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Performance Analysis and Comparison of High Lift Airfoil for Low Speed Unmanned Aerial Vehicle

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ABSTRACT
The growing interest in research of UAV, equipped with increased payload, shortened take-off and landing distances and lower stall speed, has created a need for the comparative analysis of performance of different high lift airfoils. US Army has developed high lift, low speed AAI RQ-7 Shadow UAV of such kind. Apart from the armies of various countries, some private companies are also working on to design UAVs, capable of performing rescue missions, spy missions & firefighter missions. A reasonable selection of high lift & low Reynolds number airfoil is very important part of aerodynamic design process for this kind of low speed UAVs. As a result, performance analysis and comparison of high lift airfoil for low speed UAV, has earned an enormous importance in modern day Aerospace Engineering. The methodology of this research will be useful in further development of the research of aerodynamic characteristics of high lift airfoil.
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Keywords: Airfoil, UAV, High Lift

1. Introduction

An **unmanned aerial vehicle** (**UAV**), commonly known as a **drone,** as an **unmanned aircraft system** (**UAS**), or by several other names, is an aircraft without a human pilot aboard. The flight of UAVs may operate with various degrees of autonomy: either under remote control by a human operator, or fully or intermittently autonomously, by onboard computers. Now a day there are wide ranges of applications where UAV or drones are being used. Most of these includes military and commercial surveillance, search and rescue and most importantly in research purpose. So currently a large amount of focus is given on the development of UAV structures for better performance, maneuverability, stability during operation. Keeping these facts on mind our current focus is to analyze the performance of high lift airfoil and select the best suitable airfoil for UAV, designed with high lift coefficient, low Reynolds number characteristics to perform military and research based operations. This research will lead the UAV researchers and commercial producers to design and fabricate advanced UAVs with vast range of sophisticated works.

2. Methodology

A reasonable selection of high lift & low Reynolds number airfoil is very important part of aerodynamic design process for this kind of low speed UAV. In this research work, a number of high lift airfoils suited for low Reynolds number regime and high lift capacity like EPPLER (E423, E421, E420), SELIG (S1223, S1223rtl, S2027), WORTMANN (FX74-CL5-140, FX63_137), AG35, NLF 0115, are taken into consideration for analysis by using computational analysis. As the availability of wind tunnel is rare and the cost of wind tunnel test is far more expensive than simulation based analysis, here we are using an algorithm based commercial software which includes the program for foil analysis, and several 3d analysis methods for planes such as a non-linear lifting line method for standalone wings and two vortex-lattice and a 3d panel method for the analysis of aerodynamic performance of wings and plane operating at low Reynolds numbers.

Analysis was done taking sea level conditions as reference. Factors, such as high coefficient of lift, high negative pitching moment, less drag penalties in the operating C_L range C_L vs. alpha, C_m vs. alpha graphs for each airfoil at Reynolds Number 450000, fabrication difficulty are considered and compared for each airfoil

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at same Reynolds number. Finally, the best suited airfoil for a UAV with aforementioned characteristics is suggested. The methodology of this research will be useful in further development of the research of high lift airfoil. The optimized airfoil of this research work can be used in future for designing a suitable wing for unmanned aerial vehicle with capability of increased payload, shortened take-off and landing distance.

3.0 Airfoil

An airfoil is the shape of a wing, blade of a propeller, rotor, or turbine, or sail. An airfoil-shaped body moved through a fluid produces an aerodynamic force. Subsonic flight airfoils have a characteristic shape with a rounded leading edge, followed by a sharp trailing edge, often with a symmetric curvature of upper and lower surfaces. An aircraft or airplane has four basic forces that act upon it. We know them as Lift, Drag, Thrust and obviously gravitational force. So our main work is related to these forces and their characteristics on different environmental and operational conditions.

A fluid flowing past the surface of a body exerts a force on it. **Lift** is a component of this force that is perpendicular to the oncoming flow direction.

In aerodynamics, aerodynamic **drag** is the fluid drag force that acts on any moving solid body in the direction of the fluid free stream flow.

