

Optimization of Moving Wing in Ground Effect using Response Surface Method

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Optimization of the sectional wing in ground effect (WIG) has been studied using a high order numerical procedure and response surface method (RSM). Initially, the effects of the ground clearance, angle of attack, thickness, and camber of wing have been investigated by a high-resolution scheme, which is highly strong and accurate. In the numerical simulation, Normalized Variable Diagram (NVD) scheme is applied to the boundedness criteria. In the optimization process, lift to drag ratio (L/D) is considered as an objective function and static conditions and shape parameters are noticeable to be considered as design variables; This is because the main factor in the design of WIG vehicles is moving near the ground and the distance to the ground draws attention to the significance of it. Therefore, the static conditions strenuously defend this view that they are irrefutable parameters in the aerodynamic optimization of WIG vehicles. Adaptive Neuro-Fuzzy Interface System (ANFIS) is employed to generate the surface response, because the objective function and constraints are particularly noisy. Sensitivity analysis is also done and the sensitivity amount of the objective function from design variables is explored.

Keywords: Ground effect, Wing shape, Response surface, Static condition, Optimization

Nomenclature

<i>PSO</i>	Particle Swarm Optimization
<i>NVD</i>	Normalized Variable Diagram
<i>CFD</i>	Computational Fluid Dynamic
<i>k</i>	Turbulence Model Parameter
ϵ	Turbulence Model Parameter
<i>L</i>	Lift Force
<i>D</i>	Drag Force
<i>CL</i>	Lift Coefficient
<i>CD</i>	Drag Coefficient
<i>h</i>	Ground Clearance
<i>c</i>	Cord Length
<i>AOA</i>	Angle of Attack
<i>WIG</i>	Wing in Ground
ρ	Density
μ	Dynamic Viscosity

<i>t</i>	Time
\vec{v}	Velocity Vector
\vec{S}	Source Term
\vec{T}	Stress Tensor
ϕ	Scalar Quantity
\vec{q}	Scalar Flux Vector
<i>SBIC</i>	Second and Blending Interpolation Combined
Γ	Diffusivity Coefficient
I^c	Convection Flux
I^D	Diffusion Flux
δv	Cell Volume
<i>F</i>	Mass Flux
<i>A</i>	Cell Face Area
\bar{x}	Normalized Coordinate
\mathcal{K}	SBIC Parameter
<i>a</i>	convection-diffusion coefficient
<i>Ca</i>	Camber
<i>P</i>	Pressure

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<i>ANN</i>	Artificial Neural Network
<i>gbest</i>	Global Best Position
<i>pbest</i>	Particle best Position
<i>2D</i>	Two Dimension
ω	weighting function
<i>R</i>	random function
<i>s</i>	Position of Particle
<i>m</i>	Iteration Number
<i>dv</i>	Displacement due to new Velocity
<i>Re</i>	Reynolds Number
<i>SIMP</i>	Semi-Implicit Method For Pressure –
<i>LE</i>	Linked Equation
S'_ϕ	Source Term from non-orthogonality, numerical dissipation terms and external sources

Introduction

Ground effect vehicles which operate close to the ground by the use of aerodynamic interaction between the wings and the surface known as ground effect, have been the center of researchers' attention for a long time since 1995 [1-13]. The interaction enhances the lift and decreases the drag considerably as compared to an out of ground effect vehicle. Thus, the aerodynamic enhancement promotes the efficiency of the ground effect vehicles against other transportation systems. Therefore, aerodynamicists have sought to make use of some approaches amplifying the device efficiency. One of these approaches is aerodynamic shape optimization based on computational fluid dynamics (CFD). The optimal design of WIG airfoils has been studied by only a few researchers, whereas most of them have focused on the shape geometries. Kim and Joh [14] have obtained the optimized airfoil shape by using the single-objective optimization technology; and Kim and Chun [15] have also performed computational optimization for an airfoil geometry. More recently, Park and Lee [16] have numerically performed an optimization by considering the lift coefficient, static height stability, and lift-to-drag ratio as objective functions and optimized the airfoil structure by a multi-objective optimization algorithm. Furthermore, the optimization of wing in ground effect has been performed by Lee and Lee [17] and in parallel, finding the optimum shape using multi-objective genetic algorithm and the analysis of the three-dimensional wings in ground effect have been carried out by Lee et al. [18, 19]. Another optimization design of an airfoil which moves close to the ground has been investigated by Kim et al. [20], taking into account the device shape based on lift coefficient maximization. In 2013, an aerodynamic shape optimization of WIG vehicle was conducted by three objective functions, lift coefficient, the aerodynamic center of height, and the lift-to-drag ratio [21].

