# Airfoil Iterative Design for Maximum Aerodynamic Performance at Low Reynolds number

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**Abstract –** *The improvisation of the aerodynamic efficiency of airfoils in a restricted environment is the goal of the research. The parameter considered for enhancement was aerodynamic efficiency. Nine different airfoils were generated Through inverse design method. The Reynolds number for the analysis is an optimum value at which the wind turbine blades function. The analysis was made using an opensource software XFLR5 V6 and MATLAB R2019a. After the iterations, the final airfoil generated has a subsequent increase in the aerodynamic efficiency with a small difference in angle of attack from the first reference airfoil. The final airfoil can be used for many low speed applications such as wind turbine blades for maximum aerodynamic efficiency.*

***Key Words*: Aerodynamic efficiency, Airfoil, Iterative Design, Reynolds Number, Angle of Attack, RANS, Large Eddy.**

## 1.INTRODUCTION

The development in design of airfoils is proliferating constantly. The minor modifications in the geometry of an airfoil can result in striking results. In applications of Wind Turbines, the modification in the thickness and leading edge of the airfoil can result in major usefulness during specific scenarios such as apparent wind gusts [1, 2]. To be specific, general accomplishing of an airfoil starts from a flat plate, which develops onto an airfoil. The methods considered for generating the airfoil are Inverse foil design and direct foil design [3]. Direct foil design involves modification of an existing airfoil while the inverse foil design involves accomplishing of an airfoil starts from a flat plate or a plane circle [4]. High lift generation during an interval of low velocity is no wonder a topic of considerable interest. The purpose of this research paper is to present a high lift airfoil design with a range low considerable Reynolds number range where most of the commercial wind turbines operate. Most of the wind turbine blades are feathered for optimal angles of attack and the angles are varied with respect to the direction of apparent wind and optimal aerodynamic efficiency [5]. In this paper since the turbine blades can be feathered, the parameters such as aerodynamic efficiency, pitching moment, thickness and stall results are not much concentrated against angle of attack [6]. The complete design was based on generation of a high value of lift to drag ratio at low Reynolds number and angle of attack. The Reynolds number determines whether the flow is laminar or turbulent, or whether there is going to be separation of flow. The desire to maintain laminar flow over the largest part of the airfoil is another factor in modern airfoil design. The thickness ratio has some effect on the coefficient of peak lift. The optimum Reynolds number range for a wind turbine varies from 50,000 to 300,000. For design considerations the Reynolds number chosen was 100,000. [7].

## 2. DESIGN METHODOLOGY

The design methodology adopted is called Mixed Inverse foil design. This methodology follows a procedure of design which starts with a flat plate of 1-unit length. The reason why it starts from a plate is because, the plate generates the least form drag coefficient $C_{do}$ when lift is equal to zero [8]. The basic Airfoil must have a low profile drag coefficient for the lift range used in cruising flight. One of the criteria is the total lift coefficient at low and higher Mach levels. Since the flat plate cannot be relied upon for lift generation, the NACA 4-Digit symmetric series was used to develop the airfoil further. The NACA 0018 (n0018-il) [9] was opted based the conventional thickness used in wind turbine blades, which varies from 17% to 25% of the chord at a local coordinate of 30% length of the chord. The ‘x’ and ‘y’ coordinates of the airfoils were imported onto XFLR5 V6 and chosen for inverse design of the airfoil. XFLR5 V6 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.[14]

The inverse design feature of the XFLR5 V6 has an option to modify the plot of non-dimensional local velocity (Q/ $V_{inf}$) versus non-dimensional position across the chord (X/C). The plot provides and option to vary the properties of the upper and lower surface of the airfoil separately which should be acknowledged. In accordance with the option stated above, it also provides an option to apply the changes made to a specific region in the airfoil geometry or the complete geometry itself. After modifying the NACA 0018(n0018-il) the resulting airfoils had an increase in thickness and camber. There were around 8 iteration of geometry modification until the most optimized airfoil was developed all the 8 stages are discussed in the subsections. The reference airfoil taken was NREL's S835 Airfoil (s835-nr) [10]. The optimization design methodology was based on SG6042 [11]. The Reynolds number used to compare the results of successive iterations is the optimum wind turbine operation Reynolds number which is around 1,00,000 [7].

## 3. ANALYSIS

The flow over the airfoils were simulated in XFLR5 V6 and analysis was conducted based on the variation of $C_l/C_d$ ratio with respect to one particular Reynolds number (1,00,000) and the results were observed by re-plotting the graphs on MATLAB for accurate results. The plots of the variation of aerodynamics efficiency against the AoA can be found in Chart 1.The plots of the variation of coefficient of lift against the AoA can be found in Fig 3.The plots of the variation of coefficient of drag of against the AoA can be found in Chart 2.We can observe the gradually increasing $C_l/C_d$ ratio from airfoil 1 to the final airfoil. The transition of airfoil1 to the final can be seen in Fig -1 and Fig -2 respectively.

