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Design of a Prototype Model Aircraft Utilizing Propulsive Airfoil Technology

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4. Introduction

Cross-flow fans (CFFs) are primarily used in buildings and homes for heating, ventilation, and air conditioning (HVAC). CFFs consist of a series of blades proximate to the outer radii of two circular end-plates and are available in various diameters and lengths. The energy added to the flow, provided by cross-flow fans, can be used to push air through ducts in HVAC systems. The Syracuse University Computational Fluid Dynamics (CFD) Lab has been studying the use of these fans to provide thrust for aircraft. Simulations have shown that these devices can also be used to control the flow over airfoils. Research using these fans for propulsion and flow control has to date been very limited.

The most similar contemporary research is currently being done by FanWing Ltd., which was incorporated in August 1999. The FanWing concept utilizes the same type of cross-flow fan, but differs in the way the fan is implemented. The Syracuse University design incorporates the CFF as an embedded propulsor into the trailing edge of a thick airfoil from which the lift is primarily produced by the airfoil geometry. This concept is referred to as propulsive airfoil technology. The FanWing uses a leading edge CFF that accelerates flow over a small trailing surface, relying on the fan as the primary producer of lift.

The configuration proposed at Syracuse University has primarily been studied using two-dimensional computer simulations for incompressible flow using the commercial CFD solver, FLUENT. These analyses have shown significant advantages for using the propulsive airfoil, including improved lift production and stall behavior. These characteristics are consistent with the requirements mandatory for the development of a small, practical aircraft for personal ownership.

The results from the computer simulations have warranted experimental validation of the data. To do so, a scaled extrusion of the two-dimensional propulsive airfoil was built for wind tunnel experimentation. To date, basic visual aids have been used to observe the performance of the propulsive airfoil. Attaching small fibers, or tufts, to the surface of an airfoil in a wind tunnel can reveal if the flow is attached or detached from the wing surface. Preliminary experiments using these tufts have shown that flow attachment is retained at higher angles of attack when the cross-flow fan is rotating. This simply means that the propulsive airfoil can operate in a broader range of angles with respect to the incoming flow than conventional airfoils. This is desirable for aircraft as this configuration can provide six or seven times more lift than modern airplanes.

My contribution, the prototype model aircraft, was researched as a medium for demonstrating the application of propulsive airfoil technology as a feasible source of propulsion and lift production for aircraft. The prototype aircraft, to be piloted by remote control, is approximately a one-tenth scale version of the anticipated life-size aircraft.

5. Project Description

5.1 Design Objectives

The objective of my research project was to design, develop, and fabricate a prototype aircraft utilizing propulsive airfoil technology to demonstrate the expected performance based on CFD simulations and wind tunnel experiments. The successful flight of the prototype aircraft would further validate the research done in the CFD lab at Syracuse University and provide a proof of concept for implementation of this technology.

5.2 Requirements and Constraints

The primary goal has been to show that the aircraft is flyable. Secondary is the demonstration of key performance enhancements of propulsive airfoil technology, therefore placing certain requirements on the prototype aircraft. The aircraft must first demonstrate the ability to maneuver on the ground by utilizing the thrust produced by the rotating cross-flow fans and associated inlet and exhaust nozzles. The aircraft must also take-off and establish stable, level flight. In flight, the aircraft should be maneuverable and controllable. In addition, the aircraft must land safely on the ground. The enhanced performance characteristics to be demonstrated include short take-off and landing as well as flight at high angles of attack.

The design of the prototype was constrained by the size and weight of the aircraft. A reasonable total aircraft weight was estimated at ten pounds.

The calculation to determine that value, derived in detail in section four, was based on maintaining a desired lift coefficient at cruising condition. Constraints imposed by part availability limited the selection of engines, used to drive the fans, to high-performance remote control car engines. The stiffness of the CFF blades and the quality of the bearings limited the operational RPM range of the cross-flow fans. Since three dimensional effects were not studied for this vehicle, it was essential to design the aircraft as 'two-dimensional' as possible.

5.3 Assumptions

It was assumed from the onset of the project that the computer simulations were representative of the true behavior of the propulsive airfoil and of the three dimensional wing. Adverse three dimensional effects were assumed not to have a significant effect on the performance of the vehicle because of the utilization of end-plates to delay the vortex roll-up responsible for decreasing the effective angle of attack and causing induced drag.