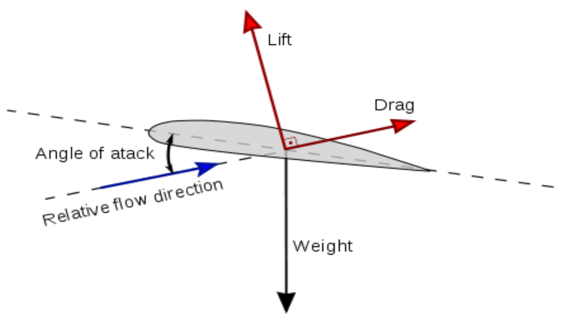

Fig: 1.0: Basic aerodynamic forces

Thrust is a reaction force that described quantitatively by newton's 2^{nd} and 3^{rd} laws. When a system expels or accelerates mass in one direction, the accelerated mass will cause a force of equal magnitude but opposite direction on that system

3.1 Coefficient of lift, C_L

The **lift coefficient** (**C_L**, **C_N** or **C_z**) is a dimensionless coefficient that relates the lift generated by a lifting body to the fluid density around the body, the fluid velocity and an associated reference area. A lifting body is a foil or a complete foil-bearing body such as a fixed-wing aircraft. C_L is a function of the angle of the body to the flow, its Reynolds' number and it's Mach number. The lift coefficient c_l refers to the dynamic lift characteristics of a two-dimensional foil section, with the reference area replaced by the foil chord.

The lift coefficient C_L is defined by

$$C_L = \frac{L}{1/(2\rho(v)2\ s)} = \frac{2L}{\rho(v)2} = \frac{L}{qS}$$

The lift coefficient can be approximated using the lifting-line theory, numerically calculated or measured in a wind tunnel test of a complete aircraft configuration.

3.2 Drag Coefficient, C_d

Fluid dynamics, the **drag coefficient** (commonly denoted as C_d) is a dimensionless quantity that is used to quantify the drag or resistance of an object in a fluid environment, such as air or water. It is used in the drag equation in which a lower drag coefficient indicates the object will have less aerodynamic or hydrodynamic drag. The drag coefficient is always associated with a particular surface area.

The drag coefficient of any object comprises the effects of the two basic contributors to fluid dynamic drag, skin friction and form drag. The drag coefficient of a lifting airfoil or hydrofoil also includes the effects of lift-induced drag. The drag coefficient of a complete structure such as an aircraft also includes the effects of interference drag.

$$C_d = \frac{D}{1/(2\rho(v)2\ s)} = \frac{2D}{\rho(v)2} = \frac{D}{qS}$$

For airfoils, the reference area is the nominal wing area. Since this tends to be large compared to the frontal area, the resulting drag coefficients tend to be low, much lower than for a car with the same drag, frontal area, and speed.

Two objects having the same reference area moving at the same speed through a fluid will experience a drag force proportional to their respective drag coefficients. Coefficients for unstreamlined objects can be 1 or more, for streamlined objects much less.

3.3 Coefficient of Moment, C_m

Pitching moment coefficient is fundamental to the definition of aerodynamic center of an airfoil. The aerodynamic center is defined to be the point on the chord line of the airfoil at which the pitching moment coefficient does not vary with angle of attack, or at least does not vary significantly over the operating range of angle of attack of the airfoil.

In the case of a symmetric airfoil, the lift force acts through one point for all angles of attack, and the center of pressure does not move as it does in a cambered airfoil. Consequently the pitching moment coefficient for a symmetric airfoil is zero.

The pitching moment is, by convention, considered to be positive when it acts to pitch the airfoil in the nose-up direction. Conventional cambered airfoils supported at the aerodynamic center pitch nose-down so the pitching moment coefficient of these airfoils is negative

$$C_m = \frac{M}{qSl}$$

3.4 Angle of attack (α)

In fluid dynamics, **angle of attack** (**AOA or α**)is the angle between a reference line on a body, often the chord line of an airfoil and the vector representing the relative motion between the body and the fluid through which it is moving.

