WIND TUNNEL TEST PLAN

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ABSTRACT

This document will outline the procedure and tasks required to confirm that the preliminary aircraft design satisfies the requirements outlined in the Preliminary Design Review. A ½-scale model of the aircraft in different configurations will be tested using a 48” x 32” closed loop wind tunnel. Two different fuselage setups will be used to test the effects of ventral strakes to increase lateral-directional stability in strong crosswinds. These tests will be run at takeoff and cruise equivalent Reynolds numbers from -5° to 15° AoA. Sideslip will be tested from -10° to 10° at the angle of attack for maximum endurance. A ⅓-scale model of a fully mechanized wing will be tested in the 12” by 12” open loop wind tunnel using the same Reynolds number as the ½-scale takeoff test. Four different flap configurations will be tested from -5° to 20° AoA to determine whether these features are required for the flight test article. The data collected from these tests will be crucial in determining whether any aerodynamic changes are required before fabrication commences.

1.0 INTRODUCTION

The purpose of wind tunnel testing is to analyze how current airfoil and fuselage design will behave in expected cruise and takeoff conditions. Aerodynamic data will be crucial in determining if the aircraft can meet the mission requirements as designed or requires design changes.

1.1 Aircraft Mission and Requirements

The Calypso aircraft is designed to complete maritime search-and-rescue missions from either ocean-going vessels or remote areas of shoreline. A typical mission profile involves autonomous launch from a catapult and climbing to 400 ft above sea level. It will then dash at 70 kts up to 18 NM to reach the last known location of a person or vessel in distress. At this location, the aircraft will search using an integrated sensor package for up to 30 minutes. If a person is detected, a life raft will be deployed to increase their chances of survival. The aircraft will then return to base to be captured by a wire recovery system. The aircraft must be capable of executing this mission up to Beaufort Force 7 wind conditions (28-33 kts).

The design is driven by following three requirements derived from the mission case and request for proposal (RFP): a maximum dash speed of 100 kts, stability in 28-33 kts of crosswind, and the ability to carry a 4-pound sensor package and deploy a 5-pound life raft.

1.2 Test Objectives

The purpose of wind tunnel testing is to verify the calculated aerodynamic performance of the flight test article. By empirical testing of an accurate model of the aircraft, unexpected behavior can be identified before flight testing begins. To sufficiently test the performance of the aircraft, two wind tunnel models will be used. The first is a ⅓-scale mechanized wing with leading and trailing edge flaps. This will be tested to obtain aerodynamic data on the effect of various combinations of flap deflection, as XFLR5 and empirical formulas for flap performance are imprecise. The second model is a ½-scale aircraft with provisions for ventral strakes along the underside of the aft fuselage. This model will be used to obtain lift, drag, and moment data at a range of angles of attack and sideslip angles. Ventral strakes can be installed to add 104 in^2 of vertical surface area. These two models will be used to obtain data to accomplish the following four objectives. These objectives will help validate the design of the flight test article.

The first test objective is to verify the effects of four different flap configurations: no flaps, leading-edge flaps, trailing-edge flaps, and both leading- and trailing-edge flaps. These tests will utilize the ⅓-scale mechanized wing and will be conducted at a Reynolds Number equivalent to the aircraft's predicted takeoff speed, 27 kts. These results can be compared to data from XFLR5. These tests will determine whether the inclusion of flaps is necessary to meet the catapult launch requirement, as they complicate manufacturing significantly.

The second objective is to gather aircraft performance data at both takeoff and cruise conditions. The information will be a baseline for future tests to be compared to. The aerodynamic performance should mirror what hand calculations and XFLR5 determined in the preliminary design phase. These tests will be conducted at a range of angles of attack and sideslip angles to determine maximum range and endurance speeds as well as the effect of crosswinds. The results obtained from these baseline tests will verify whether the design of the flight test article needs modifications to meet the mission requirements.