6. Conceptual Design

6.1 Approach

This project was approached keeping in mind that the aircraft is a prototype and would need to be robust enough to be modified during flight testing. This was accommodated by making many of the control surfaces adjustable. It was determined that the location of some of the internal components, the batteries and fuel for example, should be as adjustable as necessary if the location of the center of mass (*Cg*) needed to be changed. Adding extra weight in any of the aircraft's empty fuselage sections to further adjust the *Cg* also needed to be made possible if essential.

Keeping the design simple and maintaining similarity with modern aircraft was important, as deviating from conventional designs limits the applicability of typical aircraft flight dynamics concepts. It was decided early to utilize the convenience of employing a fairly conventional aircraft design. The aircraft components, which will be described in greater detail in section four, were designed to maintain this simple design.

The prototype aircraft is configured with a low aspect ratio propulsive wing that also serves as the fuselage and contains the fuel tank, engine, radio, batteries, and servos. The remainder of the available space in the fuselage can be used for adding additional weight to move the *Cg* location as necessary. The horizontal tail, used to keep the aircraft in level flight and for longitudinal control, is oversized to allow the airplane to maintain control when demonstrating the prototype's enhanced, low-speed behavior. The span of the horizontal tail is the same as the propulsive wing, allowing these two wings to be neatly "sandwiched" between two endplates that hold the aircraft together. Two vertical stabilizers are integrated into the endplates. Finally, two small outboard wings, one attached to each endplate, are used to provide roll control.

6.2 Design Variables

The design variables are the aircraft specifications that are changed in order for the aircraft to meet its operational goals. A table of these variables is shown, but not limited to, those in Table 6.1.

Variable	Description	Variable	Description
S	Wing Surface Area	S_t	Tail Surface Area
b	Wing Span	$X_{AC,t}$	Tail Aerodynamic Center Location
c	Wing Chord	b_t	Tail Span
X_{Cg}	Cg Location	c_t	Tail Chord
X_{NP}	Neutral Point Location	S_{OB}	Outboard Control Wing Area
SM	Static Margin		
W	Aircraft Weight		

Table 6.1. *Design variables.*

Selecting the aircraft configuration as well as the airfoils for the horizontal tail and outboard control surfaces were also important decisions made to help meet the goals for the prototype.

6.3 Sensitivities

A sensitivity study is typically done during an aircraft's conceptual design to determine how the design variables affect the performance of the vehicle. For a passenger aircraft, the performance might be quantified by the amount of people the aircraft could carry. Changing the aircraft's technical specifications is likely to affect that figure.

Quantifying this aircraft's performance is less obvious because it is a prototype, or the application of a new concept. It cannot be compared to similar aircraft and is not intended to carry cargo. Rather, the simple goal is to prove the concept, which cannot be measured by any metric.

Instead, it was important to understand the interaction between individual component designs and the sensitivity of one on another. Of critical importance was the longitudinal static stability of the aircraft, which is dependent on the *Cg* location and the aircraft neutral point. Understanding the relationships between these quantities was a design driver and defined the way many of the internal components were implemented and fabricated.

7. Preliminary Design

7.1 Weight Estimation

Aircraft weight estimation was a necessary first step in the preliminary design. With a general understanding of the aircraft components from the conceptual prototype aircraft configuration, a spreadsheet was prepared as a means for cataloging the component weights. Summing these to find the total aircraft weight was done using Eq. 7.1. An estimation of each component location was also tabulated and used to determine the chordwise aircraft *Cg*. Equation 7.2 demonstrates the method employed to make this calculation.

$$W = \sum_{i}^{N} w_i \tag{7.1}$$

$$Cg_x = \frac{\sum_{i}^{N} x_i w_i}{W} \tag{7.2}$$

The results from these analyses are shown in Table 7.1. The complete listing of components weights along with the determination of the *Cg* location is shown in Appendix A.

Total Weight (lbf)	***Cg Location (in)***
7.67	*11.02*

Table 7.1. *Weight and Cg analysis results.*

These numbers, as we will see, are critical flight parameters. The lift provided by the wings needed to overcome the weight of the aircraft, while an appropriate *Cg* location was necessary for longitudinal static stability. Confirming that these two requirements were satisfied was a significant task during the preliminary design period.

7.2 Wing Body Aerodynamic Design

The propulsive airfoil configuration utilized for the prototype aircraft used the same 34% thick modified Goettingen 570 airfoil used for the computer simulations, scaled to a chord length of 20 inches.