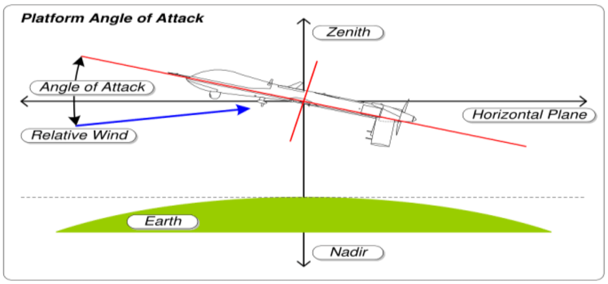

Fig 2.0: Angle of attack

Angle of attack is the angle between the body's reference line and the oncoming flow. This article focuses on the most common application, the angle of attack of a wing or airfoil moving through air.

3.5 Characteristics of flow during low Reynolds number

Airfoil characteristics are strongly affected by the “Reynolds numbers” at which they are operating. Reynolds’ number is the ratio between the dynamic and the viscous forces in a fluid.

$$Re = \frac{\rho v l}{\mu}$$

The Reynolds number influences whether the flow will be laminar or turbulent, and whether flow separation will occur. Another consideration in modern airfoil design is the desire to maintain laminar flow over the greatest possible part of the airfoil. Thickness ratio has some effect upon the maximum lift coefficient.

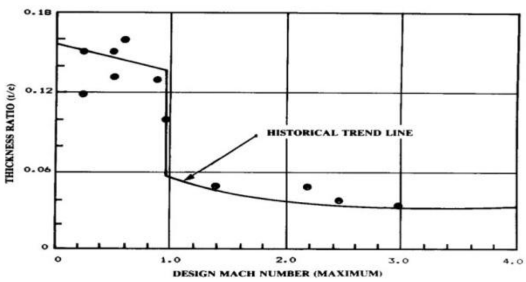

Fig 3.0: Thickness ratio vs Mach number

The drag increases with increasing thickness due to increased separation. For initial selection of the thickness ratio, the historical trend shown in figure-1 can be used. Note that a supercritical airfoil would tend to be about 10% thicker (i.e., conventional airfoil thickness ratio times1.1) than the historical trend. In incompressible flow conditions relatively high thickness to chord ratios of up to 0.2 are acceptable. The basic Airfoil must have a low profile drag coefficient for the range of lift coefficients used in cruising flight. The maximum lift coefficient both at low and higher Mach numbers are one of the requirements. The stalling characteristic where a gentle loss of lift is preferable is another need, especially for light aircraft.

3.6 Drag Polar

The **Drag Polar** is the relationship between the lift on an aircraft and its drag, expressed in terms of the dependence of the lift coefficient on the drag coefficient. It may be described by an equation or displayed in a diagram called a **polar plot.**

4.0 Analysis Method

At the beginning some airfoils known for their high lift characteristics, were selected from the UIUC Airfoil Database. These are analyzed and compared using XFLR5 software.

XFLR5 is a design & analysis tool of various parts of an aircraft. Airfoil can be designed and analyzed in this software. The primary purposes for the development of XFLR5 were to provide:

1. A user-friendly interface for XFoil
2. A translation of the original FORTRAN source code to the C/C++ language, for all developers who might have a need for it.

4.1 XFLR Code structure

Five different "Applications" have been implemented:

− Two direct design modes which are convenient to compare foils, and to design new foils with the use of B-Splines

− The mixed inverse (QDES) and the full inverse (MDES) foil design routines, virtually unchanged from the original

− The foil direct analysis routines (OPER)

− The wing, plane and body design and analysis

After that all the selected airfoils were analyzed under the same boundary condition. XFLR5 provides C_L vs C_d, C_L vs alpha, C_m vs Alpha graphs for each airfoil at different angle of attack using the following formulas-

$$L = \oint \rho . n . k . dA$$

Here, **n** is the normal unit vector pointing into the wing and k is the vertical unit vector, normal to the freestream direction.

$$C_L = \frac{L}{qS} \frac{L}{1/(2\rho(v)2\, s)} = \frac{2L}{\rho(v)2}$$

$$C_d = C_{d0} + K\,(C_L - C_{L0})^2$$

4.2 Analysis setup

Selected High Airfoils with high lift characteristics are EPPLER, (E423, E421, E420) SELIG (S1223, S1223rtl, S2027), WORTMANN (FX74-CL5-140, FX63_137), AG35, NLF 0115.

