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A GENETIC ALGORITHM BASED DESIGN OPTIMIZATION METHOD FOR WING-TAIL COMBINATIONS OF UAVs

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ABSTRACT

The aim of this study is to develop a design optimization program considering aerodynamic, performance and weight criteria which can be used in the conceptual and preliminary design stages of aircraft design which is a multidisciplinary field. For this reason, low order analysis methods were preferred in order to make the program foldable in terms of cost and time. Therefore, design analysis program was developed by using Vortex Ring Method (VRM) for aerodynamic analysis, general performance formulas for performance calculation and statistical weight estimation formulas for weight estimation. For the optimization study, genetic algorithm, which is frequently preferred in design optimization studies, was preferred. In this direction, the design analysis program has been integrated with the genetic algorithm and the design optimization program has been developed. After the programs were tested by verification studies, they were used to optimize the wing of an UAV and its system consisting of wing and tail for various purposes. The results obtained from the application were evaluated and their usability for the complex design optimization problem was examined.

Nomenclature

AR	Aspect Ratio	W_0	Aircraft Gross Weight
Arf	Airfoil	W_{HT}	Horizontal Tail Weight
b	Wingspan of Lifting Surface	W_{VT}	Vertical Tail Weight
c	Specific Fuel Consumption	W_{Vtail}	V Tail Weight
l_{arm}	Tail Moment Arm	α_{dih}	Dihedral Angle
n_z	Ultimate Load Factor	α_{inc}	Incidence Angle
q	Dynamic Pressure	α_{swp}	Sweep Angle
R	Location Vector	α_{tws}	Twist Angle
S	Lifting Surfaces Area	λ	Taper Ratio
t/c	Airfoil Thickness Ratio	η	Propeller Efficiency
V_{cruise}	Cruise Speed		

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INTRODUCTION

Air vehicle design process is a complex and multidisciplinary field of study. The reason why this process is complex is not only that the works of the different disciplines affect each other, but also each work area has too many parameters that affect the air vehicle in itself. It is inevitable that a precise calculation of the effects of combinations of these parameters on the aircraft will bring this design process to an unbearable dimension in terms of cost and time. Therefore, there is a need for fast design tools that provide approximate results for use in the conceptual and preliminary design process of air vehicles. However, because of having too many parameters, having only fast design tools is not enough to make a successful and reliable design in a short time. Therefore, optimization programs are needed together with rapid analysis methods.

Recently, the importance given to the defense industry and investments have increased in our country. Therefore, many air vehicle projects are being carried out. In the process of these air vehicle projects, knowledge of aircraft design is needed especially for the UAV. Therefore, the optimization and design analysis tools to be developed will contribute to the design processes of these air vehicles.

In the conceptual and preliminary design stages of air vehicles, panel methods have been used widely due to their quick and acceptable approximate results. As the design process is multidisciplinary and depends on many parameters, optimization and different discipline analysis tools are needed in addition to the aerodynamic analysis programs to produce a successful aircraft design.

In this context, several design optimization studies using panel methods are encountered in the literature. One of these studies is about the optimization of a single-element wing by using Vortex Lattice Method (VLM) with 2D viscous airfoil experimental data and an optimization technique including wing area, wingspan, taper ratio, leading edge sweep and geometric twist as optimization variables [Pinzon, 2008]. 2D data is taken from look-up tables according to the local lift coefficients of the wing sections obtained from VLM calculations. In another study, Hajec uses a non-linear lifting line method with 2D viscous airfoil solver XFOIL for single-wing aerodynamic analysis and an evolutionary optimization algorithm [Hajec 2009]. For the multi-element lifting surface systems Demircan uses the Vortex Lattice Method for potential flow solutions and a genetic algorithm method for the optimization of wing-tail combinations [Demircan, 2018]. In this last study viscosity effects are ignored.

The aim of this study is to develop a computer program which can optimize the wing-tail systems consisting of two or more lifting surface, to be used for various purposes, especially in unmanned aerial vehicle design works.

METHOD

In the present study, Vortex Ring Method (VRM) is applied for the solution of potential flow around lifting-surface systems (wing-tail combinations). However, in order to take into account also the viscosity effects, 2D experimental/numerical airfoil data is used. In addition, weight estimation and performance calculations were added to the program and statistical weight formulas were used for weight estimation. General performance formulas are used for performance calculations. These formulas are explained in the applications section. For the optimizations, one of the evolutionary algorithms, the genetic algorithm is preferred.

Vortex Ring Method for Multi Element Lifting Surface Systems

The Vortex Ring Method (VRM) used in this study is a version of Vortex Lattice Method (VLM). The details of its formulations for a single element wing can be found in several aerodynamics text books (see for example [Katz and Plotkin, 2001]). In the present paper a formulation of the method for multi-element lifting surfaces developed by Yükselen [Yükselen, 2015, 2017] is followed.

Both, in VLM and VRM the thickness effects of a wing are neglected and the wing is considered as a thin surface. This surface is divided into spanwise and chordwise panels as shown in Fig. 1. In VRM, vortex rings are placed on each panel and horse-shoe vortices at the trailing edge of the wing, while horse-shoe vortices placed on all of the panels in VLM.

