DESIGN OF WING FOR HIGH ENDURANCE UAV

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Abstract : The wing is one of the most important parts of an aircraft since it is the part which offers the lift force required to maintain an aircraft in air during flight. This study presents the design of fixed wing for an Unmanned Aerial Vehicle (UAV) of an all up weight of 8kg. The UAV is meant for surveillance purpose. The wing span is considered to be 3m. The wing is designed for a cruise velocity of 15m/s and Reynolds number value of 194446.34. A set of airfoils used in wings of high endurance aircrafts are compared for aerodynamic parameters. The FX 63-137 airfoil is chosen to be the airfoil for designing the wing since this airfoil offers the maximum $\frac{Cl^{\frac{3}{2}}}{Cd}$ for the operational conditions considered in comparison to the other airfoils analyzed. The wing so designed is then analyzed for different dihedral angles. The wing with a dihedral angle of 6° is found to be having the best aerodynamic performance in terms of offering high endurance out of the set of the wing dihedral variants analyzed.

***Keywords* – Unmanned Aerial Vehicle, Aspect Ratio, Endurance, Reynolds Number, and Dihedral angle.**

I. INTRODUCTION

An aircraft with no pilot on board is called an Unmanned Aerial Vehicle, commonly referred to by the acronym UAV. The UAVs can be controlled by a pilot from the ground control station (also called remote controlled aircraft) or can autonomously fly based on the flight plans which have been programmed earlier or with the help of more complex automation systems. However, UAS (Unmanned Aircraft Systems) is the acronym adopted by FAA (Federal Aviation Authority) as these systems include other elements besides the air vehicle alone. The various systems together making up a UAS are:

- Airframe
- Propulsion System
- Servo and RC
- Autopilot, Navigation and Telemetry
- Payload

Since the UAVs do not face the limitation of having a pilot on board, they can be designed to operate for maximum flight time. Endurance is the maximum time for which an aircraft is off the ground for one load of fuel or maximum capacity of the battery. Thus the choice of wing design and the propulsion system together influence the endurance of a particular aircraft.

An airfoil is the cross-sectional shape of the wing. An airfoil shaped body when moved through a fluid produces an aerodynamic force. The component of this force perpendicular to the direction of motion of the wing is called lift while the component parallel to the direction of motion is called drag. Hence the choice of an airfoil for the wing of a particular aircraft is a crucial step in the design of the wing of an aircraft.

If we offer a finite length to the airfoil, a wing will be generated. The various design parameters corresponding to the wing are:

- Chord line: The straight line which connects the leading edge and the trailing edge of the airfoil is called the chord line. The length of this straight line is referred to as chord length or chord. Chord is denoted by c.
- Angle of attack: It is the angle that the relative wind makes with the chord line.
- Wing span: It is the length of the wing. In other words, it is the distance between the two wing tips. It is denoted by b.
- Wing area: It is the area of the surface of the wing projected onto the plane perpendicular to the wing's normal axis. It is denoted by S. For a rectangular wing, wing area is given by,

$$S = b * c$$

- Wing aspect ratio: It is the ratio of square of wing span to area of the wing. It is denoted by AR.

$$AR = \frac{b^2}{S}$$

- Dihedral angle: It is the angle made by the aircraft wing with the horizontal transverse line. The dihedral angle is meant to increase the lateral stability in case of aircraft bank. This is because the lower wing of the aircraft is found to fly at a higher angle of attack than the higher wing if the wings are possessing dihedral. This tends to raise the lower wing and return the aircraft to the initial flight condition. It is denoted by Γ.