The span of the propulsive wing was determined by prescribing a desired cruise lift coefficient between *0.5* and *0.6* at a speed of *40mph*. The lift coefficient is defined as shown in Eq. 7.3.[1]

$$C_L = \frac{2L}{\rho V^2 S} \tag{7.3}$$

For cruising flight, vertical forces are balanced, thus lift equals weight. Assuming that lift contributions from other components are small, we can manipulate Eq. 7.3 to determine the total wing area, *S*. Using a constant chord we can solve for the span, shown in Eq. 7.4.

$$b = \frac{2W}{c\rho V^2 C_L} \tag{7.4}$$

Since the parameters of Eq. 7.4 are known, presuming standard air density at sea level and a chord of *20in,* we can apply the preliminary weight estimate to quantify a range of wing areas. We then find that the wing span should be between *1.87ft* and *2.25ft.* Thus a span of two feet was selected to run at a cruise lift coefficient of *0.56.*

The take-off speed was estimated by determining the velocity at which the propulsive wing could produce sufficient lift. That analysis was based on a maximum expected lift coefficient of 4.0 at 30 degrees angle of attack, which was determined through simulation. We can plot Eq. 7.3 where $L=W$, since the density and surface area are known, to show the required propulsive wing lift coefficient versus flight speed, as shown in Fig. 7.1.

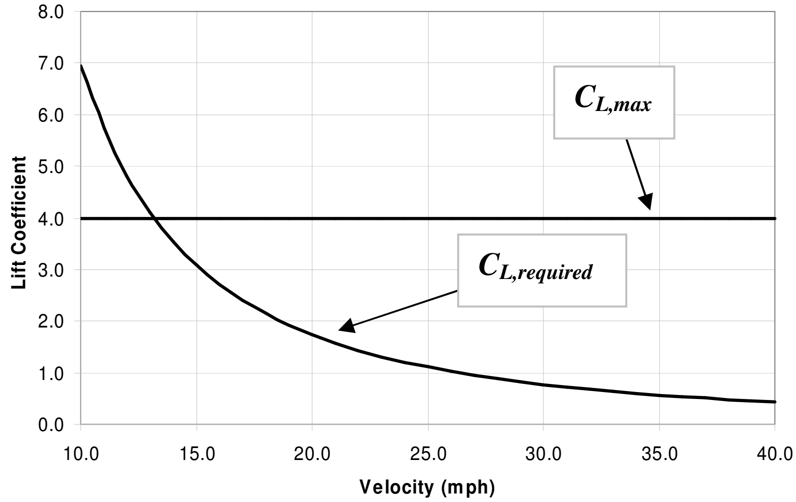

Figure 7.1. *Required propulsive wing lift coefficient versus flight speed.*

In Fig. 7.1, the horizontal line represents the maximum expected lift coefficient and the non-linear curve is a plot of Eq. 7.3, the required lift coefficient. Thus, the intersection of these two curves identifies the velocity at which sufficient lift for take-off is attained, which occurs at *13mph*.

The airfoil has been shown through simulation to achieve higher lift coefficients when the outflow from the fan is vectored such that a component of the thrust is in the lifting direction. This feature, however, present on the prototype, adds complexity to flying the model and was not considered for use other than to demonstrate low-speed flight.

The wing, which acts as the aircraft fuselage because of its large interior volume, has neither taper nor twist. This was done, assuming three dimensional effects can be minimized, to ensure two-dimensional flow into the fan inlet. This was a requirement outlined in the requirements and constraints section because only two-dimensional simulations have been run to model the behavior of the propulsive airfoil.

7.3 Wing Body Structural Design

The extreme thickness of the propulsive airfoil, as compared to airfoils used on conventional aircraft, was taken advantage of to save overall weight without compromising strength or rigidity. A high moment of inertia, representative of the resistance of an object to distortion, can be obtained by placing material far away from the bending axis.

For most wings, minimizing weight is difficult because airfoil thickness is typically limited to 10% to 15% of the chord length for aerodynamic purposes, thus limiting the size of main wing spars. They are, however, still required to sustain loads produced by longer wings that experience greater bending moments. Noting the relationship in Eq. 7.5, it follows that the wing spar experiences the greatest axial stress when the bending moment is large and the moment of inertia is small.

$$\sigma_x^B(x) \propto \frac{M_z(x)}{I_z(x)} \tag{7.5}$$

In Eq. 7.5, $\sigma_x^B(x)$ is the axial bending stress at location x, $M_z(x)$ is a function that defines the bending stress at each axial location along the beam, and $I_z(x)$ is the moment of inertia about the bending axis. Modeling the structure of the wing would have been exceedingly complex and therefore no analysis was done to calculate the actual stresses in the propulsive wing structure.