As a result of literature study, these types of designs impose high costs and lose the WIG vehicle advantages while finding the best wing for WIG vehicles remains a great challenge among the researchers. At present, most of the WIG vehicles utilize predefined static conditions such as angle of attack and ground clearance. Besides, these parameters play a central role in the device efficiency and they are irrefutable variables in the aerodynamic optimization of WIG vehicles which were neglected in the most previous studies.

The aim of the current study is to optimize the shape and static conditions of a sectional wing, moving near the ground. Aiming to achieve this goal, a highly accurate numerical simulation method and response surface methodology (RSM) are designed and the Adaptive Neuro-Fuzzy Interface System (ANFIS) is employed in order to damp the noise and find the design point perfectly near the global optimum. The influence of design variables, ground clearance, incidence angle, thickness and camber of the foil, have been initially investigated by a high resolution Normalized Variable Diagram (NVD) scheme, used in the boundedness criteria. In the optimization process, lift to drag ratio (L/D) is considered as the objective function and the design variables consist of thickness and camber of airfoil, angle of attack and ground clearance. Subsequently, sensitivity analysis is done and the amount of objective function allergy from design variables is also explored.

Governing Equation and Discretization

The basic equations, which describe conservation of mass, momentum and scalar quantities can be expressed in the following vector form which is independent from the coordinate system.

$$\frac{\delta \rho}{\delta t} + \text{div}(\rho \vec{V}) = S_m \quad (1)$$

$$\frac{\delta(\rho \vec{V})}{\delta t} + \text{div}(\rho \vec{V} \otimes \vec{V} - \vec{T}) = \vec{S}_v \quad (2)$$

$$\frac{\delta(\rho \phi)}{\delta t} + \text{div}(\rho \vec{V} \phi - \vec{q}) = \vec{S}_\phi \quad (3)$$

The stress tensor and scalar flux vector are usually expressed in terms of basic dependent variables. The stress tensor for a Newtonian fluid is:

$$\vec{T} = -P\vec{I} \quad (4)$$

and the Fourier-type law usually gives the scalar flux vector:

$$\vec{q} = \Gamma_\phi \text{grad} \phi \quad (5)$$

In this study, $k - \epsilon$ model is used for turbulence flow. The model is simple and enjoys good stability with easy convergence.

The discretization of the differential equations is carried out using a finite-volume approach utilizing the Gaussian theorem. The discrete expressions are presented to refer to only one face of the control volume, namely, e , for the sake of brevity. For any ϕ variable (which may also stand for the velocity components), the result of the integration yields:

$$\frac{\delta v}{\delta t} [(\rho\phi)_p^{n+1} - (\rho\phi)_p^n] + I_e - I_w + I_n - I_s = S_\phi \delta v \quad (6)$$

Where I 's are the combined cell-face convection I^c and diffusion I^D fluxes. The diffusion flux is approximated by central differences. The discretization of the convective flux requires special attention and it helps developing the various schemes. A representation of the convective flux for cell-face (e) is:

$$I_e^c = (\rho \cdot V \cdot A)_e \phi_e = F_e \phi_e \quad (7)$$

The value of ϕ_e is not known and it should be estimated from the values at neighboring grid points by interpolation. The expression for ϕ_e is determined by the SBIC scheme [22], that is based on the NVD technique [23] using interpolation from the nodes E, P and W. The functional relationship utilized in SBIC scheme for $\bar{\phi}_e$ is given as:

