High Lift Two-Element Airfoil Design for MALE UAV Using CFD

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ABSTRACT

Wing design for UAV applications requires a special aerodynamic approach. The main goal of operational UAV is endurance flight at relatively low speed. The endurance for propeller driven aircraft is proportional to the factor $C_{L}^{1.5}/C_D$, called endurance parameter which is to be maximized for a chosen operating point. In case of Medium Altitude Long Endurance (MALE) military UAVs which carries heavy protruding payloads, the maximum value of endurance parameter occurs at relatively higher $C_L$ and demands very high value of $C_{L_{max}}$ of the order of 2.4 at relatively low Reynolds number of 2.0 million compared to sail planes. Conventional and catalogue single element airfoils will not meet this order of $C_{L_{max}}$ requirements. A High Lift Two-Element Airfoil, RUKSAN-T20 has been designed to meet a specific requirement of $C_{L_{max}}$ of 2.4 and to replace the existing single element airfoil for MALE UAV for improving its performance. Boundary Layer coupled Euler CFD code, MSES has been used for design and analysis. Direct design methodology has been used for the initial design followed by target pressure distribution for refined design. The design and aerodynamic characteristics of Two-Element wing has been verified and validated by Wind Tunnel Testing conducted at various Reynolds number at Low Speed Wind Tunnel, IIT Kanpur. The design methodology, aerodynamic characterization of Two-Element airfoil, RUKSAN-T20 by CFD and experimental verification in the Wind Tunnel are presented in this paper.

Key Words: Airfoil, UAV, MSES, CFD, Reynolds number, Wind Tunnel Testing

1. Introduction

Present days, for the new and complex aircraft configurations, modern and innovative airfoil design concepts and methodology allow development of mission tailored, customized wings. It is more relevant for design and development of endurance UAV wings, where the use of existing catalogue airfoils becomes difficult because of the multi-mission requirement, multi-point design considerations and non-aerodynamic constraints. With the available modern CFD tools aircraft designers have the freedom to tailor the airfoil geometry and customize wings for optimum aerodynamic configurations. Also, the CFD tools are used to develop special airfoils and wings to realize long endurance flights. One of the methodologies commonly used for design of airfoils is inverse method. Many inverse approaches are well established and applied in the aerospace industry for many years. Inverse method calls for the designer’s skill and experience to greater extent to prescribe the target pressure distributions. Direct design method is yet another procedure wherein thickness and camber distributions are input along with their location on the chord. The other numerical method viz., optimization which requires objective function and constraints to be defined does not require airfoil design expertise[1].

This paper highlights the design of a two-element airfoil using CFD tools for a long endurance UAV operating at moderate Reynolds Number. In general long endurance UAVs operate at very low speeds and about 20,000 to 30,000 ft altitude which corresponds to an operating Reynolds number of less than 3 million. The wings of such aircraft are large with high aspect ratio for aerodynamic efficiency and with medium taper ratio for structural efficiency. This results in a huge variation of the Reynolds number across the span. Therefore, airfoil sections of such UAV wings encounter wide range of operating Reynolds number.

A two-element airfoil, RUKSAN-T20 has been designed using CFD code MSES. The indigenously designed airfoil shows significant increase in maximum lift coefficient and endurance parameter compared to single element airfoil. Use of second element as flap, aileron and air brake during ground run is a distinct advantage of employing two-element airfoils in UAV wings[2]. Aerodynamic performance characteristics of the designed two-element airfoil has been analysed for different Reynolds number, roughness/turbulence conditions and flap deflections using the same code, MSES. The design of airfoil, the effects of Reynolds Number, boundary layer transition and effect of flaps are verified and validated by Wind Tunnel tests.

Wind Tunnel tests are carried out at National Wind Tunnel Facility (NWTF) at IIT Kanpur to validate design and the performance characteristics of the tailor made two-element airfoil, RUKSAN-T20. A 2D airfoil model has been fabricated with a maximum number of pressure ports in order to obtain more accurate lift characteristics from the pressure integration method. The Wind Tunnel tests data and analysis show that there is a reasonable agreement in aerodynamic characteristics of RUKSAN-T20 airfoil between CFD and experiments. The Wind Tunnel results confirm the feasibility of the two-element airfoil design using MSES CFD tool for endurance UAVs.
2. MSES Code

MSES is a boundary layer coupled Euler code used for design and analysis of multi-element airfoil systems[4]. MSES is an Euler solver coupled with a two equation integral boundary layer through the displacement thickness. It solves conservative steady Euler equations on an intrinsic streamline grid. A lagged-dissipation integral method represents the laminar, turbulent boundary layers and wake and $e^N$ method is used to determine transition point. All of these discrete equations (Euler equations, boundary layer equations, transition location equations viscous/inviscid matching conditions) are solved simultaneously by a global Newton method. Falkner-Skan one-parameter velocity profile is used for laminar boundary layer prediction. Boundary layer transition is predicted by a simplified version of “$e^N$ method – the envelope method”. The effects of ambient disturbances are introduced into the initially laminar boundary layer by possible sources such as free stream turbulence, model vibration, sound or surface roughness. For 2D flows, these effects are simulated by the $N_{CR}$ transition parameter of the envelope method, that is, the log of the amplification factor of the most amplified frequency that ultimately triggers transition. The lower the $N_{CR}$ value, the higher is the disturbance level and earlier the transition. Swafford one family velocity profile is used for turbulent boundary layer computation.