The third objective is to determine if the inclusion of ventral strake improves the performance of the aircraft. As the aircraft is expected to fly in crosswinds up to 33 kts, it must have sufficient lateral-directional stability to maintain course in these conditions. The ½-scale model can be fitted with two ventral strakes that provide an additional 104 in^2 of vertical surface area. Tests will be conducted in both takeoff and cruise configurations to determine the stabilizing effect of these strakes over a range of sideslip angles. This will determine whether the final design should include strake, depending on the amount of added drag compared to the increase in stability.

The final objective is to complete flow visualization testing to produce qualitative data regarding the aerodynamic performance of the aircraft. Flow visualization will be used to identify areas of turbulent flow around the fuselage and target specific areas for aerodynamic refinement. Additionally, this information can be used to evaluate whether the vertical tail is influenced by the wing wake at high angles of attack, allowing for the creation of control limits to avoid an unrecoverable stall.

1.3 Wind Tunnel Testing Limitations

As a full-scale model will not fit into the closed-loop wind tunnel, a half-scale model will be used. To obtain the most accurate data possible, the flow velocity would be twice the cruise velocity of the flight test article. This would correspond to a flow velocity of 200 kts, or 103 m/s, which exceeds the maximum velocity available with the closed-loop tunnel. Instead, a flow velocity of 48 m/s will be used. This reduces the Reynolds Number from 1,100,000 to 500,000, which is still within the turbulent flow regime and will provide accurate data.

Another consideration for wind tunnel testing is the blockage ratio. This is a measure of how much obstruction to the flow the test model creates and how much the test section velocity will decrease. This value should be less than 8% to obtain accurate results. For the whole-aircraft model, the calculated blockage ratio is 6.5% at 20° angle of attack. The blockage ratio for the mechanized wing model is 8.5% at 20° angle of attack. This indicated that all data points for the whole-aircraft tests can be considered accurate, but tests of the mechanized wing above about 15° should be avoided. Since this range is above the predicted stall angle of attack from XFLR5 analysis, this blockage will not affect the accuracy of the data collected.

1.4 Test Configurations

The primary test article is a ½ scale model of the aircraft with provisions for ventral strakes along the aft fuselage to increase vertical stabilizer surface area by 100%. This model will be used to validate the overall lift, drag, and stability of the aircraft. Figure 1.1 shows the two configurations that will be tested. The ventral strakes are shown in orange.

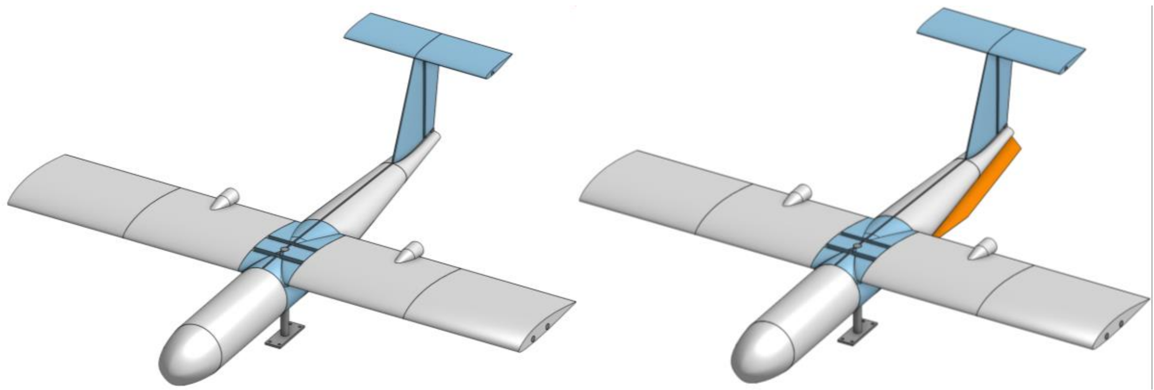

Figure 1.1: ½-Scale Aircraft Model (L: Without Strakes, R: With Strakes)

Additionally, a ⅓-scale wing, shown in Figure 1.2, will be tested to validate the performance of leading- and trailing-edge flaps for the aircraft. The flight test article design includes flaps on both edges which will complicate manufacturing significantly. The leading-edge flap can be deflected up to 10° and the trailing edge flap up to 30°. This allows for testing of four combinations of flap deflection.