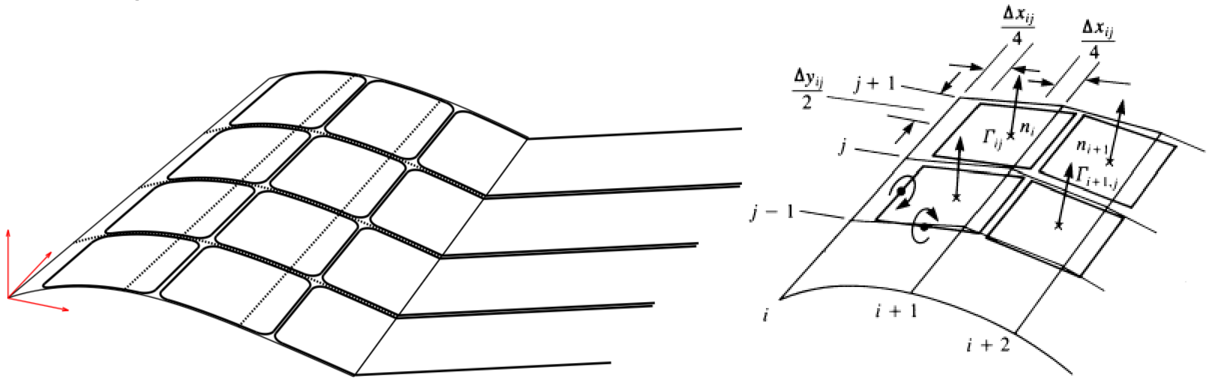

Figure 1: Vortex ring distribution and placement

The front arm of the vortex ring is located on the quarter line of a panel, while the aft arm is located on the quarter line of the next panel in the direction of chord. The trailing arms of the vortex ring are located on the left and right sides of the panel. The trailing arms of the horseshoe vortices placed on the wing trailing edge go to infinity in the direction of free flow.

The strengths of vortex rings are unknowns of the potential flow problem. In order to obtain vortex strengths, tangent flow boundary condition is applied at the control points on each panel, which results with a linear equation system. Control points are at the three quarter central point of each panel (centroid of vortex ring).

With the application of the surface boundary condition at each control points of a multi-element lifting surface system the following equations system is obtained:

$$\sum_{k_G=1}^{NW}\sum_{i_G=1}^{NI(k_G)}\sum_{j_G=1}^{NJ(k_G)} A_{(i_C,j_C,k_C)(i_G,j_G,k_G)}\Gamma_{(i_G,j_G,k_G)} = -\vec{V}_\infty \cdot \vec{n}_{(i_C,j_C,k_C)} \quad \begin{pmatrix} i_C = 1,2,...NI(k_C) \\ j_C = 1,2,...NJ(k_C) \\ k_C = 1,2,...NW \end{pmatrix} \qquad \textbf{(1)}$$

Where, $A_{(i_C,j_C,k_C)(i_G,j_G,k_G)}$ represents the normal component of the velocity induced at the control point (i_C,j_C,k_C) by the ring vortex (i_G,j_G,k_G) of unit strength. Γ is the vortex strength. $\vec{n}_{(i_C,j_C,k_C)}$ is the unit normal vector at the control point. *NW* is the total number of lifting surfaces, *NI* and *NJ* is the number of chordwise and spanwise panels, respectively.

All the ring vortex strengths are obtained by solving the linear equations system with a Gauss elimination procedure. Ones the vortex strengths are obtained, aerodynamic force coefficients are calculated on each panels by applying the following vector form of the Kutta-Joukowski law:

$$\Delta\vec{f}_{i,j,k} = \rho\,\vec{V}_{i,j,k} \times (\Gamma_{i,j,k}\Delta\vec{s}_{i,j,k}) \qquad \textbf{(2)}$$

Where, $\vec{V}_{i,j,k}$ is the total velocity induced by all the vortices and the free flow at mid-point of the leading arm of ring vortex (bound vortex). $\Delta\vec{s}_{i,j,k}$ is a line vector take place on the bound vortex. The total aerodynamic force effecting on each lifting surface and net force on the whole system is obtained by the following formulas, respectively:

$$\vec{F}_k = \sum_{i=1}^{NI(k)} \sum_{j=1}^{NJ(k)} \vec{f}_{i,j,k} \tag{3}$$

$$\vec{F} = \sum_{k=1}^{NW} \vec{F}_k \tag{4}$$

The induced drag and lift forces are calculated by projecting the force vector in the free flow direction and normal to this direction, respectively.

Calculation of the viscous drag

Since the potential flow methods give only induced drag for wings, in order to obtain viscous drag, two-dimensional data for the sections of lifting surfaces is appropriately exploited. For this purpose, a wing is assumed to consist of thin strips along its span. For any wing strip, an equivalent two-dimensional flow is considered, provided that the circulation is equal to the circulation calculated in the 3-dimensional vortex lattice method. Thus, local lift coefficient of a strip is

$$Cl_{(j,k)} = \frac{2\Gamma_{(j,k)}}{V_\infty c_{(j,k)}} \tag{5}$$

Where, (j,k) index represents j^{th} strip of k^{th} wing, $c_{(j,k)}$ is the chord length of this strip and $\Gamma_{(j,k)}$ is the total circulation around this strip, calculated as

$$\Gamma_{(j,k)} = \sum_{i=1}^{NI(k)} \Gamma_{i,j,k} \tag{6}$$

Where $\Gamma_{i,j,k}$ is the strength of bound vortex on the $(i,j)^{th}$ panel of k^{th} wing.

Once the lift coefficient of a strip is obtained, induced drag and pitching moment coefficients are taken from look-up tables for $C_d - C_l$ and $C_m - C_l$ variations, created by experimental or numerical data of that strip's airfoil.

