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WING DESIGN OPTIMIZATION OF A MALE UNMANNED AERIAL VEHICLE

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ABSTRACT

Shape optimization of wing of medium altitude long endurance (MALE) unmanned aerial vehicle (UAV) is performed by genetic algorithm solver of MATLAB® coupled with computational fluid dynamics and statistical weight equation. The selected design variables are airfoil profile, which is parameterized with cubic uniform B-splines, span length, root and tip chord lengths. As a 2D flow solver Xfoil code, which is a high order panel code with fully-coupled viscous/inviscid interaction method is used. To predict aerodynamic coefficients of wing, a non-linear lifting line code is used. Moreover, trim drag is counted in the calculations to avoid higher pitching moment by using a sample tail model. Then, endurance, maximum speed, service ceiling, climb time to specified altitudes are calculated over discrete time by using a sample internal combustion engine model. As the result of the optimization, airfoil profile, span length, root and tip chord length of the wing are obtained for maximum endurance.

INTRODUCTION

Medium altitude long endurance (MALE) systems are capable of intelligence, surveillance and reconnaissance (ISR), signals intelligence (SIGINT) missions. The systems have also capability of extended roles and great payload flexibility. Operational altitude of MALE systems with reciprocating engines varies between 15,000 - 30,000 and they have endurance range of 12-40 hours [Gundlach, 2014]. Due to their abilities, MALE unmanned aerial vehicles (UAVs) have been attracting much attention in military and civil aviation industries.

Designers have to consider many design factors, to improve aerodynamic performance of MALE UAVs. While dealing with large number of design factors, low-fidelity analysis tools give designers opportunity to scan larger design space with less computation power and time. In the present study, endurance, maximum speed, service ceiling, climb time to 25,000 and 30,000 feet are calculated over the discrete time as the objective of the optimization problem by using a sample engine model. The mission calculations require empty weight of the MALE UAV, fuel mass and aerodynamic coefficients. While keeping maximum take-off

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weight constant, wing weight is estimated with a statistical equation [Torenbeek, 1982] . Then, fuel weight is updated for new wing geometry at each optimization iteration. The aerodynamic coefficient of the aircraft consist of the coefficients of wing and fixed model of tail and estimated drag coefficient of the fuselage. Xfoil is used to calculate the lift, drag and moment coefficient of infinite span wing. Xfoil is a high order panel code with fully-coupled viscous/inviscid interaction method. It treats both laminar and turbulent layers with an e^n method determining the transition point, which cannot be determined by standard turbulence models. Then, the coefficients for finite wing is calculated through the non-linear lifting line code which uses Chattot's coupling algorithm [Chattot, 2004] based on a linearization of the Prandtl integro-differential equation. By using the tail model, trim drag is calculated at each iteration. Next, the coefficients for fuselage is added to the calculations, and the aircraft aerodynamic coefficients are obtained. Finally, these weight and aerodynamic coefficient parameters are used to calculate the endurance, maximum velocity, take-off distance, climb time to specified altitudes, and all these parameters are used to obtain the fitness value of the optimization problem.

Geometry parametrization is one of the key issue in aerodynamic shape optimization. In the present study, wing geometry is described with wing planform and airfoil section. Since we focused on constant swept, tapered wing, the wing planform is parametrized with span, root and tip chord lengths. And, cubic uniform B-splines are used to parameterize the airfoil [Salomon, 2006]. These geometric parameters are used as the design variable of the optimization problem.

Genetic algorithm is used to improve performance of the wing of the MALE UAV. Genetic algorithm is a metaheuristic search algorithm inspired by process of natural selection. It gives great opportunity to find maxima and work on discrete datasets.

In the present study, aerodynamic shape optimization of the wing of a MALE UAV is performed to improve endurance while fulfilling the maximum velocity, service ceiling and climb time requirements of the MALE UAV by using genetic algorithm.

FITNESS VALUE CALCULATION

Mission parameters of the MALE UAV is used to calculate the fitness value of the wing optimization. Accurate calculation of aerodynamic coefficients is essential for the accuracy of the mission parameters. Lift, drag and moment coefficients for the infinite wing is calculated by high-order panel code, Xfoil. Since Xfoil uses e^n method to determine the transition point and treats both laminar and turbulent boundary layers, accurate 2-D viscous aerodynamic coefficients are obtained for each airfoil sections throughout the optimization.