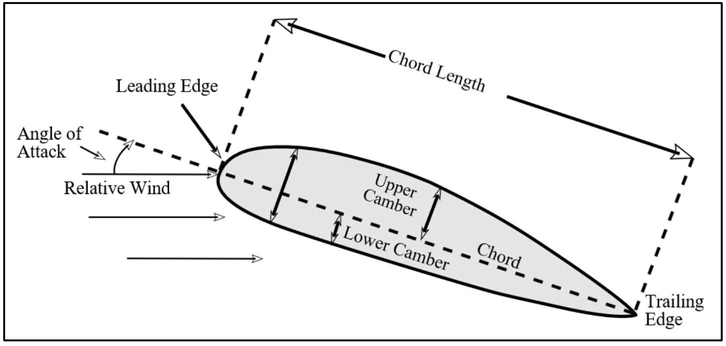

Fig 1.1 AIRFOIL

The flow over a wing can be either laminar or turbulent. The nature of flow is characterized by a dimensionless quantity called Reynolds number. It is denoted by Re.

$$Re = \frac{\rho V c}{\mu}$$

Where, ρ = density of the fluid
V = velocity of the fluid
μ = dynamic viscosity of the fluid

The total time that an airplane takes to stay in the air on one load of fuel or maximum battery capacity is called endurance. In level flight or cruise condition (no acceleration), the throttle is set to maintain constant airspeed. Thus,

$$P_A = P_R = D*V$$

Where P_A is Power Available and P_R is power required.
For steady level unaccelerated flight, lift force(L) is equal to weight(W). Thus,

$$L = W$$

Using the same assumptions,

$$E = \int_{W2}^{W1} \frac{\eta}{c}\frac{dW}{DV} = \int_{W2}^{W1} \frac{\eta}{c}\frac{L}{DV}\frac{dW}{W}$$

Since, $L = W = \frac{1}{2}\rho V^2 SC_L$, $V = \sqrt{\frac{2W}{\rho SC_L}}$

$$E = \int_{W2}^{W1} \frac{\eta}{c}\frac{C_L}{C_D}\sqrt{\frac{\rho SC_L}{2}}\frac{dW}{W^{3/2}}$$

If we assume that C_L, C_D, η, c and ρ are all constants,

$$E = \frac{\eta}{c}\frac{{C_L}^{3/2}}{C_D}\sqrt{2\rho S}\left(\frac{1}{\sqrt{W1}} - \frac{1}{\sqrt{W2}}\right)$$

Where, η = Propeller efficiency
c = Specific fuel consumption
C_L = Lift coefficient
C_D = Drag coefficient
W1=Empty weight
W2=Takeoff weight

II. EXISTING SYSTEM

A set of airfoils are selected in order to design the wing for the mini UAV (Unmanned Aerial Vehicle) under consideration. The aircrafts in which these airfoils have been used earlier are listed out and the characteristic features of these aircrafts are studied and tabulated as in Table 2.1. This is done in order to analyze the reasons for the choice of the airfoils in designing the wings of the corresponding aircrafts.

AIRCRAFT	Vogt LO 150	Haufe Buzzer 2	Utva 65	Vought XF2U	ULF-1
AIRFOIL	Clark Y	NACA 2412	NACA 4412	N-22	FX 63-137
WING SPAN	15	10.36	12.22	10.97	10.4
WING AREA	10.9	11.52	19.4	29.54	13.4
ASPECT RATIO	20.6	8	7.697	4.07	8.07
EMPTY WEIGHT	200	177	700	1152	45
GROSS WEIGHT	310	272	1890	1772	120
WING LOADING	28.44	26.25	97.42	59.98	8.96
NUMBER OF SEATS	1	1	1	2	1

Table 2.1 AIRCRAFT SPECIFICATIONS

III. CHOICE OF UAV PROPULSION SYSTEM

For the UAV to stay in air during flight, the all up weight of the UAV should be compensated by the equal and opposite force, which is the lift. Thus,

$$W=L$$

$$L=0.5\rho V^2 SC_L$$

Since the UAV under consideration is a surveillance UAV, the cruise velocity of the UAV is largely determined by the resolution of the cameras used on the UAV. As the cruise velocity for such surveillance, mini UAVs usually varies from 12m/s to 15m/s, the cruise velocity which would be the best for the UAV of weight 8kg with a fixed wing span of 3m is decided upon by finding the aspect ratio of the wing for varying values of velocity. The Cl value is assumed to be unity initially while deciding the cruise velocity.