Total profile drag and pitching moment coefficients of a wing element k is calculated by the summation of drag and pitching moment coefficients of all strips as follow:

$$C_{d_k} = \frac{1}{S_k} \sum_{j=1}^{NJ(k)} C_{d_{(j,k)}} S_{(j,k)} \tag{7}$$

$$C_{m_k} = \frac{1}{\bar{c}_k S_k} \sum_{j=1}^{NJ(k)} C_{d_{(j,k)}} S_{(j,k)} c_{(j,k)} \tag{8}$$

Where, S_k and $\bar{c}_k$ is the k^{th} wing's reference area and mean chord length, respectively, and $S_{(j,k)}$ and $c_{(j,k)}$ is the reference area and chord length of of j^{th} strip on this wing.

Validation

Experimental data given in NACA Technical report 1422 [Sivells, 1947] was used to validate the VRM program. Geometric properties of the wing used for verification are given in Table 1. Figure 3 shows that the results obtained from the VRM program are very close to the experimental results, especially at low angles of attack.

Table 1: Wing features used in verification study

$Parameters$	$Value$
S	$2.32\ m^2$
AR	9
λ	0.4
α_{dih}	0^o
α_{inc}	0^o
Arf	$NACA\ 65210$

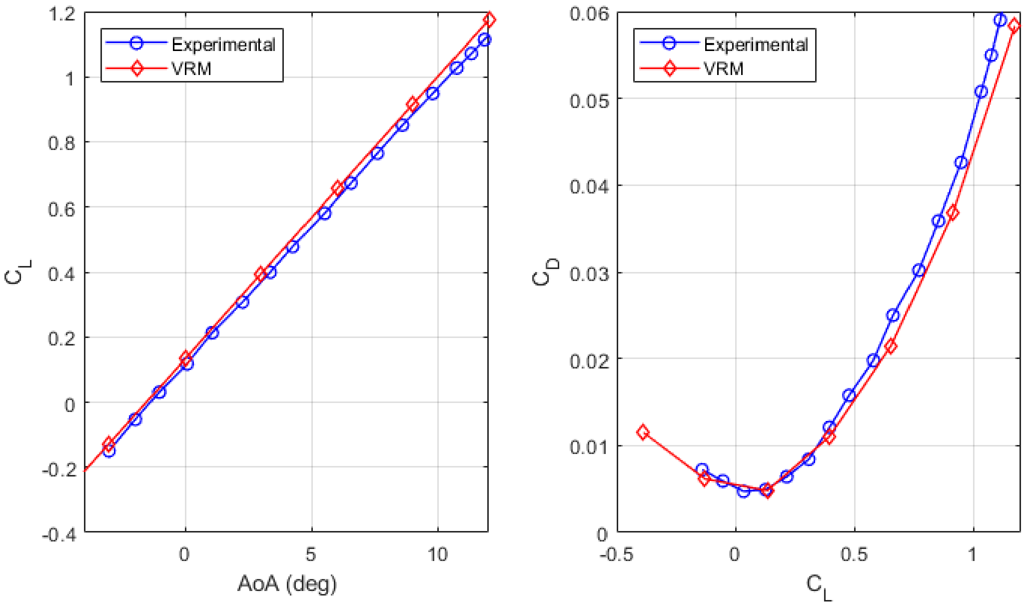

Figure 2: Verification test result comparison

Structural Weight Estimation Methodology

In an aircraft design study, weight of an aircraft is always a limiting factor. In addition, aircraft weight is one of the most important parameters affecting the performance of aircraft. Therefore, in order to remain within the required weight targets, weight estimation and follow-up it regularly is necessary during each design process. For this purpose, equations for various types of aircraft have been given in the literature, to be used in conceptual and preliminary design operations. But, the equations related to wing-tail weight estimations are mostly for manned aircrafts and there is no many derived formulas for unmanned aerial vehicles. Essari tested the applicability of the existing formulas for a Tactical Unmanned Air Vehicle (TUAV) by applying them to 15 different TUAV with composite-supported aluminum structure, in the range of 100-500 kg [Essari, 2015].

Wing Weight Estimation Methods

Essari has shown that the USAF's equation for general aviation aircraft, Torenbeek's equation for light transport aircrafts and Gundlach's equation for manned sailplane provide reasonable results for TUAV wing weight estimation [Essari, 2015]. The variables in these formulas are listed in Table 2.

Table 2. Wing weight estimation method sensitivity to wing parameters

Method	Wing weight as a function of …							
	Wo	S	AR	λ	α_{swp}	t/c_{wing}	n_z	V_{cruise}
USAF	✓	✓	✓	✓	✓	✓	✓	✓
Torenbeek	✓	✓	✓		✓	✓	✓	
Gundlach	✓	✓	✓	✓		✓	✓	

Estimated wing weights of RQ-7B Shadow aircraft with these formulas are compared in Figure 3.