Viscous finite wing effect are calculated by nonlinear lifting line theory. The correction can be made through circulation (Γ) based and angle of attack (α) based methods. Angle of attack based methods concerns at $C_{l,max}$ since the equation used for angle of attack correction is invalid at the point [Gallay et al., 2015]. In the present study, endurance values for the aircraft calculated above the $1.2V_{stall}$ for the safety. That is, endurance is calculated below the $C_{l,max}/1.44$ point of the $C_l - \alpha$ curve. Therefore, we decided to use gamma based methods which are capable of the correction at the maximum lift angle of attack. Anderson's Γ method requires several hundreds of iterations to converge machine accuracy and unable to converge in the post-stall region [Gallay et al., 2015]. Chattot uses Newton's method to linearize Prandtl integro-differential equation and adds artificial viscosity term to converge in the post-stall region [Chattot, 2004]. Also, Chattot's Γ method is able to converge about a hundred iterations. Therefore, a nonlinear lifting line code based on Chattot's method is developed to correct the aerodynamic coefficients for the finite wing throughout the optimization steps.

Eq. 1 illustrates the linearized form of the Prandtl integro-differential equation [Chattot, 2004].

$$\left(1-\frac{1}{2}c_j\frac{dC_{lj}}{d\alpha}\frac{\alpha_j}{1+\omega_{indj}^2}+2\mu\right)\frac{\Delta\Gamma_j}{\omega}=\frac{1}{2}c_jC_{lj}-\Gamma_j^n+\mu\left(\Gamma_{j+1}^n-2\Gamma_j^n+\Gamma_{j-1}^{n+1}\right) \quad (1)$$

Artificial dissipation term, μ, is considered according to following inequalities. And, the iteration is stable for some underrelaxation ($\omega < 1$).

$$\mu \geq \sup\left(\frac{1}{4}c_j\frac{dC_{lj}}{d\alpha}\frac{\alpha_j}{1+\omega_{ind}^2};0\right)$$

In Eq. 1 downwash is calculated as

$$\omega_{ind} = -\frac{1}{4\pi}\Sigma_{k-1}^{jx-1}\frac{\Gamma_{k+1}-\Gamma_k}{y_j-\eta_k}, \qquad j=2,\dots,jx-1.$$

The values for $\Gamma_j, c_j, C_{lj}, \alpha_{0j}$ and ω_{indj} are placed at the nodes y_j

$$y_j = -\cos(\frac{j-1}{(jx-1)}\pi\,, \qquad j=1,\dots,jx.$$

And, the integration points η_k are placed between these nodes.

$$\eta_k = -\cos\left(\frac{k-\frac{1}{2}}{jx-1}\pi\right), \qquad k=1,\dots,kx.$$

After convergence of the iteration on Γ, the code calculates effective angle of attack and interpolates the corresponding viscous data for the correction of finite wing effects.

In the preliminary stage of the present study, airfoils are optimized without considering the pitch moment coefficient in the calculation of endurance. However, heavier and complicated structural support might be needed to cope with the high moment. In addition, to balance the moment, larger tail or higher control surface deflections might be needed. In order to penalize the higher pitch moment, trim drag is calculated. A linear relationship between C_m and control surface deflection is obtained by using the data of sample tail model. Then, using deflection vs C_l and C_d curves of the model, trim drag and lift contribution of the tail is calculated.

In addition to wing and tail aerodynamic coefficients, fuselage drag coefficient is estimated. Thorough considering these aerodynamic coefficients, overall MALE UAV aerodynamic coefficients are obtained and used as the input to mission parameter calculations.