3. Two-Element Airfoil Design

To improve the aerodynamic performance of existing single-element airfoil, ADELS-E2 employed in MALE UAV in terms of $C_{l_{max}}$, endurance parameter and service ceiling, a two-element airfoil, RUKSAN-T20 has been designed to achieve a $C_{l_{max}}$ of 2.4 by using a CFD tool, MSES[5]. Direct design methodology has been used for the initial design followed by inverse method to refine the geometry. The target pressure distribution for the present design point, $C_{ldesign}$ of 1.7 and Reynolds number of $2.0 \times 10^6$ is shown in Fig. 1. Geometrical details of the designed airfoil, RUKSAN-T20, the horizontal overlap & vertical gap are given in Figs. 2 and 3 respectively. A very high thickness ration of about 20% has been chosen in order to carry sufficient amount fuel in the wings to accomplish a long endurance mission. Arrangement of main and flap elements, shoulder shape, overhang and overlap are adopted from similar class of two-element wing UAVs.

Fig. 1 Design Pressure Distribution for RUKSAN-T20 Airfoil
Chord of Main Element: 75.8% C
Maximum Thickness: 19.8% C
Angle made by Main Element Chord with reference line ($\theta_{\text{main}}$): -7.4˚
Angle made by Flap Element Chord with reference line ($\theta_{\text{flap}}$): 8.8˚
Hinge point location: $(X/C, Y/C) = 0.77, -0.02$

Fig. 2 RUKSAN-T20 Airfoil Geometry Details with Different Flap Positions

Fig. 3 Horizontal Overlap and Vertical Gap of RUKSAN-T20 with Flap Deflections

4. CFD Analysis of Airfoil

A detailed analysis of the designed airfoil RUKSAN-T20 has been carried out using MSES code for different flap deflections. The surface grids generated for CFD computation are show in Fig. 4. The pressure contours over the airfoil with $\delta_F = 0^\circ$ and $15^\circ$ at $\alpha = 0^\circ$ and close to stall condition are shown in Fig. 5.

Fig. 4 Grid Generated for RUKSAN-T20
The basic aerodynamic characteristics are plotted for various flap deflections and shown in Fig. 6. The designed airfoil has been studied for $N_{crit} = 9$ at different Reynolds numbers based on mac, root chord and tip chord of MALE UAV wing. The airfoil has also been analysed for different flap deflections. It can be seen that at $Re = 2.0 \times 10^6$, the flap is effective up to a deflection of $+25^\circ$. The Reynolds number effect on aerodynamic characteristics of airfoil has also been shown for a range of $1.0 \times 10^6$ to $3.0 \times 10^6$ in Fig. 7. From these results it can be seen that the lift curve slope does not change for all the three Reynolds numbers but a difference in maximum lift is seen as expected, but the drag at $Re = 1.0 \times 10^6$ is significantly higher. Pitching moment coefficient, $C_m$ is plotted about quarter chord of airfoil.
Fig. 6 (Cont.) Aerodynamic Characteristics of RUKSAN-T20 at $Re = 2.0 \times 10^6$ for various $\delta_F$ from MSES

Fig. 7 Basic Aerodynamic Characteristics of RUKSAN-T20 for Different Reynolds Numbers at $\delta_F = 0^\circ$ from MSES
5. Experimental Validation by Wind Tunnel Tests

In order to validate the aerodynamic characteristics of the airfoil designed by CFD and to study effect of Reynolds number a low speed Wind Tunnel tests on 2-D airfoil model of RUKSAN-T20 have been conducted at NWTF, Dept of Aerospace Engg, IIT Kanpur. A pressure model of 2.25 m span with chord length of 750 mm has been fabricated out of metal which is to be mounted between floor to ceiling of of 2.25 mX 3.5 m, tests section of the tunnel. A maximum possible number of surface pressure ports has been chosen as 74 to capture pressure distribution with boundary layer and laminar separation bubble details[3]. The tunnel speed has been varied from 14 m/s to 55 m/s to achieve Reynolds number range of 0.7 million to 2.5 million approximately. Second element, the flap of the wing has been deflected about the offset hinge point from -35° to +70° in steps of 5° upto 40° and in steps of 10° from 40° to 70°. The tests have been carried out to generate the aerodynamic characteristics such as $C_{l_{\text{max}}}$, $C_{d_{\text{min}}}$, $C_m$ etc and to validate CFD data.