$$\begin{aligned} \bar{\phi}_e &= \bar{\phi}_p, \quad IF \bar{\phi}_p \notin [0, 1] \\ \bar{\phi}_e &= -\frac{\bar{x}_p - \bar{x}_e}{\mathcal{K}(\bar{x}_p - 1)} \bar{\phi}_p^2 + \left(1 + \frac{\bar{x}_p - \bar{x}_e}{\mathcal{K}(\bar{x}_p - 1)}\right) \bar{\phi}_p, \\ IF \bar{\phi}_p &\in [0, \mathcal{K}] \\ \bar{\phi}_e &= \frac{\bar{x}_p - \bar{x}_e}{\bar{x}_p - 1} + \frac{\bar{x}_p - \bar{x}_e}{\bar{x}_p - 1} \bar{\phi}_p, \\ IF \bar{\phi}_p &\in [\mathcal{K}, 1] \end{aligned} \quad (8)$$

Where

$$\begin{aligned} \bar{\phi}_p &= \frac{\phi_p - \phi_W}{\phi_E - \phi_W}, & \bar{\phi}_e &= \frac{\phi_e - \phi_W}{\phi_E - \phi_W} \\ \bar{x}_p &= \frac{x_p - x_W}{x_E - x_W}, & \bar{\phi}_e &= \frac{x_e - x_W}{x_E - x_W} \end{aligned} \quad (9)$$

The limits on the selection of \mathcal{K} could be determined in the following way. Obviously, the lower limit is $\mathcal{K} = 0$, which would represent switching between upwind and central differencing. It is not favorable, because it is essential to avoid the abrupt switching between the schemes in order to achieve the converged solution. The value of \mathcal{K} should be kept as low as possible in order to attain the maximum resolution of the scheme. The final form of the discretized equation from each approximation is given as:

$$a_p \cdot \phi_p = \sum_{m=E,W,N,S} a_m \cdot \phi_m + S'_\phi + S_{dc} \quad (10)$$

Where a 's are the convection-diffusion coefficients. The term S'_ϕ in Eq. (10) contains quantities arising from non-orthogonality, numerical

dissipation terms and external sources. For the momentum equations, it is easy to separate the pressure-gradient source from the convection momentum fluxes. S_{dc} is the contribution due to the adapted deferred correction procedure.

RSM Algorithm

This approach is an approximation-based optimization method which is capable of finding good solutions for intricate engineering optimization problems by computing specific values of the objective function for different combinations of the design variables [24, 25]. Indeed, this method has been successfully applied for solving complex engineering problems [26-28]. The main argument to all these problems is the fact that inherent merit functions generally involve both intensive and expensive numerical or experimental tests. However, the number of tests required for the optimization process should be minimized. This method consists of numerical methods in which all design variables are discretized either according to a simple parametric scheme or using a given numerical planning, such as factorial design, orthogonal design, or central composite design [29]. After acquiring data, it is necessary to fit a mathematical equation to describe the behavior of the response according to the levels of values studied. The importance of adopted fitting model is in using an accurate method, Adaptive Neuro-Fuzzy Interface System (ANFIS) [30]. Once the surface response is available, conventional optimization techniques, such as gradient-based techniques or global optimization techniques, may be applied to estimate the function optimal point by searching in the constructed surface. In the present study, active-set methodology is employed to find the optimal point and KKT (Karush-Kuhn-Tucker) condition. Also Quasi-Newton algorithms are utilized. The accuracy of the obtained optimal value naturally depends on the selected design and the adopted fitting model [30]. The remaining steps of the RSM-based optimization methodology are aimed to improve the quality of the obtained optimal solutions. Additional numerical tests are performed in order to acquire additional response surfaces until a convergence criterion is satisfied. If the difference between the optimum values obtained from the surface response and the values obtained via the numerical simulation reaches a given threshold, the optimization process is stopped. The flowchart of the process is depicted in Fig. 1.

