_\text{tot})^2; \) %lbf/ft^2
\( \text{Wind Speed}_{\text{Corrected}} = \text{Wind Speed} \cdot (1 + \text{Epsilon}_\text{tot}); \) %fps
\( \text{Wind Speed}_{\text{Corrected}} \text{ mph} = \text{Wind Speed}_{\text{Corrected}} \cdot (3600/5280); \)
\( \text{Mach Number} = \text{Wind Speed}_{\text{Corrected}} / \text{Speed of Sound}; \) %NonDimensional
\( \text{Reynolds Number} = ((\text{Density} \cdot \text{Root Chord}) \cdot \text{Wind Speed}_{\text{Corrected}}) / \text{Kinematic Viscosity}; \) %NonDimensional
\( \text{Flight Parameters} = [\text{Mach Number} \ \text{Reynolds Number} \ q_{\text{Corrected}}]; \)

%individual forces and moments for each sensor:

\%NEW NOTATION
\( \text{NF}_\text{test}(i,:) = \text{sample data}(i,4); \)
\( \text{PM}_\text{test}(i,:) = \text{sample data}(i,5); \)
\( \text{SF}_\text{test}(i,:) = \text{sample data}(i,7); \)
\( \text{YM}_\text{test}(i,:) = \text{sample data}(i,8); \)
\( \text{AF}_\text{test}(i,:) = \text{sample data}(i,6); \)
\( \text{RM}_\text{test}(i,:) = \text{sample data}(i,9); \)

\%----------------------------------------------------------------------
\%V. - Subtract the effect of the static weight with the tare polynomials above
\%----------------------------------------------------------------------
\( \text{NF}_\text{eval} = \text{polyval}(\text{NF}_\text{poly}, \theta); \)
\( \text{PM}_\text{eval} = \text{polyval}(\text{PM}_\text{poly}, \theta); \)
\( \text{SF}_\text{eval} = \text{polyval}(\text{SF}_\text{poly}, \theta); \)
\( \text{YM}_\text{eval} = \text{polyval}(\text{YM}_\text{poly}, \theta); \)
\( \text{AF}_\text{eval} = \text{polyval}(\text{AF}_\text{poly}, \theta); \)
\( \text{RM}_\text{eval} = \text{polyval}(\text{RM}_\text{poly}, \theta); \)

\( \text{NF}_{\text{resolved}} = \text{NF}_\text{test} - (\text{NF}_\text{eval}); \)
\( \text{PM}_{\text{resolved}} = \text{PM}_\text{test} - (\text{PM}_\text{eval}); \)
\( \text{SF}_{\text{resolved}} = \text{SF}_\text{test} - (\text{SF}_\text{eval}); \)
\( \text{YM}_{\text{resolved}} = \text{YM}_\text{test} - (\text{YM}_\text{eval}); \)
\( \text{AF}_{\text{resolved}} = \text{AF}_\text{test} - (\text{AF}_\text{eval}); \)
\( \text{RM}_{\text{resolved}} = \text{RM}_\text{test} - (\text{RM}_\text{eval}); \)

\( \text{Forces minus tare} = [\text{NF}_{\text{resolved}}, \text{AF}_{\text{resolved}}, \text{PM}_{\text{resolved}}, \text{RM}_{\text{resolved}}, \text{YM}_{\text{resolved}}, \text{SF}_{\text{resolved}}]; \)

\%----------------------------------------------------------------------
\%VI. - CORRECT FORCES AND MOMENTS FOR BALANCE INTERATIONS (body axis)
\%----------------------------------------------------------------------
\%USING THE REDUCTION EQUATIONS
\%LET US SET A MAXIMUN NUMBER OF INTERATIONS (FOR AVOIDING AN INFINIT LOOP)
MAXIT=100;
%SET THE LIMIT FOR THE DIFFERENCE BETWEEN INTERATIONS (CRITERIA FOR FINISH THE INTERATIONS)
LIMIT = 10E-14;

%MATCHING EACH NAME WITH THE DATA
% Prof. Reeder added:
MNF = NF_resolved(i);
MAF = AF_resolved(i);
MPM = PM_resolved(i);
MRM = RM_resolved(i);
MYM = YM_resolved(i);
MSF = SF_resolved(i);