Angle of attack has been varied from -13.5° to +21° for zero flap deflection. Both mean and rms pressures at 74 ports on the surface of the airfoil have been acquired using ESP scanners of 2.5 PSI, 10″ and 20″ H₂O rating. A 10″ and 20″ H₂O ESP scanners were used to measure pressures at the wake of 2.13 chord length down stream. Force and moment coefficients including hinge moment have been computed from the mean pressure coefficients. Total drag coefficient has been computed using momentum deficit from the wake measurement.

A 2D geometrical details of main element and flap with port locations are shown in Fig. 8. A modular construction approach has been followed to fabricate Wind Tunnel model of RUKSAN-T20 wing out of metal. The details of the model construction, the pressure port routings etc and the model mounted inside the tunnel with wake rake is shown in Fig.9.

![Fig. 8 Wind Tunnel Model Geometrical Details of RUKSAN-T20](image1)

![Fig. 9 Modular Construction of RUKSAN-T20 and Model Mounted in Wind Tunnel Test Section](image2)
Lift, drag and pitching moment obtained from Wind Tunnel tests are compared with MSES simulation for Reynolds number of $2.0 \times 10^6$ as shown in Fig.10. Though lift curve slope is closely matching with experimental data, $C_{l_{\text{max}}}$ is overpredicted by MSES, there is good comparison of drag between WT data and MSES for lift coefficient of 1.0 and above. Performance characteristics like glide ratio and endurance parameter are compared at design point that shows good match as given in Fig. 11. Pressure distribution and transition location on the main element at $C_l$ of 1.6 are compared in Fig. 12. The location of transition is at about 30%C which has been predicted by both experiment and MSES simulation.

The effect of flap deflection on $C_{l_{\text{max}}}$ is shown in Fig. 13 for Reynolds number of 2 million. Maximum lift coefficient, $C_{l_{\text{max}}}$ achieved with flap deflection of $+25^\circ$ is 3.0 at about $\alpha 10^\circ$. It is seen from Fig. 6 that the MSES predictions also shows the same value. Wind Tunnel testing shows that flap deflection of $-20^\circ$ produces $C_{l_{\text{max}}}$ of 1.6 at about $\alpha 20^\circ$ that confirms the value predicted by MSES as shown in Fig.6. Wind Tunnel testing shows that there is no increase in $C_l$ beyond flap deflection of $+25^\circ$.

Wind Tunnel testing of Reynolds number effect is shown in Fig 14. Drag polar is closely matching with MSES predicted values. Wind Tunnel shows no significant increase in $C_{l_{\text{max}}}$ with Re to the magnitude as predicted by MSES.
Fig. 11 Comparison of Performance Characteristics-WT Data and MSES

C_l/C_d vs C_l

C_l/C_d: MSES Ncrit:9
Wind Tunnel: Re No: 2.0X10^6

Design Point

Fig. 12 Comparison of Cp Distribution-WT Data and MSES

C_p Distribution-Comparison with MSES Data

C_p: MSES Ncrit:9
Wind Tunnel: Re No: 2.0X10^6

Design Point

C_l = 1.66
Fig. 13 Wind Tunnel Lift Curve for Various Flap Angles-Reynolds Number 2.0X10^6

Fig. 14 Wind Tunnel Cl vs α and Drag Polar of RUKSAN-T20 for Different Reynolds Numbers at δ_f=0°
6. Conclusions

A High Lift Two-Element Airfoil, RUKSAN-T20 has been designed to achieve a $C_{\text{max}}$ of 2.4 and to improve the performance of existing single element airfoil employed in MALE UAV. A CFD tool, MSES which is a boundary layer coupled Euler code has been used for design and analysis of airfoil. Direct design methodology has been used for initial design and to refine, a target pressure distribution has been specified. Airfoil analysis has been carried out for different Reynolds number and flap settings using same MSES code. The aerodynamic characteristics of RUKSAN-T20 airfoil generated by CFD simulation have been verified and validated with Wind Tunnel experiments conducted on 2-D model of RUKSAN-T20 airfoil at NWTF, IIT Kanpur for various Reynolds number and flap angles. The pressure distributions measured in the Wind Tunnel have also been compared with the one obtained by CFD at design point. It has been found that the aerodynamic performance characteristics of high lift two-element airfoil, RUKSAN-T20 such as $C_{\text{pit}}, C_{\text{max}}$ of basic and with flap deflections including pressure distribution, transition location etc., obtained by MSES simulations and Wind Tunnel data are closely matching and confirmed the design & analysis procedures.

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