### 3.1 Abbreviations and Acronyms

$C_{do}$ Zero lift- drag coefficient

Q Local flow velocity over the airfoil surface

$V_{inf}$ Free stream velocity of the flow

X Local chord location(abscissa)

C Chord

AoA Angle of Attack (in degrees)

$C_l$ Two-dimensional coefficient of lift

$C_d$ Two-dimensional coefficient of drag

### 3.2 Airfoils and Charts

**Fig -1** Airfoil 1 (NREL's S835)

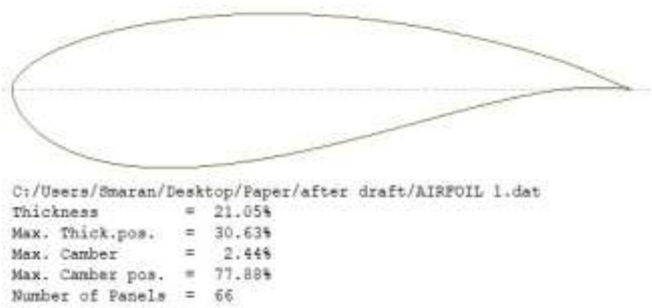


**Fig -2** Final Airfoil

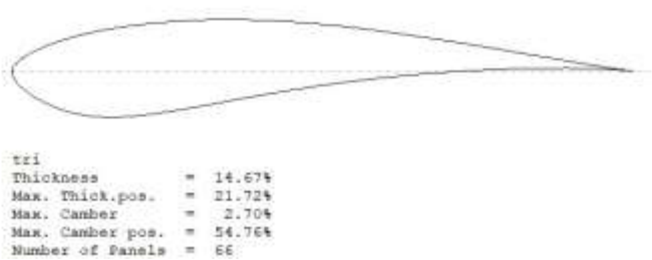


**Chart -1**: Aerodynamic efficiency as a function of angle of attack

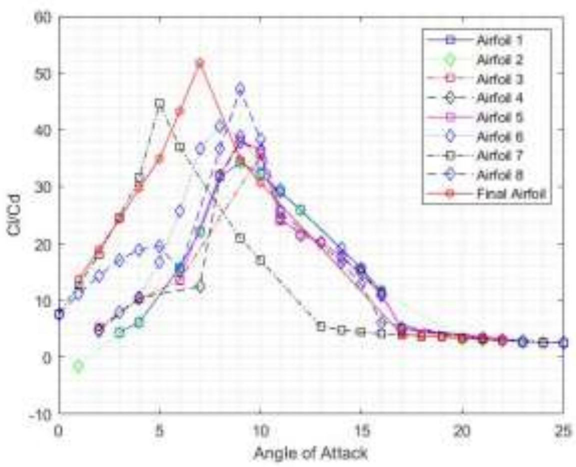

**Chart -2**: Coefficient of drag as a function of angle of attack

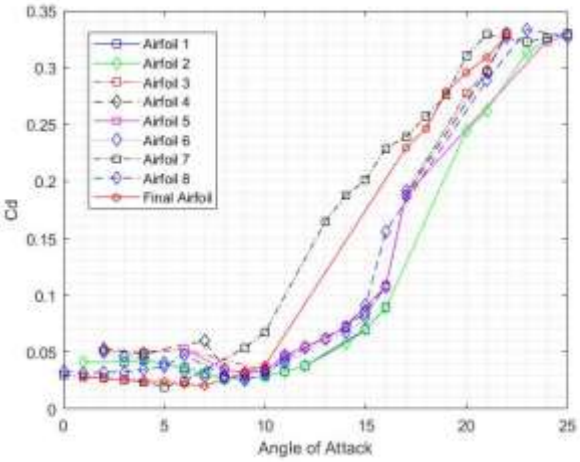


**Chart -3**: Coefficient of lift as a function of angle of attack

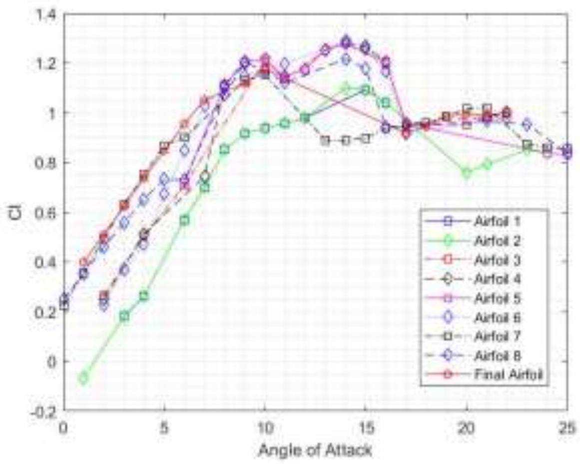


**Table -1:** Cartesian Coordinates of Final Airfoil

| **X-Y Coordinates of the Final Airfoil** | | | |
|---|---|---|---|
| X | Y | X | Y |
| 1.00000 | -0.00006 | 0.00026 | 0.00322 |
| 0.99593 | 0.00051 | 0.00023 | 0.00294 |
| 0.98421 | 0.00212 | 0.00002 | 0.00006 |
| 0.96621 | 0.00476 | 0.00111 | -0.00692 |
| 0.94354 | 0.00829 | 0.00638 | -0.01880 |
| 0.91740 | 0.01256 | 0.01744 | -0.02849 |
| 0.88806 | 0.01751 | 0.03168 | -0.03937 |
| 0.85489 | 0.02317 | 0.04928 | -0.04925 |
| 0.81806 | 0.02944 | 0.06960 | -0.05890 |
| 0.77810 | 0.03617 | 0.09343 | -0.06667 |
| 0.73544 | 0.04323 | 0.12093 | -0.07210 |
| 0.69057 | 0.05043 | 0.15199 | -0.07470 |
| 0.64394 | 0.05753 | 0.18614 | -0.07376 |
| 0.59600 | 0.06432 | 0.22347 | -0.06971 |
| 0.54718 | 0.07051 | 0.26354 | -0.06363 |
| 0.49794 | 0.07571 | 0.30590 | -0.05616 |
| 0.44863 | 0.07972 | 0.35024 | -0.04798 |
| 0.39960 | 0.08233 | 0.39635 | -0.03958 |
| 0.35147 | 0.08330 | 0.44406 | -0.03142 |
| 0.30463 | 0.08258 | 0.49326 | -0.02377 |
| 0.25963 | 0.08018 | 0.54376 | -0.01687 |
| 0.21701 | 0.07634 | 0.59536 | -0.01089 |
| 0.17722 | 0.07134 | 0.64770 | -0.00584 |
| 0.14070 | 0.06530 | 0.70033 | -0.00169 |
| 0.10773 | 0.05794 | 0.75250 | 0.00151 |
| 0.07862 | 0.04959 | 0.80321 | 0.00374 |
| 0.05353 | 0.04056 | 0.85129 | 0.00499 |
| 0.03271 | 0.03115 | 0.89512 | 0.00519 |
| 0.01652 | 0.02140 | 0.93255 | 0.00437 |
| 0.00537 | 0.01212 | 0.96213 | 0.00288 |
| 0.00357 | 0.00992 | 0.98326 | 0.00135 |
| 0.00199 | 0.00778 | 0.99582 | 0.00028 |
| 0.00087 | 0.00501 | 1.00000 | -0.00006 |