Another input parameters for the mission parameter calculations are the fuel and the wing weight of the UAV. Since the maximum take-off and the zero-fuel weight, excluding the wing weight, of the UAV is fixed, fuel weight can easily be calculated after the wing weight estimation. The wing mass estimation is performed by using a statistical equation, Eq. 2 [Torenbeek, 1982].

$$W_{w_{basic}} = 4.56*10^{-3}k_{no}k_\lambda k_e k_{uc} k_{st}\big(k_b n_{ult}(W_{des} - .8W_w)\big)^{.55} b^{1.675}\left(\frac{t}{c}\right)_r^{-.45}\cos\left(\Lambda_{\frac{1}{2}}\right)^{-1.325} \quad (2)$$

In the Eq. 2, k_{no} represents weight penalties due to skin joints, non-tapered skin, etc. And, it is calculated as follows.

$$k_{no} = 1+\frac{\sqrt{b_{ref}}}{b_s}\,, b_{ref} = 1.905\,m$$

k_λ represent the correction for taper of the wing.

$$k_\lambda = (1+\lambda)^{.4}$$

Since the analysed MALE UAV configuration has no engine on the wings, $k_e = 1$. Undercarriages are mounted on the wing in the configuration, that is, $k_{uc} = 1$. Furthermore, since the UAV is low subsonic and wings are cantilever, $k_{st} = 1$ and $k_b = 1$, respectively. And, the factor n_{ult} is defined as

$$n_{ult} = 1.5 * (limit\ load\ factor)$$

In Eq.2 W_{des} and W_w represent the initial estimate of the empty weight of the aircraft and wing, respectively.

Mission parameters, which are endurance, climb time to specified altitudes, service ceiling, and maximum velocity, are calculated to obtain fitness value of the optimization problem. While calculating the endurance, the aircraft sustain the level flight. That is, endurance velocity is obtained by using weight and C_L values. Since the required power is multiplication of endurance velocity and drag force acting on the aircraft, it is easily calculated. Next, consumed fuel and power available are calculated through sample reciprocating engine model. This process iterates over discrete time until power available cannot supply the power required. In this way, endurance values of the UAVs with different wing designs are obtained throughout the optimization. Climb rate is calculated throughout specific excess power concept [Filippone, 2012]. Then, climb time to specified altitudes are calculated over discrete distances. While calculating climb rate, service ceiling is also calculated for specified climb rate. Next, maximum speed of the UAV is obtained by equating the available and required power equations.

Fitness function evaluation is represented in Eq. 3.

$$Cost = -endurance + e^{V_{max,desired} - V_{max}} + e^{(ceiling_{desired} - ceiling)/200} + \Sigma_{i=1}^{n} e^{(-climb\ time_{i_{desired}} + climb\ time_i)/0.5} \quad (3)$$

DESIGN PARAMETERS

Wing geometry can be described with wing planform and airfoil. In the present study, wing planform is parametrized with span length and root and tip chord length of the wing. Since we assumed quarter chord swept of the wing is zero, there is no need to define a new parameter for the wing swept. Airfoil shape of the wing is parametrized with cubic uniform b-spline curves [Solomon, 2006]. This open-end curve is defined by n+1 control points, and each spline segments are defined by four control points. In order to obtain closed-end curve and sharp trailing edge, number of control points are increased to n+5, then, last and first three control points have equated each other. The formulation of the b-spline curves illustrated in Eq. 4.

$$P_i(t) = \frac{1}{6}(1\ t\ \ t^2\ t^3)\boldsymbol{M}\begin{pmatrix} P_{i-1} \\ P_i \\ P_{i+1} \\ P_{i+2} \end{pmatrix} \quad (4)$$

Where, $0 \le t \le 1$

In Eq. 4, P_i represents the control point of the spline, and M is the coefficient matrix, obtained throughout the solution of the linear equation system derived from 3rd order continuity [Solomon, 2006].

$$\boldsymbol{M} = \begin{bmatrix} -1 & 3 & -3 & 1 \\ 3 & -6 & 3 & 0 \\ -3 & 0 & 3 & 0 \\ 1 & 4 & 1 & 0 \end{bmatrix}$$

Each control points defined in the present study have 2 degrees of freedom (DOF), along x and y directions. However, x-coordinates of the control points are kept constant to decrease the number of design variables. Furthermore, mutation rule of the genetic algorithm modifies the design variables randomly within upper and lower boundaries. This causes strange airfoil shapes. To avoid the problem, NACA0012 airfoil is considered as base airfoil and its control points are determined by fitting the cubic b-spline on the base airfoil. Then, differences between y-coordinates of the NACA0012 and the airfoil at the current is considered as design variable. In this way, we guarantied at least airfoil like shapes for the infinite wing analysis. Contrary to control points, planform variables are directly used as design variables since there is no chance to form strange planform geometry.

