Airfoil Designing for propeller

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Abstract:

"The aim of this project is to design an airfoil for the taken conditions by doing a literature review on the selected domain and to understand the procedure to develop an airfoil. In this project, an airfoil which can be used to make propeller blade for high-speed quadrotor will be designed and its performance is shown. "

Keywords: Pitch; Blade; velocity and pressure distribution

List of symbols:

C_l=Lift coefficient;

C_d=drag coefficient;

d=Diameter of propeller(m);

P =power (W);

T= thrust (N);

R=Radius of the propeller (m);

Re=Reynolds number;

L/D=Lift to drag ratio

L=Lift (N);

P=Pitch (cm);

I. Introduction

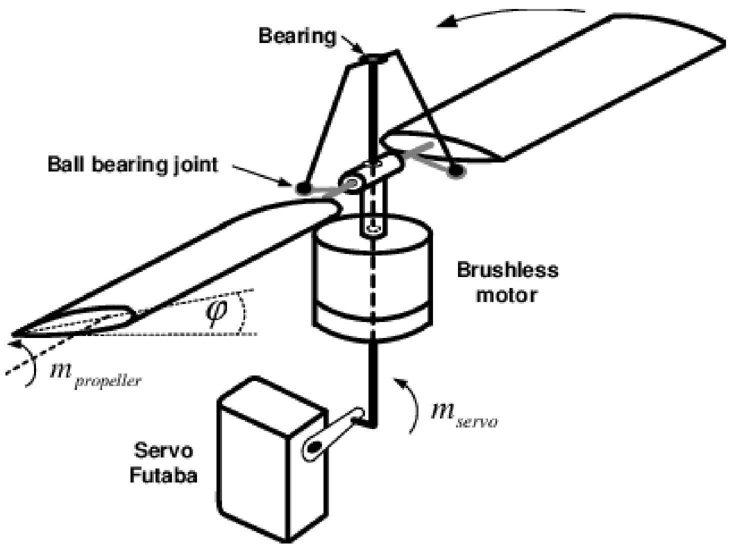
Airfoil design is important in making a propeller blade. These propellers, when rotated at high speeds generate thrust using which the aircraft fly. Propeller blades are even used in modern jet engine combustors. Before the invention of the jet engine, propeller blades were the main part to generate thrust. The parameters of a propeller are Diameter(D), Pitch(P), angle of twist, and RPM (rotations per minute). To keep the coefficient of lift constant across the rotating propeller due to different airflow speeds from the propeller root to the propeller tip, a helical twist is given to the propeller blade. The helical twist is the overall blade angle. It usually varies from 8° to 10°. The diameter of the propeller is the distance from the root blade to the tip blade.

Pitch is the amount of airflow displacement the propeller will displaced per 1 rotation. There are two types of propellers.

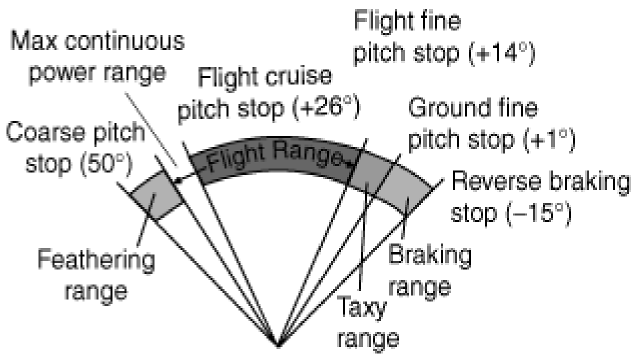
FIXED PITCH PROPELLERS:

Fixed pitch propellers are used to deliver maximum efficiency in the acceleration of top speed. Fixed propellers were used in the first flight made by the Wright Brothers. Currently, fixed propellers are used in quadcopters. Pitch is an important parameter for propeller blades. The fixed propeller had a limitation when it comes to speed, since the pitch can't be changed, even after having attained maximum RPM is attained the speed was not enough, and journeys were long. Even after setting the pitch of the blade to attain maximum speed possible, the acceleration was slow, and thus, a long runway was needed for take-off. To overcome this limitation, variable pitch propellers were introduced.

- ## **VARIABLE PITCH PROPELLERS:**

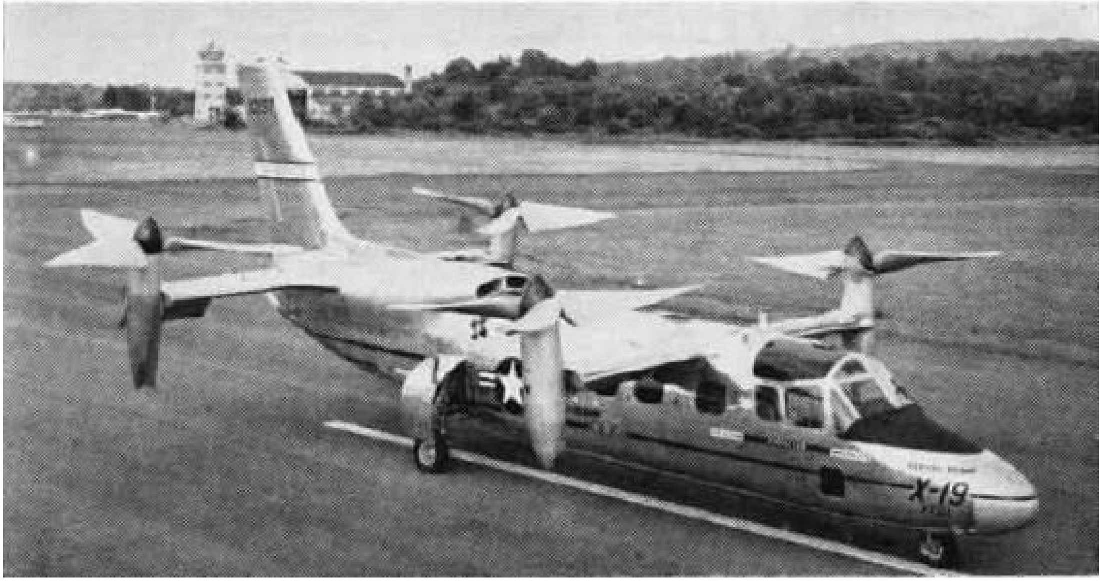


Variable pitch propellers, as the name suggests, these types of propellers have 2 or more pitches, and this is attained by moving the propellers at two or more positions. A 2-pitch propeller has 2 positions, position 1 is set to take-off, and position 2 is for maximum airspeed. After using a 2-pitch propeller, aircraft could cover a large distance in half of time compared to a fixed pitch propeller. Constant pitch propellers, feathering propellers, and reverse pitch propellers are a few more types of variable pitch propellers.