Instead, a comparison of the prototype wing design to that of a conventional model aircraft wing was made. The maximum allowable material stresses are equal, assuming the same materials and construction techniques would be employed as when building a traditional model airplane.

Thus, the right hand side of Eq. 7.5 must be maintained or minimized so as not to exceed the stresses encountered by typical model airplanes. Noting that the bending moment for short wings is small and the moment of inertia of the propulsive wing is larger than that of model airplane wings, we find the right hand side of Eq. 7.5 is smaller than for conventional RC airplanes. Thus, we can justify employing common building practices to maintain structural integrity of the prototype aircraft by this simple comparison.

Torsional rigidity was not addressed by this analysis and was determined to be a concern after the final design. The effect of torsional distortion was mitigated during the building process by adding truss members near the surface of the wing to the wing structure.

7.4 Propulsion System Design

The CFD simulations suggested that ¾ to 1 horsepower would be required at approximately 5,000-10,000 rpm to achieve the desired fan performance. An appropriate nitro-methane burning, remote control car engine was selected that could provide 2.0 hp at 32,000 rpm. The engine was overpowered to provide a factor of safety, the cost of which was only an increase in weight of two ounces.

For stability, which will be discussed later, the engine needed to be placed as far forward as possible. The propulsion system configuration was designed to accommodate this requirement, shown in Fig. 7.2.

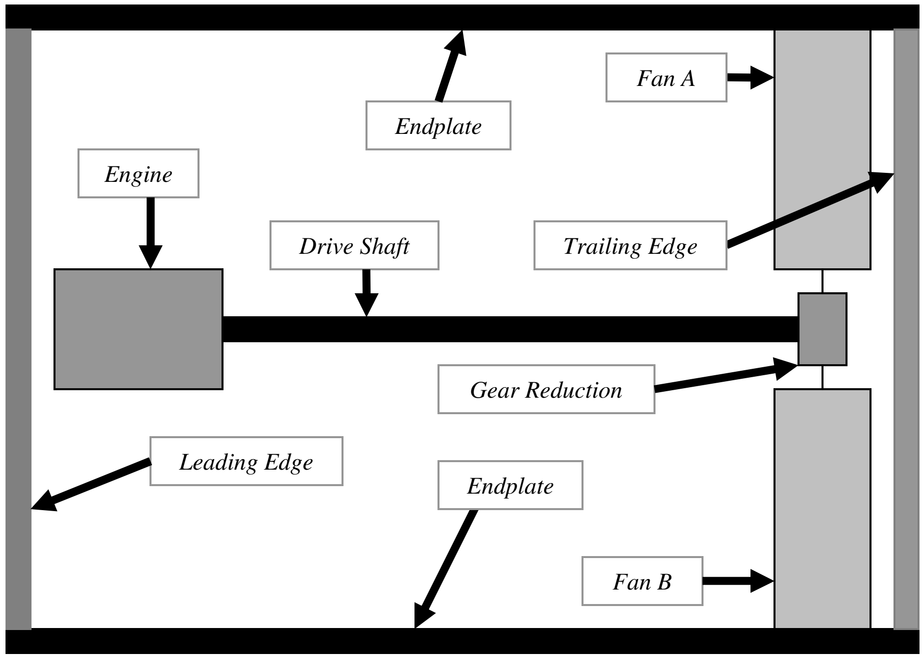

Figure 7.2. *Propulsion system configuration.*

As shown, two fans are placed along the full length of the wingspan, separated by a gear reduction, whose purpose is to provide the peak power output to the fans at the correct fan rotation speed, determined through simulation. The gear reduction boxes available only provided 3:1 reduction ratios. At full throttle, the fans would then be spinning at 10,000 rpm, which is high for many of the propulsion system components. Thus, the cross-flow fans were modified by adding wire straps midway down the cylindrical device to reduce bending, which was a resultant of high blade loading at high speeds. The gear reduction and engine are connected by an aluminum drive shaft that is supported midway down the shaft with a bearing.