Sl. No.	VELOCITY(m/s)	CHORD(m)	ASPECT RATIO	REYNOLDS NUMBER
1	12	0.30	10.11	245616.43
2	13	0.25	11.87	221737.05
3	14	0.22	13.77	210138.50
4	15	0.19	15.80	194446.34

Table 3.1 VARIATION OF WING DIMENSIONS WITH VELOCITY

Since the wing aspect ratio is maximum and the chord is minimum at the velocity of 15m/s, this value of velocity is chosen as the cruise velocity of the UAV. The total power requirement of the UAV is found to depend on the all up weight of the UAV.

Total AUW of the UAV = 8kg = 17.636 lbs

Considering 18 lbs of AUW and performance (Trainer slow flying scale model) 80 watt/lb,

Total power requirement = 80*18 lbs = 1440 watts

So the electric motor to power the aircraft must be having a rating which is more than 1440 watts. Since 1500 watts motor is the one which is commercially available and nearest to the required rating, it is used for the UAV considered.

If 8 cell 8s 1pack lipo batteries are used, the available voltage is 29.6V. Hence the continuous current drawn by the motor will be 50.67A. Thus 60A ESC is required.

Thus the NTM50-60 380KV which can offer 2665W power is used for the UAV propulsion system. A slow fly or reduction drive propeller of dimensions 10*6 is chosen for the UAV.

IV. ANALYSIS OF AIRFOIL CHARACTERISTICS

The aircrafts whose airfoils are to be compared for high endurance and better performance are grouped as per their weight class. Thus Vogt LO 150 and Haufe Buzzer 2 come under a single weight class, Utva 65 and Vought XF2U come under a different weight class, while the micro lift glider ULF-1 is analyzed separately. There are other airfoils which are used for high endurance applications. One such airfoil is the S1223 airfoil. The comparison is done on the basis of aerodynamic parameters like Cl, Cd and Cm. The XFLR5 software is used for obtaining the comparison plots for the evaluated chord length and Reynolds number value.

Sl. No.	AIRFOIL	PRESSURE DISTRIBUTION PLOT	Sl. No.	AIRFOIL	PRESSURE DISTRIBUTION PLOT
1	CLARK Y		4	NACA 4412	
2	NACA 2412		5	FX 63-137	
3	N22		6	S1223	

Table 4.1 PRESSURE DISTRIBUTION PLOTS FOR THE AIRFOILS CONSIDERED

4.1 Clark Y versus NACA 2412

Clark Y is the airfoil used in Vogt LO 150 while NACA 2412 is the airfoil used in Haufe Buzzer 2. Since the gross weight of Vogt LO 150 is 310kg and that of Haufe Buzzer 2 is 272kg, these two aircrafts belong to the same weight class. Hence the airfoils used in these aircrafts are compared with each other for performance. Further, the reason for the use of these airfoils in their respective aircrafts is also analyzed.