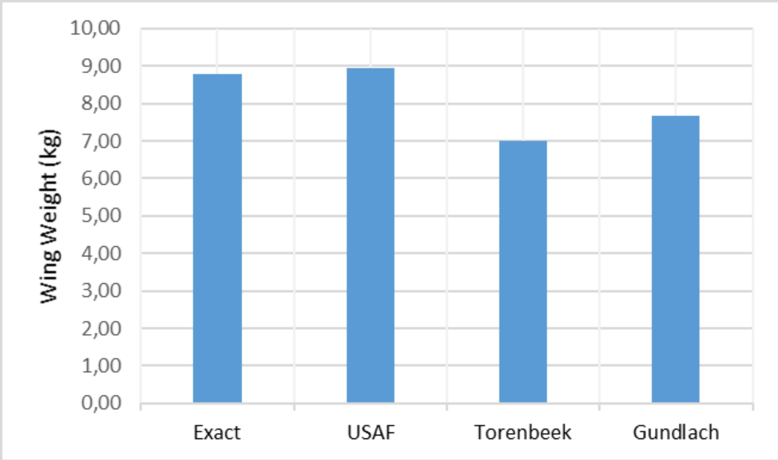

Figure 3: Wing weight estimation comparison

As seen from this figure, the USAF method gives the closest result for this aircraft. In addition, the USAF equation depends on the variables to be used in an optimization study, such as aspect ratio, taper and sweep angle. Therefore, the following USAF formula is used in this paper for estimating wing weight:

$$W_{wing} = 96.948 \left(\left(\frac{W_0 \times n_Z}{10^5} \right)^{0.65} \left(\frac{AR}{\cos(\alpha_{swp})} \right)^{0.57} \times \left(\frac{S}{100} \right)^{0.61} \times \left(\frac{1+\lambda}{2 + t/c_{wing}} \right)^{0.36} \times \left(1 + \frac{V_{cruise}}{500} \right)^{0.5} \right)^{0.993} lb \qquad \textbf{(9)}$$

Empennage Weight Estimation Methods

Essari has shown that Gundlach's equation for manned sailplane, USAF's equation for general aviation aircraft, Torenbeek's equation for light transport aircrafts and Raymer's equation for general aviation aircraft provide reasonable results for TUAV empennage weight estimations [Essari, 2015]. In addition, Yi and Hepping derived V tail weight estimation formula for HALE UAVs [Yi and Hepping,2006]. Torenbeek's and Gundlach's equations depend only on the wing area and ultimate load factor. Therefore, these formulas are not considered in this study. The variables in rest of formulas are shown in Table 3.

Table 3. Empennage weight estimation method sensitivity to tail parameters

Method	Empennage weight as a function of …								
	Wo	S	AR	α_{swp}	λ	t/c_{tail}	n_z	q	l_{arm}
USAF	✓	✓	✓	✓		✓	✓		✓
Raymer	✓	✓	✓	✓	✓	✓	✓	✓	
Yi	✓	✓	✓		✓	✓	✓		

By using these formulas, the empennage weight of the RQ-7B Shadow aircraft was estimated. USAF's and Raymer's equation has been derived for conventional tail types. Hence, in order to estimate the weight of the inverse V tail by USAF and Raymer methods, Gundlach's following conversion formula was applied [Gundlach, 2012]:

$$W_{Vtail} = W_{HT} \,.\, \cos^2(\alpha_{\mathrm{dih}}) + W_{VT} \,.\, \sin^2(\alpha_{\mathrm{dih}}) \qquad \textbf{(10)}$$

The results are compared with the actual weight of the aircraft in Figure 4.

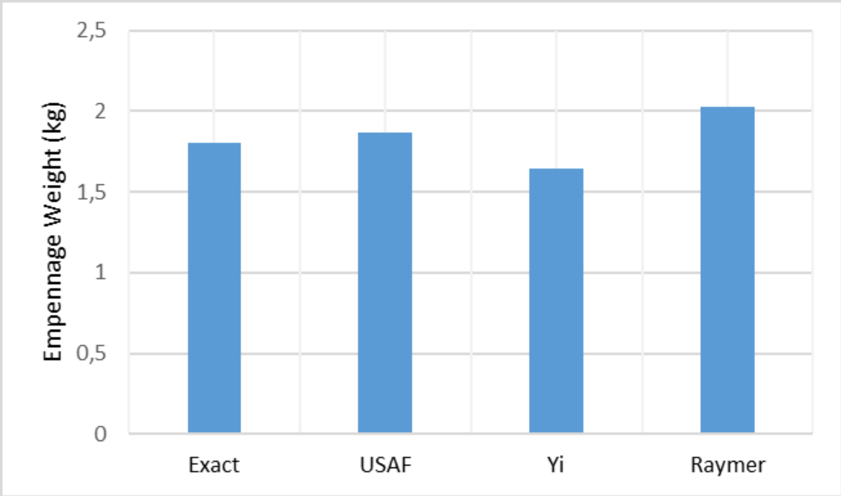

Figure 4: Empennage weight estimation comparison

As seen from this figure, the USAF model is most accurate. Therefore, the following USAF weight estimation formula was used for weight estimation in this study:

$$W_{ht} = 127 \times \left(\left(\frac{W_o \times n_z}{10^5} \right)^{0.87} \times \left(\frac{S_{ht}}{100} \right)^{1.2} \times 0.289 \times \left(\frac{l_{arm}}{100} \right)^{0.483} \times \left(\frac{b_{ht}}{t/c_{ht}} \right)^{0.5} \right)^{0.485} lb \quad \textbf{(11)}$$

$$W_{vt} = 98.5 \times \left(\left(\frac{W_0 \times n_z}{10^5} \right)^{0.87} \times \left(\frac{S_{vt}}{100} \right)^{1.2} \times 0.289 \times \left(\frac{b_{vt}}{t/c_{vt}} \right)^{0.5} \right)^{0.458} lb \quad \textbf{(12)}$$

For weight estimations of V tails these formulas are used in Equation (10).