II. Quadcopters:

Quadcopters are Aerial Vehicles with four rotating motors attached with fixed pitch propellers, thus creating thrust, which is used as lift and take-off vertically. The very first quadcopter was flown in 1908 by a French aircraft designer named Louis Breguet at an altitude of double-digit numbers. Even though the first quadrotors flew in the 1900s, there were no practical quadrotors until recently, since controlling four rotors with small bandwidth was nearly impossible. Curtis-Wright X-19A was the only manned quadrotor helicopter to leave ground effect.



CURTIS-WRIGHT X-19A

But it still lacked a proper stable system to reduce pilots' control workload. Quadcopters move, rotate and change its yaw by manipulating the rotation speed of four rotors, for example, the quadrotor move in forward direction when the rotors behind are rotating at higher RPM (or) producing more thrust compared to the front ones. These manipulations are generally done by flight controller which gives the data of how fast they show rotate to rotors.

• DRONE:

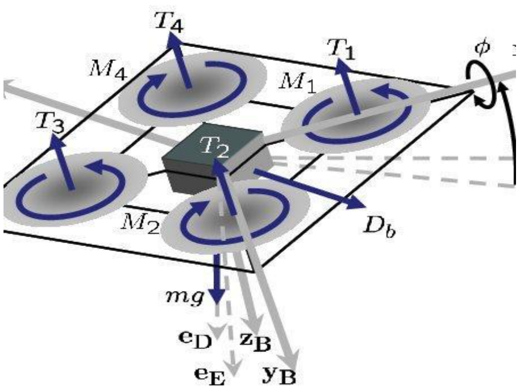
In the last few years, a specific type of quadcopters, called Unmanned Aerial Vehicles (UAVs) or Drones, has become famous due to their greater maneuverability and hovering ability. The use of four rotors helps the quadrotors to have a simple design and yet it is highly reliable and maneuverable. A quadcopter drone is easy to build and control due to technological advancements. Quadrotor drones are used to deliver packages, search places with harsh environments, conduct rescue operations, spy on the enemy's base, and in many more fields. Drones are generally equipped with a camera, flight controllers, and GPS, which makes them easy to control from longer distances. The recent inventions of micro-processors and inertial sensors have helped to increase the accuracy of and stabilize the flight controllers. Even though the quadrotors are simple and easy to control, their aerodynamics are complex to solve. These complex equations are usually solved by using computational methods. Quadrotors are popular as testbeds for small UAV development, since their aerodynamics are complex, it is necessary to accurately model them to enable precise and easy controls. Most of the works on drones has yielded successful results, but their application was limited to low altitudes and low velocities. Quadrotor drones are helicopters with additional propellers and without complicated swash plates. The quadrotor helicopter has proven to be a useful autonomous platform for high-speed flights outside the hover regime.

In the above picture the drone is being used to deliver packages. Since it has GPS and flight controller the path can be pre-set and with statins in between the deliveries can be sent to far distances. High-speed drones are usually used for delivering items and in racing sports like drone races. Drones with high power or high thrust are used in making videos and capturing images in an unknown location with a harsh environment.

III. Literature Review:

1. **AERODYNAMIC EFFECTS:**

The two main aerodynamic parameters which are affected by the design are blade flapping and total thrust variation. Blade flapping has temporary effect on altitude control whereas total thrust variation affects the thrust generated and thus having great impact on altitude control.



Free body diagram

- ## **BLADE FLAPPING:**

A rotor in translational flight undergoes an effect known as blade flapping. The advancing blade of the rotor has a higher velocity relative to the free stream, while the retreating blade sees a lower effective airspeed. This causes an imbalance in lift, inducing an up-and-down oscillation of the rotor blades [25]. In steady state, this causes the effective rotor plane to tilt at some angle off vertical, causing a deflection of the thrust vector (see Figure 2). If the rotor plane is not aligned with the vehicle's center of gravity, this will create a moment about the center of gravity (C.G) that can degrade attitude controller performance [9]. For stiff rotors without hinges at the hub, there is also a moment generated directly at the rotor hub from the deflection of the blades. Due to the quadrotor's bilateral symmetries, moments generated by lateral deflections of the rotor plane cancel. The backward tilt of the rotor plane through a deflection angle a_{1s} generates a longitudinal thrust, causing a moment

$$M_{b,lon} = T*h*\sin(a_{1s}).$$

Where, (i) h = vertical distance **from** the rotor plane to the C.G.
(ii) T = Thrust.

- The moment at the rotor hub from the bending of the blades is

$$M_{b,s} = k_\beta * a_{1s}$$

Where, (i) k_β = stiffness of the rotor blade in Nm/rad

The total longitudinal moment created by the blade flapping M_{bf} is

$$M_{bf} = M_{b,lon} + M_{b,s}$$

- ## **TOTAL THRUST VARIATION:**

Total Thrust Variation takes place only when there is: effective translation lift and a change in thrust due to angle of attack. The rotation of the rotor causes a change in momentum of the airstream and thus generating lift. This generated lift is called translational lift (since the motor's motion is translational). Similar to aircraft wings, as the Angle Of Attack(AOA) of the rotor increases, the generated lift also increases, thus increasing thrust.