Analysis was done taking standard value of wing area, relative wind speed, Reynolds number for conventional low speed unmanned aero vehicles.

Relative air speed= 40 km/hr

Wing area= 1.2 m^2

Reynolds Number=4, 50, 000

Angel of attack range= -3 to 15 degree

Drag polar for light aircraft. C_{D0}= 0.017, K = 0.075 and C_{L0}= 0.1. The tangent gives the maximum L/D point.

4.3 Simulation Graph

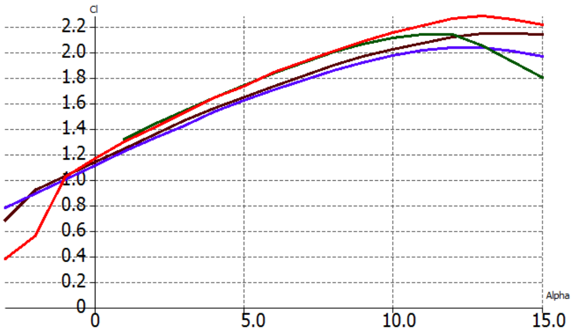

Fig 4.0: C_L vs Alpha Graph

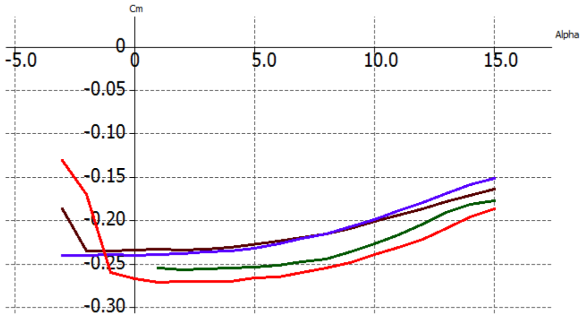

Fig 5.0: C_m vs Alpha Graph

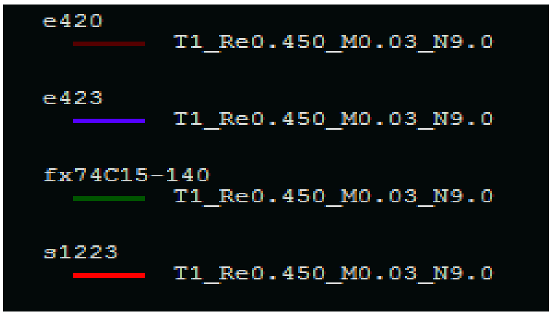

Fig 6.0: Reference lines for different airfoil

As can be seen from the Figure 4 and Figure 5, airfoils namely S2027, AG35 and NLF 0115 display relatively low C_L and low negative pitching moment, hence straightaway discarded.

FX74-CL5-140 despite having good Cm characteristics fails when compared with others on grounds of high lift.

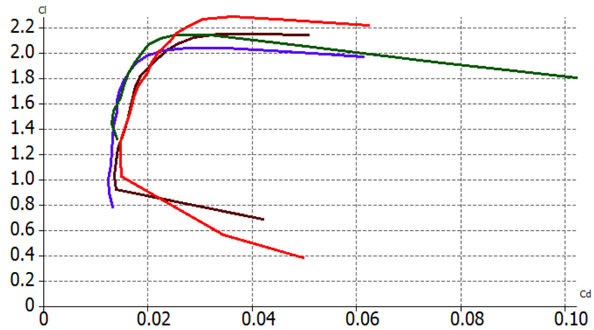

Fig 7.0: C_L vs C_d Graph

The remaining ones were examined by their drag polar at same Re as shown in Figure-7 which reduced the list to E420, E423, FX74-CL5-140and S1223 as these incur less drag penalties in the operating C_L range (1.4-2.0). It offers wider speed range and subsequently would be less affected by slight inaccuracies of flying.

5.0 Selected Airfoil Characteristics

After processing and applying some test using XFLR5 we have derived the exact airfoil for our purpose.

(a) **EPPLER 420**: Designated high lift airfoil mainly proposed for special purpose & military aircraft.