Genetic Algorithm for Optimization of Lifting Surfaces

Genetic algorithm is one of the most common methods of evolutionary algorithms [Sivanandam and Deepa,2008]. This algorithm, based on principle of survival of the strongest, is an application of the evolution theory to artificial systems. In contrast to other optimization methods, the genetic algorithm does not use the derivatives of the system's mathematical model. Instead, it looks for the best individual in a completely probabilistic way. Therefore, generally, the genetic algorithm is preferred in design processes which depend on too many variables and for which it is difficult to construct any mathematical model.

Since the system in a genetic algorithm is linked to the cell structure, before an artificial system is optimized with genetic algorithm, it is necessary to simulate the artificial system with cell structure. According to this simulation, the system to be optimized is referred to as an individual. Each feature used to represent an individual is called a gene. When genes combine for subsystems, chromosomes are formed. With the combination of chromosomes, the genotype representing all the genes of the individual is formed. The physical appearance of the genotype that forms the system is called the phenotype.

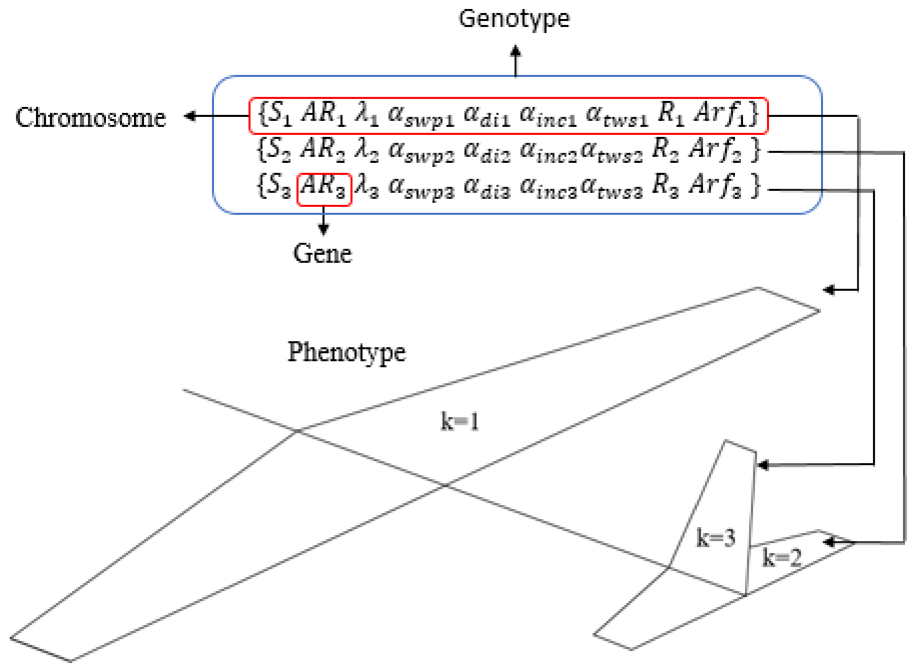

Figure 5: Representation of relevant terms in the genetic algorithm

Genetic algorithms start by creating a random initial population from the sample space around the user-defined limitations. The individuals in the created generation are evaluated with programs prepared according to the evaluation purpose. The results obtained as a result of the necessary evaluations are evaluated for their suitability by using the fitness functions determined to optimize them. The individuals are then matched via the roulette wheel method from a pool of genes constructed according to their fitness values. In this gene pool, number of individuals are proportional to their fitness values, thus increasing the likelihood of matching a high suitability individual. By crossing the genotypes of individuals identified as a result of matching, an individual is formed to generate the next generation. Some genes of some of the individuals formed are randomly modified to add diversity to the population during the mutation phase. After the mutation phase, the formed individuals are evaluated and their suitability is calculated. The suitability of individuals created as a result of these procedures is compared with their parents. If the newly created individual is more suitable than their parents, it is added to the next generation. If the new individual is not successful from their parents, the parents are transferred to the next generation. The new generation generated as a result of these operations continues as shown in Figure 6. These operations continue until the termination criteria are met.

APPLICATION

Genetic algorithm is a heuristic method and is an optimization method that seeks the best person in the field of solution using evolutionary cycles. Theoretically, the best individual can be achieved by the number of generations that last forever. This leads to unendurable dimensions in terms of calculation time. Therefore, stop criteria such as maximum production are entered into the program. As a result, the individuals obtained from the analysis are the best results close to the optimum individual. It is not possible to make any guesses about closeness to the best individual. Furthermore, evolutionary algorithms suffer from convergence to local maximum / minimum points. Therefore, the applications were repeatedly repeated and tried to ensure that the results did not converge to a local point and that the result was close to the optimum individual.