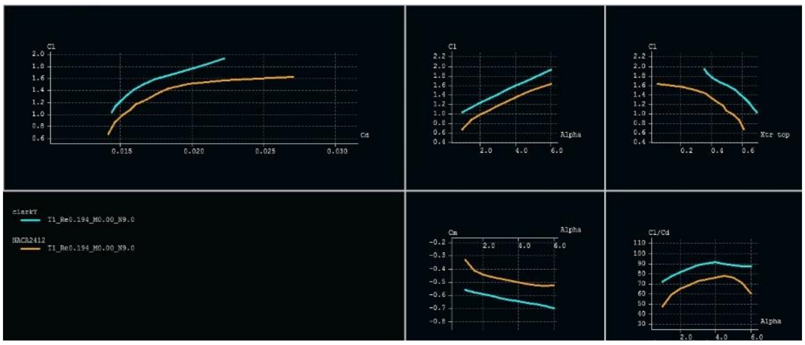

Fig 4.2 COMPARISON PLOTS FOR CLARK Y AND NACA 2412 AIRFOILS

The following observations are made from the graphs plotted,

- From the graph plotted for Cl versus Cd, it is evident that the Clark Y airfoil offers a better Cl/Cd ratio than NACA 2412 airfoil for a given value of angle of attack.
- The graph plotted for Cl versus α suggests that the Clark Y airfoil offers a slightly higher lift coefficient than NACA 2412 for a particular value of α. The stall angle is almost same for both the airfoils.
- The graph plotted for Cl/Cd versus α indicates that the Cl/Cd value is maximum for NACA 2412 at an α value of around 4˚. The maximum value of Cl/Cd obtained for NACA 2412 is higher than that obtained for Clark Y.
- The Clark Y airfoil offers a more negative Cm value than that obtained for NACA 2412 at a particular value of angle of attack.

Thus it can be inferred that,

- Clark Y offers a slightly higher Cl than NACA 2412 owing to its slightly higher camber.
- The stall angle for both the airfoils is almost the same due to which the two airfoils are used in aircrafts belonging to the same weight class.
- Clark Y is used on Vogt LO 150 which uses flaps for glider control as it is easier to mount flaps on a wing made of Clark Y airfoil than a wing made of NACA 2412 airfoil. Thus Clark Y is used in designing the wing of Vogt LO 150 which uses flaps for glider control.

4.2 NACA 4412 versus N-22

NACA 4412 is the airfoil used in Utva 65 aircraft while N-22 is the airfoil used in Vought XF2U aircraft. Since the gross weight of Utva 65 is 1890kg and that of Vought XF2U is 1772kg, these two aircrafts belong to the same weight class. Hence the airfoils used in these aircrafts are compared with each other for performance. Further, the reason for the use of these airfoils in their respective aircrafts is also analyzed.

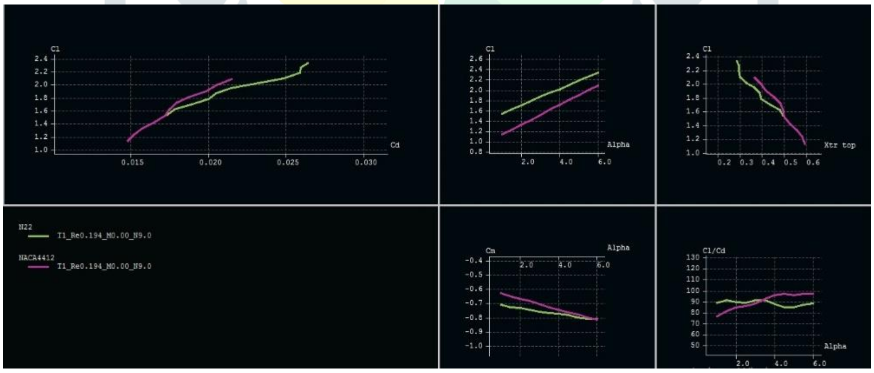

Fig 4.3 COMPARISON PLOTS FOR N22 AND NACA 4412 AIRFOILS

The following observations are made from the graphs plotted,

- From the graph plotted for Cl versus Cd, it is evident that the NACA 4412 airfoil offers a better Cl/Cd ratio than N-22 airfoil for a given value of angle of attack.
- The graph plotted for Cl versus α suggests that the N-22 airfoil offers a higher lift coefficient than NACA 2412 for a particular value of α. However, NACA 4412 has a greater stall angle than N-22.
- The graph plotted for Cl/Cd versus α indicates that N-22 offers a greater Cl/Cd ratio than NACA 4412 at a given α value.
- The NACA 4412 airfoil offers a more negative $\frac{dCm}{d\alpha}$ value than that obtained for N-22 for a given angle of attack value.

Thus it can be inferred that,

- Since Cl is higher for N-22 than NACA 4412, N-22 is used to design the wings of heavier aircraft (For example, Vought XF2U). This is because a greater amount of force is required to lift a heavy aircraft.
- The stall angle is lesser for N-22 than NACA 4412. Hence very high variations in angle of attack is not possible for a wing made of N-22 airfoil. Thus N-22 can be used to design the wings of heavy aircrafts wherein high angle of attack variations is not permissible keeping stability considerations in mind.
- NACA 4412 can be used for the wings of light as well as heavy aircrafts (For example, Utva 65).

