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Application of Mathematics-Fabrication of Box Wing Plane

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ABSTRACT: This paper deals with the design of a Box-Wing UAV from scratch and comparing it with a conventional UAV using only simulation results.

Constraints such as volumetric, payload capacity and flight velocity were defined. Detailed design process was initiated by selecting the type of airfoil through Analytic Hierarchy Process (AHP) trade-off. This continued with the design of wing and winglets using the software tool XFLR5. Static and dynamic analyses were performed and this process repeated until optimal design was obtained. These satisfactory results paved way for the fabrication of box wing**.**

The best airfoil for the box wing was found to be MH78. The static stability was achieved with a margin of 25%. The drag coefficient of conventional plane was found higher at 4.70e-2 than that of the box wing plane which is 1.17e-2. Using CFD analysis the lift was found to 6.97N and the drag was found to be 1.93N. The wing structure was designed using balsa wood ribs and carbon fibre spars. On conditions of loading, maximum stress was found to be 29.55 MPa which was well within the permissible level for the selected material. The plane successfully met the criteria of load test and drop tests. A concrete procedure is developed for the design and fabrication of box winged micro UAV. As a future scope, theoretical estimation of the aircraft performance is suggested. Upon satisfactory evidence of stable performance over expected operational domain, a prototype can be built, tested and validated.

Key words: Fabrication**,** Unmanned Aerial Vehicle (UAV), Oswald’s efficiency factor, Reflexed Airfoil, Box Wing, AHP trade-off, Wing design.

1. INTRODUCTION

Model planes or unmanned aerial vehicles (UAV) are those which fly with indirect human control and are guided and controlled by a remote device. The casualties due to natural disaster and public unrest during recent war times have promoted the use of remote sensing and aerial surveillances. Hence, these UAVs have emerged as an alternative in such instances where they are capable of capturing high definition images and videos, apart from feeding real-time data to the controlling base station in all weather conditions. Their features such as easy flight over large distances, ease of transportation and assembly, smooth and simple operating procedure along with less operation and maintenance cost are attracting their usage and commercialization. These characteristics have created a great demand for commercial model planes, thereby garnering the interest of the industries.

This reduction in angle of attack results in a local reduction inthe angle of the lift vector relative to the incoming velocity vector and produces an induced drag.For a closer look into induced drag, equation 1.1 for induced drag component can be separately written as

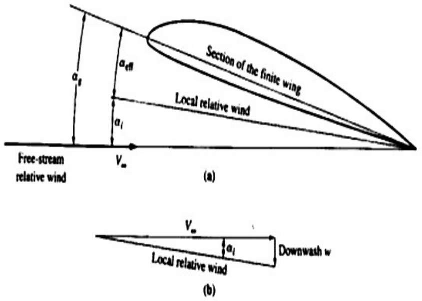

Figure 1.1: Illustration of induced and effective angle of attack caused by downwash

$$C_{D_i} = \frac{C_L^2}{\pi e AR} \qquad (1.1)$$

Where,

C_{D_i} = Induced Drag Coefficient

C_L = Lift Coefficient

e = Oswald's efficiency factor

AR = Aspect Ratio

Oswald's efficiency factor or span efficiency factor accounts for the non-optimal lift distribution along the span. It can be seen that the coefficient of drag depends mainly upon parasite and induced drag while compressibility drag is only present in the transonic and supersonic flight regime and thus has no contribution to the complete drag budget.

2. LITERATURE SURVEY

Prandtl's [1] `best wing system' showed that a closed rectangular lifting system would produce `the smallest possible induced resistance for a given span and height'. Prandtl established that all biplanes have less induced drag than the equivalent monoplane when the spans are equal and that biplane drag decreases as wing gap increases. Frediani [2] states that for a box wing or Prandtl Plane as he calls it, the aerodynamic efficiency is strongly linked to stability of flight and the challenge is to obtain a stable aircraft with equal lift on both wings which is the condition for Prandtl's `best wing system'.