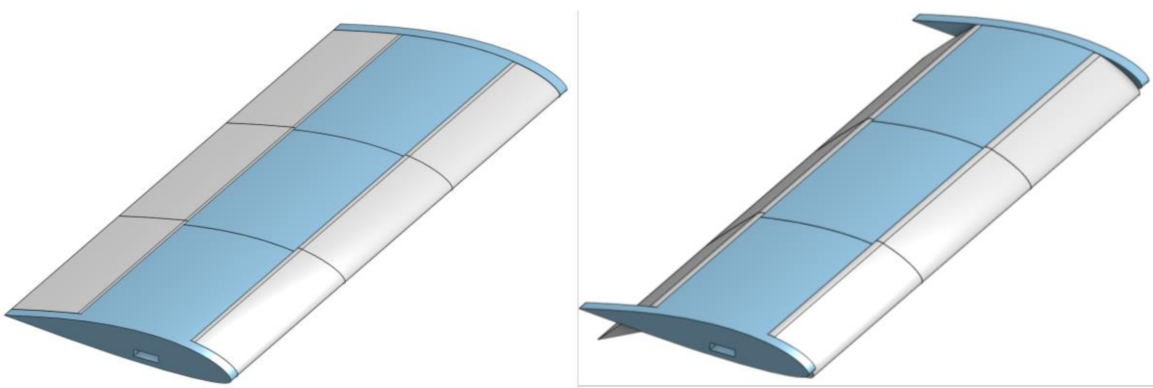

Figure 1.2: ⅓-Scale Mechanized Wing Model (L: Flaps Up, R: Flaps Down)

The model uses a chord of 4.67” and span of 12” to allow testing in the 12” by 12” open-loop wind tunnel while the closed-loop wind tunnel is in use. This wing uses the same 20% chord length for the leading-edge flap and 40% chord length for the trailing-edge flap that the preliminary design used, with a span ratio of 95%.

2.0 TEST ARTICLE CONSTRUCTION

To expedite the fabrication of the wind tunnel test articles, many of the parts are constructed of 3D printed plastic. This method allows for the accurate reproduction of complex geometry and is a good fit for aerodynamic features. The mechanized wing model is shown in Figure 2.1 along with its major components. This model allows for the positioning of both flaps by using friction-fit pegs on the central frame which the flaps slot onto. The angle will be set using a protractor placed at the pivot location. This reduces the mechanical complexity of the model and simplifies production.