%INPUT OF THE CONSTANTS VALUES FROM THE MATRIX FOR SENSITIVITIES AND INTERATIONS

%COMPUTE THE UNCORRECTED FORCES AND MOMENTS BY CONSIDERING THAT THE PRIME SENSITIVITY CONSTANTS ARE ALREADY APLIED:
NF1 = MNF;
AF1 = MAF;
PM1 = MPM;
RM1 = RRM;
YM1 = MYM;
SF1 = MSF;

%FOR THE FIRST INTERACTION LET US INIZIALICE THE VALUES OF FORCES AND
%MOMENTS WITH THE VALUES OF THE UNCORRECTED FORCES AND MOMENTS

NF(1)=NF1;
AF(1)=AF1;
PM(1)=PM1;
RM(1)=RM1;
YM(1)=YM1;
SF(1)=SF1;

%DOING THE INTERACTION EQUATIONS:

for n=2:MAXIT;

NF(n)=NF1-((K(2)*AF(n-1))+(K(3)*PM(n-1))+(K(4)*RM(n-1))+(K(5)*YM(n-1))+(K(6)*SF(n-1))+(K(7)*NF(n-1)')^2)+...
   (K(8)*(NF(n-1)*AF(n-1)))+(K(9)*(NF(n-1)*PM(n-1)))+(K(10)*(NF(n-1)*RM(n-1)))+(K(11)*(NF(n-1)*YM(n-1)))+...
   (K(12)*(NF(n-1)*SF(n-1)))+(K(13)*(AF(n-1)^2))+(K(14)*(AF(n-1)*PM(n-1)))+(K(15)*(AF(n-1)*RM(n-1)))+...
   (K(16)*(AF(n-1)*YM(n-1)))+(K(17)*(AF(n-1)*SF(n-1)))+(K(18)*(PM(n-1)^2))+(K(19)*(PM(n-1)*RM(n-1)))+...
   (K(20)*(PM(n-1)*YM(n-1)))+(K(21)*(PM(n-1)*SF(n-1)))+(K(22)*(RM(n-1)^2))+(K(23)*(RM(n-1)*YM(n-1)))+...
   (K(24)*(RM(n-1)*SF(n-1)))+(K(25)*(YM(n-1)^2))+(K(26)*(YM(n-1)*SF(n-1)))+(K(27)*(SF(n-1)^2)));

AF(n)=AF1-((K(28)*NF(n-1))+(K(30)*PM(n-1))+(K(31)*RM(n-1))+(K(32)*YM(n-1))+(K(33)*SF(n-1))+(K(34)*NF(n-1)')^2)+...
   (K(35)*(NF(n-1)*AF(n-1)))+(K(36)*(NF(n-1)*PM(n-1)))+(K(37)*(NF(n-1)*RM(n-1)))+(K(38)*(NF(n-1)*YM(n-1)))+...
   (K(39)*(NF(n-1)*SF(n-1)))+(K(40)*(AF(n-1)^2))+(K(41)*(AF(n-1)*PM(n-1)))+(K(42)*(AF(n-1)*RM(n-1)))+...
   (K(43)*(AF(n-1)*YM(n-1)))+(K(44)*(AF(n-1)*SF(n-1)))+(K(45)*(PM(n-1)^2))+(K(46)*(PM(n-1)*RM(n-1)))+...
   (K(47)*(PM(n-1)*YM(n-1)))+(K(48)*(PM(n-1)*SF(n-1)))+(K(49)*(RM(n-1)^2))+(K(50)*(RM(n-1)*YM(n-1)))+...
   (K(51)*(RM(n-1)*SF(n-1)))+(K(52)*(YM(n-1)^2))+(K(53)*(YM(n-1)*SF(n-1)))+(K(54)*(SF(n-1)^2));