- A rotor generates thrust by inducing a velocity on the air that passes through it. At hover thrust T_h, the induced velocity v his derived from momentum analysis as

V_h =

Where, A= area swept by rotors

ρ = density of air

- Induced velocity,

V_i =

- Using this expression for V_i, the ideal thrust T for a given power input P can be computed as

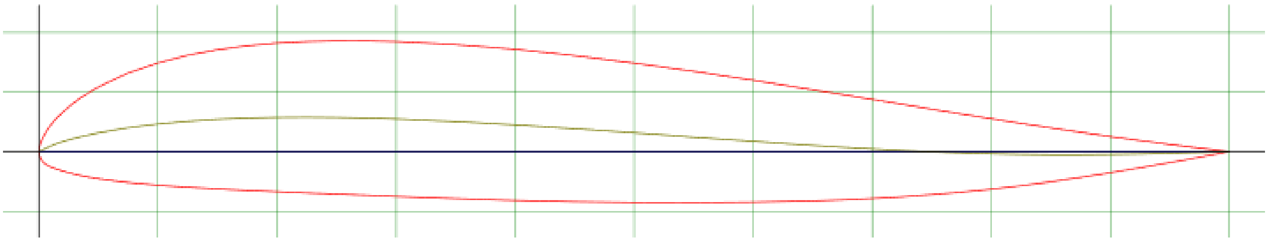
T=

Here, $vi - v\infty sin\alpha$ = airspeed across the rotors.

- The power input required for a nominal thrust at hover P_h, can be calculated as

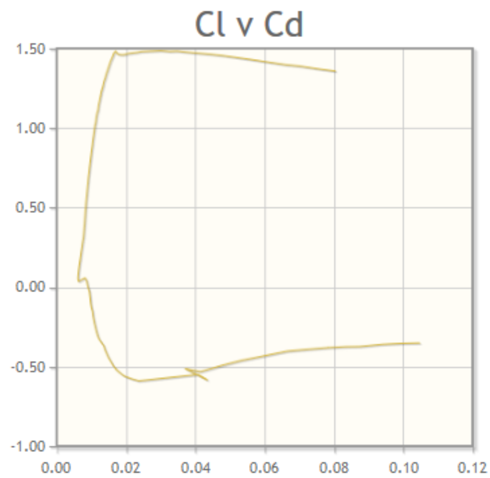
P_h =

- <u>EXAMPLE</u> <u>AIRFOIL</u>:



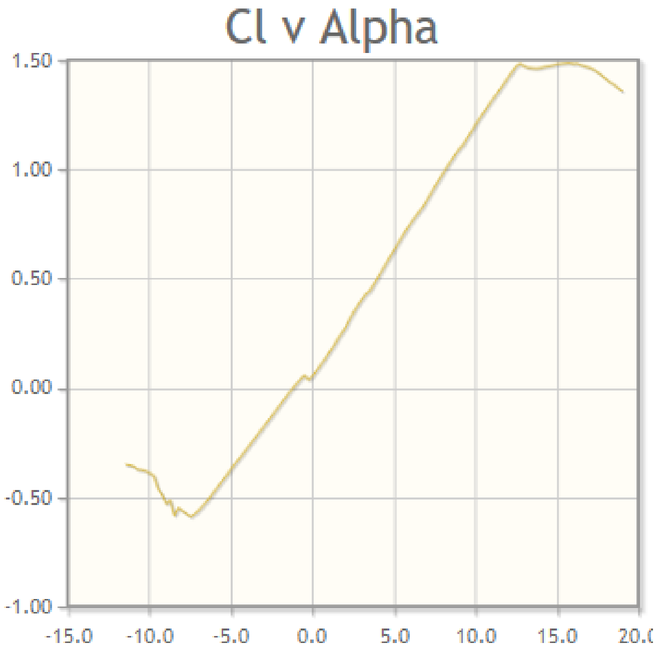
The airfoil in the above picture is EPPLER-625(E625). E625 has a maximum camber thickness 13% at 30% chord and maximum camber 2.9% at 22.5%. The performance for this airfoil is shown below. These performances were calculated using airfoil tools. After varying Reynolds number and going through the plots the optimum Reynolds number for this airfoil is Re = 10^6.

⍰ C_l vs C_d :



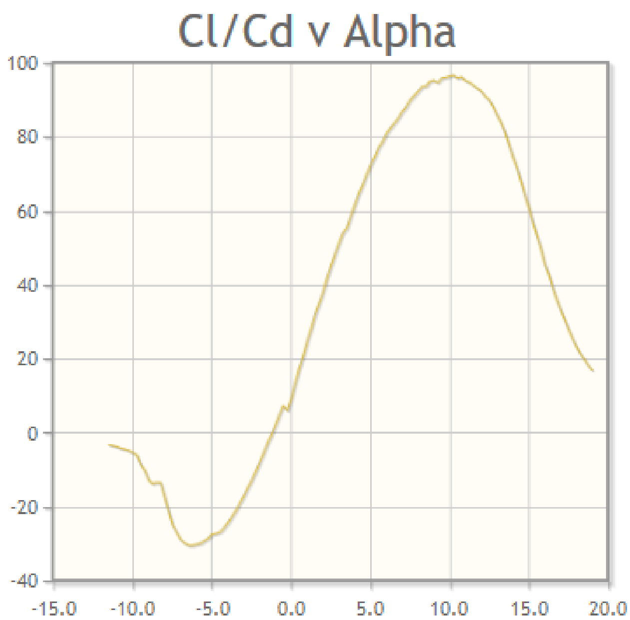
- From this plot, we can see that there is a positive amount of drag at zero lift.