The best number of control points is investigated through a study to obtain appropriate airfoil parametrization. It is observed that mean value of the distance between target airfoil and current airfoil is remains nearly same for 12 and higher number of control points (Figure 1). In the present study, two additional control point is added to increase the leading-edge flexibility. Since the solution of the 2-D analysis is sensitive to leading edge changes.

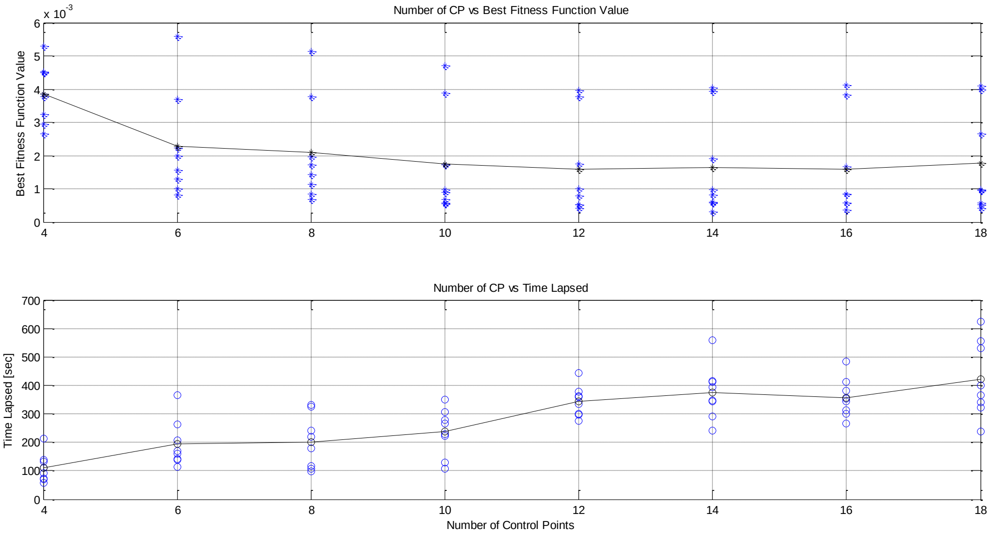

Figure 1: Illustration of the effect of the number of control points to fitness tolerance (upper line-graph) and time lapsed to convergence (lower line-graph)

Control points for the NACA0012 are obtained throughout curve fitting, and the NACA0012 profile and its control points are represented in Figure 2.

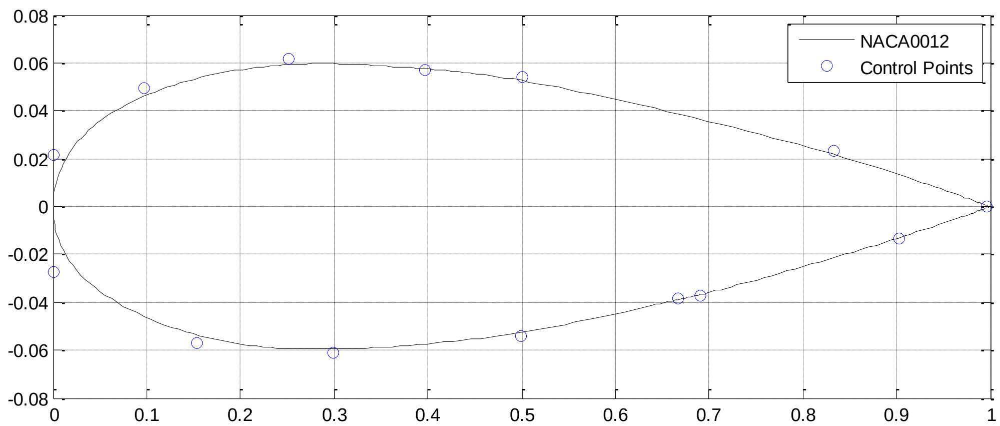

Figure 2: Illustration of NACA0012 airfoil and control points that form the NACA0012 airfoil.

