Proceedings of EOC'23:
ME8710: Engineering Optimization
Clemson University
Clemson, SC, December 4-7, 2022

EOC2023-09

DESIGN OPTIMIZATION OF THE WING FOR HIGH-ALTITUDE LONG-ENDURANCE UNMANNED AERIAL VEHICLE

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ABSTRACT

The paper underscores the crucial aspects of optimizing the lift-to-drag ratio and improving aerodynamic efficiency in self-propelled fixed-wing UAVs, addressing considerations such as natural gliding capabilities, structural optimization for increased payload capacity, and composite development. It explores challenges related to low Reynolds number operating conditions in HALE UAV flight profiles and the optimization of aerofoil sections for high lift coefficients. Noteworthy approaches by Rajagopal and Ranjan and Parviz and Mohsen, utilizing multi-fidelity models for efficient aerodynamic shape optimization, are discussed, emphasizing their application to a Blended Wing Body (BWB) UAV. The study introduces a HALE UAV design using XFLR5, modifying design variables for optimization and focusing on lift-to-drag ratio enhancement. The methodology includes conceptual design, XFLR5 aerodynamic analysis, and a brute-force optimization technique in MATLAB for calculating maximum endurance. Results showcase UAV wing design parameters and performance, including maximum endurance and optimal fuel consumption rate. The paper concludes by addressing limitations in model integration and debugging while highlighting its contributions to advancing high-altitude unmanned aerial vehicle design methodologies.

METHODOLOGY

Conceptual design

Baseline UAV Design Overview: The foundational design of our High-Altitude Long Endurance (HALE) UAV wing is shaped by essential constraints such as wing-span, maximum weight, cruise altitude, and maximum speed. Drawing inspiration from the innovative Blended Wing Body (BWB) design within the CAPECON project, our baseline model is characterized by a cruise altitude of approximately 20,000m (~65,000ft) and a cruise speed of 180m/s. To bring this vision to life, we employ XFLR5 for the 3D modeling of the wing based on the specified baseline configuration.

Aerodynamic Analysis Details:

The Global Hawk, utilized as the baseline aircraft in the CAPECON HALE BWB design process, sets the standard for performance, cost, and safety. From the inception of the design effort, we have assumed that any newly created aircraft should be comparable to the Global Hawk in these critical aspects.

Objective functions:

Maximize:
(Endurance obj. function)

$$F_1=\left(\frac{2n_p}{C}\right)\left(\frac{C_l^{\frac{3}{2}}}{C_D}\right)\left(\sqrt{\frac{\rho * b^2}{A_r}}\right) * \left(\sqrt{\frac{1}{W_0-W_i}}-\sqrt{\frac{1}{W_0}}\right)$$

Maximization $F_2=\left(\frac{C_l^{\frac{3}{2}}}{C_D}\right)$

Subjected to:

$$0.75 < n_p < 0.85$$
$$130 < C < 140$$
$$0.4 < C_l < 0.8$$
$$0.01 < C_D < 0.05$$
$$0.07 < \rho < 0.09$$
$$28 < b < 35$$
$$20 < A_r < 25$$
$$11621 < W_i < 11622$$
$$1316.6 < W_0 < 6583$$

where,
F_1 is the objective function for Endurance,
F_2 is the Lift/Drag ratio,
n_p= Efficiency based on fuel used,
C =Fuel consumption rate in [kg/hr-Watt],
C_l=Coefficient of lift,
C_D= Coefficient of drag,
ρ = Density based on the altitude in [kg/m^3],
b =Wing Area in [m^2],
A_r=Aspect Ratio,
W_i= Current weight based on the position of the aircraft in [kg],
W_0= Initial weight of the aircraft in [kg]

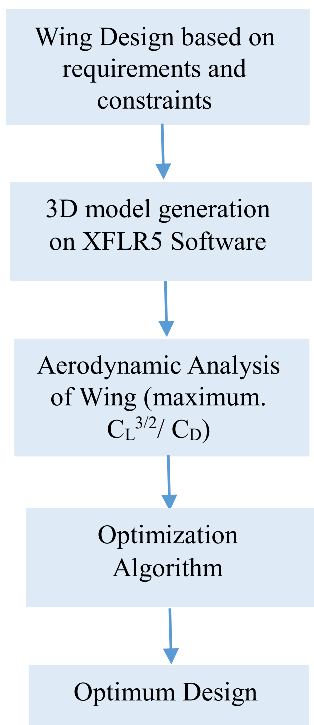

Figure 1: Methodology for UAV Design and Optimization process

Optimization technique

The initial HALE UAV was carried out to determine realistic wing platform size and geometry. We have started our optimization on 'modeFRONTIER' which takes certain parameters as input variables. A DOE Sequence Table and Calculator were added that feeds the output to calculate maximum endurance. An optimization model that calculates maximum endurance is shown in Figure below.