PM(n)=PM1-((K(55)*NF(n-1))+(K(56)*AF(n-1))+(K(58)*RM(n-1))+(K(59)*YM(n-1))+(K(60)*SF(n-1))+(K(61)*NF(n-1)')^2)+...
   (K(62)*(NF(n-1)*AF(n-1)))+(K(63)*(NF(n-1)*PM(n-1)))+(K(64)*(NF(n-1)*RM(n-1)))+(K(65)*(NF(n-1)*YM(n-1)))+...
   (K(66)*(NF(n-1)*SF(n-1)))+(K(67)*(AF(n-1)^2))+(K(68)*(AF(n-1)*PM(n-1)))+(K(69)*(AF(n-1)*RM(n-1)))+...
   (K(70)*(AF(n-1)*YM(n-1)))+(K(71)*(AF(n-1)*SF(n-1)))+(K(72)*(PM(n-1)^2))+(K(73)*(PM(n-1)*RM(n-1)))+...
   (K(74)*(PM(n-1)*YM(n-1)))+(K(75)*(PM(n-1)*SF(n-1)))+(K(76)*(RM(n-1)^2))+(K(77)*(RM(n-1)*YM(n-1)))+...
   (K(78)*(RM(n-1)*SF(n-1)))+(K(79)*(YM(n-1)^2))+(K(80)*(YM(n-1)*SF(n-1)))+(K(81)*(SF(n-1)^2));
RM(n)=RM1-((K(82)*NF(n-1))+(K(83)*AF(n-1))+(K(84)*PM(n-1))+(K(86)*YM(n-1))+(K(87)*SF(n-1))+(K(88)*NF(n-1)^2)+...
   (K(89)*(NF(n-1)*AF(n-1)))+(K(90)*(NF(n-1)*PM(n-1))+(K(91)*(NF(n-1)*RM(n-1)))+(K(92)*(NF(n-1)*YM(n-1)))+...
   (K(93)*(NF(n-1)*SF(n-1)))+(K(94)*(AF(n-1)^2))+(K(95)*(AF(n-1)*PM(n-1)))+(K(96)*(AF(n-1)*RM(n-1)))+...
   (K(97)*(AF(n-1)*YM(n-1)))+(K(98)*(AF(n-1)*SF(n-1)))+(K(99)*(PM(n-1)^2))+(K(100)*(PM(n-1)*RM(n-1)))+...
   (K(101)*(PM(n-1)*YM(n-1)))+(K(102)*(PM(n-1)*SF(n-1)))+(K(103)*(RM(n-1)^2))+(K(104)*(RM(n-1)*YM(n-1)))+...
   (K(105)*(RM(n-1)*SF(n-1)))+(K(106)*(YM(n-1)^2))+(K(107)*(YM(n-1)*SF(n-1)))+(K(108)*(SF(n-1)^2)));

YM(n)=YM1-((K(109)*NF(n-1))+(K(110)*AF(n-1))+(K(111)*PM(n-1))+(K(112)*RM(n-1))+(K(114)*SF(n-1))+(K(115)*NF(n-1)^2)+...
   (K(116)*(NF(n-1)*AF(n-1)))+(K(117)*(NF(n-1)*PM(n-1)))+(K(118)*(NF(n-1)*RM(n-1)))+(K(119)*(NF(n-1)*YM(n-1)))+...
   (K(120)*(NF(n-1)*SF(n-1)))+(K(121)*(AF(n-1)^2))+(K(122)*(AF(n-1)*PM(n-1)))+(K(123)*(AF(n-1)*RM(n-1)))+...
   (K(124)*(AF(n-1)*YM(n-1)))+(K(125)*(AF(n-1)*SF(n-1)))+(K(126)*(PM(n-1)^2))+(K(127)*(PM(n-1)*RM(n-1)))+...
   (K(128)*(PM(n-1)*YM(n-1)))+(K(129)*(PM(n-1)*SF(n-1)))+(K(130)*(RM(n-1)^2))+(K(131)*(RM(n-1)*YM(n-1)))+...
   (K(132)*(RM(n-1)*SF(n-1)))+(K(133)*(YM(n-1)^2))+(K(134)*(YM(n-1)*SF(n-1)))+(K(135)*(SF(n-1)^2));