GENETIC ALGORITHM

Genetic algorithm is an evolutionary algorithm which can be used to solve constrained and unconstrained optimization problems. The algorithm inspired from natural selection, which is the process drives the biological evolution. Genetic algorithm can be applied to solve the highly nonlinear, discontinuous and nondifferentiable problems. Also, the algorithm allows to reach maxima, whereas standard gradient based optimization methods generally converge to local maximum. Therefore, the genetic algorithm is decided to optimize the aerodynamic shape of the wing of the MALE UAV.

In genetic algorithm, there are three main rules, selection, crossover and mutation rules. Selection rule specifies which parents in the population contribute the next generation. Crossover rule determines how two parents form a child for the next generation. Mutation rule randomly changes genome of the individual parents to form children.

Genetic algorithm solver of the MATLAB® is used in the present study. For selection rule, uniform stochastic selection function, selectionstochunif, is used. Gaussian mutation function, mutationgaussian, and scattered crossover function, crossoverscattered, is used for mutation and crossover rules, respectively. Furthermore, initial seeds, consist of long endurance airfoils, is formed and used to seed initial population. If the size of the seeds is less than initial population, then, creation function, CreationFcn, of the tool is used to complete the remaining of the initial population.

General layout of the optimization progress is illustrated in Figure 3.

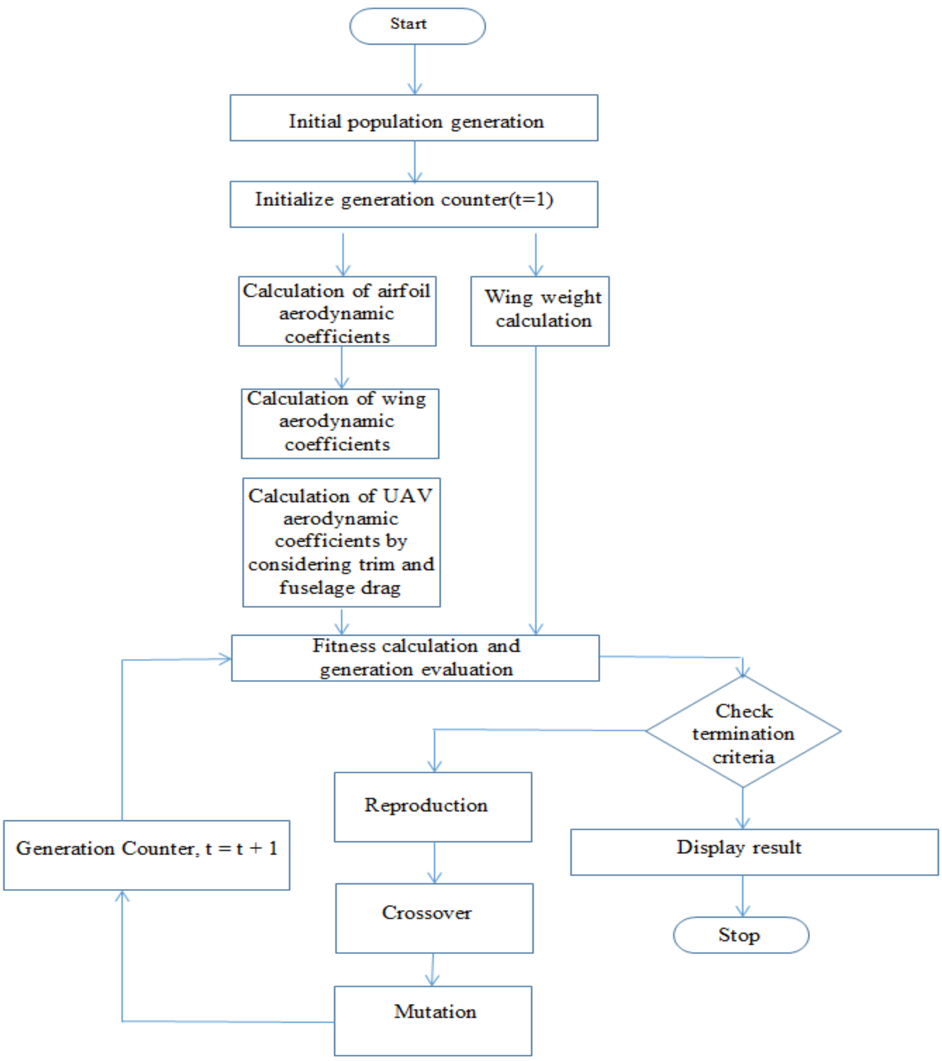

Figure 3: General layout of the optimization progress.