Aldo Frediani [2][3] and Rizzo [4]say that the Prandtl [1] Plane configuration has the potential for achieving, simultaneously, the top level objectives which include

- *Strengthening the competitiveness of the manufacturing industry in the global market* (more economical, safe, clean and better quality aircraft could be designed).
- *Improving environmental impact with regard to noxious emissions and noise* (the Prandtl Plane concept is based on an increase of aircraft performances during cruise flight and low speed flight).
- *Improving aircraft safety* (Damage Tolerance properties of wing structures, pure moment pitch control, total separation of engines, fuel separation, smooth stall, etc.).

Most of the literature on joined/box wing aircraft is credited to Wolkovitch [5][6][7][8] but prior to this time, work was carried out on similar concepts by Prandtl [1]. However, it was Wolkovitch who published the initial extensive work on the concept and he is quoted by most researchers of the joined/box wing aircraft configuration. Wolkovitch views the joined/box wing aircraft configuration as a highly integrated concept that connects structural and aerodynamic properties in novel ways.

Wolkovitch [6] sums up airfoil issues by stating that the use of off the shelf monoplane airfoils for such configurations is disadvantageous and is no longer necessary in view of the current state of airfoil design technology. He also states that because the effective beam depth, d, of a joined/box wingis primarily determined by the chord of its airfoils as sketched in Figure 1, their thickness is secondary making joined/box wings suitable for thin airfoils. This means lower weight penalties than for a cantilever wing. He suggests the use of twin fins of approximately 60 degrees dihedral to reduce the unsupported column length of the aft wing. The use of twin fins for joined/box wing aircraft is also subscribed to by **Frediani** [3]. Apart from structural reasons, Frediani [4] highlights the enhanced aerodynamic efficiency of the configuration due to the aerodynamic channel defined by the top of the rear fuselage, aft wing under surface and the twin tail; although special design of this portion is required for the claimed efficiency.

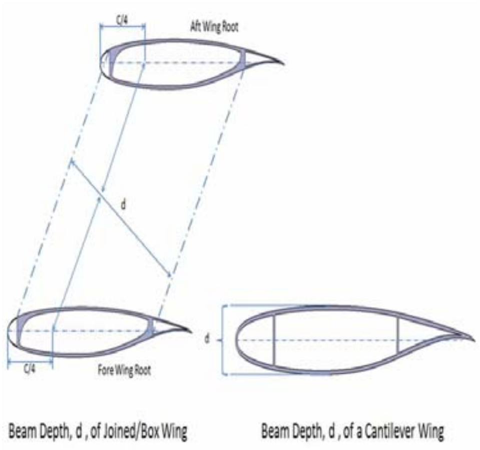

Figure 1: Comparison of beam depths of

Box wing and cantilever wing

3. METHODOLOGY

3.1 Top Level Design Approach

Before starting the design of plane, the constraints that should be met by the design were fixed. These constraints helped by providing the minimum standard for thedesign.One of the most important constraints that was thought of is the volumetric constraint in which the plane should fit in. Through literature survey, a cubical volumetric constraint of 1m×0.75m×0.2m was fixed. Apart from this the plane had to weigh around 750 grams including the planes empty weight and should fly at an approximate velocity of 15m/s. The main challenge was to stabilize the plane in pitch. Since the box-wing configuration does not have a separate horizontal stabilizer to balance the negative moment produced due to the camber of the airfoil, the team found two alternatives through literature survey:

1) Geometric Twist, positive cambered airfoil. 2) Reflexed Airfoil.

An analytic hierarchy process (AHP) trade-off was done to find the better of the two. Depending upon the result of the previous tradeoff five airfoils were selected by conducting a literature survey. The best airfoil as per the requirement was selected. The AHP trade off method itself was used again for selecting the best airfoil. Once the airfoil was finalized the dimensions of the aircraft such as span, chord etc. were fixed such that the wing had enough area that it could carry sufficient payload at a required velocity. The stability of the plane had to be taken care of. This was the most complex step in the design of a box wing aircraft, because for pitch stability; the positive moment is increased either by increasing the reflex of the airfoil, or by giving geometric twist. Both the steps lead to decrease in the lift coefficient thereby reducing the payload capacity. To compensate the decrease in lift coefficient camber of the airfoil was increased, then the pitch moment coefficient would be negative thereby making the aircraft unstable in pitch. Apart from this two suitable vertical stabilizers were designed in order to make the plane directionally stable.