⍰ C_l vs α:



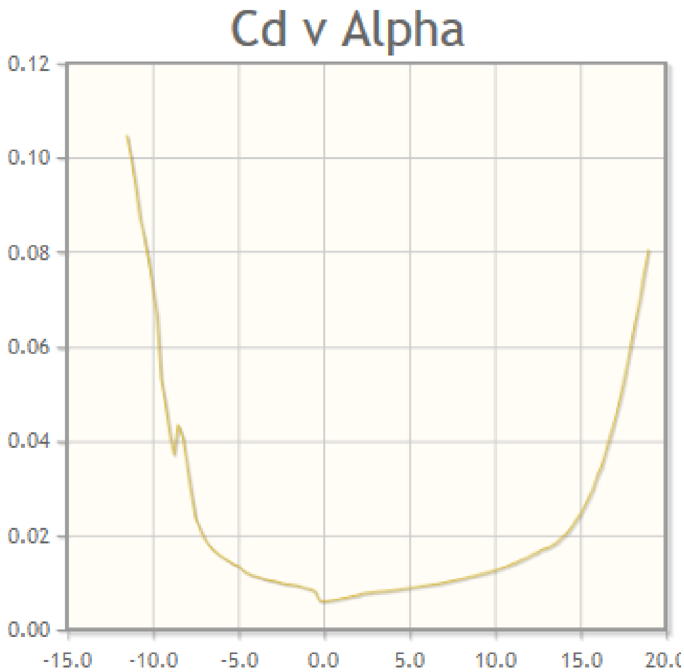
- From this plot, we can say that the airfoil generates positive lift at zero angle of attack.

? C_l/C_d vs α:



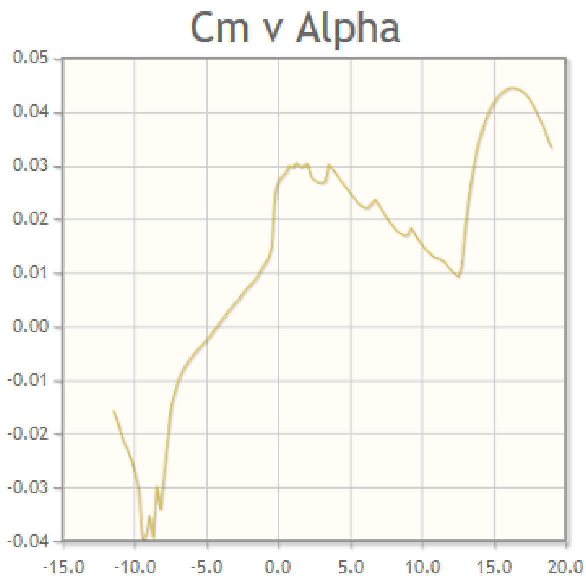
- This plot shows us the variation of the coefficient of lift coefficient of drag ratio and different angles of attack.

? C_d vs α:



- From this plot, we get that there is a positive amount of drag at zero angle of attack.

- **C_m vs α:**
  - From this plot we can say that the moment acting at zero angle of attack is negative with means there is an anti-clockwise moment acting.



- **DESIGN PARAMETERS:**

A few design parameters to be considered are,

(1) The propeller diameter must vary from 5” to 7”.

(2) The pitch must vary from 8°-10°
(3) The propeller diameter must be inversely proportional to the RPM of the motor chosen, i.e. greater the RPM, the smaller the diameter of the propeller.

IV. Designing an Airfoil:

Designing an airfoil is important in the research and development part of the aerospace industry. Airfoil design was a work for a long time, even though there were no proper methods. The engineering problem of airfoil design has been of great theoretical interest for almost a century and has led to hundreds of papers written and dozens of methods developed over the years. Initial methods were all based on Zhukovsky's theorem. Presently, most of the designing and calculations are done by computer using applications such as MATLAB, MS Excel, XFOIL, etc. Different airfoils satisfy different flight characteristics. Like the famous Clark Y airfoil, it can generate lift in the subsonic range but is not useful once speed reaches the sonic or supersonic range. The classic design goal is to minimize drag subject to required lift and thickness values to meet aerodynamic and structural constraints.

Payload, speed, and purpose decide the shape of the airfoil.

An airfoil is designed in such a way that its shape helps the airflow over it to have a pressure difference, thus producing lift. Airfoils that are thin and offer little resistance or drag are not always suitable because of their instability at higher speeds, and also cannot generate enough lift sometimes during take-off. Thus, airfoil design must be done so that its characteristics and performance can be calculated on paper instead of using a wind tunnel experiment. There are 2 ways to airfoil design.

(i) Direct Method:

The direct airfoil design methods involve the specification of a section geometry and the calculation of pressures and performance. One evaluates the given shape and then modifies the shape to improve the performance. The main problems in this method are the identification of the measure of performance and the method to modify the airfoil to increase its performance. This method is easy, but once the required performance characteristics are complex, this method takes a lot of time, and the error in results increases. A few examples of complex characteristics are:

(a) Minimize C_d with a constraint on C_{lmax}.
(b) To reduce the drag at high speeds while trying to keep the maximum C_l greater than a certain value.
(c) Maximize L/D or C_l/C_d or C_{lmax} / C_d @ $C_{l\ design}$.

(ii) Inverse design method:

Firstly, one chooses an existing airfoil that has characteristics close to the requirements. Once the airfoil is chosen, we can change its velocity profile or pressure distribution to get the desired characteristics. And this can be done either by hand or using computational and numerical methods. There are so many airfoils that satisfy many requirements. The Availability of many airfoils makes this method easier to do. Inverse design of an airfoil can be done with the help of specific applications, like XFOIL and

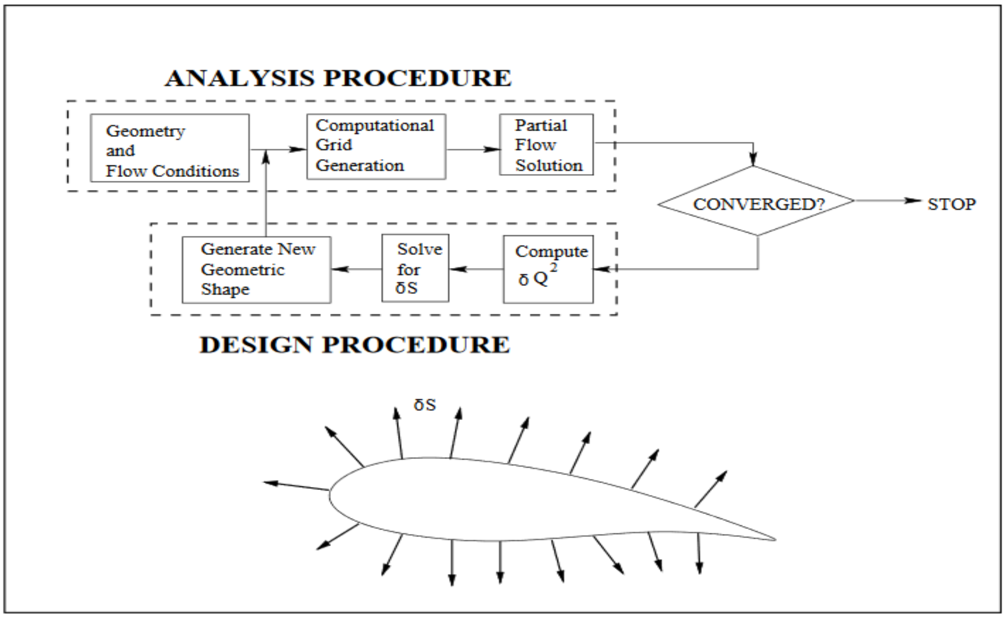
XFLR5. Inverse designing in this software is easier due to its detailed report and simple inputs.

