DESIGN OF AIRFOIL FOR LOW REYNOLDS NUMBER FLIGHTS USING PYTHON AUTOMATION CODE

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Abstract. The design of airfoil represents a facet of aerodynamics. The low-Reynolds number flight vehicle manufacturers/designers are seeking the efficient and effective method of airfoil design code for design and development. This research paper presents an efficient, low-speed airfoil design using the Python automation code. The main objective is to design the airfoil to achieve high aerodynamic performance for future fixed-wing micro aerial vehicle (MAV) applications. In this study, the fixed-wing micro aerial vehicle travel with the speed range between 6-20 m/s and the Reynolds number 2x10^3 are considered. The Python automation code is developed to achieve the optimum airfoil as per the user requirements. The designed airfoil is analysed using ANSYS Fluent and is validated with wind tunnel experiments. According to the findings, the designed airfoil has a high lift aerodynamic performance at low Reynolds number and could be ideal for the design and development of micro aerial vehicles. The maximum variation of the coefficients of lift and drag from reference (S1223 airfoil) and designed airfoil numerical results are 13.64% and 16.66%, respectively at 10° angle of attack (AOA). The maximum range and endurance estimated for both reference and designed airfoil. The maximum 6% increased for designed airfoil as compared to the reference airfoil. It is strongly recommended that any aerodynamic design engineer can use this Python automation code to design the airfoil as per the user requirements. Keywords: Low-Reynolds Number, Airfoil Design, Python Automation Code, Micro Aerial Vehicle, Low Speed Wind Tunnel.

1. INTRODUCTION

Airfoil plays a significant role in the aerodynamics of the low Reynolds number flights. The design or selection of airfoil processes is essential for the design and development of low Reynolds number flight vehicles and significant at the earliest low Reynolds number flight vehicle design stage to support design engineers in selecting or designing an appropriate airfoil as required by the user. The airfoil aerodynamic characteristics include the coefficient of lift, drag and pitching moment that are essential to evaluate by performing the test at the desired working condition of the airfoil [1].

The concept of low Reynolds number in aerodynamics predominant for civil and military applications. These include high altitude devices, wind turbines, human-powered vehicles, remotely piloted vehicles, sailplanes, unmanned aerial vehicle and micro aerial vehicle [2-5]. In the 21st century, the micro aerial vehicles (MAVs) and unmanned aerial vehicles (UAV’s) are becoming increasingly curious, required extensive and in-depth research into 2D airfoils and 3D wings [6]. The Python programming language was created by Guido van Rossum in the late 1980s. In IT industries such as NASA, Industrial Light and Magic, Yahoo, Facebook, and Google, Python is used mainly for software development. The knowledge of the python community can accomplish great things with python, but the beauty of python is that it is open to beginning programmers and allows them to deal with interesting problems faster than many other, more complex languages that have a steeper learning. Sunanda et al. [8] At Re = 4000, the author analysed thirteen different airfoils. This study was carried out by adjusting the geometry of the airfoil, i.e., camber, thickness, and airfoil roughness. Kunz [9] studied the low Reynolds number airfoil geometry effects on performance by varying camber, thickness, and leading and trailing edge shape at Re = 10000. The optimized airfoil achieved a maximum lift-to-drag ratio five percent at Re = 2000 and an average lift-to-drag ratio of about 4 percent at Re = 6000. It was found that the camber line plays an important role in achieving the maximum lift-to-drag ratio. Mateescu and Abdo [10] Many NACA airfoils were tested at different angles of attack and the Reynolds number ranged from 400 to 6000. The lift-to-drag ratio depends on camber, thickness, and Reynolds number. Pranesh et al. [11] studied NACA 0008 airfoil aerodynamic characteristics at Re = 2000 and 6000. Srinath and Mittal [12] studied aerodynamic characteristics of the NACA 0012 airfoil at Re ≤ 500 at a different angle of attack. Interesting was the optimized airfoil and different geometry shapes were obtained. It has been concluded that more design space leads to better aerodynamic forms. Kumar et al. [13] proposed a method to optimize the shape with a wide range of design variables.
For $Re = 1000$ and $Re = 10,000$ at $\alpha = 4^\circ$, the optimized airfoil was designed. Large ranges of low Reynolds number airfoils reported in the literature, particularly for free flight model aircraft, sailplanes, and heavy-lift radio-controlled aircraft.[14-16] Arvind Santhanakrishnan et al. [17] studied experimental and numerical investigations on NACA 4415 airfoil at chord-based Reynolds number lesser than 100000, by varying static camber the stall angle of attack increased. S. S. Talya et al. [18] multidisciplinary optimization of gas turbine airfoil design was studied, despite various limitations on airfoil geometry. Using the Kreisselmeier-Steinhauser (K-S) function method, the restricted multi-objective optimization problem is solved.