Figure 2.1: Top level design approach. The specifications of the aircraft are as shown in Table 3.1

Table 3.1: Specifications of the aircraft

Sl. No:	**Category**	**Requirement**
	Wing	Fixed Wing only
	Dimensions	Aircraft must fit in a box of size 1 m X 0.75m X 0.2m
	Aircraft Systems • Propulsion • Structure • Power	Electric motor only Weight 700g Thrust of 10N
	Payload requirements	Aircraft must carry at least 200 gm of payload leading to a total weight of 700 gm

4. FABRICATION OF BOX WING PLANE

Material for the fabrication was selected based on stresses at different parts of the plane obtained through analysis done in the previous chapter. This chapter deals with the fabrication of the box wing plane. The plane was then fabricated as per the designed structure.

Material Selection

The choice of materials depends on following factors:

i) Strength to weight ratio ii) Availability and Cost
iii) Impact resistance iv) Ease of Fabrication

Based on these factors, the properties of following materials are studied and material for fabrication is finalized.

4.1 Balsa

The scientific name of balsa wood is Ochroma Pyramidale. Balsa is a naturally available material that excellent ability to form lightweight aircraft structures. It is the prominent building material in wooden designs, but it requires high skills. Although light weight and strong, it splinters and requires a lot of maintenance andlessdurability.Itisstrongerforitsweightthananyothermaterialexceptforcertainalloy steels. Its strength to weight ratio and stiffness to weight ratio is high. Balsa also absorbs shock and vibration to a good extent. Due to its porosity, it very readily deteriorates when exposed to moisture.

Cost: Rs.498 per sheet of 5mm×960mm×100 mm

- Working Temperature : -80 C to 120 C
- Strength to Weight Ratio: 108 kN-m/kg

The mechanical and thermal properties of Balsa are as shown in Table 3.1.

Table 4.1: Mechanical Properties of Balsa

Compressive Strength Low	4.7MPa 12.1MPa 19.5MPa
Tensile Strengt	7.6MPa 19.9MPa 32.2MPa
Elastic Modulus –Compression Elastic Modulus –Tension	460 ± 71MPa 1280 ± 450MPa

[Low Density=75kg/m³; Medium Density=150kg/m³; High Density = 225 kg/m³]

4.2 Carbon Fiber

Carbon fiber has special properties making it attractive for use in aerospace and automobile industry. Carbon parts are lighter and stronger than some of their metal counter parts. Hence, carbon fiber is being extensively use d in the aerospace industry. High-end vehicles are using carbon to develop one piece vehicle frames. Carbon fiber construction has excellent strength and stiffness at a lower density than traditional metal materials. The high temperature epoxy resins with which the fibers are cured are highly resistant to water, fuel, anti-freeze, and solvents which might cause wear or deterioration and they can be protected from ultraviolet radiation using the same paint finishes used on metallic airplane components.

Carbon fibre tube is used to replace aluminium or steel tubes in a wide range of projects. Its superior mechanical properties mean that tubes of the same weight as an aluminium or steel tube are much stronger. This tube is manufactured using high modulus pre-preg carbon fibre oriented to provide maximum strength in the lateral direction (length-ways).The mechanical properties of the carbon fibre tube are as shown in Table 3.2.

Table 4.2: Mechanical Properties of Carbon fibre hollow tube

Tensile Strength	200 Mpa
Tensile Modulus	40 Gpa
Flexural Strength	700 Mpa
Flexural Modulus	38 Gpa
Compressive Strength	380 Mpa

Cost: Rs.225 for 5mm hollow tube of thickness 1 mm, length 750mm.