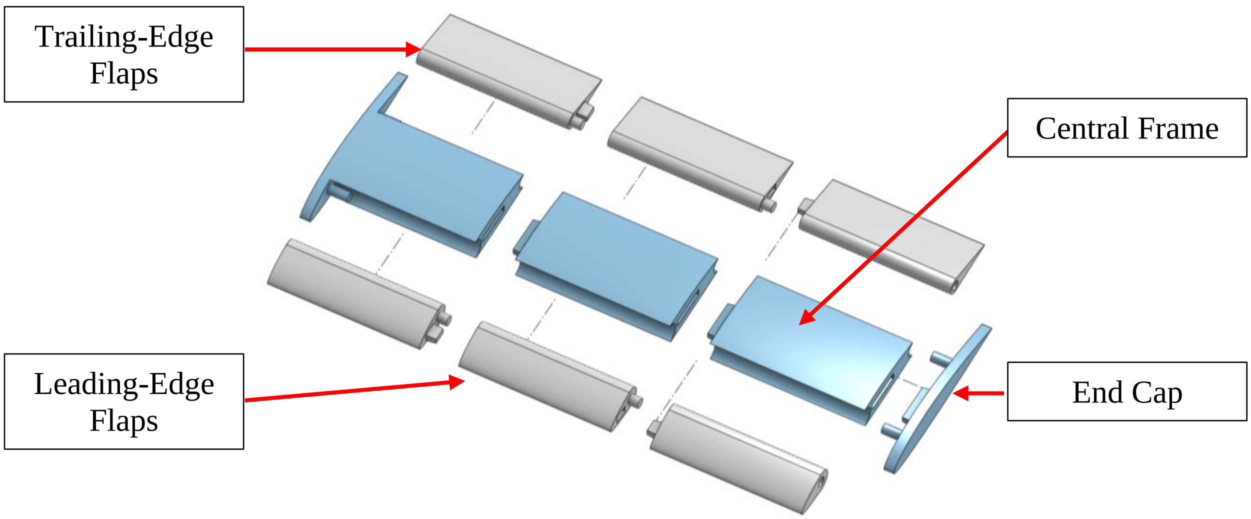

Figure 2.1: Exploded View of ⅓ Scale Mechanized Wing

For the whole-aircraft model, a steel frame was used to reinforce the aircraft sufficiently for testing at high loads. Figure 2.2 shows the model and its major components. Each of these components slide onto the steel frame, then are bonded together. The ventral strakes index into slots along the aft fuselage and can be bonded for increased strength. Since these parts are not intended to be removed, tests will be grouped by whether the strakes are installed.

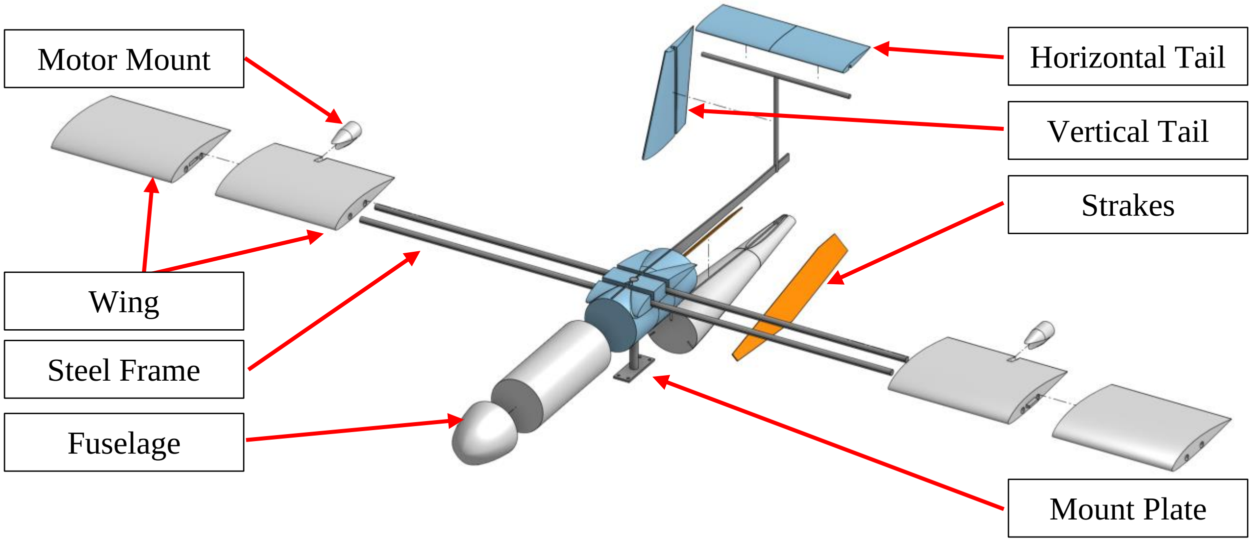

Figure 2.2: Exploded View of ½ Scale Aircraft Model

The center of gravity of the model, shown in Figure 2.3, is placed above the mount plate to minimize torque on the pyramidal balance to improve results. The center of gravity of the model is further aft than the flight test article, which will be taken into account with the data collection software used with the wind tunnel.