In this research work, the author developed a Python automation code to design the optimum airfoil as per the user requirements for both civilian and military applications. For a selected S1223 reference airfoil, the author principally interested in maximizing lift-to-drag ratio to increase the overall aerodynamic efficiency of the low Reynolds number flights. The lift-to-drag ratio depends on wing geometry and the flow conditions. The designed airfoil results validated with ANSYS Fluent, experiments results from the literature, and wind tunnel experiments.

2. Methods & Materials

2.1 Python Automation Code

Python is a general-purpose programming language of interpretation developed by Guido van Rossum and first released in 1991. The python program is a language-construct an approach that aims to help programmers write clear, logical code for small and large-scale research projects [7]. The python automation code with Xfoil solver generated to design low Reynolds number airfoil for different application based on the user requirements. The python automation code sequence of operation, as shown in Figure 1.

![Figure 1](image)

**Figure 1.** Block diagram of the python automation code for design the airfoil as per the user requirements

The low Reynolds number S1223 airfoil, considered as a reference airfoil and investigated in this research work, has a maximum thickness of 12.1% at 19.8% chord, a maximum camber of 8.1% at 49% chord, and the S1223 airfoil profile is shown in Figure 2. This airfoil exclusively designed and used for low Reynolds number applications [8]. The outcome of the Python automation code generated new airfoil coordinates as per the user requirements. The designed airfoil maximum thickness of 14.7% at 20.1% chord, a maximum camber of 10.8% at 47.7% chord, and the designed airfoil profile is shown in Figure 3.
2.2 Numerical techniques
The numerical simulations of the flow around S1223 reference airfoil and designed airfoil were carried out using the commercial CFD software, ANSYS 15. Using ICEM-CFD, the C-type domain generated with pressure-far-field boundary conditions, as shown in Figure 4. The total number of elements found that 34740 with 0.03 mm first spacing. Figure 4 shows the grid generation over the airfoil.
Table 1. Detailed information on the setup of CFD solvers for both reference and optimized airfoil used in this study

| Mesh          | 2-D structured                  | Reference values |
|---------------|---------------------------------|------------------|
| First cell thickness | 0.03 % chord                     | Area (m)         | 1 |
| Total mesh elements | 34740                           | Density (kg/m³)  | 1.225 |
| Solver        | Pressure based                   | Length (m)       | 0.3048 |
| Viscous model | laminar                          | Temperature (k)  | 288.16 |
| Pressure      | 101325                           | Velocity (m/s)   | 9.63 m/s |
| Fluid         | Air                              | Viscosity (kg/m-s) | 1.79E-05 |
| Angle of Attack | -4 to +14 Degrees (for every 2° of intervals) | The ratio of Specific Heat | 1.4 |
| Boundary conditions | Pressure-far-field               | Reynolds Number  | 200000 |

Table 1 shows detailed information on the setup of CFD solvers for both reference and optimized airfoil used in this study. The reference and optimized airfoil are simulated for the above-mentioned conditions and extracted aerodynamic characteristics.

2.3 Wind Tunnel Experimental Setup

The experiments were conducted in a low Reynolds number wind tunnel shown in Figure 5. It is open circuit suction type, made up of sheet metal, consists of test cross-section 21 × 13 × 15 cm, air-speed up to 15 m/s and contraction ratio 9:1. The overall size of the low Reynolds number wind tunnel 127 cm (L) × 36 cm (B) × 36 cm (H). Experimental data were captured at Reynolds number of were captured at Reynolds number of 2 × 105, to compute the coefficients of lift and drag. The pressure readings on designed airfoil model were recorded by using multi-tube manometer.

Figure 5. Wind tunnel experimental setup to analyse aerodynamic coefficients over a designed airfoil
3. Results and Discussion:

