https://doi.org/10.26552/aer.C.2024.2.2

AERODYNAMIC OPTIMAZATION OF LONG ENDURANCE UAV WING

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Abstract

With recent growth in UAV sector, UAVs are progressively used more than ever before. With growth of UAV use is closely tied growth of possible uses of such aircraft. Missions conducted by any aircraft put requirements on the aircraft itself. This leads to necessity of optimization of aircraft for specific mission profile to maximize its mission efficiency. This article focuses on optimization of UAV wing for long endurance flight.

Keywords

Unmanned aerial vehicle, aerodynamics, optimization

1. Introduction

The UAVs historically were mainly used in military applications. Nowadays however, UAVs are progressively used more in civilian sector as well. Many of such UAVs are rotorcrafts which are cheap to produce and have advantage in the ease of control. Fixed wing UAV used in civilian sector also exist. The use of UAV in civilian sector is quite wide encompassing uses such as aerial photography, aerial surveying, atmosphere sampling and many others (Austin, 2010). The advantage of fixed wing UAVs in comparison to rotorcraft UAVs is speed, range and carrying capacity (Heaphy et.al., 2017). Fixed wing UAVs are therefore optimal platform for long endurance flights. Such flights may be needed during long term atmospheric surveillance (Austin,2010). On the other should the UAV be designed with the speed in mind, an UAV for short range quick mission profiles can be created. The aerodynamic design of UAV similar to manned aircraft has to adjust based on the mission requirements. This means that based on a mission profile a specialized UAV will have its own advantages and disadvantages (Gudmundsson,2014). For example, an UAV designed for long range operations and high endurance will use high aspect ratio wing to improve aerodynamic efficiency of the UAV. This however leads to increased drag due to increased frontal cross-section. On the other hand, an UAV designed for higher speeds will use sweep of a wing to reduce its drag making it easier to reach higher speeds. This, however, reduces the lift of the wing leading to lower total aerodynamic efficiency (Bertin, 2009). In this article we will take closer look at design of wing for long endurance aircraft.

2. Wing design

Wing design of UAV is very important part of entire design of UAV. It is responsible for big part of UAVs aerodynamic performance. Wing design also influences the stability of the aircraft and its controllability. It is also important from structural point of view. Should the wing design use airfoil that is too thin it can complicate construction process (Gudmundsson, 2022). It also reduces internal volume of the wing which can be used for installation of electronics, fuel tanks and other systems needed in UAV.

2.1 Long endurance UAV wing design

Long endurance UAV wing design must maintain as high aerodynamic efficiency as possible. This leads to high lift generation at relatively smaller drag which helps with increase of total range of flight. To achieve this a high aspect ratio wing is generally used. (Ma et.al., 2024). These wings are susceptible to wind gust due to their large total area. To help stabilize the aircraft a wing dihedral angle can be used (Gudmundsoon, 2022). Aerodynamic performance can be furthermore increased by targeting ideal elliptical lift distribution. This can be achieved in multiple ways. In theory easiest way is to use elliptical wing. Elliptical wing from aerodynamic point of view is most efficient due to ideal lift distribution which leads to reduction of induced drag. It also improves stall characteristics of wing by stalling everywhere equally (McCormick, 1979). This however is not the best solution from structural point of view as constructing an elliptical wing is harder than regular straight wing. Therefore, to get as close to elliptical lift distribution different approaches are used in practice. Tapered wing creates similar lift distribution to elliptical wing whilst being easier to construct than elliptical wing (Güzelbey et. al., 2019). Should however a constant wing chord be needed on the entirety of wingspan wing taper cannot be used. In the case neither of these two wing platforms can be used a wing twisting can be used to adjust lift distribution. Geometrical wing twist can be used to adjust the lift distribution by change of angle of incidence leading to increased lift generation. It is therefore possible to increase lift at the wing root and gradually decrease it until wingtip. By locally increasing angle of attack however drag increases as well. This is due to increase in frontal cross section of the wing (Prajwal et. al., 2024). This may seem as counter intuitive as with increase of lift there is also associated increase of drag and therefore the increase in the aerodynamic efficiency should be non-existent. However, lift generally increases more with increase in angle of attack than drag is and therefore this adjustment often leads to improvement of aerodynamic efficiency at 0 degrees of angle of attack. Additionally, by locally increasing angle of attack a local stall angle also changes. This can be easily explained on example of wing with stall angle of 15 degrees of angle of attack. This wing as expected upon reaching 15 degrees of angle of attack would stall. Now should we adjust this wing by introducing a geometrical wing twist in which a wing root angle of incidence is 5 degrees progressively reducing to 0 degrees at wing tip. This wing now stalls earlier with first stall being at wing root at angle of attack of 10 degrees as local angle of attack of wing root is sum of angle of incidence and total angle of attack of the wing. This phenomenon can prove beneficial by inducing vibrations to fuselage indicating the loss of lift of the wing to the pilot (Prajwal et. al., 2024). It however is not ideal for aircraft which may experience sudden increases in angle of attack and quick changes in direction of flight. During such conditions a sudden loss of lift on wing can lead to loss of control of aircraft. Another way of changing the lift distribution without need of geometrical twist of wing is aerodynamical twist of wing. This is done by changing the airfoil in certain sections of the wing to change aerodynamic characteristics of wing sections and therefore adjust the lift distribution of the wing. This however can prove problematic especially if the airfoil shape is vastly different from each other leading to design and construction complications (Scholz, 2015).