The objective function for maximizing the lift to drag ratio and design variables, being considered here, consist of the thickness (t/c), camber (Ca/c) of wing section, angle of attack (AOA), and distance from the ground (h/c). The study of the related bibliography allows the designer to define the following interest area: $[t/c_{min}-t/c_{max}][Ca/c_{min}-Ca/c_{max}][AOA_{min}-$

$AOA_{max}][h/c_{min}-h/c_{max}]=[0.09-0.15][0-0.04][2.5-7.5][0.1-0.8]$. A balanced multilevel design is primarily matriculated with 3 levels for each factor and the numerical simulation is performed for all levels.

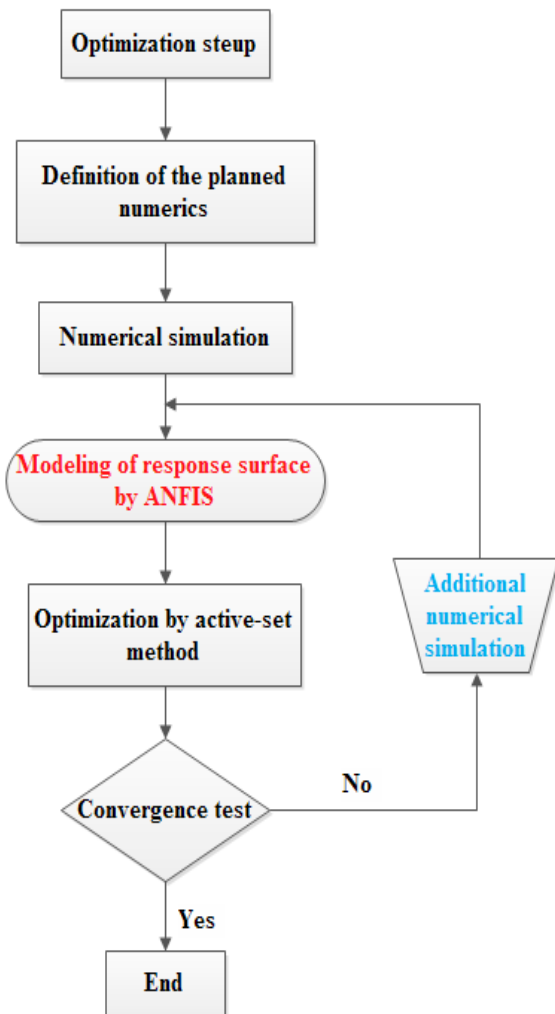


Figure 1. Flow chart of RSM method

Results and Discussion

Grid generation and validation

In the numerical simulation, grid and domain independency and comparison of the current result with the published results data should be investigated. The grid structure that is used in CFD simulation is created by a structured mesh employed because of its simplicity and applicability to the current flow configuration (i.e., with a near-by ground). Schematic shape of these two-dimensional structured grids is illustrated in Fig. 2(a). According to Fig. 2(b), the dimension of domain has been obtained after doing several various lengths for b, f, u and independent lengths have been chosen.

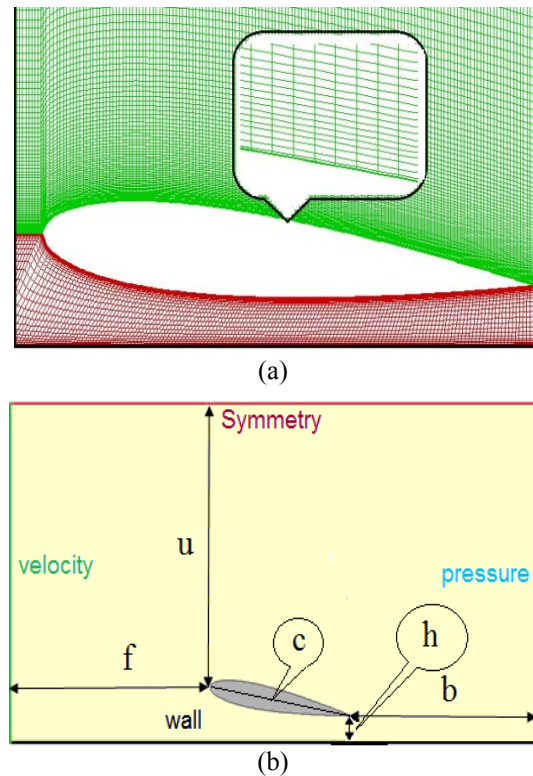


Figure 2. (a) H grid topology and H grid. (b) Dimension and boundary condition of 2D domain