3.1 Python Automation Code Results

The lift and drag coefficients of the designed airfoil at various angle of attack were calculated from the automated python code using Xfoil solver. Figure 6(a) shows the profiles of lift and drag coefficients vs. angle of attack and lift-to-drag polar plot. The lift and drag coefficients of the designed airfoil as a function of AOA and lift-to-drag ratio plot are shown. These graphs are the result of the integration of surface pressure distribution around designed airfoil computed in Xfoil with the help of python automation code. At Reynolds number $2 \times 10^5$, coefficient of lift smoothly increases linearly till 12 AOA. It describes, the laminar boundary layer remains attached to the designed airfoil surface and leaves at the trailing edge to satisfy the Kutta condition. The recorded maximum coefficient of lift value is 2.466, and the corresponding coefficient of drag is 0.04922. Further increasing the AOA, it will lead to a stall, the coefficient of drag increases and decreases the coefficient of lift due to the adverse effect. Similarly, it was observed that by increasing the AOA (-4° - 14°) the drag coefficient also increases. The Figure 6(b) shows the lift-to-drag vs. angle of attack. From the Xfoil results, the recorded maximum lift-to-drag ratio of 67.40 at 4° angle of attack. The L/D ratio increases drastically at 4° angle of attack. It is due to the effect of adverse pressure gradient is insignificant over the upper surface of the airfoil. Further increasing the AOA, the L/D ratio gradually decreases when the adverse pressure gradient is significant.

![Figure 6](image_url)

Figure 6. The designed airfoil Xfoil results; (a) Lift and Drag coefficients vs. angle of attack; and (b) lift-to-drag vs. angle of attack

3.2 Numerical Results

Lift and Drag Coefficients: The lift and drag coefficient characteristics for the reference and designed airfoil is presented in Figure7. The aerodynamic parameters, lift and drag coefficients for a different angle of attack ranging from $-4^\circ$ to $14^\circ$ at Re $= 0.2 \times 10^5$ were computed. From the graph, it is demonstrable that the maximum coefficient of lift for the designed airfoil is higher than that for the reference airfoil. The corresponding values reported for the reference, and designed airfoil is 2.0177 and 2.3364 at an angle of attack $10^\circ$, respectively.
Further increasing the AOA it will lead to a stall, due to adverse effect, the coefficient of drag increases and decreases the coefficient of lift for the case of low Reynolds number conditions. Similarly, the corresponding drag coefficient values reported for the reference and designed airfoil are 0.0588 and 0.0636 at an angle of attack 10°, respectively. Because, at higher AOA, the coefficient of drag rapidly increases due to increases of frontal area and also the increases of boundary layer thickness.

**Figure 7.** Lift and drag coefficient vs angle of attack for designed airfoil CFD results

**Lift-to-Drag ratio:** The lift-to-drag ratio is conferred as L/D at a different angle of attack (AOA) for both reference and designed airfoil in Figure8. From the graph, it is evident that the lift-to-drag ratio for the designed airfoil is higher than that for the reference airfoil. The corresponding values reported for the reference, and designed airfoil is 76.99 and 81.18 at an angle of attack 2°, respectively. Beyond this angle of attack, the lift-to-drag ratio is substantially reduced due to drag penalty as the reference and optimized designed airfoil approaches stall angle of attack. The average increment of lift-to-drag ratio compared to the reference and designed airfoil is 3.2% for a different angle of attack.

**Figure 8.** Lift-to-drag ratio vs. angle of attack for designed airfoil CFD results
3.3 Wind Tunnel Experimental Results

In this work, investigated aerodynamic performance characteristics over a designed airfoil using low Reynolds number wind tunnel experiments. The wind tunnel experiments were conducted for different flight conditions, i.e. angle of attack 0° to 20° degrees at Reynolds number $2 \times 10^5$. Figure 9 shows the profiles of the lift and drag coefficients vs. AOA and lift-drag polar plot.

![Figure (a)](image)

![Figure (b)](image)

**Figure 9.** The designed airfoil lift and drag coefficients; (a) airfoil Lift and Drag coefficients vs. angle of attack; and (b) lift-drag polar curve
From the experimental results, the recorded maximum lift and drag coefficients is 2.46 and 0.1412 at Reynolds number 2 × 10^5, respectively. The lift coefficient increases linearly by increasing the AOA (0° to 16°) and it reaches the maximum at 16° AOA. Further increasing the AOA it will lead to stall. Similarly, it was observed that by increasing the AOA (8° - 20°) the drag coefficient also increases.

The Figure 9(b) shows the lift-to-drag vs. angle of attack. From the experimental results, the recorded maximum lift-to-drag ratio of 71.49 at 4°angle of attack. The L/D ratio increases drastically at 4° angle of attack. It is due to the effect of adverse pressure gradient is insignificant over the upper surface of the airfoil. Further increasing the AOA, the L/D ratio gradually decreases when the adverse pressure gradient is significant.