4.3 Polycarbonate

Polycarbonates (PC) are a particular group of thermoplastic polymers. Polycarbonate is a durable material. It has **highest impact-resistance** among plastics and has low scratch-resistance. It is usable over a greater temperature range and is highly transparent to visible light, with better light transmission than many kinds of glass. Its characteristics are:

- excellent physical properties
- excellent toughness
- very good heat resistance
- fair chemical resistance

The mechanical and thermal properties of the polycarbonate sheet are as shown in Table 3.3. Cost: Rs.350 per sheet of 5mm×1000mm×1000 mm

Table 4.3: Properties of Polycarbonate sheet

Tensile Strength	70 MPa
Notched Impact Strength	60 – 80kJ/m²
Working Temperature	40 C to 120 C
Strength to Weight Ratio:	55 o 99 kN m/kg

4.4 Depron

Depron is an extruded polystyrene foam product in the form of sheets. It is extremely lightweight and resistant to moisture. Depron has a wide variety of uses such as food packaging, wall insulation, but more recently in modeling due to its light weight and rigidity

The applications of Depron are as follows:

- **Model Aircraft**& Boats
- **R/C Aircraft**
- Architectural Models

The mechanical and thermal properties of the Depron foam are as shown in Table 3.4.

Table 4.4: Properties of Depron

Application Temperature	-60°C to 70°C
Compressive Stress	0.15MPa
Tensile Stress	1.30Mpa

Cost: Rs. 600 per a sheet of

6mm×625mm×400 mm

4.5 Styrofoam

Styrofoam is closed-cell extruded polystyrene foam widely used for thermal insulation and craft applications. It is owned and manufactured by The Dow Chemical Company. It is composed of ninety-eight percent air, making it lightweight and buoyant.

The mechanical and thermal properties of the Styrofoam are as shown in Table 3.5.

Cost: Rs.400 per sheet of 25mm×600mm×600 mm

Table 4.5: Properties of Styrofoam

Tensile strength	0.45Mpa to 1Mpa
Compression Strength	0.35Mpa to 0.4 Mpa
Working temperature	50 C to 75 C

Based on the above study, Balsa was selected for airfoils because of its high strength to weight ratio was selected for aerofoils. Also, the ease of fabrication with Balsa led for its selection. The low moisture resistant Balsa requires it to be covered with a special moisture resistant sheet called Monokote.

- Since high stresses were observed at rods placed in the internal structure during stress analysis, 5mm carbon fibre rods were used as major internal support structure for aerofoils.
- Since this micro UAV is hand-launched and does not employ a landing gear, it is important that it undergoes minimal damage in these stages where the impact loads are significant. Hence, polycarbonate, which has high impact resistance, is used as material for fuselage construction.
- Depron foam and Styrofoam, although lightweight, were rejected due to very low tensile strength and less working temperature range compared to other materials.

4.6 Fabrication Process

The plane is designed to be hand launched and belly landed. Therefore the major load is taken by the fuselage. Polycarbonate has a higher strength compared to balsa and hence it was used to make the fuselage.

Hollow polycarbonate sheets which are easily available and commonly used for roofing were procured and used to build the fuselage. The sheets were later cut as per the dimensions and were glued to each other using Cyanoacrylate 777P and saw dust was used for to increase the bonding strength.

Conventionally, model planes have a separate wing and fuselage. Since the designed airplane has a mid-wing, the wing and fuselage cannot be fabricated separately. Therefore the following method was adopted.

Figure 4.1: Fuselage fabrication using hollow polycarbonate sheet.

Once the fuselage was completed, holes were drilled through the sides of the fuselage in order to pass through the carbon rods which act as spars for the wings. The hollow sheets when drilled did not provide enough support for the carbon rods, hence 5mm balsa wood sheets were fixed on the inner side of the fuselage. This concluded the fabrication of the fuselage. Figure 4.1 shows the fabricated fuselage.

Once the fabrication of the fuselage was completed the next step was to fabricate the wings. As decided earlier in the internal structure design the ribs were to be manufactured using balsa wood. The ribs were therefore laser cut out of the 3mm sheets of balsa wood. In order to laser cut the airfoils, the airfoil profile had to be represented on a software called CorelDraw. This was done by exporting the airfoil profile from SolidWorks to DFX file format.