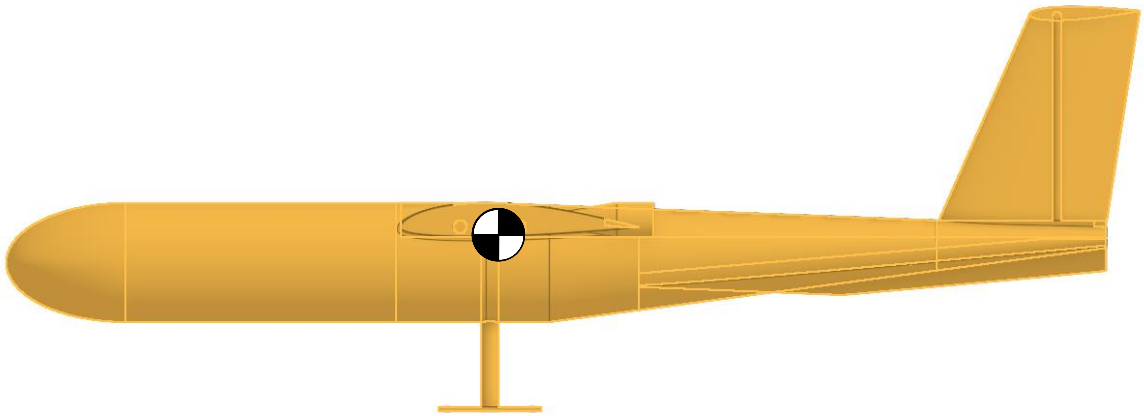

Figure 2.3: Center of Gravity of Aircraft Model

2.1 Component Material Selection

The 3D printed components are made of two different types of plastic. High strength parts, shown in blue in Figure 2.1 and Figure 2.2 are printed from ABS (Acrylonitrile Butadiene Styrene) which is more rigid and dimensionally stable. Since ABS is relatively expensive, all parts that are not required to have structural strength are printed from PLA (Polylactic Acid), which is lighter and less strong than ABS. These parts are shown in light grey. The wing for the ½-scale model is printed in four sections and the fuselage in five to fit onto the printers available. The ⅓-scale wing has its aerodynamic surfaces printed in three sections each for the same reason. All parts composed of multiple segments have features to maintain alignment.

A frame made of low carbon steel, shown in dark grey in Figure 2.2, is used to provide additional structural reinforcement to the aircraft model. Two 0.375” diameter wing spars at 25% and 75% of the chord are used to reinforce the wing, with a single 0.25” diameter spar is used in the horizontal and vertical tails. A 1” thick by 0.1” tall plate is used to join the wing and tail together and transfer loads between the two. These parts will be welded together.

2.2 Mounting

The aircraft model will be mounted to the balance with a mount plate fabricated with mild steel. A 0.5” diameter rod is welded to the steel frame, extending down 6” to a 0.1” thick plate with the same mounting pattern as the pyramidal balance. The plate will then be bolted to the balance to secure it. The mechanized wing model uses a blade mount specific to the 12” by 12” wind tunnel. This blade fits into a slot in the model and a socket in the wind tunnel. It is secured with a bolt at both points to prevent rotation. Figure 2.4 shows the pyramidal balance mounting plate and the blade mount used in the 12” by 12” wind tunnel. The blade mount image shows the bottom surface of the tunnel and the socket below which holds the mount.