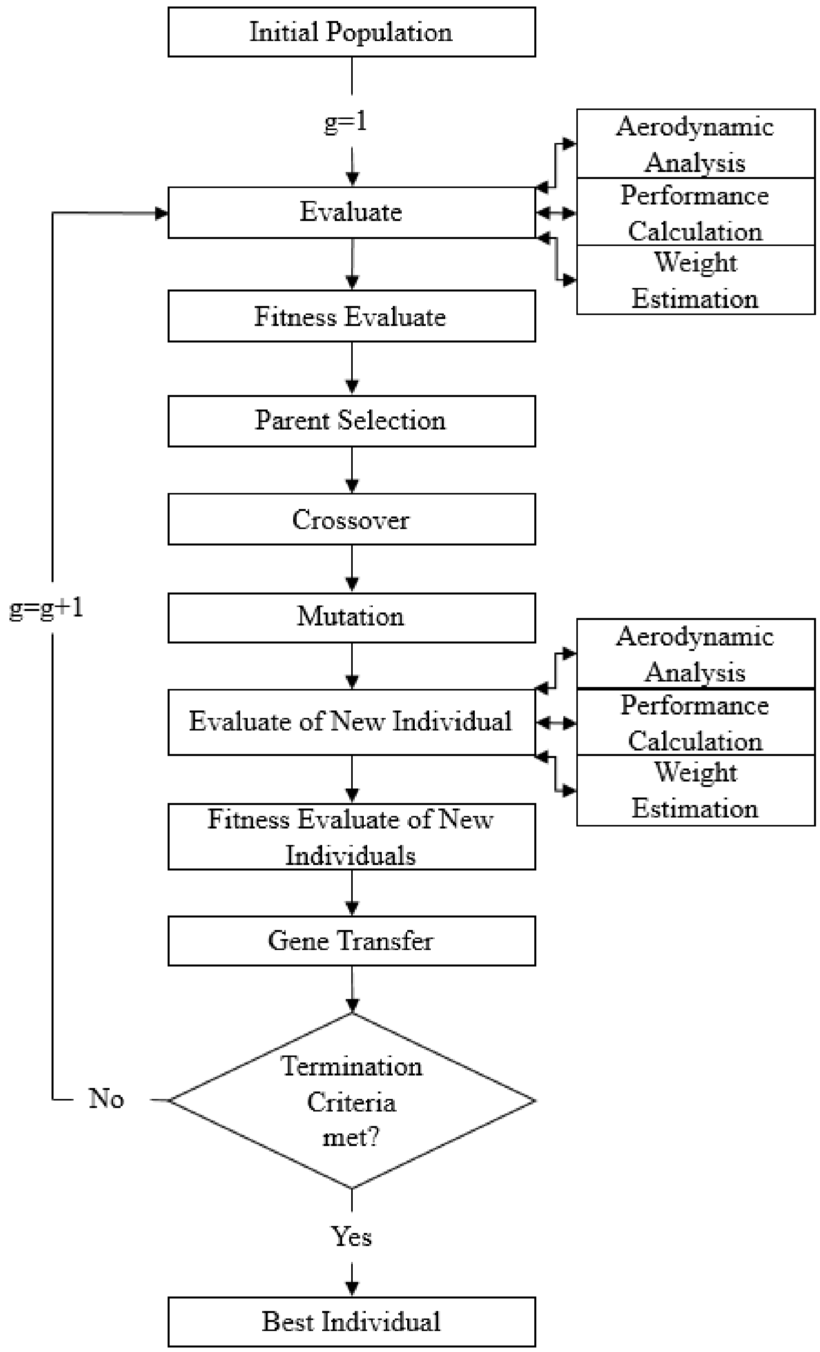

Figure 6: Genetic algorithm flow chart

Aerodynamic Optimization of a Lifting Surface

In this application, the aerodynamic optimization problem of the wing of RQ-7B Shadow UAV is investigated. The geometric characteristics of the wing of the RQ-7B, defined as the initial individual, are given in Table 4.

The purpose of this optimization problem is to obtain a wing with minimum drag which provides the required lift coefficient within the given limits. Therefore, the fitness value is determined as:

$$f_{fitness} = \frac{1}{C_L * C_D} \quad \textbf{(13)}$$

Table 4. Geometric properties of the initial individual

Parameters	Value
S	2.62
AR	7.07
λ	1
α_{swp}	0^o
α_{dih}	0^o
α_{inc}	0^o
α_{tws}	0^o
Arf	$NACA\ 4415$

The results obtained from the aerodynamic analysis of individuals produced by genetic algorithm are evaluated by Equation (13). It is aimed to increase the lift coefficient of the current wing to 0.33 for cruise flight. Therefore, the boundary condition is put in the program so that the fitness value of the wings whose lifting coefficient is less than this value is 0.
Aspect ratio, taper ratio and sweep angle are considered as the hereditary genes for this application. The allowed minimum and maximum values for these variables are given in Table 5. Individuals created through genetic algorithms are formed by taking these limit values into consideration.

Table 5. Value range of hereditary genes

Parameters	Minimum Value	Maximum Value
AR	6	9
λ	0.4	1
α_{swp}	0^o	45^o

Using the aerodynamic coefficients obtained by VRM program, individuals are evaluated with the fitness function given in Equation (13). The number of populations was 20. Evolutionary cycles are repeated until the termination criteria were met, by searching the best individual at each cycle. The characteristics of the initial individual and the optimized individual obtained as a result of evolutionary cycles are given in Table 6.

Table 6. Analysis result

Parameter	Initial Individual	Optimized Individual
S	2.62	2.62
AR^*	7.07	9.00
λ^*	1	0.60
α_{swp}^*	0^o	18.90^o
α_{dih}	0^o	0^o
α_{inc}	0^o	0^o
α_{tws}	0^o	0^o
Arf	$NACA\ 4415$	$NACA\ 4415$
C_L	0.3147	0.3302
C_D	0.0120	0.0113
$Fitness$	0	269.12

As seen from the table, aspect ratio of the optimized wing approaches to the allowed maximum value for aspect ratio. The main reason for this is that the induced drag decreases with increasing aspect ratio. In addition, if the effects of sweep angle on lift and induced drag is considered, it is expected that the sweep angle of optimized wing will be directed towards the maximum allowed sweep angle, since the induced drag will decrease with the increase of sweep angle. On the other hand, since the lift coefficient decreases with increasing sweep angle, the target lift coefficient entered into the program is a limit for the sweep angle.