- **Inverse Designing of an airfoil:**

The inverse design method is based on computational fluid dynamics (CFD) and is one of the effective design methods of advanced airfoils. Inverse design is more computationally efficient than direct optimization because changes in the geometry can be related to the required change in performance, thus requiring fewer flow solutions to obtain an updated profile. The important task while doing the inverse design method is to find a proper existing airfoil that has characteristics as near as possible to the required characteristics. A lot of research must be done, and so many trial-and-error methods should be used. The change in the graph will not always produce an airfoil, so while editing the velocity profile, change it in a way that all basic conditions stay the same. Airfoil theory can be used to solve for the shape of the camber line that produces a specified pressure difference on an airfoil in potential flow.

The second part of the design problem starts when one has somehow defined an objective for the airfoil design.

Generally, the inverse design method process is started with specifying an airfoil. Then performance analysis is made over this airfoil and then the resulted pressure distribution is compared with required pressured distribution and modified to get meet the requirements.



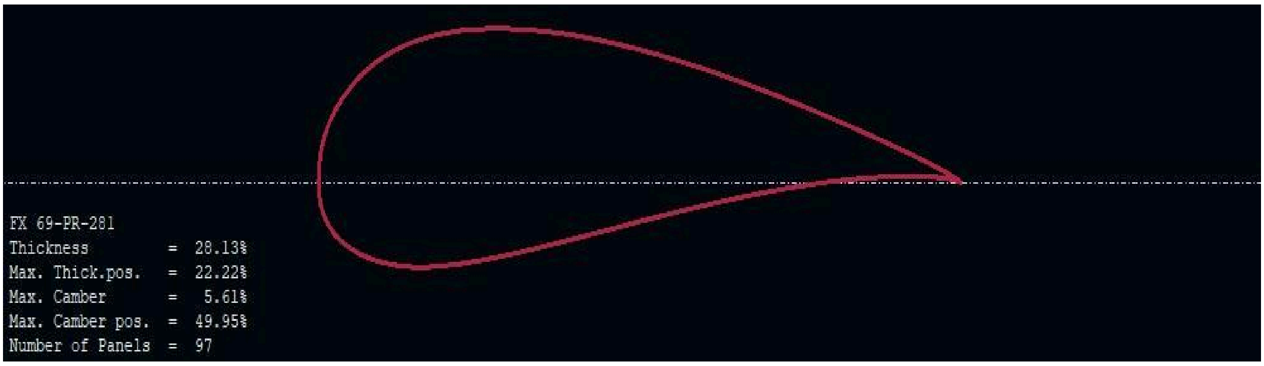
Airfoil design started with direct problems, and the methods to see their performance were to use them in a flight or wind tunnels. Modifications are made until the design parameters are reached. Advancements in aerodynamic theory permitted aerodynamic analysis to be conducted outside of the wind tunnel. Theodorsen published an exact solution to the direct airfoil problem in 1932. The theory was well understood before the turn of the century, but the lack of computational resources greatly slowed its application to the airfoil problem. Goldstein5 later greatly improved the utility of the method through an approximation to Theodorsen's theory that incurred only a minimal decrease in accuracy. Inverse airfoil design has its roots in conformal mapping and dates back to the early days of NACA. Practical application of an inverse technique was initially severely hindered by the computational requirements involved in obtaining the final airfoil shape. Another method developed at NASA is the direct iterative surface curvature (DISC) method by Campbell and Smith. By the 1970s, the inverse approach had developed into a very powerful tool for airfoil design. But still this design had many drawbacks, such as the solution to the integral constraints was in terms of arclength instead of angular co-ordinates, which made the formation of the airfoil hard. Later, Eppler published his theory on multipoint inverse airfoil design, the method has been improved and made readily available as a computer program. The Eppler method implements a multipoint design by dividing the airfoil into a desired number of segments. The velocity distribution is prescribed over each segment along with the design angle of attack that achieves the desired velocity distribution. This allows multipoint design requirements to be satisfied during the actual design process, not iteratively through post-design analysis. In 1992, Selig and Maughmer extended the theory of multipoint inverse design of Eppler. The new formulation allowed for prescription velocity over each segment in terms of arc length and made this method applicable for both cusped and trailing edge angle airfoils. The thickness, pitching moment, and other design parameters can also be specified. These extensions to the Eppler theory create a powerful method for inverse airfoil design in incompressible potential flow.

Two other inverse design methods are given by Dulikravich and Baker and yu et. Dulikravich and Baker presented an inverse design method based on analytical Fourier series solution to a pair of linear differential equations with interrelated boundary conditions. And the method by yu et changes airfoil shape with the help of small perturbation equation derived from streamline moment equation, continuity and isentropic relations.