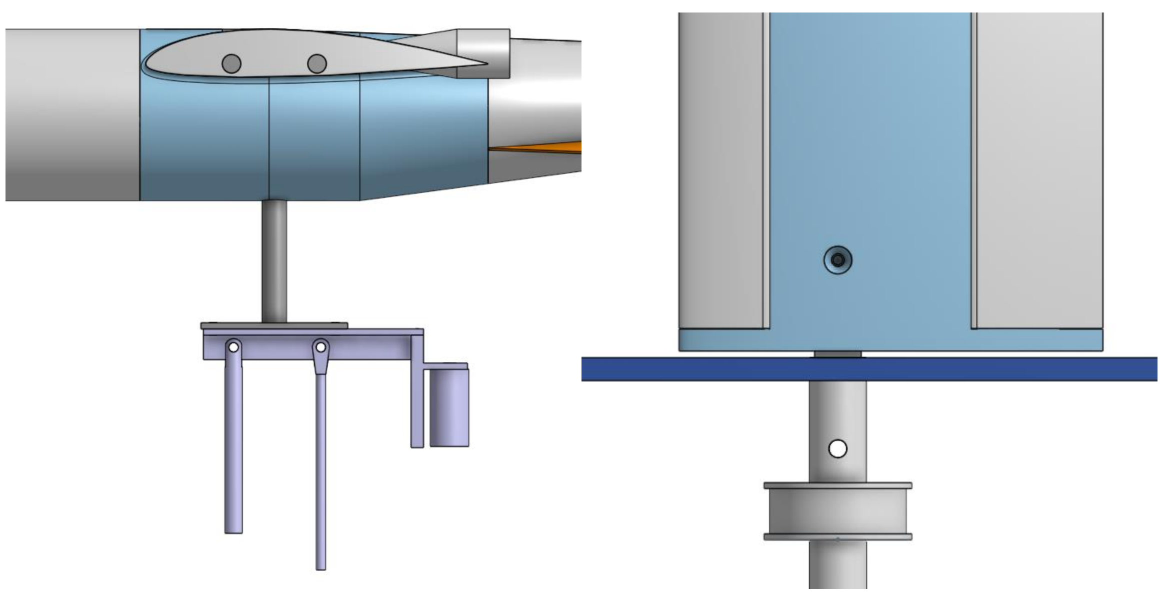

Figure 2.4: Wind Tunnel Mounts (Pyramidal Balance Left, Blade Mount Right)

2.3 Structural Strength of Wind Tunnel Models

The extensive steel reinforcement throughout the half scale aircraft model will allow it to withstand 40 lbf of aerodynamic lift, preventing any damage to the wind tunnel caused by failure of the model. The size of the reinforcing rods and plates were selected to take this load in addition to 10 lbf of aerodynamic lift from the horizontal tail. These sizes were determined based on the load testing completed with the preliminary flight test article. Before testing, the model will be tested by suspending the aircraft from the mount and loading it with sandbags up to the required 40 lbf to ensure there is no permanent deformation of the model.

The third scale wing model utilizes ABS for the center span, resulting in sufficient strength to withstand the estimated 5 lbf of aerodynamic lift at maximum deflection. This model did not require any additional reinforcement other than printing the parts with 50% infill and thicker walls. To verify the strength of these parts, a cantilever load test with 5-pounds of weight at the wingtip will be conducted.

3.0 AERODYNAMIC TEST PLAN

This section details the specific test parameters that will be used to test the two wind tunnel models.

3.1 Flow Conditions

Wind tunnel testing will utilize Embry-Riddle's open loop 12" by 12" wind tunnel and the 48" by 32" closed loop wind tunnel. The open loop wind tunnel will operate at a flow velocity of 22 m/s in the test section to simulate a takeoff configuration for the wing model. The closed loop wind tunnel will operate at a flow velocity of 15 m/s in the test section to simulate takeoff and 48 m/s to simulate a cruise condition for the aircraft model. The Reynolds Numbers corresponding to these conditions are summarized in Table 3.1.

Table 3.1: Flow Conditions for Wind Tunnel Testing

Test Case	Air Density	Air Viscosity	Flow Velocity	Aerodynamic Chord	Reynolds Number
Wing Model – Takeoff	$1.05\ \frac{kg}{m^3}$	$1.76 * 10^{-5}\ \frac{kg}{m * s}$	22 m/s	0.118 m (4.67 in)	150,000
Aircraft Model – Takeoff			15 m/s	0.178 m (7 in)	150,000
Aircraft Model – Cruise			48 m/s	0.178 m (7 in)	500,000

3.2 Test Cases

The test cases that will be completed can be divided by the model used. The specifics of these cases are detailed in the following sections.