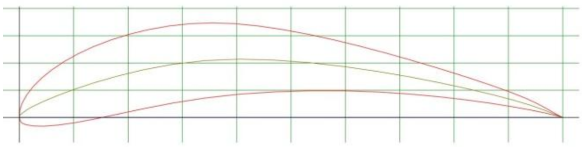

Fig 8.0: Airfoil shape (EPPLER 420)

(b) **FX-74-C15-140**: Another high lift airfoil suggested based on our test result. It's a modified wortman high lift airfoil.

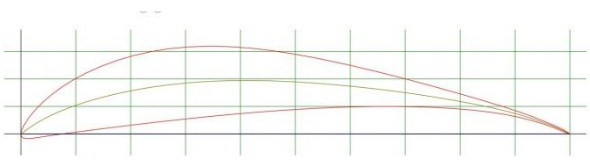

Fig 9.0: Airfoil shape (FX -74-C15-140)

(c) **EPPLER E423:** High lift airfoil suggested for next generation vertical takeoff and land unmanned aerial aircraft.

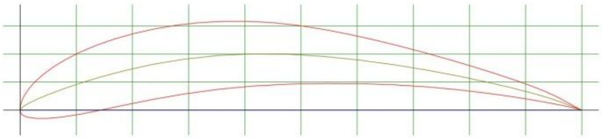

Fig 10.0: Airfoil shape (EPPLER E423)

(d) **S1123**: It's a high lift low Reynolds number airfoil with a Max thickness 12.1% at 19.8% chord Max camber 8.1% at 49% chord.

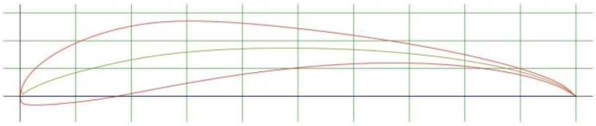

Fig 11.0: Airfoil shape (S1223)

6.0 Result

The results derived from the characteristics are shown below in tabular form-

Table 1 Data obtained from the analysis

Name of Airfoil	Max Cl at Re= 450000	Max Negative Cm at Re= 450000	Stall Angle	Cd at Cl-1.4	Cd at Cl-2.0
S1223	2.36	-0.263	14	0.017	0.021
Eppler 420	2.13	-0.234	14.5	0.017	0.014
Eppler 423	2.01	-0.246	13.5	0.016	0.025
FX74-CL5-140	2.19	-0.252	12	0.016	0.020

E423 seems to be a good option as it possess widest drag bucket supported by farthest downstream transition, but is rejected due to early occurrence of stall. Critical point location, curtailed the airfoil list to FX74-CL5-140, S1223 and E420. Fx74-CL5-140 airfoil also faces early stall, which is in between 11 to 12 degree angle of attack. Hence, it is rejected. Comparing E420 and S1223, it is visible that S1223 shows the best Cl and Cm characteristics. Though S1223 has a little smaller stall angle than E420, it can be overlooked. After comparing all the characteristics, it's found that S1223 is the most suitable airfoil for Low Speed, Low Reynolds' Number UAV.

7.0 Conclusion

After maintaining test parameters and following necessary procedure we have been successful to derive the best possible solution for the necessary airfoil. It can be used for the unmanned aerial vehicle for performing high lift reconnaissance. All the data were taken accordingly and test was performed under deep expert supervision. This similar method can be followed for several other hybrid airfoils for interceptor type jet fighter or UAV for better maneuverability.

8.0 Future development scopes

XFLR5 is trusted for the analysis of low speed aircrafts. As wind Tunnel Test is expensive and not available everywhere, XFLR5 can be a great tool to analyze and find out best suited airfoil for low speed aircrafts as per the requirement. Furthermore, new airfoil can be designed and analyzed according to the need with a very low cost.

NOMENCLATURE

C_L : Coefficient of Lift,
C_D : Coefficient of Drag,
C_m : Coefficient of Pitching Moment
L : Lift, (*N, stands for Newton*)
D : Drag, (*N, Stands for Newton*)
p : Air Density (kg/m^3)
S : Wing Area (m^2)
v : Velocity (m/s)
q : Dynamic pressure, (N/m^2)

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