The grid sizing is determined after grid independence which is found by doing several different trials which illustrate the surface pressure coefficient distribution. For example, the effect of grid size is exposed in Fig. 3. For other cases, the above process is utilized for grid and domain independences. The setting of numerical simulation are shown in Table 1. The Reynolds number in this study is 2.4×10^5 .

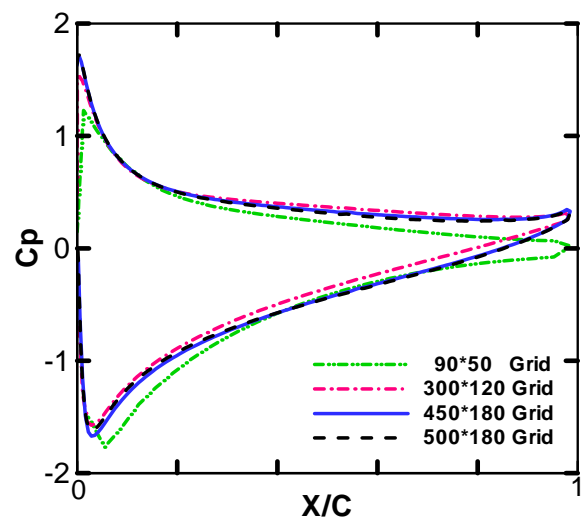


Figure 3. Effect of grid sizing on pressure distribution on the surface of the airfoil for 10° and $h/c=0.2$ angle of attack

Table 1. Settings for Numerical Simulation.

Flow	turbulent
Solver	2D Double Precision
Momentum Equation Solver	Normalize variable diagram
Algorithm	SIMPLE
turbulent model	$k - \epsilon$
Bounded scheme	SBIC

In Fig. 4, the pressure distribution on the surface of NACA0015 airfoil moving near the ground is indicated and validated with experimental data [1]. Figs. 5.a and 5.b demonstrate the velocity profile behind the airfoil at $x/c=0.5$ and $x/c=1$ from trailing edge for $AOA=5^\circ$ and $h/c=0.1$, then these results are compared with the experimental data [1]. These comparisons prove the numerical results are in a good argument with experimental data.

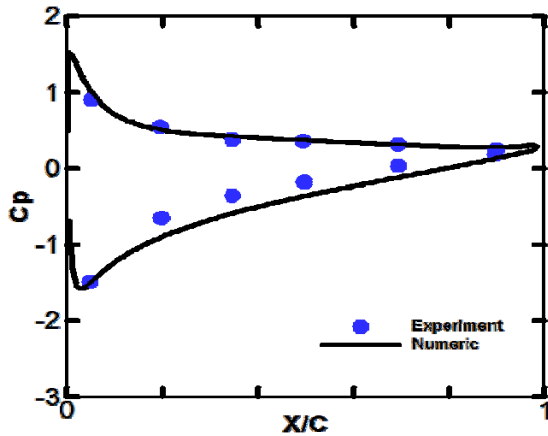


Figure 4. Comparison between the present numerical results with experimental data, (a) Pressure coefficient distribution for airfoil NACA 0015 for an AOA 10° and $h/c=0.2$,