3. Airfoil choice

Airfoil choice is very important part of wing design process. This is due to fact that airfoil choice is capable of heavily influencing the total aerodynamic wing performance (Gudmundsson, 2022). The best example of this would be comparison of symmetrical and asymmetrical airfoil. Using asymmetrical airfoil on regular straight wing leads to a wing with good lifting performance. This lifting performance is however only present in positive angles of attack. Should an aircraft using such wing find itself flying upside down, the wings lifting performance would drastically worsen. This is not the case for symmetrical airfoil which would have identical performance in both regular flight and flight upside down. Symmetrical airfoil however has worse aerodynamic performance than asymmetrical airfoil in regular flight as it needs higher angle of attack to generate same lift as asymmetrical airfoil does at 0 degree of angle of attack (Gudmundsson, 2022).

3.1. Long endurance UAV airfoil choice

Airfoil choice for long endurance UAVs follows same basic principles as wing design for these UAVs. That being that the airfoil should allow to reach as high aerodynamic efficiency as possible. This means that the airfoil must generate as little drag as possible whilst generating as high lift as possible. Due to expected low flight speeds for these UAVs a low Reynold's number of airfoils can be used (Gudmundsson, 2022). These airfoils are specifically designed for flight at lower speeds. This allows for low drag generation and high lift generation even at low angles of attack. To increase a total lift generated by airfoil an increase in pressure fields generated by airfield may be targeted. This is usually the goal of laminar flow profiles. These profiles maintain laminar flow for longer percentage of airfoil chord length therefore increasing a total lift generated. The disadvantage of these profiles is that they must be always kept clean to maintain laminar flow around them otherwise the total lift generated lowers (Gudmundsson,2022).

4. Wing design process

Based on described requirements of long endurance UAV wing, a design process must considere the airfoil choice and design of wing geometry. In this article initial 3D model is created in Autodesk Inventor and subsequently tested in Ansys Fluent. Testing in Ansys Fluent provides necessary acting forces information.

4.1. Long endurance UAV design description

The long endurance wing design described as part of this article was designed as part of a project to create long endurance UAV for atmospheric surveying. Due to necessity of long endurance a high-wing half span of 2.85 meters. Total wingspan is 5.7 meters. A dihedral angle is introduced on the wing 0.9 meters from the wing root. This is done to improve the stability of the wing and to reduce the bending moment acting on the root of dihedral part of the wing. Wing chord is 0.305 meters. To improve stall characteristics an angle of incidence of 3 degrees is present at the wing root. This causes wing root to stall earlier warning the pilot of imminent loss of lift. Furthermore, this geometrical wing twist leads to improvement of lift distribution. It increases lift near the wing root and gradually reduces it to the wing tip. This optimization of lift distribution was chosen to keep the wing area as large as possible improving lifting capability of wing. The wing therefore meets basic design criteria for long endurance flight. The design of the wing can be seen in figure 1.