OPTIMIZATION

MALE UAV Configuration and Performance Requirements

In the present study, fixed wing UAV is specified as MALE with V-tail and reciprocating engine. Empty mass of the MALE is estimated at 1050 kg without wing mass and maximum take-off mass of the UAV is considered as 1650 kg. That is, summation of fuel and wing masses are assumed as 600 kg for the mission parameter calculation. Wing is specified as constant cross-section. Since the MALE UAV is a low-subsonic UAV quarter chord swept is also considered as zero. A generic MALE fuselage is analysed and its drag coefficient is estimated as $C_{df0} = 0.0260$ for the reference area of $14\,m^2$. Endurance altitude is considered as 25,000 ft.

In the present study, maximum velocity that the UAV must sustain at 20,000 feet is specified as 135 knots. Also, the climb times from sea level to 25,000 and 30,000 feet are specified as 70 and 90 mins, respectively. These mission objectives are used to calculate the fitness value (Eq. 3) throughout the optimization process.

Initialization and Boundaries

Nine long endurance airfoils are decided to feed the initial populations of the optimization. Population size is considered as 30, that is, remaining 21 individuals is created by creation function of the genetic algorithm tool of the MATLAB®. Number of generation is considered as 5.

Boundaries used in the present study for the control points are given in Figure 4. While considering these boundaries, about 4.5% thickness variation is allowed along the optimization process. Furthermore, $0.3 < c_t < 0.8$, $0.9 < c_r < 2.0$ and $15 < b < 25$ are considered for the upper and lower boundaries of the wing planform parameters.

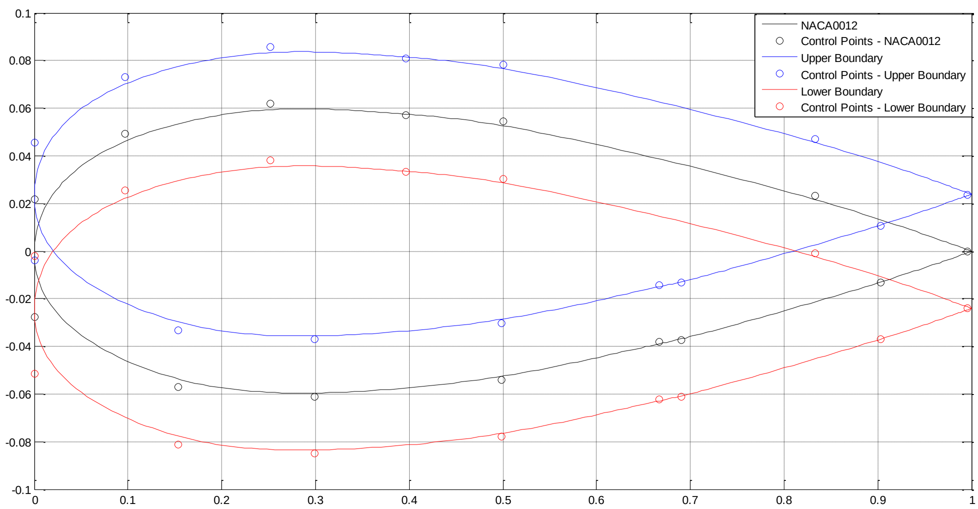

Figure 4: Representation of lower (red) and upper (blue) boundaries for the control points.

Results

9 wings are imported and 21 wings are created for the initial population. Next, the algorithm generates five other 30-invidual generations. Convergence history of the process is illustrated in Figure 5. In the initial population, the mean value of the population is 2.2645 whereas the best individual has the value of -27.8050. In the study, we luckily obtain the good performance wing in the initial population, thanks to the creationFcn. In the last generation, the mean value of the population is -25.0351, and the best wing in the generation has the cost value of -30.0610.