In this research work Barnhart, et al.’s MAV 2 battery-powered model [20] considered to validate the aerodynamic performance characteristics i.e. maximum endurance and range for both reference and designed airfoil. The following empirical relation used to calculate the maximum Endurance and Range.

\[ E_{\text{max}} = \frac{\eta_{\text{tot}} V \times C}{\sqrt{\frac{2}{\rho S}} C_{D0}^{\frac{1}{2}} \left(2W \sqrt{\frac{k}{3}}\right)^3} \text{ Hour} \]

\[ R_{\text{max}} = \frac{\eta_{\text{tot}} V \times C}{\sqrt{\frac{1}{\rho S}} C_{D0}^{\frac{1}{2}} \left(2W \sqrt{\frac{k}{3}}\right)^3} \sqrt{\frac{2W}{\sqrt{\frac{k}{3}}} C_{D0}^{\frac{1}{4}}} \times 3.6 \text{ KM} \]

4. Validation:

The reference and designed airfoil aerodynamic characteristics were numerically investigated at various AOA and aerodynamic performances were validated with wind tunnel experiments and literature. Figure 10 shows the lift coefficient versus angle of attack for the reference and designed airfoil data at= 0.2 × 10^6 respectively. In general, the present data agree with their measurements, thus providing validation for the present research results. The lift and drag coefficients validation process carried out for different conditions as follows.

Case 1: The maximum variation of the coefficients of lift and drag from reference and designed airfoil CFD results are 13.64% and 16.66% at 10°AOA.

Case 2: The maximum variation of the coefficients of lift and drag from Xfoil solver and CFD solver for designed airfoil are 1% and 33% at 10°AOA.

Case 3: The maximum variation of the coefficients of lift and drag from Xfoil solver and experimental results from the literature are 1% and 0% at 10°AOA.

Case 4: The maximum variation of the coefficients of lift and drag from CFD solver and experimental results from the literature is 22.95% and 33.33% at 10°AOA.
Case 5: The maximum variation of the coefficient of lift from Reference airfoil (literature) and wind tunnel experiments results is 14.63% at 16° AOA.

![Figure 10](image.png)

**Figure 10.** Lift coefficient vs. angle of attack for the designed airfoil

**Lift-to-Drag Ratio:** The lift-to-drag ratio is presented as L/D at a different angle of attack (AOA) for both reference airfoil and designed airfoil in Figure 11. From the graph, it is evident that the lift-to-drag ratio for the designed airfoil is higher than that for the reference airfoil.

The lift-to-drag ratio validation process carried out for different conditions as follows.

**Case 1:** The maximum variation of the lift-to-drag ratio from reference and designed airfoil CFD results are 5.16% at 2° AOA.

**Case 2:** The maximum variation of the lift-to-drag ratio from Xfoil solver and CFD solver for designed airfoil are 18.18% at 2° AOA.

**Case 3:** The maximum variation of the lift-to-drag ratio from Xfoil solver and experimental results from the literature are 23.07% at 2° AOA.

**Case 4:** The maximum variation of the lift-to-drag ratio from CFD solver and experimental results from the literature are 38.27% at 2° AOA.

**Case 5:** The maximum variation of the lift-to-drag ratio from Reference airfoil (literature) and wind tunnel experiments results is 24.46% at 4° AOA.
Conclusions

In low Reynolds number airfoil design problems, based on the applications and user requirements, different constraints may be considered to the airfoil geometry. In this research, developed the Python automation code interface with Xfoil solver to design the low Reynolds number airfoil geometry for both conventional and commercial applications as per the user requirements. Based on the developed code, the user can constraint two parameters, i.e. (i) maximize the lift coefficient (ii) maximize the lift-to-drag ratio. In this paper, the author constrained to maximize the lift-to-drag ratio parameter at $R = 0.2 \times 10^6$ for low Reynolds number flight applications. Based on the results, the following major conclusion made.

1. The developed python automation code interface with Xfoil solver tested based on the user-defined input, the designed airfoil achieved as per the user requirements.
2. The maximum variation of the lift and drag coefficients from CFD solver and experimental results from the literature are 38.27% at 2° AOA.
3. The designed airfoil lift-to-drag ratio (airfoil efficiency) increases by 38.27%, low Reynolds number flight with the higher lift-to-drag ratio are more efficient than those with lower lift-to-drag ratios.
4. High lift-to-drag ratio airfoils are suitable for low Reynolds number applications < 10 $[19]$.
5. In these experiments, the maximum endurance and range estimated for reference airfoil to be 1.924 hours and 31.92 km. The maximum endurance and range estimated for designed airfoil to be 1.938 hours and 33.96 km.
6. The maximum range and endurance estimated for reference airfoil to be 1.924 hours and 31.92 km. The maximum endurance and range estimated for the designed airfoil to be 1.938 hours and 33.96 km. The maximum range 6% increased for designed airfoil as compared to the reference airfoil.
7. The designed high lift-to-drag ratio airfoil is strongly recommended for low Reynolds number flight applications.
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