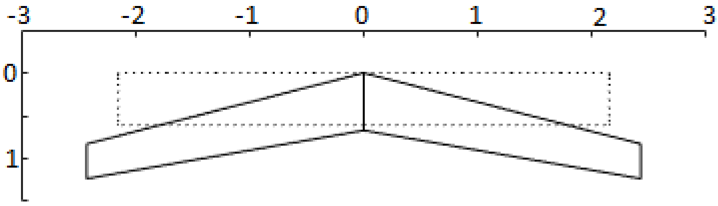

Figure 7. Optimized wing (the dashed line is the initial wing)

As can be seen from the results of the optimized wing, the optimization variables are directed to the limit values of hereditary genes. The reason for this is that the information obtained from the low-order aerodynamic method is limited. Therefore, in order to obtain useful results in optimization studies using low-order aerodynamic methods, it would be useful to add new methods to the program that will limit the geometric characteristics of the individual to be optimized. In addition, since the design of aircraft is a multidisciplinary field, the optimization of a lifting surface with only a low order aerodynamic analysis program will not yield usable results. Therefore, weight and performance tools were added to the program to obtain reasonable results from the program.

Design Optimization of a Lifting Surface

In this application, optimization problem for RQ-7B Shadow's wing reconsidered with the aim to minimize the structural weight of wing and to increase the aerodynamic efficiency of the wing. It is also expected that the optimized wing has lift coefficient at least 0.33. Initial geometric properties of the wing are the same as given in Table 4.

In this study, two different programs were used: VRM code for the aerodynamic analysis and a code for USAF formulation of weight estimations. The inputs given in Table 7 are entered into the program for weight estimation, in addition to the inputs required for the aerodynamic analysis given in Table 4.

Table 7. Parameters required for wing weight estimation

$Paremeters$	$Value$
W_0	$170\ kg$
n_Z	3.6
t/c_{wing}	0.15

In order to combine the results obtained from two separate programs, instead of using a coupling method, the following fitness function is determined:

$$f_{fitness} = w_1 * \frac{\left(\frac{L}{D}\right)_{evaluated}}{\left(\frac{L}{D}\right)_{initial}} + w_2 * \frac{W_{initial}}{W_{evaluated}} \quad \textbf{(14)}$$

Where w_1 and w_2 are the weighting factors for the aerodynamics and the wing weight. For this application, it is accepted that the increase in aerodynamic efficiency and the decrease of the structural weight of the wing are of equal importance. Therefore, w_1 and w_2 values are taken as 0.5. In addition, the hereditary genes are determined as the aspect ratio, taper and sweep angle. Ranges for these hereditary genes are the same as before given in Table 5.

Using aerodynamic coefficients obtained by VRM program and wing weights obtained by USAF formula, the individuals are evaluated with fitness function given in Equation (14). The number of populations was 20. The best individual was searched until the termination criteria were met. The characteristics of the optimized individual obtained as a result of evolutionary cycles are given in Table 8.

Table 8. Analysis results

Parameters	Initial Individual	Optimized Individual
S	2.62	2.62
$AR*$	7.07	7.98
$\lambda*$	1	0.40
$\alpha_{swp}*$	0^o	5.40^o
α_{dih}	0^o	0^o
α_{inc}	0^o	0^o
α_{tws}	0^o	0^o
Arf	$NACA$ 4415	$NACA$ 4415
C_L	0.3147	0.3300
C_D	0.0120	0.0117
W_{wing}	8.6402	8.1833
$Fitness$	0	1,0623

The top view of the optimized wing obtained is shown in Figure 8. Compared to the first application, it is seen that the results obtained in this application are more useful and usable.

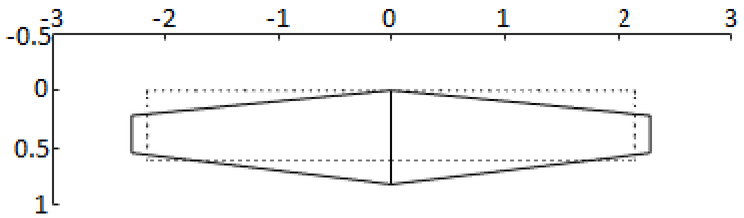

Figure 8. Optimized wing (the dashed line is the initial wing)

Design Optimization of RQ-7B Shadow Lifting Surfaces

In this application, optimization of lifting surfaces (wing and tail) of RQ-7B Shadow aircraft is discussed. The aim of the study is to increase the range of the aircraft while minimizing the structural weight and to make it aerodynamically more efficient. The initial geometries of the wing and tail of the Shadow UAV are given in Table 9.

Table 9. Geometric properties of the initial individual

$Parameters$	$Wing$	$Inverse\ V\ Tail$
S	2.62	0.60
AR	7.07	3.50
λ	1	1
α_{swp}	0^o	0^o
α_{dih}	0^o	-36^o
α_{inc}	0^o	0^o
α_{tws}	0^o	0^o
Arf	$NACA$ 4415	$NACA$ 0012
R	[0 0 0]	[2 0 0.48]

During the optimization study, 3 different programs were used to evaluate the individuals: VRM program for aerodynamic analysis, USAF program for weight estimation and a performance program including the Breguet range formula. The information required for aerodynamic analysis is given in Table 9 and the information required for weight estimation and range calculation is given in Table 10.