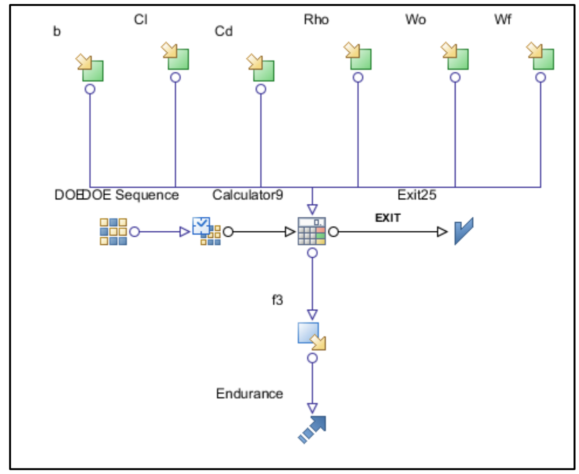

Figure 2: Optimization model formulation to calculate maximum endurance.

So, we have used brute force optimization method that calculates maximum endurance from MATLAB. XFLR5 was used to compute maximum lift to drag ratio for aerodynamic efficiency.

Here is a breakdown of code on how it is done only using MATLAB afterwards.

a) *Initialization of parameters*
At first, we have defined the coefficient of lift to drag ratio for UAV and initial amount of fuel onboard in kilograms. It also defines a fuel consumption rate to check varying from 100 to 1000 kg per hour with a step size of 0.1kg per hour.

b) Brute force optimization
We have used a brute-force optimization method that calculates maximum endurance and the corresponding optimal fuel consumption rate. Brute force optimization is a technique used in problem-solving where an exhaustive and systematic approach is employed to search for a solution within a defined search space. It's characterized by evaluating all possible options
without applying heuristics, shortcuts, or sophisticated algorithms.

RESULTS AND DISCUSSIONS

UAV Wing Design Results

Wing Design : Our UAV wing design, derived from the method outlined in the preceding section, is characterized by specific parameters essential for optimal performance. The table below outlines the key design variables.

Table 1: Parameters for wing design

Wingspan [m]	28
Aspect ratio [degree]	14
Taper ratio	0.333
Root chord [m]	3.0
Tip chord [m]	1.0
Wing Area [m^2]	56
Root-tip Sweep	-1.759

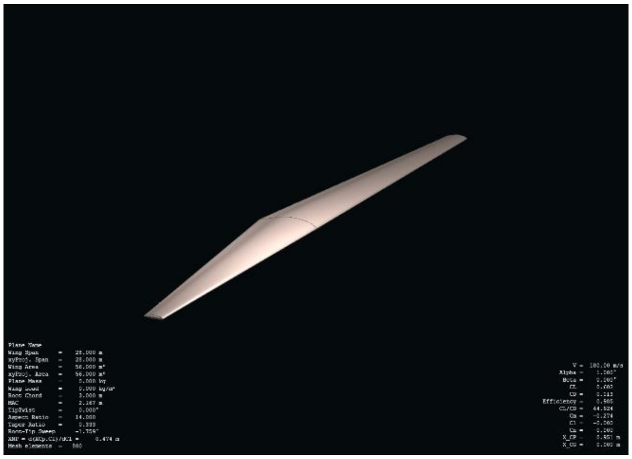

Figure 3: 3D wing model on XFLR5

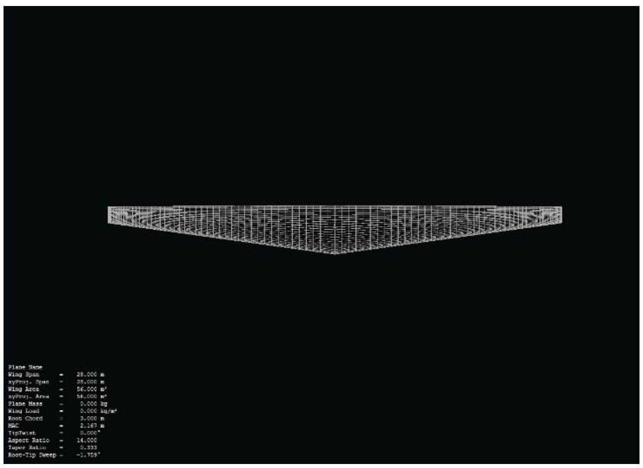

Figure 4:Wing grid generated in XFLR5 for analysis.