## 4. OBSERVATIONS AND RESULTS

The Inverse design involves plotting an airfoil from basic cartesian coordinates as a first step towards the process. The plotted airfoil is analyzed for a 2-D turbulent flow of air (turbulence model being large eddy mathematical model). The properties of air are standard and are being considered at sea level. The current optimizations in airfoil design have been observed in applications such as Viscous continuous adjoint method which use compressible RANS (Reynolds- Averaged Navier-Stokes) flow solver, FLO103-MB, a point-to-point matched multi-block grid system and the message passing interference (MPI) parallel solution methodology for both the flow and adjoint calculations[13]. This research work involves a similar mathematical approach for the large eddy mathematical turbulence model air flow around Mach 0.3 considering the effects of linear compressibility. The iterations are based on gradual upgradations of existing geometry of airfoil with major modifications being a minimum increase or gradient of thickness of 5% and the y-coordinate of mean camber line with a deflection of 2% - 5% from chord. The successive iterations comprised of constant geometrical changes involves a 5% decrease in thickness and corresponding increase in camber. Each iteration had a viable increase the aerodynamic efficiency a minimum of 12% while the final foil had an increase of 53.625% which is drastic increase from what was originally observed in the first iteration. The maximum ratio of lift to drag coefficients can be observed to be 51.804 at an AoA of 7degrees. The maximum coefficient of lift (Cl) is1.175 at an AoA of 10 degrees. The coefficient of drag (Cd) at an AoA of 14 degrees is 0.038.

## 5. APPLICATIONS

The growing interest in Unmanned Ariel Vehicles (UAV) science, equipped with increased payload, shorter take-off and landing distances and lower stall speed, has created a need for comparative design of various high-lift airfoils. Applications of low Reynolds number high lift airfoils can be foreseen with respect to UAV's noise reduction applications and optimum operation conditions of wind turbines. Low speed high lift airfoils can be used for short take-off and landing (STOL) [12]. All the data was taken accordingly and the design procedure was carried out under the guidance of an expert. A similar design methodology can be used to design different families of airfoils, optimizing the geometry and performance of the airfoil.

## 6. CONCLUSION

Among all the iterative solution optimizations derived, the final airfoil really seems to have the best relative characteristics with respect to aerodynamic efficiency. All the values and constants taken for the analysis are standard cases. The Increase regarding the aerodynamic efficiency is about 52.365% with a difference in AoA of about 1 degree. The difference in this AoA can be taken care by the blade feathering to modify itself for efficient aerodynamic condition.

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