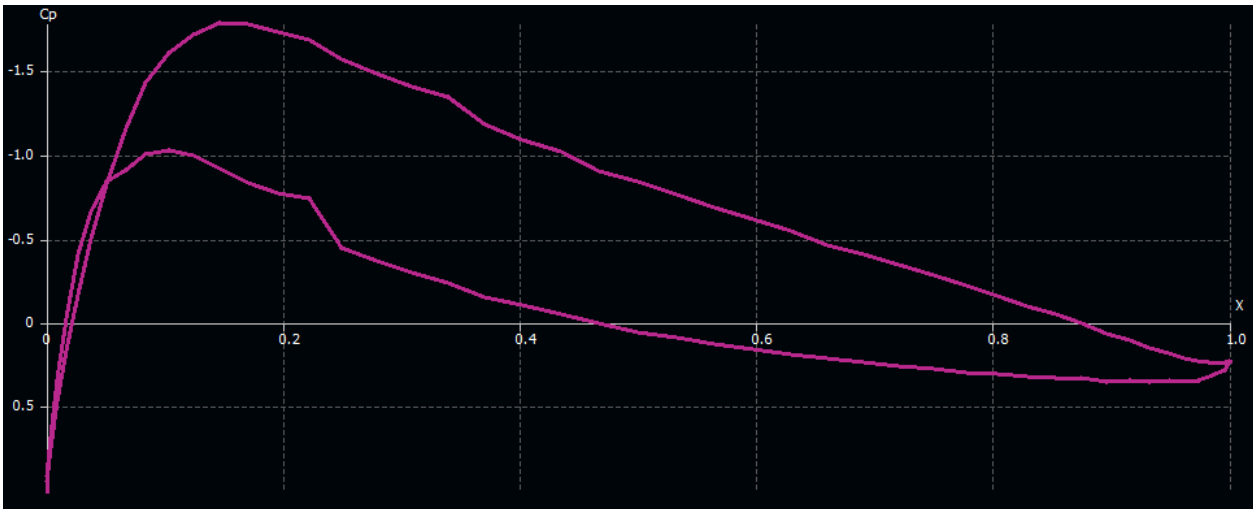
- Designing Airfoil:

Selected airfoil is Fx-69-pr-281. Since it has better lift compared to all existing airfoils, it has been chosen. C_l of the chosen airfoil at zero A.O.A is 0.658. since the aim is to make an airfoil for racing drone the lift must be as high possible.

Fx-69-pr-281 airfoil:

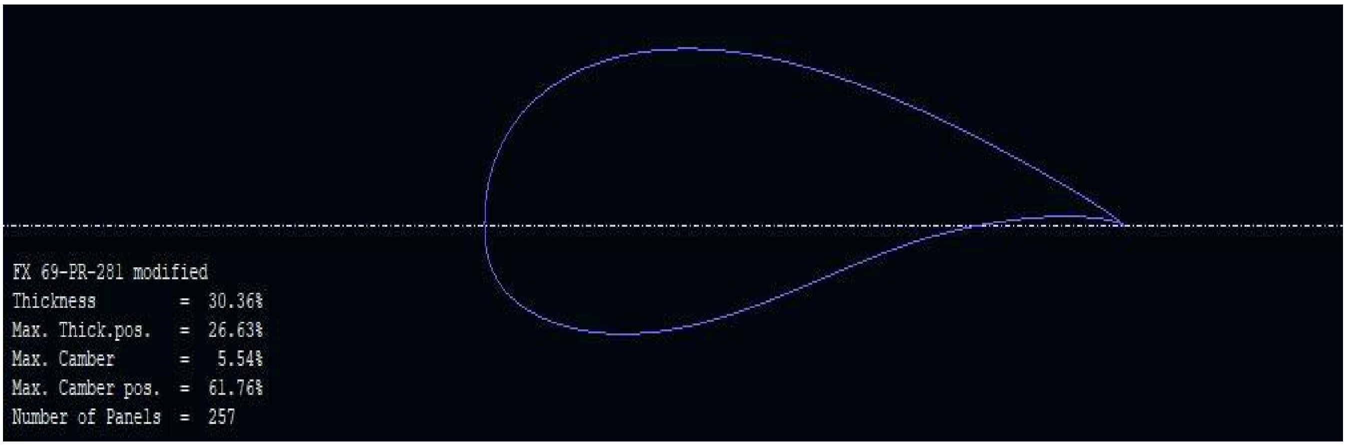


- Its pressure distribution is,

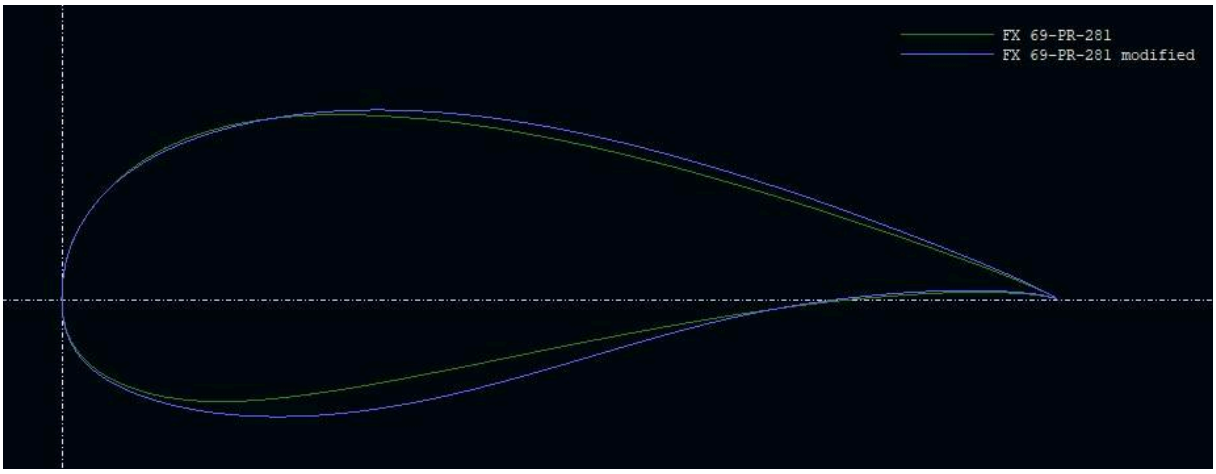


The airfoil is modified using xflr 5 by inverse designing method. xflr 5 is one of the most commonly used application for analyzing and modifying airfoils. The goal was to generate more lift than the original airfoil and decreasing drag force so that the lift produced is high(thrust for propellers). The velocity distribution of the graph has been edited with the help of spline feature so that the required conditions have been met. The airfoil with higher lift and less drag compared to existing model has been modified with the help of xflr and the formed airfoil is shown below along with comparison of both shapes.