The airfoils profiles were closely placed such that least amount of balsa wood was wasted. The lower wing was fabricated first, the laser cut airfoils along with carbon rods were precisely placed.

The ribs and spars were reinforced with leading edge and trailing edge. Apart from reinforcement, these sheeting of balsa are responsible for providing a profile shape of the airfoil with the monokote covering. The 1mm sheet is first wetted in water to provide the required flexibility in order to cover the full leading edge of the wing. Figure 4.2 shows the wing with leading and trailing edges.

Figure 4.2: Leading edge and trailing edge of the bottom wing

Monokote gets bonded on other surface when it is heated over the surface on which it has to be applied. Monokote was used to cover the complete wing using an iron box to apply heat. The bottom wing being completed the fabrication of the top wing was started. The airfoils were again laser cut and the skeleton of the wing consisting of spars and ribs was completed. Figure 4.3 shows the plane in this phase of completion.

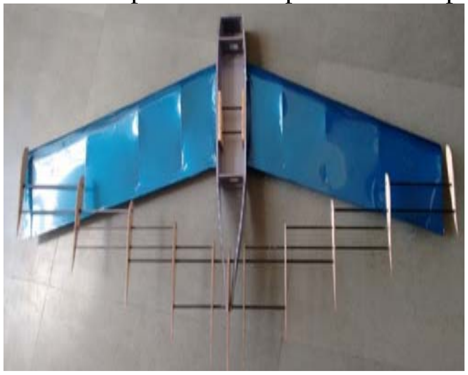

Figure 4.3: Spars and ribs of top wing.

The elevons are to be provided for the upper wing. Therefore the trailing edges of the airfoil where the ailerons are to be provided, are cut by 4cm from the tip. An additional spar of cross-section 5mm×5mm is fixed at the rear end of the remaining section of the back wing which functions as a hinge holder for the elevon. A leading edge is also provided in a similar way as provided to the bottom wing. Figure 4.4 shows the plane at this stage.

Figure 4.4: Skeleton of the top wing before fixing elevon.

The elevons are next fabricated using the trailing edges that were cut from the wing earlier. The trailing edges that were cut are first fixed on a spar of 5mm×5mm of balsa wood. Then trailing edges are provided on it by using 1mm thick balsa sheets.

The balsa spars on the wing and the elevon are provided with slits so that hinges for the elevon can be fixed. Next small pieces of cyano sheet are cut which are used as hinges. These pieces are inserted in the slits cut earlier, and are glued in position only on the elevon side. The Figure 4.5 shows the elevons fixed to top wing.

Next the wings are to be covered with monokote, but since servo motors are to be placed here, only the bottom surface of the wing is initially covered with monokote. Next the servo motors are affixed to the spars of the wing and are reinforced with balsa wood pieces as shown in Figure 4.6. Servo wires are to be attached to the receiver, which is to be placed in the fuselage. Therefore servo extension wires are connected to it. In order to connect the servo extension wire to the receiver, the extension must be passed through the ribs, therefore holes should be made in the ribs.

Figure4.5Elevons fabricated for the top wing

Figure4.6 Servo fixture on the top wing to control the elevon.elevon.

Once the top wing is monokoted vertical stabilizers are fixed on the sides of the plane. The vertical stabilizers are ideally supposed to be made from NACA 0010 airfoils, but the behavior of a flat plate and NACA 0010 are similar. Hence it was decided to use flat plates. Simple sheets of hollow polycarbonates cut to the dimension easily would serve the purpose and were used. Next control rods were fixed connecting the servo arm and the control hon of the respective elevon. The control rods were bent at the appropriate locations in order to lock it in place as well as to provide the required degree of freedom to it using a nose plier and a cutting plier. Figure 4.7 shows the connecting rod fixed between the servo arm and the control hon.

Figure 4.7: Connecting rod fixed between the servo arm and the control hon.

This concludes the fabrication part.