4.3 FX 63-137 versus Clark Y, NACA 2412, N22, NACA 4412 and S1223

FX 63-137 is the airfoil used in ULF-1 aircraft. Since the gross weight of ULF-1 is 120kg, this aircraft does not belong to the same weight class as that of the rest of the airfoils. Hence the airfoil used in this aircraft is compared with the other airfoils for performance. Further, the reason for the use of this airfoil in ULF-1 and not in the other aircrafts corresponding to the rest of the airfoils compared is also analyzed.

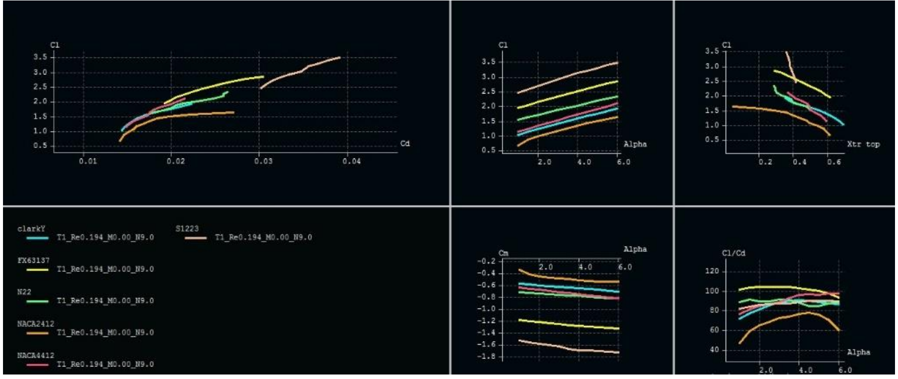

Fig 4.4 COMPARISON PLOTS FOR ALL AIRFOILS CONSIDERED

The following observations are made from the graphs plotted,

- From the graph plotted for Cl versus Cd, it is evident that the FX 63-137 airfoil offers a better Cl/Cd ratio than the rest of the airfoils considered for a given value of angle of attack.
- The graph plotted for Cl versus α shows that the FX 63-137 airfoil offers a lower lift coefficient than S1223 for a particular value of α. However, FX 63-137 has a greater stall angle than the remaining airfoils chosen for comparison.
- The graph plotted for Cl/Cd versus α indicates that the Cl/Cd ratio obtained for FX 63-137 is higher than the rest of the airfoils at a given α value ranging from 0˚ to 6˚. Beyond 10˚of angle of attack, there are huge fluctuations in the value of Cl/Cd found for FX 63-137.
- The FX 63-137 airfoil offers the least Cm value out of the set of six airfoils compared in the operational range of α.

Thus it can be inferred that,

- FX 63-137 airfoil offers high Cl and high stall angle in comparison to the other airfoils considered.
- However, FX 63-137 does not offer Cl as high as that of N-22. Hence it is not used in the wing design of heavy aircrafts.
- S1223 offers a greater Cd than the rest of the airfoils which does not allow it to be used for the design of a wing with large wing area.
- Since stall angle is high, FX 63-137 can also be used in aircrafts which need to be launched at high angle of attack (For example, ULF-1 which is launched at 15˚ angle of attack).
- FX 63-137 airfoil can exploit the lift due to feeble air movements, thus it is used in designing wings of micro lift gliders.
- The lesser thickness of FX 63-137 airfoil towards the trailing edge makes it difficult to mount flaps or other control surfaces on the wing designed with this airfoil.

The FX 63-137 airfoil offers the highest value of the $\frac{Cl^{\frac{3}{2}}}{Cd}$ ratio out of the set of airfoils considered. Hence the FX 63-137 airfoil is chosen as the airfoil for the design of the wing of the UAV under consideration. The values of Cl and Cd obtained and the $\frac{Cl^{\frac{3}{2}}}{Cd}$ values evaluated for 2˚ angle of attack are noted in Table 4.5.