7.5 Tail design

The tail design was intended to meet two critical operational requirements. First, it was necessary to choose an appropriate area for the tail to operate at reasonable lift coefficients during take-off, climb, cruise, and during low-speed flight. Specifically, the tail needed to be large enough to balance the aircraft pitching moment at low speeds. Appropriately sizing the horizontal tail and selecting an airfoil section were also necessary to achieve a positive aircraft static margin.

Maintaining a span of two feet, the required tail chord length was determined in much the same way the propulsive wing span was found. Summing moments about the *Cg* at cruise speed revealed the required restoring moment required from the tail. The airfoil pitching moment, location of the center of pressure of the wing relative to the *Cg*, and the thrust all contributed to the aircraft pitching moment. Similar to the analysis done using Eq. 7.4, we can determine the tail chord length required to maintain level flight, shown in Eq. 7.6.

$$c_{tail} = \frac{2F_T}{\rho b V^2 C_{L,T}} \tag{7.6}$$

In Eq. 4.6, ρ is the air density at sea-level and $C_{L,T}$ is the desired tail lift coefficient of *0.33* at cruise velocity. The parameter F_T is the tail force necessary to balance the aircraft pitching moment if the tail is at fixed position, $\left(c \cdot \overline{X}_{AC,T}\right)$, where $\overline{X}_{AC,T}$ is the distance from the wing aerodynamic center (AC) to the aerodynamic center of the tail, normalized by the wing chord length, *c*. A chord length of *7in* was calculated by plugging these parameters into Eq. 4.6.

The aircraft can only take-off when the tail can provide pitch control to maintain attitude. Thus it was important to determine the speed at which pitch control could be established. That analysis was based on a maximum expected lift coefficient of *1.5* for a plain flap elevator.[2] We can plot Eq. 7.7, since the density and surface area are known, to show the required tail lift coefficient versus flight speed.

$$C_{L,tail} = \frac{2F_T}{\rho V^2 S_{tail}} \tag{7.7}$$

In Fig. 7.3, the horizontal line represents the maximum expected tail lift coefficient and the non-linear curve is a plot of Eq. 7.7, the required tail lift coefficient. Thus, the intersection of these two curves identifies the velocity at which sufficient lift is attained to maintain attitude control, or the stall point, which occurs at *17mph*. Thus the take-off rotation velocity can be no less than 17*mph*. At cruise, the tail lift coefficient is approximately *0.37*.

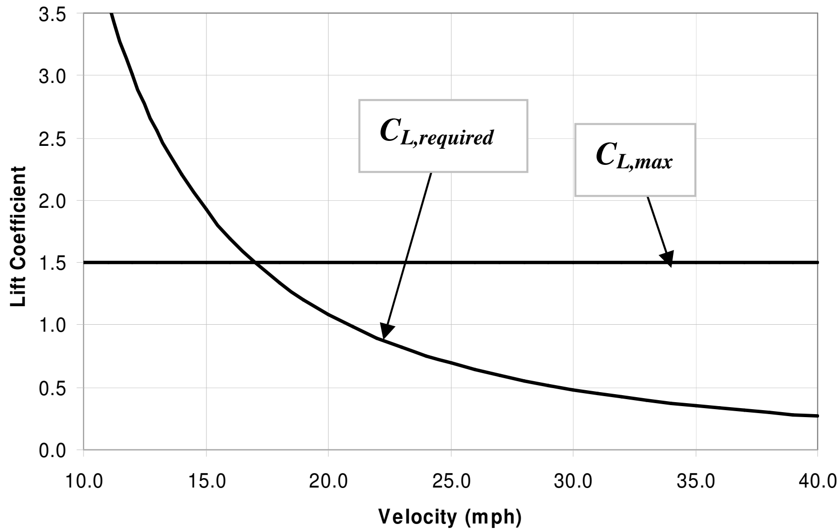

Figure 7.3. *Required horizontal tail lift coefficient versus flight speed.*

Aircraft longitudinal static stability is determined through consideration of an aircraft's pitching behavior. An aircraft cruising in stick-fixed straight and level flight should tend to return to its cruise condition after any perturbation in pitch. In terms of the aircraft pitching moment coefficient, shown in Eq. 7.8,

$$\frac{\partial C_m}{\partial \alpha} < 0 \tag{7.8}$$

the slope of the aircraft pitching moment coefficient versus angle of attack curve must be negative.