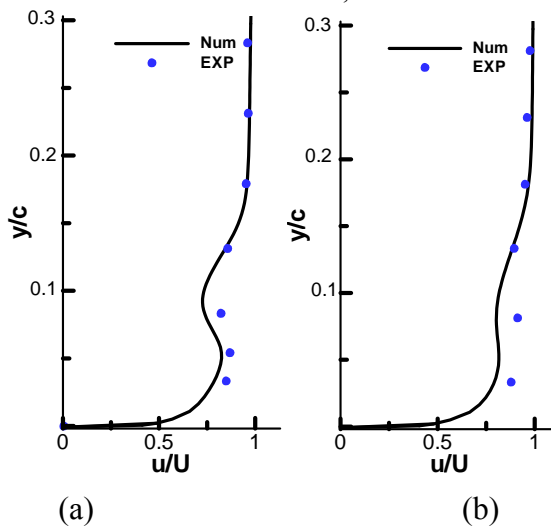


Figure 5. Distributions of mean velocity in the wake region of the airfoil for $AOA=5^\circ$, $h/c=0.1$ (a) $x/c=0.5$ and (b) $x/c=1$

Subsequently, Table 2 draws an analogy between the lift and drag coefficients for the present numerical results and the experimental data [1] and it can be concluded that the numerical results are highly congruent with the experimental data. It is noteworthy that the difference between drag coefficients from the numerical simulation and the experiment data is attributed to the airfoil configuration near the ground, turbulent models and the amount of uncertainty in the experimental procedures. Furthermore, the same behaviors are observed in some related publication such as [32], where all of cases in this research are under the same conditions.

Table 2. Comparison of the experimental and current numerical aerodynamic coefficients of airfoil NACA 0015 at $AOA=2.5^\circ$.

		CL	CD
h/c=0.1	Experimental data	0.370	0.0112
	Numerical data	0.368	0.0178
h/c=0.5	Experimental data	0.297	0.0115
	Numerical data	0.275	0.0220
h/c=0.8	Experimental data	0.261	0.0118
	Numerical data	0.265	0.0230

Numerical simulation results

In this research, the effect of the camber and thickness of the airfoil have been numerically investigated in ground proximately for different angles of attack and ground clearances. However, the lift and drag coefficients and lift to drag ratio have been initially analyzed at 3 levels for each factor with special angles of attack: 2.5° , 5° and 7.5° degrees. Moreover, the ground clearance in this study is fallen into 3 main categories: $h/c=0.1$, 0.5 and 0.8 . Besides, to attain the best airfoil in the present condition, the camber and thickness of airfoils were to be taken into consideration; therefore, a broad range of them have been designated and both of these parameters have been divided into 3 segments. The aerodynamic characteristics of these five different 2D airfoils have been initially examined according to the assumed cambers and thicknesses. Tables 3(a)-(e) represent the lift and drag coefficients and L/D in the variant angles of attack as varying ground clearances. In fact, the tables demonstrate some significant trends; for instance, the lift has an upward trend for all cases when the airfoils closely approach the ground. In almost all of the cases, the lift coefficients are dramatically risen by a gradual growth of the camber contrast a slight drop of the thickness. Actually, this behavior lays emphasis on the flow blockage, which has happened.

Furthermore, drag has the same trend with lift when the ground clearance is slightly changed; while this behavior is in agreement with the experimental data [9,11]. On the other hand, this

simulation confirms that the drag coefficient in thin airfoils is reduced consistently down from AOA= 2.5° to 5°, after that there is a tendency to rise and the drag tends upward to AOA=7.5°.

Table 3. Lift and drag coefficients of the mentioned airfoils

h/c AOA (deg)	0.1		0.5		0.8	
	CL	CD	CL	CD	CL	CD
2.5°	0.322	0.0123	0.312	0.0130	0.298	0.0142
5°	0.680	0.0192	0.556	0.0222	0.539	0.0224
7.5°	0.890	0.0398	0.775	0.0390	0.753	0.0405

(a) $t/c=0.09$

h/c AOA(deg)	0.1		0.5		0.8	
	CL	CD	CL	CD	CL	CD
2.5°	0.315	0.0140	0.308	0.0175	0.295	0.0180
5°	0.645	0.0220	0.555	0.0230	0.535	0.0256
7.5°	0.860	0.0350	0.765	0.0380	0.743	0.0395