SF(n)=SF1-((K(136)*NF(n-1))+(K(137)*AF(n-1))+(K(138)*PM(n-1))+(K(139)*RM(n-1))+(K(140)*YM(n-1))+(K(142)*NF(n-1)^2)+...
   (K(143)*(NF(n-1)*AF(n-1)))+(K(144)*(NF(n-1)*PM(n-1)))+(K(145)*(NF(n-1)*RM(n-1)))+(K(146)*(NF(n-1)*YM(n-1)))+...
   (K(147)*(NF(n-1)*SF(n-1)))+(K(148)*(AF(n-1)^2))+(K(149)*(AF(n-1)*PM(n-1)))+(K(150)*(AF(n-1)*RM(n-1)))+...
   (K(151)*(AF(n-1)*YM(n-1)))+(K(152)*(AF(n-1)*SF(n-1)))+(K(153)*(PM(n-1)^2))+(K(154)*(PM(n-1)*RM(n-1)))+...
   (K(155)*(PM(n-1)*YM(n-1)))+(K(156)*(PM(n-1)*SF(n-1)))+(K(157)*(RM(n-1)^2))+(K(158)*(RM(n-1)*YM(n-1)))+...
   (K(159)*(RM(n-1)*SF(n-1)))+(K(160)*(YM(n-1)^2))+(K(161)*(YM(n-1)*SF(n-1)))+(K(162)*(SF(n-1)^2));

% SET THE LIMIT FOR THE DIFFERENCE BETWEEN INTERATIONS(CRITERIA FOR FINISH
THE INTERATIONS)

DIFFNF(n)=abs(NF(n)-NF(n-1));
DIFFAF(n)=abs(AF(n)-AF(n-1));
DIFFPM(n)=abs(PM(n)-PM(n-1));
DIFFRM(n)=abs(RM(n)-RM(n-1));
DIFFYM(n)=abs(YM(n)-YM(n-1));
DIFFSF(n)=abs(SF(n)-SF(n-1));

if DIFFNF(n)&DIFFAF(n)&DIFFPM(n)&DIFFRM(n)&DIFFYM(n)&DIFFSF(n) < LIMIT
   break

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Corrected_Data(:,i)= [NF(n);AF(n);PM(n);RM(n);YM(n);SF(n)];

%VII.- Calculation of the Axial, Side, & Normal Forces from the corrected balance forces in the Body Axis reference frame

Forces_b(:,i) = [Corrected_Data(2,i); Corrected_Data(6,i); Corrected_Data(1,i)];

%Calculation of the Drag, Side, & Lift Forces in the Wind Axis reference frame

Forces_w = [Forces_b(1,:).*cos(theta').*cos(si')+Forces_b(2,:).*sin(si')+Forces_b(3,:).*sin(theta').*cos(si');
 -Forces_b(1,:).*sin(si').*cos(theta')+Forces_b(2,:).*cos(si')-Forces_b(3,:).*sin(theta').*sin(si');
 -Forces_b(1,:).*sin(theta')+Forces_b(3,:).*cos(theta')];

%First entry is the moments calculated by the balance or direct calculation in the Body Reference Frame. Balance measures Roll (l), Yaw is about the z-axis (n), and Pitch is about the y-axis (m). Distances from strain gages to C.G. are in INCHES. Moments are in-lbf

m = Corrected_Data(3,i);
n = Corrected_Data(5,i);
l = Corrected_Data(4,i);

Moments_b(:,i) = [l; m; n];

%Second entry is the conversion from the "Balance Centeric" moments to the Wind Reference moments with respect to the Balance Center (bc)

Moments_w_bc = [Moments_b(1,:).*cos(theta').*cos(si')-Moments_b(2,:).*sin(si') +Moments_b(3,:).*sin(theta').*cos(si');
 -Moments_b(1,:).*sin(si').*cos(theta')+Moments_b(2,:).*cos(si')+Moments_b(3,:).*sin(theta').*sin(si');
 -Moments_b(1,:).*sin(theta')+Moments_b(3,:).*cos(theta')];

%Finally, the balance centered moments are converted to moments about the Model's Center of Mass (cm) or Center of Gravity (CG)

cgdist=sqrt((X_cmb)^2+(Z_cmb)^2); %Obtaining the direct distance between the center of the balance and the center of mass
w=atan(-Z_cmb/X_cmb); %Obtaining the angle between cgdist and the x axes at zero angle of attack