3.2.1 Mechanized Wing Test Cases

The mechanized wing model will be tested in the 12" by 12" open loop wind tunnel at a Reynolds Number of 150,000 corresponding to takeoff conditions. Four cases will be run at a range from -5° to 20° angle of attack with a different flap configuration in each. These cases will be designated by the MW prefix and are listed in Table 3.2.

Table 3.2: Wing Model Test Matrix

Test Designation	Velocity, (m/s)	AoA, °	Sideslip, °	LE Flap Angle, °	TE Flap Angle, °	Re
MW-1	22	-4:2:20	0	0	0	150K
MW-2	22	-4:2:20	0	10	0	150K
MW-3	22	-4:2:20	0	0	30	150K
MW-4	22	-4:2:20	0	10	30	150K

3.2.2 Aircraft Model Test Cases

The whole-aircraft model will be tested in the 48” x 32” closed loop wind tunnel with three categories of test cases. The first are takeoff (TO) cases. These are run at a Reynolds Number of 150,000. Four TO cases will be tested to gather data at a variety of angle of attack and sideslip angles, with and without the use of strakes. Another four cruise (CR) cases will be run at a Reynolds Number of 500,000 with the same set of configurations as the TO cases. Finally, two flow visualization (FV) cases will be run after tufts are attached to the model. Both cases will cover a range of angles of attack, with one at 150,000 Re and the other at 500,000 Re. These ten cases are detailed in Table 3.3.

Table 3.3: Aircraft Model Test Matrix

Test Designation	Velocity, (m/s)	AoA, °	Sideslip, °	Strakes	Tufts	Re
TO-1	15	-4:2:20	0	N	N	150K
TO-2	15	α_{C_L}Max	-10:1:10	N	N	150K
CR-1	48	-4:2:20	0	N	N	500K
CR-2	48	$\alpha_{L/D}$Max	-10:2:10	N	N	500K
TO-3	15	-4:2:20	0	Y	N	150K
TO-4	15	α_{C_L} Max	-10:2:10	Y	N	150K
CR-3	48	-4:2:20	0	Y	N	500K
CR-4	48	$\alpha_{L/D}$Max	-10:2:10	Y	N	500K
FV-1	15	-4:2:20	0	N	Y	150K
FV-2	48	-4:2:20	0	N	Y	500K

4.0 TEST PROCEDURE

All wind tunnel testing will be performed at the Wind Tunnel building at Embry Riddle Aeronautical university. Dr. Lance Traub will be supervising the use and procedures. An Aerolab 6-component pyramidal balance with acquisition programming will be datalogging all testing conducted in the closed loop wind tunnel. The open loop wind tunnel uses a strain gauge balance with a custom data acquisition program. The testing procedures outlined below were provided by Dr. Traub for use with the closed loop wind tunnel. Most procedures for this tunnel apply to the open loop tunnel as well. Any differences in procedure will be noted separately.

4.1 Initial Setup

The following steps must be completed before data acquisition can begin.

1. Turn on fan breaker outside of wind tunnel building (closed loop only).
2. Turn on balance, motor control, and computer. Wait ~30 minutes for balance to warm up.
3. Open data acquisition program.
4. Import model geometry.
5. Record ambient conditions and input into program.
6. Set up output file for data collection.
7. Zero the balance with the wind tunnel off.
8. Once recorded forces and moments stop fluctuating, testing may begin.

4.2 Tare Data Acquisition

Before testing the model, tare data is collected to remove the influence of the mount from the test results.

1. Before mounting the model, ensure model geometry and ambient conditions and loaded.
2. Zero the balance with the wind tunnel off.
3. Turn on the wind tunnel.
4. Set the tunnel to the desired velocity.
5. Sweep the angle of attack through testing range.
6. Acquire data at each angle of attack increment.
7. Record data and save the data file.
8. Turn off the wind tunnel.