Wing Aerodynamic Analysis

The aerodynamic analysis is twostep process it starts with the foil analysis and then using the defined constraints for constant speed cruise the results are computed. Following section discuss the results from XFLR analysis.

Foil Analysis: The selected airfoil, integrated into XFLR5, underwent a meticulous analysis across the specified flight Reynolds number range. The calculated values for Reynolds numbers are Re_{tip} = 1,125,704 and Re_{root} = 3,377,111. The polar curves, illustrating the relationship between lift coefficient (C_L) and drag coefficient (C_D), are depicted in the figure below.

The results obtained from XFLR5 are attached below.

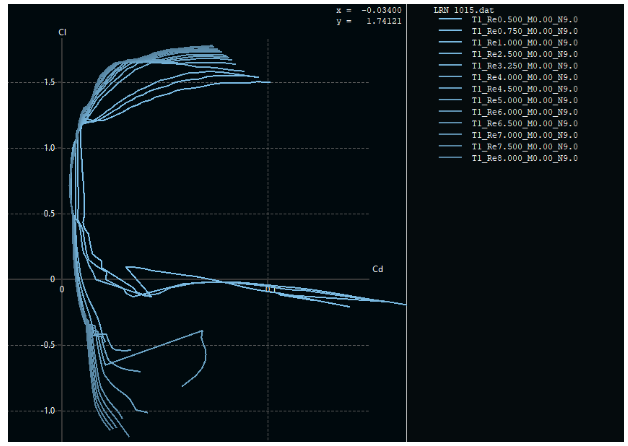

Figure 5: Plot of coefficient of lift (C_L) vs coefficient of drag (C_D) from XFLR5

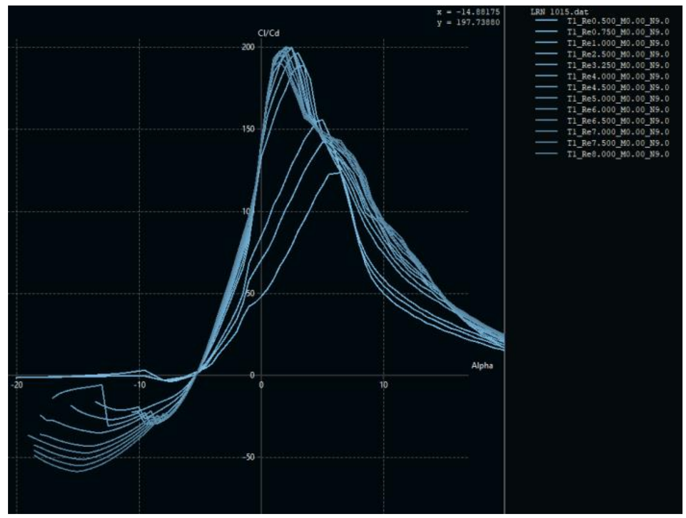

Figure 6: Plot of C_L/C_D with different angle of attack from XFLR5

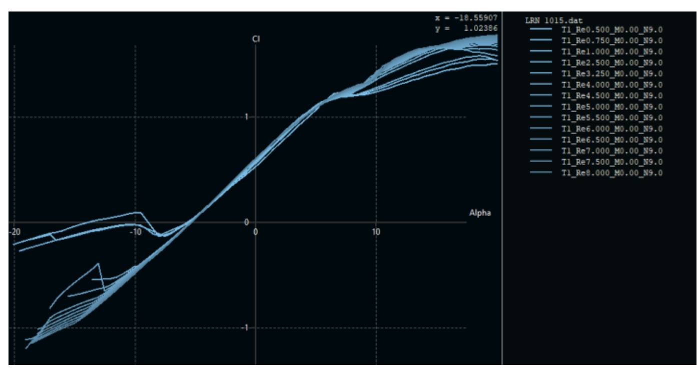

Figure 7: Plot of coefficient of lift (C_L) vs different angle of attack from XFLR5

Wing Analysis: We use fixed speed wing analysis varying the different angle of attack. Lifting line lattice method is used in XFLR5 and the wing was analyzed on the design altitude. Following curve shows the resulting C_L and C_D configuration.

The attached polar curves above illustrate the model's performance, showcasing key parameters such as maximum C_L/C_D and max sqrt($C_L^{3/2}/C_D$).

Table 2: Performance parameters for UAV design

Cruise velocity [m/s]	180 m/s
C_L	0.602
C_D	0.013
C_L/C_D	44.924
Alpha at max. C_L/C_D [deg.]	1

Optimization Results

The plot of C_L vs C_D is also shown in figure below.