X_cm(i,:)= cos(theta(i,:)+w)*cos(si(i,:))*cgdist);
Y_cm(i,:)= Y_cmb + X_cm(i,:)*tan(si(i,:));
Z_cm(i,:)= -sin(theta(i,:)+w)*cgdist);
Moments_w_cg_u = [Moments_w_bc(1,:) + Z_cm(i,:)*Forces_w(2,:) + Forces_w(3,:)* Y_cm(i,:);
Moments_w_bc(2,:) - Forces_w(3,:)* X_cm(i,:) + Forces_w(1,:)* Z_cm(i,:);
Moments_w_bc(3,:) - Forces_w(1,:)* Y_cm(i,:) - Forces_w(2,:)* X_cm(i,:)];

% VIII.- Calculation of the actual Lift and Drag nondimensional Coefficients, uncorrected for tunnel effects, (%(Cl and Cd)
%**********************************************************************************************
C_D_u = Forces_w(1,:) ./ (q_Corrected' .* Wing_Area);
C_Y_u = Forces_w(2,:) ./ (q_Corrected' .* Wing_Area);
C_L_u = Forces_w(3,:) ./ (q_Corrected' .* Wing_Area); %Keuthe & Chow pg 178
Coefficients = [C_L_u; C_D_u; C_Y_u]';
Ave_Cl = mean(Coefficients(:,1));
Ave_Cd = mean(Coefficients(:,2));

end

% IX          Drag Coefficient Correction
%**********************************************************************************************
C_D_o = min(Coefficients(:,2));
C_L_u_sqrd = Coefficients(:,1).^2;
Delta_C_D_w = ((delta * Wing_Area) / X_Section) .* C_L_u_sqrd;
C_D_Corrected = C_D_u' + Delta_C_D_w;

% X.- Angle of Attack due to upwash Correction
%**********************************************************************************************
alpha = sample_data(:,1);
Delta_alpha_w = ((delta * Wing_Area) / X_Section) .* (57.3 * C_L_u);
alpha_Corrected = alpha + Delta_alpha_w';

% XI.- Pitching Moment Correction
%**********************************************************************************************
c_bar = (mean([7.42, 7.42, 7.42, 3.7442, 0])) / 12; %ft = Mean Chord of wing taken at five equal stations
Cl_w_cg = Moments_w_cg_u(1,:) ./ (q_Corrected' .* (Wing_Area * Span*12));
Cm_w_cg_u = Moments_w_cg_u(2,:) ./ (q_Corrected' .* (Wing_Area * c_bar*12));
Cn_w_cg = Moments_w_cg_u(3,:) ./ (q_Corrected' .* (Wing_Area * Span*12));

Cm_w_cg_corrected = Cm_w_cg_u; %No Tail
Corrected_Moment_Coefficients = [Cl_w_cg' Cm_w_cg_corrected' Cn_w_cg'];

% OBTAINING THE MOMENTS COEFFICIENTS CORRECTED ABOUT THE CENTER OF THE %BALANCE
Cl_w_bc = Moments_w_bc(1,:) ./ (q_Corrected' .* (Wing_Area * Span*12));
Cm_w_bc_u = Moments_w_bc(2,:) ./ (q_Corrected' .* (Wing_Area * e_bar*12));

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\[ C_{n_{w\ bc}} = \frac{\text{Moments}_{w\ bc}(3,:)}{(q_{\text{Corrected}}' \cdot (Wing_{\text{Area}} \cdot \text{Span} \cdot 12))}; \]

\[ C_{m_{w\ bc\ corrected}} = C_{m_{w\ bc\ u}}; \]
\[ \text{Corrected\_Moment\_Coefficients}_{bc} = [C_{l_{w\ bc}}' \ C_{m_{w\ bc\ corrected}}' \ C_{n_{w\ bc}}']; \]