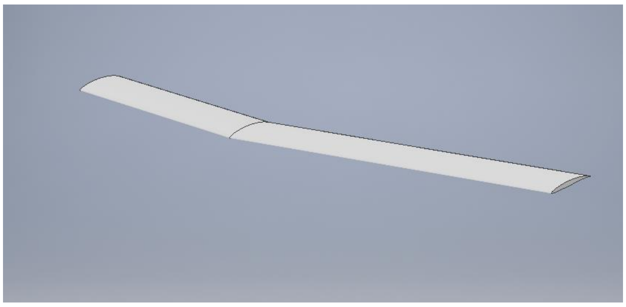

Figure 1. Proposed wing design

4.2. Wing airfoil choice

The most important factor in finishing the wing was airfoil choice. The use of low Reynolds number airfoils is possible as expected speed of flight sits in around 40-60 kilometres per hour. The Reynolds number at those speed ranges from $2.2x10^5$ to $3.4x10^5$. Another possible usable airfoil is laminar flow airfoil. By increasing area of low-pressure zone by use of laminar flow airfoil a high lift generation is expected. Series of models was tested as a part of design process with multiple airfoils being tested. The tested airfoils included:

- MH139
- Series of Modified NACA 4-digit airfoils
- Eppler E387

- Eppler E67
- Eppler E393

These airfoils were chosen based on their 0 degree angle of attack lift coefficient and drag coefficient. This was done to perform initial estimation of aerodynamic efficiency of the wing.

Table 1. Aerodynamic coefficients of tested airfoils

Airfoil	**Lift Coefficient**	**Drag Coefficient**	**Aerodynamic efficiency**
MH139	0.5	0.012	41.7
Eppler E387	0.4	0.0098	40.8
Eppler E67	0.4	0.013	30.8
Eppler E393	0.51	0.011	46.4
NACA modified series	~0.68	~0.05	13.6

The drag and lift coefficients for modified NACA series is not specific due to differences from each airfoil tested. The average values are instead present for all the airfoils tested. Despite the unexpectedly low aerodynamic efficiency of NACA series airfoils the resulting aerodynamic efficiency of the wing was one of the best. This may be caused by difference in measurement method used by application which was used to generate these airfoils.

Use of these airfoils allowed the wing to reach values of aerodynamic efficiency higher than 26 on average. There were however few outliners which reached values higher or close to 30. These were subsequently chosen for further testing and improvement. The airfoils in question are:

- NACA 4 digit (45xx) modified series
- Eppler E387
- Eppler E393

NACA 4-digit modified airfoils were modified in such a way as to increase the camber of trailing edge section of the airfoil. This adjustment increases lift generated by the airfoil. Additionally, a relatively high maximum camber of 4 % was used. This was again done to increase lift generation. To make the area of resultant pressure fields as large as possible the position of maximum camber and thickness of the airfoil is in its middle. This location causes the pressure to be minimal in the middle improving the pressure gradient of the airfoil. Improvement in pressure gradient results in increased area of lower pressure zone. This effectively creates a laminar flow airfoil. The disadvantage of this solution is increase of airfoil pitching moment as the centre of pressure moves more aft.

By adjusting the maximum thickness of airfoil there were totally 3 NACA 4-digit airfoils tested:

- NACA 4512
- NACA 4510
- NACA 4509

The best aerodynamic results of the wing were gained by use of Eppler E387 airfoil and modified NACA 4509 airfoil. These results will be further described.

4.3. CFD wing testing results

Series of models, differing by airfoil used, were tested in CFD environment of Ansys Fluent. The mesh of model consisted of fluid domain with body of influence around the wing. Additionally face sizing was added to the wing itself to improve accuracy of simulation. Both body of influence and face sizing were set to 0.005 meters. Volume meshing was performed in fluent mesher by use of poly-hexcore method. The testing was conducted with SST-ω viscous model. The NIST real gas model was used in simulation. This model uses fluid properties close to real life fluids, in our case air. The flow velocity was set to 14 m/s which is approximately 50 kph. The simulation iteration limit was set to 250, however convergence was reached before this limit in all cases. Two best results for simulated wings will be described below. The airfoils used in these models were Eppler E387 low Reynolds number airfoil and modified NACA 4509. The resulting acting forces on the wing are shown in table 1. Graphical comparison of results can be seen in figure 2.