<u>Fx-69-pr281 Modified:</u>



- Comparison of modified and original airfoil shapes:



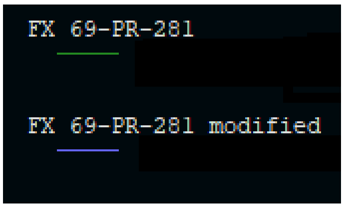
- **Designing propeller:**

  The obtained airfoil is now converted into ".dat" file. The designing of the propeller blade is done with the help of software called "QBlade". This is an open source software and easy to use. Now we have to insert the modified airfoil into the software. Once the airfoil is uploaded have to find its performance analysis and start designing. The formed propeller blade is shown in results.

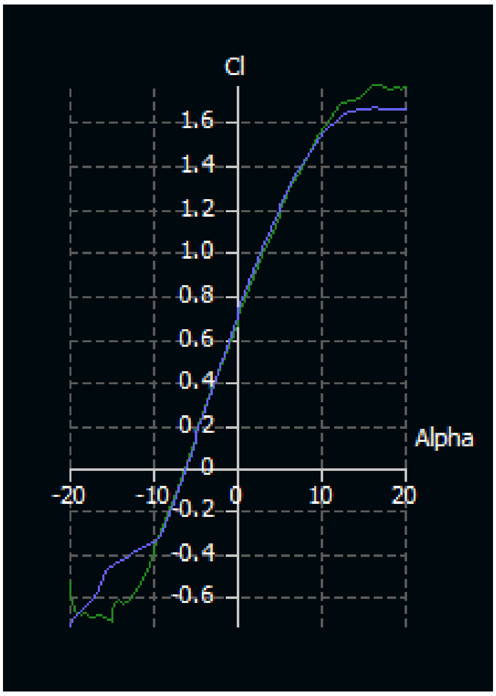
v. Results:

The airfoil meeting required conditions has been designed and the propeller using the designed airfoil was also designed using appropriate softwares.

The performance of the designed airfoil in comparison to existing airfoil are given below and the graph indication is

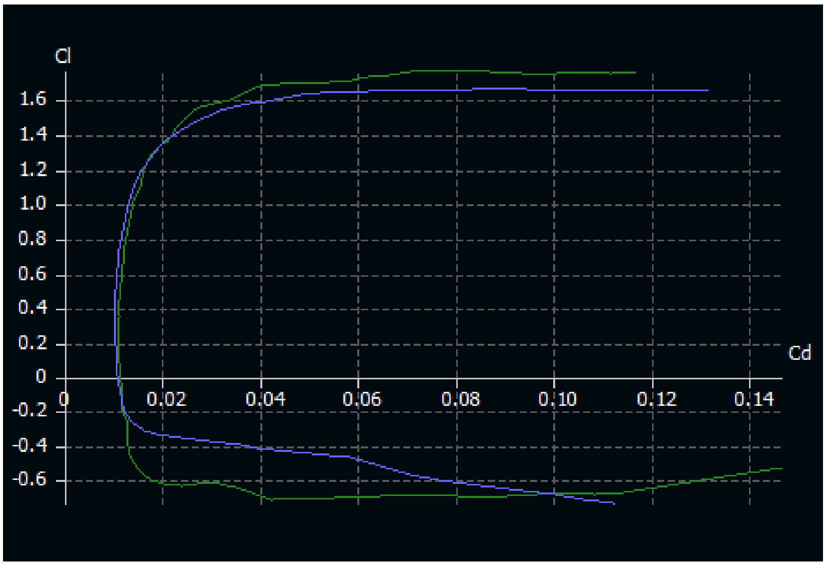


(1) C_l Vs α:



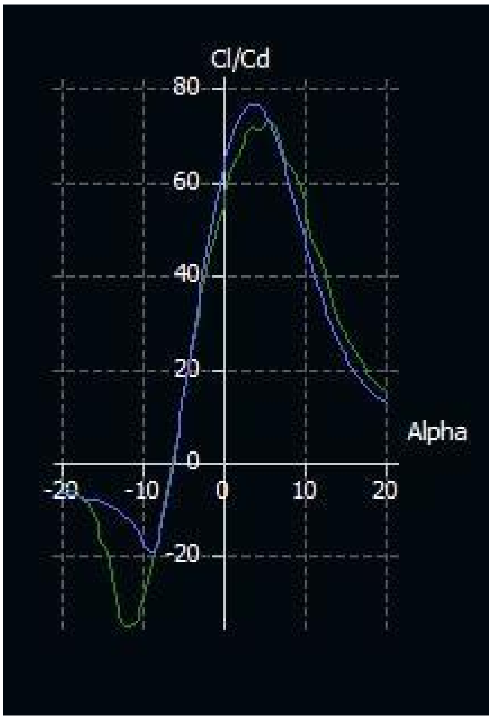
- We can see almost same cl for both airfoils for α < 4. Once the value of α gets higher we can see that modifies airfoil has larger value of C_l.