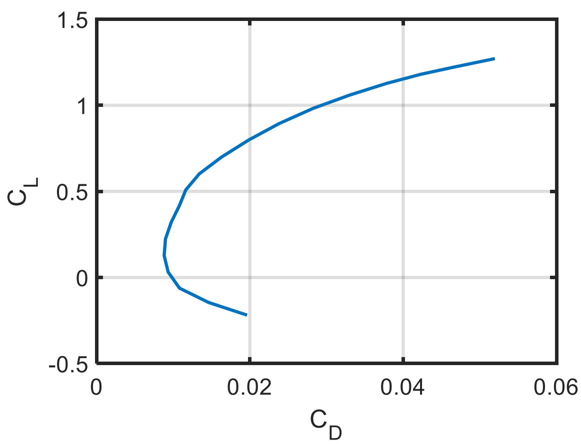

Figure 8: Plot of coefficient of lift (CL) vs coefficient of drag (Cd)

The plot of C_L/C_D with angle of attack is shown below with maximum C_L/C_D value at an angle of attack of 1 degree.

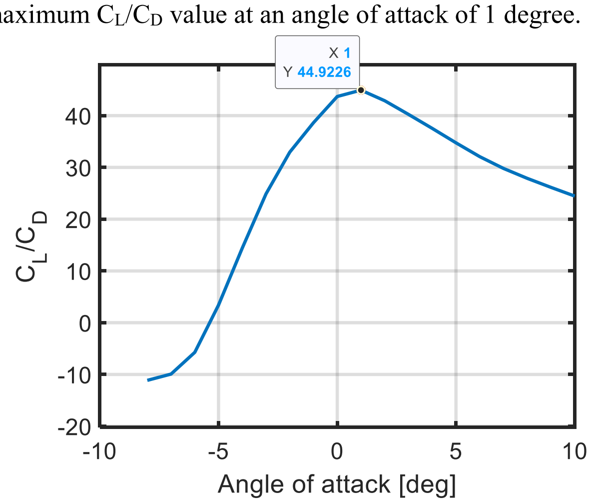

Figure 9: Plot of C_L/C_D for different angle of attack in degrees

The maximum coefficient of lift to drag was found at an angle of attack of 1 degree. So, for further calculations we have used this value of angle of attack.

The plot of $C_L^{3/2}/C_D$ with angle of attack is also shown below that gives the aerodynamic efficiency of the wing.

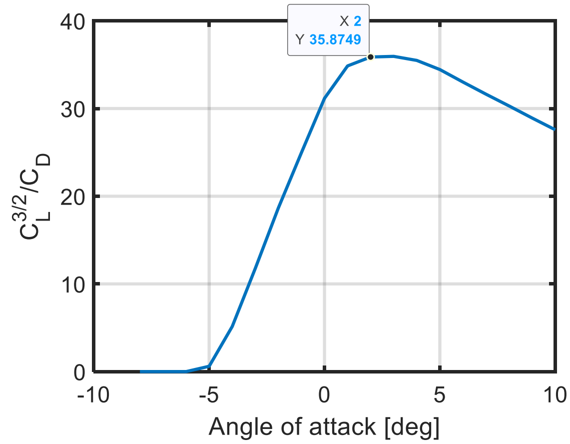

Figure 10: Plot of $C_L^{3/2}/C_D$ for different angle of attack

The maximum value of $C_L^{3/2}/C_D$ was found at an angle of attack of 2 degree as shown in Figure 10.

The code calculates the endurance based on the given parameters, such as the coefficient of Lift-to-Drag ratio and initial fuel onboard, iterating through various fuel consumption rates from 100 to 1000 kg/hour. For each rate, it computes the endurance the UAV can achieve and updates the maximum endurance along with the corresponding optimal fuel consumption rate. Additionally, it randomly generates a placeholder value for bending moment, which is used to find the minimum bending moment and its associated optimal fuel consumption rate within the tested range. The displayed results showcase the maximum endurance achieved and the corresponding optimal fuel consumption rate, as well as the minimum bending moment attained and its corresponding optimal fuel consumption rate within the specified range. However, it's important to note that the actual bending moment calculation in the code is a placeholder and should be replaced with accurate calculations or simulations for a precise evaluation of the UAV's structural integrity.

CONCLUSIONS

To sum up, this study focused on optimizing the wing design for a High-Altitude Long Endurance (HALE) Unmanned Aerial Vehicle (UAV) with a key emphasis on maximizing aerodynamic efficiency and endurance. XFLR5 was used for modelling and MATLAB for brute-force optimization, we achieved a 40-hour endurance at an optimal fuel consumption rate of 100 kg/hour. However the future work should address integration complexities and incorporate more precise structural evaluations to further enhance UAV design for extended and efficient missions.