4.7 Installation of Propulsion System

At first one hole of the size of motor shaft is drilled in the center of the fire wall. Next four more holes are drilled in order to secure the motor mount to the fire wall using screws and nuts. One important thing when mounting the motor is that the motor axis must not be perfectly aligned with axis of the fuselage. This is because the moment of inertia of the plane is lower about its exact axis compared to another axis which is at a slight angle. Therefore the counter-torque effects of rotating the propeller are significantly decreased. Hence two washers each are provided before the motor for two screws which are on the same side of the axis, thereby creating a slight angle between the fuselage axis and the motor axis.

Next the ESC is connected to the motor, a battery and a receiver. The two servo extensions connected to servo on one side are connected to the receiver as well. This completes the plane and is ready for the testing phase. The Figure 4---------------------.8 shows the complete plane.

Figure 4.8: Complete fabricated plane.

4.8 Centre of Gravity Balancing

For a plane to be stable dynamically the position of the Centre of gravity (CG) should be at a desired location. CG is the point on the plane where the weight of the plane is assumed to be acting. While designing it is assumed to be at 155mm from the front face of the plane and at the center along the width of the plane. The height of the CG from the base of the plane is not of great importance as its effects can be compensated by initial setup or by trimming of the elevons.

CG should be as per the design position because if the position is different pitching moments will be developed on the plane, usually tending towards instability. In order to maintain the CG at designed position the placement of the components inside the fuselage must be calculated accurately based on their weight. The position of the servos for movement of elevons has to be in the rear wing and the position of hones should be at the middle of the elevons both along the X axis and Z axis. The position of these servos is as shown in the Figure 4.9.

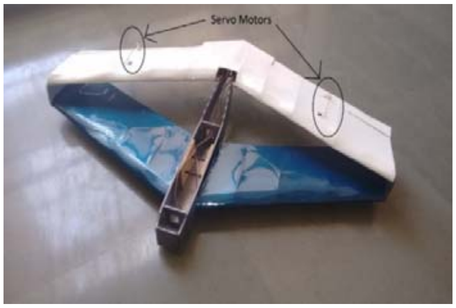

Figure 4.9: Position of servo motors on the plane

Since most of the plane's body weight is at the rear art of the plane the heavy parts like payload, battery, ESC and receiver are placed at the front part of the fuselage close to bulkhead.

Once all the placement is finalized the position of CG is checked manually by trying to balance the plane by holding it with a fingers. The position of CG along X axis is verified by balancing the plane on finger tips holding it at below the wings. This is demonstrated in Figure 4.10.

Figure 4.10: Verification of the position of CG along X axix

Figure 4.11: Verification of position of CG Along Z axis.

The position of CG along Z axis is verified by balancing the plane on finger tips holding it at the extreme positions along Z axis. This is demonstrated in Figure 4.11.
By this process the position of CG is verified and the plane is ready to be tested.

5 CONCLUSION AND SCOPE FOR FUTURE WORK

The paper deals with the design of a Box-Wing UAV from scratch and comparing it with a conventional UAV that was designed using the same constraints, using only simulation results. Next the Box-Wing was fabricated, propulsion system was selected and test flights were also conducted. This report provides concrete procedure which can serve as guidelines for anyone wanting to design and fabricate Box-Wing model planes.

- A Box-wing plane using MH-78 airfoil, which flies at 15.2 m/s and capable of carrying a total weight of 700 grams was designed. Simulation to prove the worthiness of the design was carried out on the CFD package STAR-CCM+.
- The Drag coefficient of the box wing was found to be less than half of the drag coefficient of the conventional UAV. The total drag coefficient of the Box-Wing was found to be 0.01l6531315, while the total drag coefficient of the Conventional UAV was found to be 0.04705. Proving the advantage of the box wing compared to the conventional UAV.
- The Internal structure of the wing was designed. A completely new approach was adapted, which does not have any full length spars. Hollow carbon rods were used as spars, while the ribs were laser cut out of 3mm thick balsa wood sheets. The fuselage was decided to be made out of corrugated sheets of polycarbonate.

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ABBREVIATIONS

AHP - Analytic Hierarchy Process, AR – Aspect Ratio, CFD – Computational Fluid Dynamics, CG – Centre of Gravity, LOA – Line of Action, OEF – Oswald’s Efficiency Factor.