AIRFOIL	Cl	Cd	$\frac{Cl^{\frac{3}{2}}}{Cd}$
NACA 4412	1.325	0.016	95.320
NACA 2412	0.979	0.015	64.577
N22	1.695	0.019	116.145
FX 63-137	2.137	0.021	148.760
Clark Y	1.219	0.015	69.725
S1223	2.677	0.031	141.289

Table 4.5 AERODYNAMIC PARAMETERS OF AIRFOILS

V. MODELLING

The model of the wing is designed in CATIA. The FX 63-137 airfoil coordinates are obtained for 2˚ angle of attack and chord length of 0.19m. Initially, the wing is designed with no dihedral angle. Then the dihedral angle of the wing is sequentially increased in steps of 2˚ up to a value of 6˚ dihedral. The wing models designed are shown in Figure 5.1.1, Figure 5.1.2, Figure 5.1.3 and Figure 5.1.4.

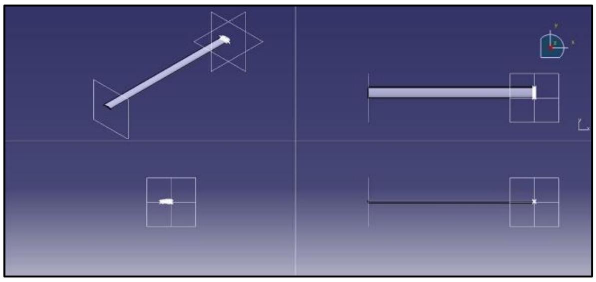

Fig 5.1.1 WING WITH 0˚ DIHEDRAL ANGLE

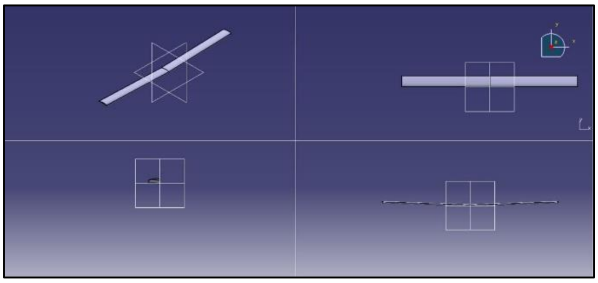

Fig 5.1.2 WING WITH 2˚ DIHEDRAL ANGLE

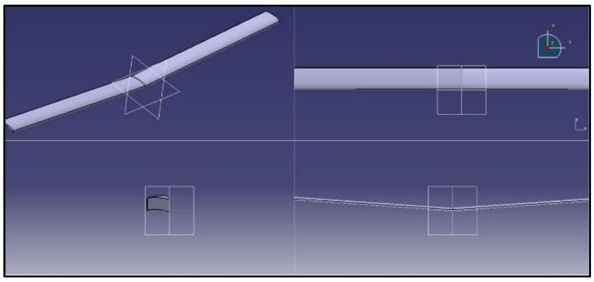

Fig 5.1.3 WING WITH 4˚ DIHEDRAL ANGLE

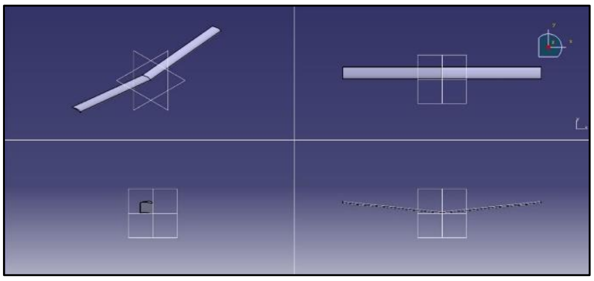

Fig 5.1.4 WING WITH 6˚ DIHEDRAL ANGLE

VI. MESHING

Discretization of a continuous domain comprising infinite number of points into finite number of regions called elements is the main reason why meshing is carried out. The region of flow around the wing under consideration is meshed in order to record the variation of flow parameters in the flow region accurately. The accuracy of the values obtained is influenced by the size and shape of the mesh and also the number of elements in the mesh. The flow domain and meshing for the wing models with varying dihedral angles are shown in Figure 5.2.1, Figure 5.2.2, Figure 5.2.3 and Figure 5.2.4.