(b) $t/c=0.12$

h/c AOA(deg)	0.1		0.5		0.8	
	CL	CD	CL	CD	CL	CD
2.5°	0.368	0.0178	0.275	0.0220	0.265	0.0230
5°	0.600	0.0230	0.550	0.0235	0.520	0.0290
7.5°	0.803	0.0335	0.740	0.0340	0.730	0.0380

$t/c=0.15$

h/c AOA(deg)	0.1		0.5		0.8	
	CL	CD	CL	CD	CL	CD
2.5°	0.545	0.0182	0.446	0.0265	0.429	0.0280
5°	0.777	0.0271	0.683	0.0289	0.661	0.0324
7.5°	0.987	0.0353	0.890	0.0402	0.880	0.0450

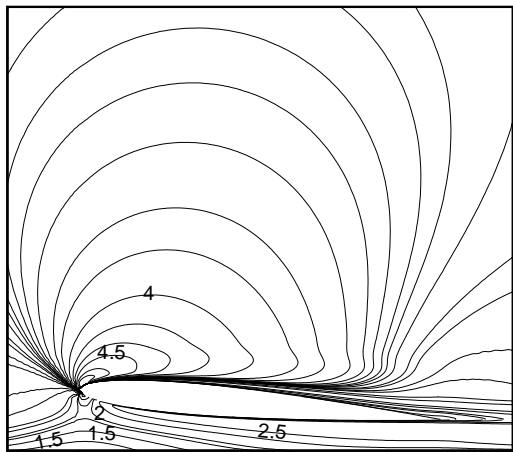
(c) $Ca/c=0.02$

h/c AOA(deg)	0.1		0.5		0.8	
	CL	CD	CL	CD	CL	CD
2.5°	0.710	0.0280	0.665	0.0285	0.636	0.0295
5°	0.970	0.0340	0.860	0.0350	0.825	0.0360
7.5°	1.110	0.0450	1.051	0.0470	1.017	0.0500

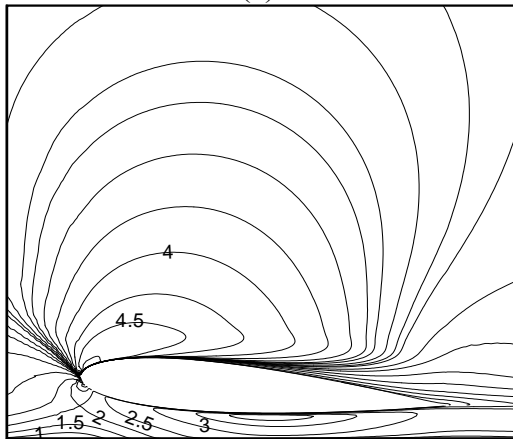
(d) $Ca/c=0.04$

It can be clearly seen that the lift coefficient is sharply grown when h/c is slightly decreased, as other parameters (camber, thickness, AOA) remained unchanged; the reverse behavior is also observed in the drag coefficient. Likewise, these trends are true when the thickness is gently lowered; while the reasons for these behaviors can be explained by the contour of velocity around the airfoils for different thicknesses, which are depicted in Figs. 6(a) and (b), respectively. These figures show that the increase of thickness obviously leads to the

formation of convergent-divergent passage between the airfoil and ground; consequently, it plays a significant role in the growth of velocity in the mentioned zone (Fig.7) and it is an irrefutable proof for pressure disturbance changes on the airfoil surfaces. Actually, the thickness reduction drastically enhances the pressure along the lower surface of airfoil and affects the pressure along the upper surface as demonstrated in Fig. 8. It can be concluded that the airfoil under the mentioned conditions causes flow blockage.