\[
\begin{align*}
\alpha &= \text{sample\_data}(;,1); \\
\text{fprintf}(\text{\ 'Mach Number Reynolds Number Dynamic Pressure(Psf)/r'}); \\
\text{Flight\_Parameters} \\
\text{fprintf}(\text{\ 'r'}); \\
\text{fprintf}(\text{\ 'Load\_are\ in\ lbf\ and\ arranged\ [D\ S\ L]\ across\ the\ top\ and\ increments\ of\ alpha\ down\ the\ side\ \text{\ 'r'}\}) \\
\text{Forces\_w'} \\
\text{fprintf}(\text{\ 'r'}); \\
\text{fprintf}(\text{\ 'Moments\ are\ in\ in-lbf\ and\ arranged\ [L\ M\ N]\ down\ the\ side\ and\ increments\ of\ alpha\ along\ the\ top\ \text{\ 'r'}\}) \\
\text{Moments\_w\_cg\_u} \\
\text{fprintf}(\text{\ 'r'}); \\
\text{fprintf}(\text{\ 'Cl\_u\ C\_d_u\ CY\_u\ \text{\ 'r'}\}); \\
\text{Coefficients} \\
\text{fprintf}(\text{\ 'r'}); \\
\text{fprintf}(\text{\ 'Del\_CD\_w\ CD\_u\ CD\_Corrected\ \text{\ 'r'}\}); \\
\text{Compare\_CD} = [\text{Delta\_C\_D\_w\ C\_D\_u'}\ C\_D\_Corrected] \\
\text{fprintf}(\text{\ 'r'}); \\
\text{fprintf}(\text{\ 'Del\_alpha\_w\ alpha\_g\ alpha\_Corrected\ \text{\ 'r'}\}); \\
\text{Compare\_alpha} = [\text{Delta\_alpha\_w'}\ alpha\ alpha\_Corrected ] \\
\text{fprintf}(\text{\ 'r'}); \\
\text{fprintf}(\text{\ 'Cl\_cg\_wind\ Cm\_cg\_corrected\_w\ Cn\_cg\_wind\ \text{\ 'r'}\}); \\
\text{Corrected\_Moment\_Coefficients} \\
\text{fprintf}(\text{\ 'r'}); \\
\text{fprintf}(\text{\ 'M#\ Re#\ q\_c\ Uoo\ alpha\_c\ C\_L\ C\_D\_c\ Cl\_cg\_w\ Cm\_cg\_c\_w\ C\_Y\_w\ \text{\ 'r'}\}); \\
\text{YY}=[\text{Flight\_Parameters\ (Wind\_Speed\_Corrected\ \cdot\ (3600/5280))\ alpha\_Corrected\ C\_L\ u'}\ C\_D\_Corrected\ Corrected\_Moment\_Coefficients\ C\_Y\_u']\text{\ '%pressure']}; \\
\text{XX}=[\text{M#\ 'Re#'\ 'q\_c'\ 'Uoo'\ 'alpha\_c'\ 'C\_L'\ 'C\_D\_c'\ 'Cl\_cg\_w'\ 'Cm\_cg\_c\_w'\ 'Cn\_cg\_w\ \text{\ 'r'}\}]; \\
\text{ZZ}=[\text{XX}; \text{YY}]; \\
\text{wk1write('output.xls',YY,2,1)}
\]
Bibliography


Vita

Brett Lewis Jones was born in Visalia, CA. He graduated from Tulare Union High School in 1999 and received an appointment to the United States Naval Academy in 2000. He earned a degree in Ocean Engineering and received a Commission into the United States Navy designated a Navy pilot. After graduation in May 2004, he began his officer career at the Air Force Institute of Technology. Brett enjoys competitive sports, recreational activities, and long walks along the beach.
Experimental Investigation Into the Aerodynamic Ground Effect of a Tailless Chevron-shaped UCAV

This experimental study adequately identified the ground effect region of an unmanned combat air vehicle (UCAV). The AFIT 3’ x 3’ low-speed wind tunnel and a ground plane were used to simulate the forces and moments on a UCAV model in ground effect. The chevron planform used in this study was originally tested for stability and control and the following extends the already existing database to include ground effects. The ground plane was a flat plate mounted with cylindrical legs. To expand the capabilities of the AFIT 3’ x 3’ low-speed wind tunnel, hot-wire measurements and flow visualization revealed an adequate testing environment for the use of the ground plane. Examination of the flow through the test section indicated a significant difference in test section transducer velocity and the hot-wire measured velocity. This disparity along with the velocity difference due to the ground plane were accounted for as wind tunnel blockage. In addition, the flow visualization revealed the horseshoe vortices that built up on the front two mounted legs of the ground plane.

The ground effect region for the chevron UCAV was characterized by an increase in lift, drag, and a decrease in lift-to-drag ratio. These trends were also noted in previous studies of similar aspect ratio and wing sweep.