Table 2. Force results of tested models

Airfoil	**Lift**	**Drag**	**Efficiency**
Eppler E387	45.82	1.45	31.55
NACA 4509 modified	58.87	1.85	31.82

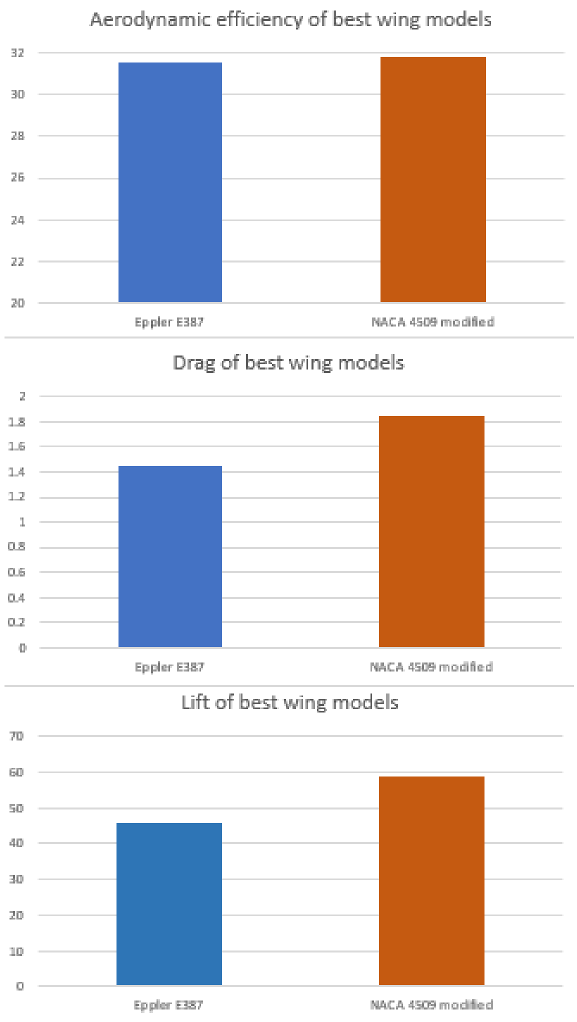

Figure 2. Graphical comparison of aerodynamic properties of wing models

From the gained forces aerodynamic coefficients can be calculated. Calculated aerodynamic coefficients are shown in table 2.

Table 3. Aerodynamic coefficients of tested models

Airfoil	**Lift Coefficient**	**Drag Coefficient**
Eppler E387	0.45	0.014
NACA 4509 modified	0.57	0.018

The gained results show that the aerodynamic efficiency performance of both models is practically identical. The percentual difference is 0.88 %. Bigger difference can be seen in drag and lift. The NACA 4509 modified airfoil generated more lift than Eppler airfoil. The total percentual difference between the two models in left generation was 28 %. The drag was also higher for NACA airfoil. The total drag difference was 27 %. The marginal gain in aerodynamic efficiency on NACA airfoil can be therefore explained by higher lift increase to drag increase. This change is however minimal and would have very little performance impact. Considering the efficiency is very similar a deciding factor in choice between these two airfoils would boil down to drag and lift needs. Should the final model of UAV prove to be heavier than expected a higher lift generation may prove beneficial. Additionally, by generating higher lift it is possible to lower the speed of flight of model whilst maintaining enough lift. By lowering the speed of flight, the drag reduces as well. Should a reduction in drag be more important than lift generation then Eppler airfoil is better choice due to having less drag than NACA airfoil. The difference in drag and lift of the airfoils can be described based on the velocity and pressure field acting on the wing. The pressure fields of Eppler airfoil can be seen in figure 3 and NACA airfoil in figure 4.