(2) C_l Vs C_d :



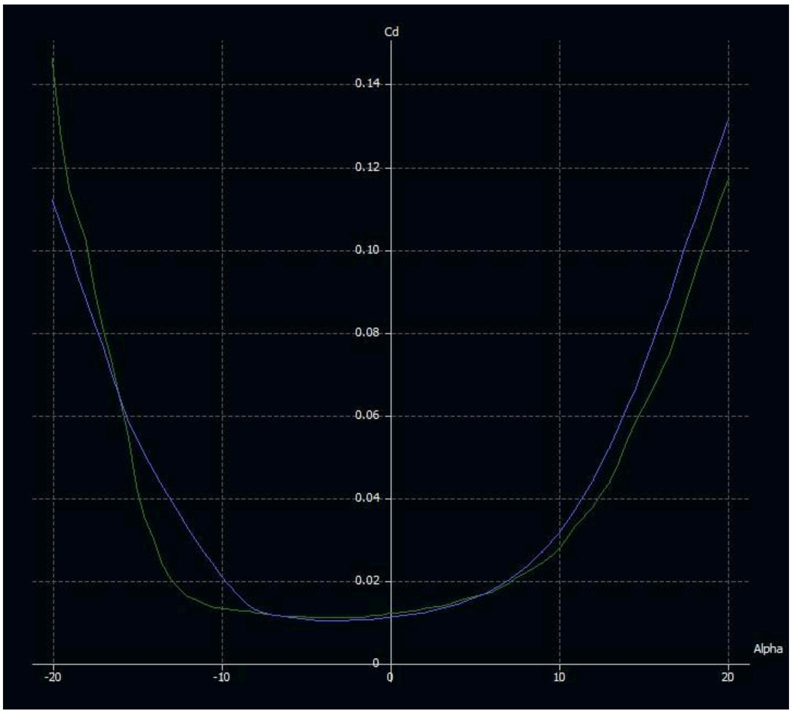
- From the above graph we see that modified airfoil has less drag since its drag co-efficient is less at optimum flight angle of attacks.

(3) C_l/C_d Vs α:



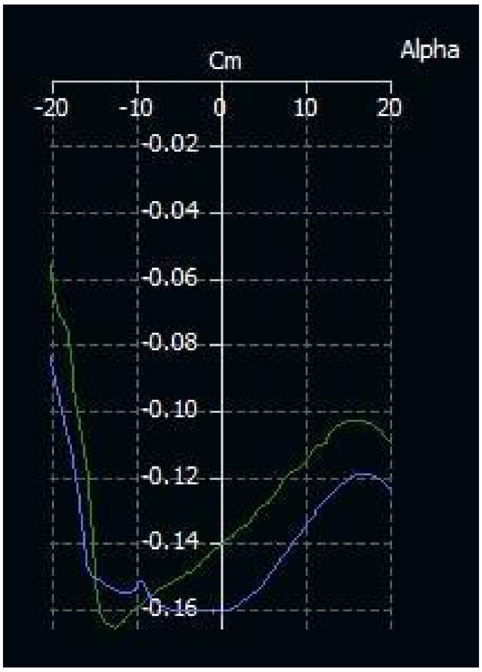
- As shown the performance of the modified airfoil is better.

(4) C_d Vs α:



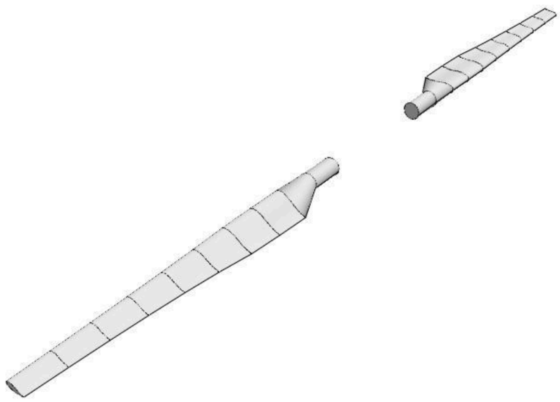
- From this we can see that the drag co-efficient of the modified airfoil is greater than the base airfoil.

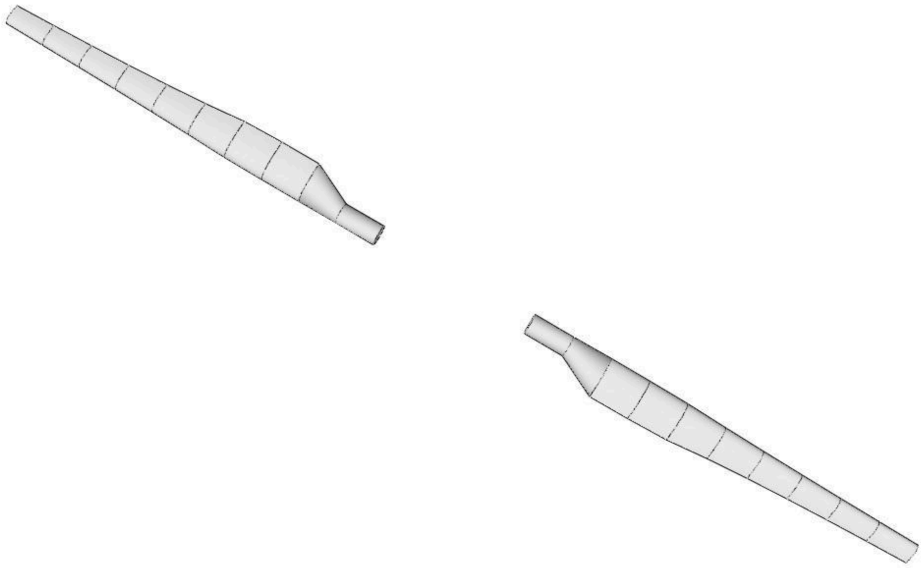
(5) C_m Vs α:



- The performance graph shown above proves that the modified airfoil has better performance.

- **Propeller:**





The blade shown is an optimized version. Optimization was done using bertz method in the software.

VI. Inference:

Through this mini-project I learned how to design airfoils using different methods such as thin airfoil theory and inverse design method. I have now proper idea of designing a propeller and also can design wings and airfoils. The things I inferred from this mini project are:

(a) The shape of airfoil changes even with small change in requirements.
(b) Airfoils can be classified on their performance and for which it is used.
(c) The modification of an airfoil has many complexities which yet have to be resolved.
(d) The performance of airfoil also changes at different altitudes it is going to be used, since Reynolds number changes.
(e) At zero angle of attack, the lift co-efficient is positive so the airfoil is efficient
(f) Each and every existing airfoil are not total number of airfoils which can be made. New requirements always develop new airfoils.
(g) The increase in drag co-efficient was observed and this is because of improper modification of velocity performance.

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