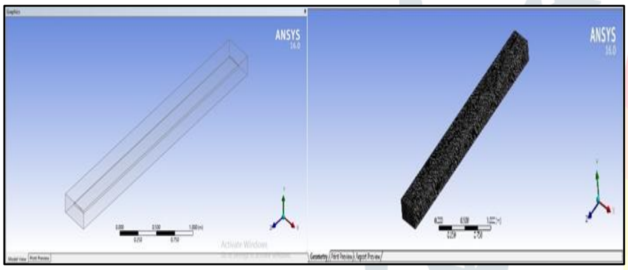

Fig 5.2.1 WING WITH 0˚ DIHEDRAL ANGLE

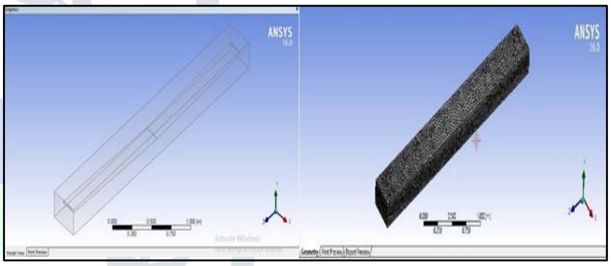

Fig 5.2.2 WING WITH 2˚ DIHEDRAL ANGLE

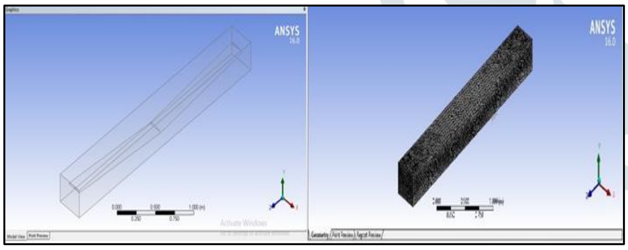

Fig 5.2.3 WING WITH 4˚ DIHEDRAL ANGLE

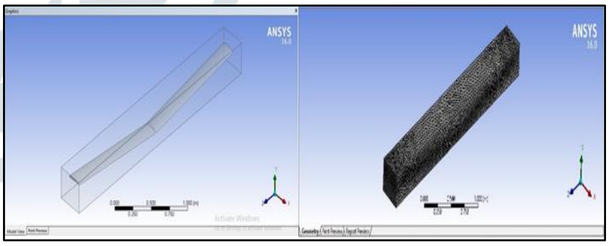

Fig 5.2.4 WING WITH 6˚ DIHEDRAL ANGLE

VII. WING ANALYSIS

The wing models are analyzed in ANSYS Fluent software. The readings are obtained for 300 iterations in order to attain better accuracy of results. The residuals obtained during analysis of the wing models are shown in Figure 5.3.1, Figure 5.3.2, Figure 5.3.3 and Figure 5.3.4. The effect of the change in dihedral angle on the aerodynamic performance of the wing is analyzed. The changes in the Cl value or the Cd value is the criteria that is examined for analyzing the effect of changes in the wing dihedral. Thereby, the most feasible dihedral angle is predicted for the wing to be designed taking the weight of the UAV and the endurance criteria into consideration. Since the wing is to be designed for high endurance, the $\frac{Cl^{\frac{3}{2}}}{Cd}$ value, or the $\frac{L^{3}/_{2}}{D}$ value is found for the wing models.