A location exists for every aircraft where the inequality in Eq. 7.8 is exactly zero, called the neutral point. If the *Cg* is located at the neutral point, the aircraft is said to have neutral longitudinal static stability. The neutral point can be calculated using Eq. 7.9.[3]

$$\bar{X}_{NP} = \frac{\bar{X}_{AC\,wf} + \frac{C_{L\alpha h}}{C_{L_{\alpha wf}}} \eta_h \frac{S_h}{S} \bar{X}_{AC_h} \left(1 - \frac{d\varepsilon}{d\alpha}\right)}{1 + \frac{C_{L\alpha h}}{C_{L_{\alpha wf}}} \eta_h \frac{S_h}{S} \left(1 - \frac{d\varepsilon}{d\alpha}\right)} \tag{7.9}$$

It can also be written as shown in Eq. 7.10.[3]

$$\bar{X}_{NP} = \frac{\bar{X}_{AC_{wf}} + \frac{\partial C_{L_h} / \partial\alpha}{\partial C_{L_{wf}} / \partial\alpha} \eta_h \frac{S_h}{S} \bar{X}_{AC_h} \left(1 - \frac{\partial\varepsilon}{\partial\alpha}\right)}{1 + \frac{\partial C_{L_h} / \partial\alpha}{\partial C_{L_{wf}} / \partial\alpha} \eta_h \frac{S_h}{S} \left(1 - \frac{\partial\varepsilon}{\partial\alpha}\right)} \tag{7.10}$$

Static stability is often defined by the static margin, which is the distance between the aircraft neutral point and *Cg* location, normalized by the wing chord length. A positive static margin occurs when the *Cg* is forward of the neutral point. Typically, a minimum static margin of 5% is acceptable for highly maneuverable aircraft. It is recommended, however, that a 10% positive static margin exist for most aircraft.

The terms in Eq. 7.10 were generally known for the prototype aircraft, obtained from published data and CFD simulations, with the exception of $\partial\varepsilon / \partial\alpha$, which describes the change in downwash angle with angle of attack. Estimating a reasonable range of values for $\partial\varepsilon / \partial\alpha$ allowed for a calculation of a range for the aircraft neutral point, which was calculated to be between 12*in* and 16*in* aft of the aircraft leading edge – the forward most point on the aircraft. From this, using the calculated aircraft *Cg* location of 10*in* aft of the leading edge, the minimum and maximum static margins were calculated, as shown.

$$SM_{\max} = \frac{X_{NP,\max} - X_{CG}}{c} = \frac{16in - 10in}{20} = 0.3$$
$$SM_{\min} = \frac{X_{NP,\min} - X_{CG}}{c} = \frac{12in - 10in}{20} = 0.1$$

Thus, it was determined that the aircraft has positive static stability. This analysis did not consider the contribution from the outboard control surfaces. Since these control wings are small and only slightly aft of the aircraft Cg their effect on the neutral point location and on the static margin is negligible and could only improve the static margin.

It is important to recognize inherent limitations to the application of this concept to the prototype aircraft. Any assumptions in the derivation of these equations must be considered, as they may invalidate the results of this analysis for this particular configuration. In doing so, we find that it was assumed that the aircraft pitching moment coefficient is only a function of angle of attack. For the prototype aircraft, the pitching moment is also a function of the fan rotation speed. If the fan rotation speed is held constant, however, it does not affect the aircraft longitudinal static stability. Regardless, we must recognize that the prototype aircraft is susceptible to fluctuations in the aircraft static margin when the fan rotation speed, or throttle setting, is changed. Thus it is not recommended to rapidly change throttle settings during flight testing, at least initially, until this relationship is better understood.

7.6 Endplate design

The endplates were designed for two purposes. They were to provide airframe rigidity and also to delay the vortex roll-up produced by the low aspect ratio propulsive wing, so as not to affect the flow uniformity at the inlet to the cross-flow fans.

Structurally, the end plates were designed to have three layers. Aircraft grade microlite plywood was used for the two outer layers to provide stiffness and rigidity to the aircraft. The inner layer was designed of lightweight balsa to minimize the mass of the endplates. Various cuts through the three layers, at various locations, were determined to be possible without compromising rigidity, as a weight saving measure.

Vortex roll-up, which is more prominent in low aspect ratio wings, occurs because of the steep pressure gradient at the wingtips. As an aerodynamic tool, the endplates extend approximately one inch beyond the wing surface at each end of the wing to help delay vortex roll-up aft of critical components of the propulsion system.