Table 10. Parameters required for range and weight calculation

$Parameters$	$Value$
W_0	$170\ kg$
n_Z	3.6
t/c_{wing}	0.15
t/c_{tail}	0.12
η	0.795
c	$1.473 * 10^{-5}\ kg/Ns$
W_{final}	$84\ kg$

The suitability of the individuals for the purpose to be optimized is evaluated by the fitness function, and the fitness function is determined as the weight function including the outputs of these three programs.

$$f_{fitness} = w_1 * \frac{\left(\frac{L}{D}\right)_{evaluated}}{\left(\frac{L}{D}\right)_{initial}} + w_2 * \frac{W_{initial}}{W_{evaluated}} + w_3 * \frac{R_{evaluated}}{R_{initial}} \tag{15}$$

The values of weighting factors w_1, w_2 and w_3 are selected according the purpose of the application as 03, 0.5 and 0.2, respectively. The hereditary genes were determined as aspect ratio, taper, sweep angle and dihedral. The ranges for these genes is given in Table 11.

Table 11. *Value range of inherited genes*

	$Wing$		$Tail$	
$Parameters$	$Min.Value$	$Max.Value$	$Min.Value$	$Max.Value$
AR	6	9	3	5
λ	0.4	1	0.4	1
α_{swp}	0^o	20^o	0^o	20^o
α_{dih}	0^o	2^o	-40^o	-35^o

The population number was 20 and evolutionary cycles were performed. The best individual was searched until the termination criteria were met. The properties of the optimized individual obtained as a result of evolutionary cycles are given in Table 12.

Table 12. Analysis results

	$Initial\ Individual$		$Optimized\ Individual$	
$Parameters$	$Wing$	$Tail$	$Wing$	$Tail$
S	2.62	0.60	2.62	0.60
AR^*	7.07	3.50	7.05	3.00
λ^*	1	1	0.4	1
$\alpha_{swp}{}^*$	0^o	0^o	7^o	19^o
$\alpha_{dih}{}^*$	0^o	-36^o	1.86^o	-40^o
α_{inc}	0^o	0^o	0^o	0^o
α_{tws}	0^o	0^o	0^o	0^o
Arf	$NACA\ 4415$	$NACA\ 0012$	$NACA\ 4415$	$NACA\ 0012$
R	[0 0 0]	[2 0 0.48]	[0 0 0]	[2 0 0.48]
C_L	0.3110		0.3128	
C_D	0.0217		0.0214	
$Weight$	$10.46\ kg$		$9.46\ kg$	
$Range$	$55.63\ km$		$57.74\ km$	
$Fitness$	1		1.0666	

The top view of the optimized wing obtained is shown in Figure 9. The first individual is given in dashed lines and the change between the first individual and the optimized individual is observed.

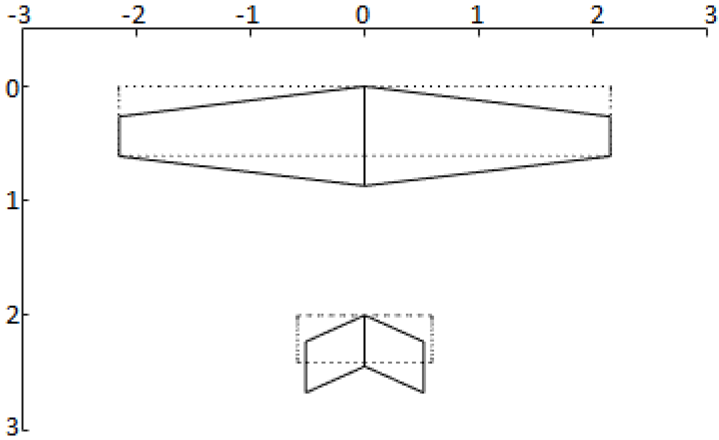

Figure 9. Optimized wing (the dashed line is the initial wing)

CONCLUSION

In this study, a design optimization program has been developed for the systems of multi-element lifting surfaces. The program is intended to be used in preliminary and conceptual design processes. Therefore, the program was developed by using low order analysis methods. The analysis program developed in this direction contains vortex ring method for the aerodynamic analysis, general performance formulas for the performance calculations and a statistical weight estimation method. Genetic algorithm was preferred for the optimization study.

Since, the VRM for aerodynamic analysis of lifting surfaces neglects the viscous effects, 2D airfoil data obtained numerically/experimentally is used for the calculation of viscous drag. Validation studies was performed and the consistency of the results obtained from the aerodynamic analysis program was shown.

For the weight estimations, empirical formulas given in the literature were applied to RQ-7B Shadow aircraft and the results were compared with the actual structural weight values. As a result of comparison, it was observed that USAF formulation gave consistent results for wing and tail weight estimation. A code was also developed for performance calculation by using known performance formulas in the literature.

For the optimizations, a code using genetic algorithm was developed and combined with aerodynamic analysis, weight estimation and performance programs into a design optimization frame. By using this code, optimization of single and multi-element lifting systems was realized according to the determined purpose.

Although the used methods are low order ones, it has been shown that the program gives reasonable results, and can be used in the stages of conceptual design and preliminary design of aircraft lifting surfaces.

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