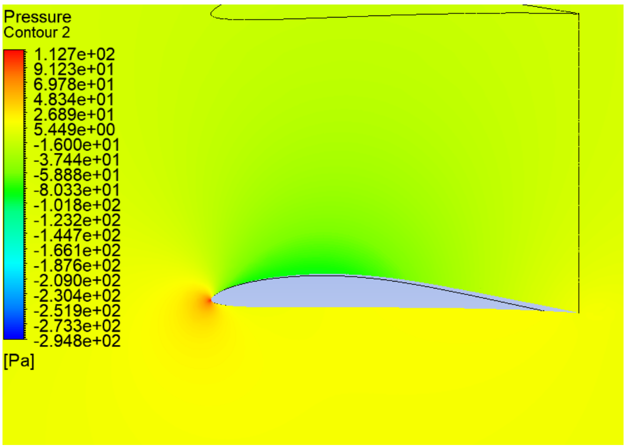

Figure 3. Pressure distribution of Eppler airfoil on wing model

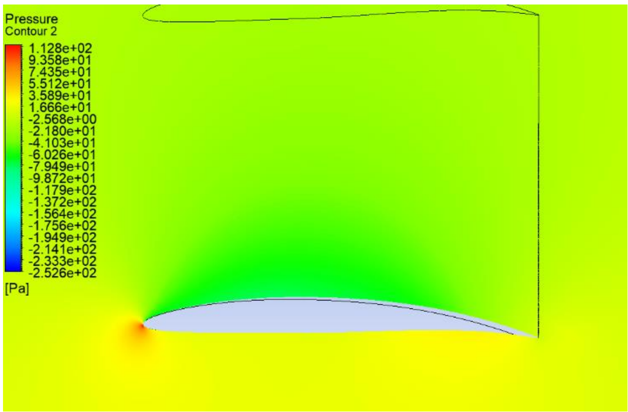

Figure 4. Pressure distribution of NACA 4509 modified airfoil

There are two important factors in terms of pressure distribution and that is size of the pressure field and pressure magnitude. In terms of pressure magnitude Eppler airfoil comes out on top reaching lower pressure on top of the airfoil. This peak of low pressure is however small in comparison to modified NACA 4509 which maintains the area of lower pressure on large part of its total chord. This is also supported by the velocity fields which can be seen in figure 5 for Eppler airfoil and Figure 6 for modified NACA airfoil.

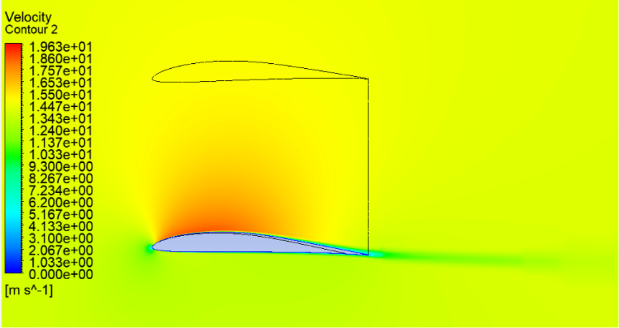

Figure 5. Velociy Distribution of Eppler airfoil

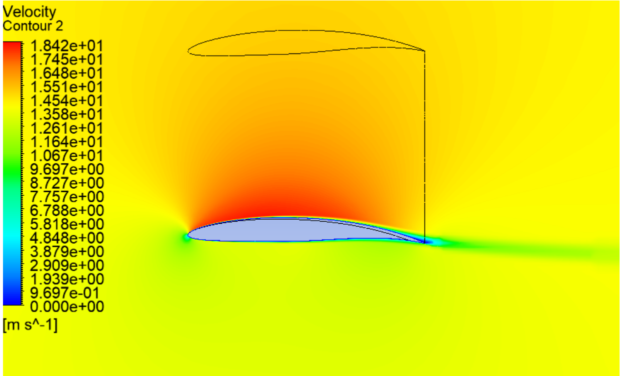

Figure 6. Velocity distribution of NACA 4509 modified airfoil

By comparing the velocity fields, we can see that average maximum velocity is maintained in larger area above NACA airfoil compared to Eppler airfoil. This is the reason behind the higher lifting capability of the airfoil. From the drag point of view the higher drag may be caused by the larger separation area behind NACA 2509 airfoil in comparison to Eppler which shows much smoother flow near the trailing edge of the airfoil. Additionally, by increasing the camber of trailing edge on the NACA 2509 airfoil there is a larger area of positive pressure near the trailing edge which can influence the drag of the model.

5. Conclusion

An initial wing design's aerodynamic properties were successfully optimized by aerofoil selection process. The initial average value of aerodynamic efficiency was around 26 with final aerodynamic efficiency of the wing was 31. This represents a 19 % improvement in terms of aerodynamic efficiency. The two best airfoils tested differed very slightly in area of aerodynamic efficiency. Their difference was however much more visible in terms of drag and lift. Therefore, the final choice of airfoil for wing boils down to priority of lift and drag requirements.

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