7.7 Outboard Control Surfaces Design

Two outboard wings were included for roll control. Sizing of the outboard wings was somewhat arbitrary, because of the unconventional nature of the prototype. Similarly, sizing these control surfaces with those on model airplanes was done in the absence of a relationship to correlate the outboard wing area with the aircraft roll rate. If the outboards are considered insufficient during flight testing, they can be removed and replaced with larger control wings.

The placement of these outboard control surfaces was an important consideration, because these small wings produce forces in all three directions. To limit the coupling of pitching and rolling, the outboards were placed near the aircraft *Cg*.

Adding dihedral to conventional aircraft gives a v-shape to the wing when looking from the front. The vector components of a banked wing with dihedral produce a restoring moment, acting as a source of roll stability. Five degrees of dihedral was added to the outboards to provide roll stability as is typical.[2]

8. Final Design

8.1 CAD Model of Aircraft

The prototype aircraft CAD models were generated as a tool for visualizing the final product, understanding how components were to be assembled, and as a means for recognizing possible production issues. Two computer models were generated using PTC Pro|Engineer during the preliminary and final design phases.

A solid model was first generated during the preliminary design, shown in Fig. 8.1, as a means for visualizing the appearance and configuration of the prototype.

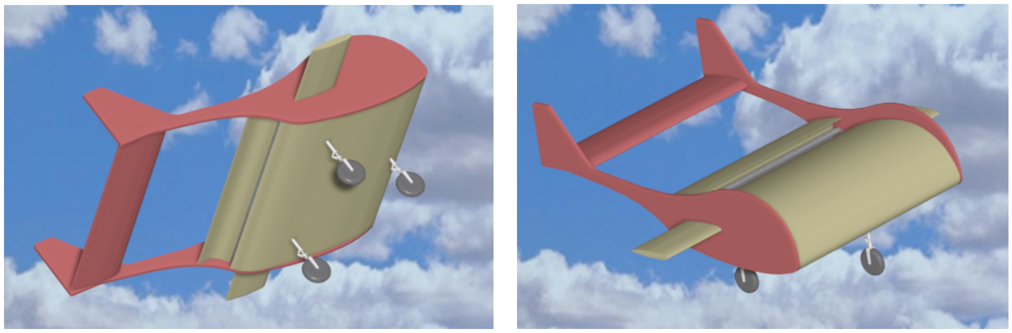

Figure 8.1. *Preliminary solid CAD assembly.*

The preliminary solid model was useful when determining the placement of the aircraft components, such as the horizontal tail, landing gear, endplates, outboard control surfaces, and the CFF housing. It was also used to identify necessary changes for the final CAD model.

The final CAD model, shown in Fig. 8.2, is representative of the final aircraft design. As shown, the entire structure was modeled by the assembly of the collection of parts necessary to build the aircraft, rather than the solid model generated during the preliminary design. The skin of the aircraft has been removed in this model to reveal the structural members of the prototype and the cross-flow fans.

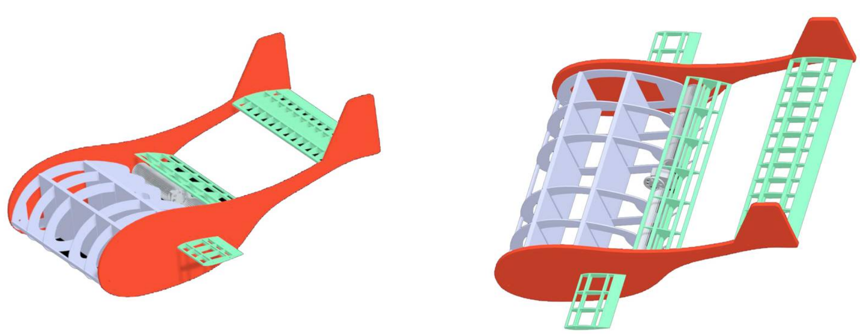

Figure 8.2. *Final CAD assembly.*

The parts, which were also modeled in Pro|Engineer, were converted to two-dimensional objects and printed using the College of Engineering's 36"x 36" plotter. These drawings were used as templates for cutting the structural components during production. These two-dimensional drawings can be found in Appendix A.

8.2 Manufacturing Process

Fabrication of the prototype aircraft began at the end of August 2004, after the completion of final CAD model. A team of experienced student hobby-modelers was established to aid this process. The manufacturing process can be grouped into three categories; the acquisition of materials, fabrication of the components, and the assembly of these components into the final aircraft.