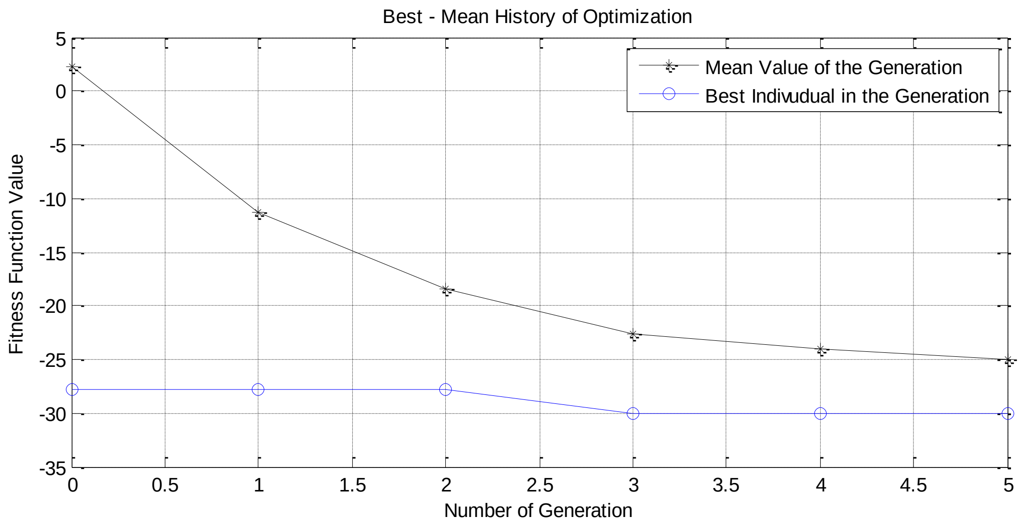

Figure 5: Convergence history of the optimization process.

Shape of the airfoil of the best wing in the last generation is illustrated in Figure 6. Also, performance and planform parameters of the best individual are tabulated in Table 1. In addition to these parameters, details about calculated parameters are tabulated in Table 2.

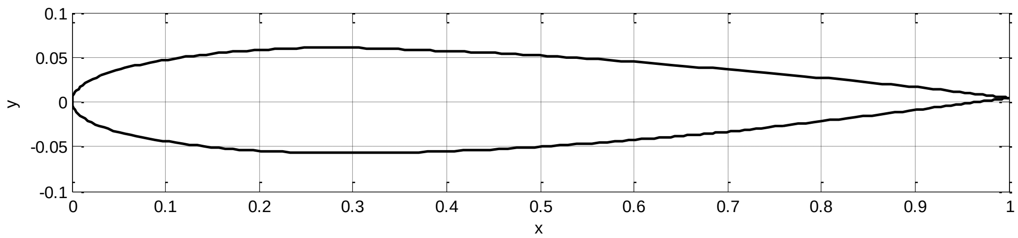

Figure 6: Airfoil geometry of the best individual in the last generation

Table 1: Performance and planform parameters of the best individual in the last generation.

Endurance [hours]	30.250
Ceiling [feet]	40,661
Maximum Velocity [knots]	136.468
Climb time to 25,000 feet [mins]	56.212
Climb time to 30,000 feet [mins]	72.528
Root chord length [m]	1.200
Tip chord length [m]	0.342
Span length [m]	19.568

Table 2: Mass and aerodynamic coefficients of the best wing in the last generation.

Estimated Wing Mass [kg]	215.503
Fuel Mas [kg]	384.497
$C_{L,wing}$ at Maximum Endurance	0.918
$C_{D,wing}$ at Maximum Endurance	0.0224

CONCLUSION

In the present study, aerodynamic shape optimization of the wing of a MALE UAV is performed. Genetic algorithm is used as optimization algorithm. Wing planform and profile is used as design parameters. In order to decrease the number of design parameters, airfoils are parametrized by using uniform rational b-spline curves. Aerodynamic coefficients for mission parameter calculations are obtained by using Xfoil, non-linear lifting line code. Also, fuselage drag coefficient and trim drag is also taken into account while obtaining the aerodynamic coefficients. In addition, performance parameter calculations require weight of the UAV and engine performance values. The weight of the aircraft kept constant and fuel mass is updated with change in wing mass. Wing mass is estimated by a statistical equation. Sample internal combustion engine is used to complete the performance calculations.

Performance parameters are used in the fitness calculation to slightly increase the fidelity of the optimization. In the absence of the climb rate and maximum velocity requirements, the best wing tends to enlarge planform dimensions. That is, other mission parameters are also considered whereas the primary objective of the study is increase the endurance of the MALE UAV.

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