4.3 Test Data Acquisition

Once tare data has been acquired, test articles can be installed and test cases corresponding to those described in Section 3.0 can be completed.

1. Adjust test article to use correct flap position/strake configuration.
2. Mount the test article to the balance using four bolts on the mount plate (closed loop) or single cross-screw (closed loop).
3. Close and secure the test section door.
4. Open data acquisition program and input ambient conditions and model geometry.
5. Set up output file for data collection.
6. Set the angle of attack to zero/sideslip to desired value.
7. Zero the balance.
8. Turn on the wind tunnel and adjust to desired flow velocity.
9. Set desired angle of attack.
10. Wait for measurements to stabilize, then record data point.
11. Repeat steps 9-10 for each angle of attack required.
12. Turn off the wind tunnel and adjust sideslip angle. Repeat 6-11 for each sideslip angle required (sideslip test only).
13. Shut down the wind tunnel.
14. Save the data file and exit data acquisition program.

4.4 Test Abort Procedure

In the event of emergency, the wind tunnel will be turned off and aircraft removed from the testing mount. This includes any misfunctioning of the wind tunnel, failure of mounting hardware, damage to the scale models, excessive vibrations, software failure, or computer errors.

5.0 DATA ANALYSIS

Each test run will output a CSV file which will be transferred to a flash drive. These output sheets will be converted into plotted graphs to view the aerodynamic data. Tare values will be removed from the data before final graphs are generated using the data provided.

5.1 Output Data

To obtain useful results from the wind tunnel testing, the parameters summarized in Table 5.1 will be used to produce plots describing the aircraft's overall performance.

Table 5.1: Data Analysis Plots

Independent Parameter	Dependent Parameter
α	C_L
α	C_D
α	C_M
α	L/D
β	C_n
β	C_Y
β	L/D
C_L	C_D

This data will allow for the determination of whether the flight test article design meets the mission requirements and if fabrication can begin. Additionally, photos and video of the flow visualization tests will allow for further refinement of the aerodynamic design by highlighting problematic areas of the fuselage and aerodynamic surfaces.

5.2 Design Significance

The test cases using the mechanized wing allow for the validation of 2D airfoil data found using XFLR5, specifically the effect of flaps on the lift and drag curves. As XFLR5 is a relatively simple tool compared to CFD, having reliable data on a flapped wing from wind tunnel testing allows for more confidence in the aerodynamic performance of this feature.

Likewise, the whole-aircraft model will validate the aerodynamic performance of the aircraft that was determined using XFLR5 and hand calculations. XFLR5 simulations neglected viscous effects and do not consider the effects of fuselage-wing interference and shadowing from the fuselage and wing on the tail. Additionally, the simulations completely neglected the fuselage, so the fuselage drag was determined using the drag coefficient of a cylinder. Wind tunnel testing is a much more rigorous way to find the lift, drag, and stability of the aircraft than these simulations.

By performing flow visualization tests, the aerodynamics of the fuselage and its integration with the wing can be validated. The interaction between these components is complex and without CFD analysis is still unknown. By using tufts on the surface of the model, qualitative information about the integration of these components can be obtained to improve the shaping of the fuselage.

These results will allow for the selection of two important design features: flaps on the wing and ventral strakes. If the use of only trailing-edge flaps can increase the wing's $C_{L_{max}}$ to above 2.0, leading-edge flaps can be omitted from the design, simplifying the manufacturing process and design overall. If the inclusion of ventral strakes significantly increases the aircraft's lateral-directional stability without decreasing the overall L/D by more than 0.5, they will be added to the design to improve the aircraft's performance in adverse weather conditions. This would have the added benefit of improving the aircraft's capability to survive a motor-out event, increasing the reliability of the aircraft.

Overall, wind tunnel testing will further validate the aircraft's performance which was determined in the preliminary design phase. This aerodynamic performance affects nearly every other subsystem and is critical to verify before further detail design work. Following this testing, the propulsion system, internal structure, and payload delivery system can be finalized.