It was first necessary to determine the materials to be obtained and from whom they could be purchased. Most of the components were ordered from internet-based hobby stores and the remainder from local hobby shops. The items that were purchased and the manufacturers are shown in Fig 8.3. Less important pieces, such as screws and connecters, were omitted from this list simply because of the quantity of such types of items.

Item	Manufacturer	Item	Manufacturer
6 Ch. Radio Package	Futaba	Fuel	Tower Hobbies
GS-P01 0.21 Buggy Engine	GS Engines	Servos	Futaba
Tuned Pipe	Traxxas	1/8" Microlite Birch Ply	Midwest Products
Wheels (2 per set)	Dubro	3/16" Balsa	Midwest Products
DuBro Nosegear Strut	Dubro	3/8" x 3/8" Balsa Spars	Midwest Products
Landing Gear Wires		3/16" x 3/16" Balsa Spars	Midwest Products
Fuel Tank	Dubro	1/32" Sheet Balsa	Midwest Products
Gear Reduction		Bearings	
CFF	Eucania	1/4" Aluminum Drive Shaft	
Sig Bond Glue (8 oz.)	Sig	MonoKote (6' x 26")	MonoKote
MonoKote (6' x 26")	TopFlite		

Figure 8.3. *Parts list.*

The construction process began by cutting parts for each of the main structural components of the aircraft using the full scale versions of the two-dimensional engineering drawings in Appendix A. These parts were manufactured using scroll saws, handheld rotary tools, hobby knives, and sandpaper.

Assembling the parts into the aircraft components (e.g. the endplates, outboard wings, propulsive wing, horizontal tail, and the CFF housing) began after each of the parts was built. At the same time, these components were assembled onto the aircraft. This was done using wood glue, epoxy, and cyanoacrylate (CA glue). Putting the components together was relatively simple, but the order of assembly of the entire vehicle was critical, thus causing delays. Modifications to specific aircraft components delayed the assembly of other components.

9. Flight Testing

The first goal of flight-testing is to taxi, showing that the thrust produced by the cross-flow fans is sufficient enough to propel the aircraft. Initially, taxiing on pavement is preferable, as opposed to grass, because grassy surfaces tend to be very rough. Taxi speeds increase slowly over a few tests until the airplane produces considerable lift and begins to hop. At this point, the elevator should be fluctuated up and down to determine the elevator control effectiveness without taking off. This is done to determine the speed at which the elevator establishes pitch control.

Quick touch-and-go's, only flying a few feet above the ground, are possible when the elevator control speed has been determined. It is important not to try to take off before the tail can produce a sufficient restoring moment to balance the aircraft's natural pitching tendency for controllability. Naturally, this type of testing requires a long runway. This phase of testing of the prototype aircraft will take place at a class E uncontrolled civilian airport. No roll or yaw maneuvers should be attempted at this point.

Small roll maneuvers can be attempted after having established short periods of straight level flight. More dramatic turns can be attempted when the pilot becomes reasonably comfortable with the aircraft performance. Time should be spent performing simple maneuvers to get familiarized with the aircraft.

Low-speed flight can be tested by establishing cruise, vectoring the thrust, reducing throttle, and pitching up as necessary to maintain altitude. This should be done in a series of tests at increasingly slower speeds.

10. Summary

The design and construction of the first model aircraft utilizing a propulsive wing is a milestone in the development of the propulsive airfoil technology. This first generation prototype plays a critical role as a link between research, which revealed the enhanced performance characteristics of this technology, and its application.

Simple analyses during the conceptual, preliminary, and final design phases of the prototype aircraft development showed that the propulsive airfoil concept could be feasibly applied to a compact aircraft configuration. It also exposed areas of uncertainty that could not be addressed directly using conventional aircraft flight mechanics concepts. Flight testing, which serves as a proof of concept for the application of this technology, also provides the opportunity to explore these unknowns and evaluate the flight performance.

Future generations of aircraft utilizing this technology will be developed based on the successes and failures of the first prototype. Changes will be made to improve upon weaknesses found during testing. These revisions will boast improved performance and will be optimized to demonstrate the use of the propulsive airfoil technology for specific purposes and missions. Specifically, each addition to the family of propulsive airfoil prototype aircraft will serve as another step toward advancing this technology as a means for personal air transportation.

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