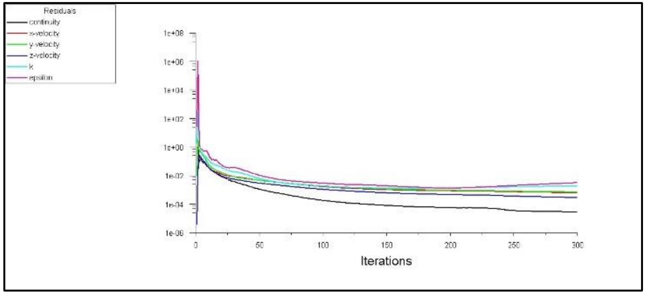

Fig 5.3.1 WING WITH 0˚ DIHEDRAL ANGLE

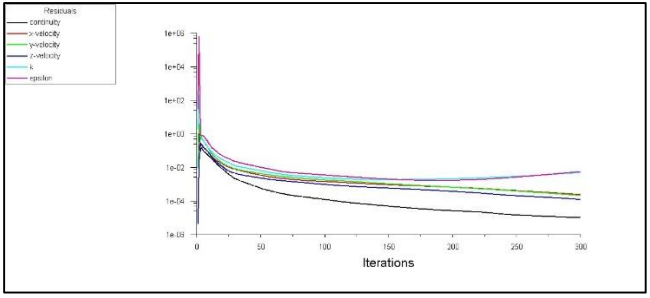

Fig 5.3.2 WING WITH 2˚ DIHEDRAL ANGLE

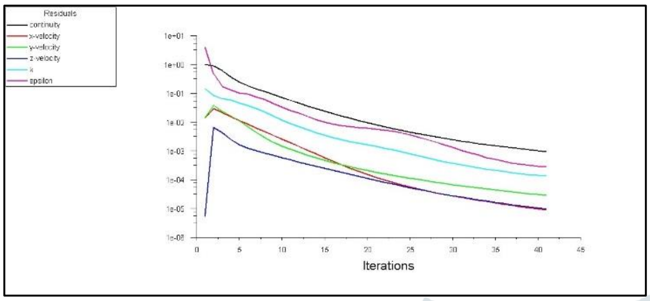

Fig 5.3.3 WING WITH 4˚ DIHEDRAL ANGLE

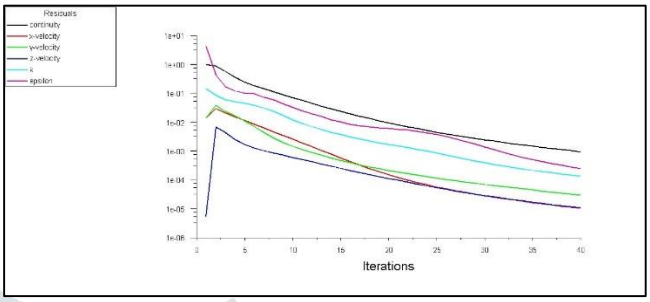

Fig 5.3.4 WING WITH 6˚ DIHEDRAL ANGLE

The lift and the drag forces that are obtained from the analysis are noted and the wing model which is found to offer the best endurance out of the set of wing models considered is chosen.

	0˚ DIHEDRAL	2˚ DIHEDRAL	4˚ DIHEDRAL	6˚ DIHEDRAL
LIFT FORCE(N)	8.1210	13.0650	17.4707	21.0499
DRAG FORCE(N)	3.1319	3.4755	3.7635	4.0060

Table 5.4 FORCES ACTING ON WING MODELS

VIII. CONCLUSIONS

1. A set of airfoils were chosen for comparison of aerodynamic characteristics. The applications of the airfoils chosen in high endurance airplanes was noted and studied.
2. The FX 63-137 airfoil was chosen as the airfoil to be used for the design of the wing of UAV weighing 8kg since this airfoil offered maximum $\frac{Cl^{3/2}}{Cd}$, which is 148.76 for 2˚ angle of attack.
3. The lift and drag characteristics of the FX 63-137 airfoil were found for the chord length of 0.19m and Reynolds number of 194446.34. The wing span was taken as 3m.
4. The propulsion system for the UAV was chosen based on the weight and endurance of the UAV considered as the constraints.
5. The effect of change in the dihedral angle of the wing on the aerodynamic characteristics of the wing was analyzed. Since the wing with 6˚ dihedral offered the highest $\frac{L^{3/2}}{D}$ out of the set of wing models considered, the wing with 6˚ dihedral is found to be the best design in terms of offering high endurance. From the existing UAVs and the literature survey, it was evident that 6˚ was the optimal dihedral angle considering aerodynamic as well as design constraints.

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