(a)



(b)

Figure 6. Counter of velocity around the airfoil at (a) $t/c=0.09$, (b) $t/c=0.15$ and $AOA=7.5^\circ$ and $h/c=0.1$

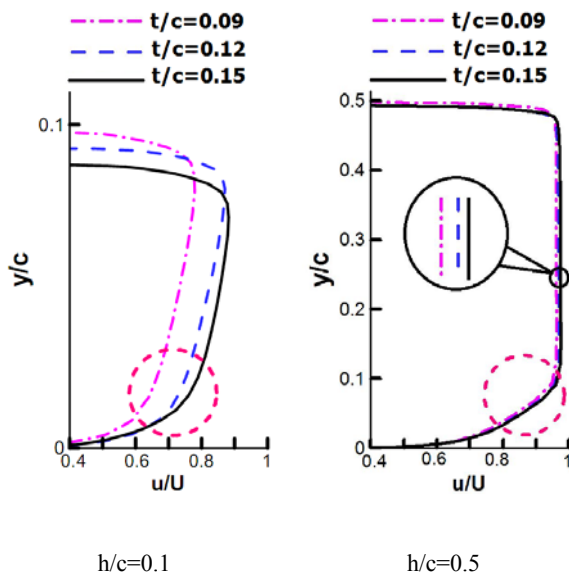


Figure 7. Velocity profiles between the airfoils and ground surfaces for various thickness values and $AOA=5^\circ$.

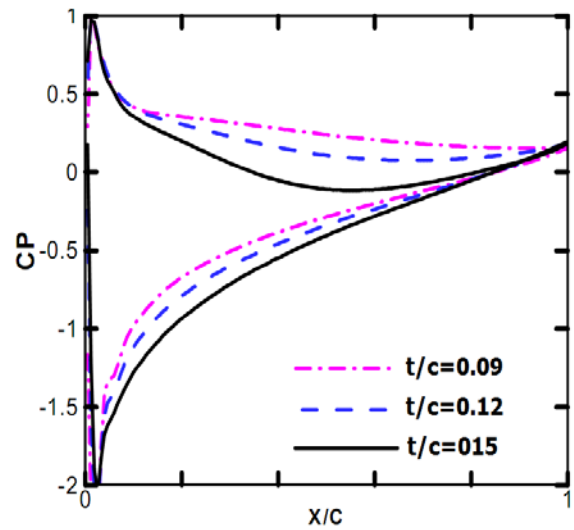


Figure 8. Pressure coefficient distribution on the surface of the airfoils for different thickness at $AOA=5^\circ$ and $h/c=0.1$

However, the L/D is marginally dropped in the close proximity of the ground while the camber of airfoil is consistently risen; but in the high ground clearance, the L/D is dramatically risen, until it reaches a plateau and then there is a plunge, as shown in Fig.9. The trends are rooted in the air blockage in the area between the ground and the sectional wing surfaces; when the camber of airfoil is grown and the wing comes closer to the ground, the flow blockage would be so strong. Therefore, the thickness of the boundary layer in this area would be pressed and the lift coefficient is sharply grown (Fig.10). Nonetheless, the effect of air blockage decreases when the airfoil goes up.

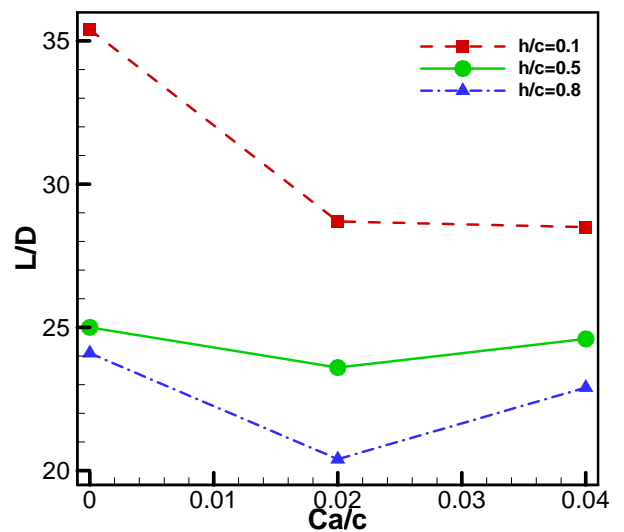


Figure 9. Behavior of L/D as varying camber (ca/c) and h/c for the airfoils under study.

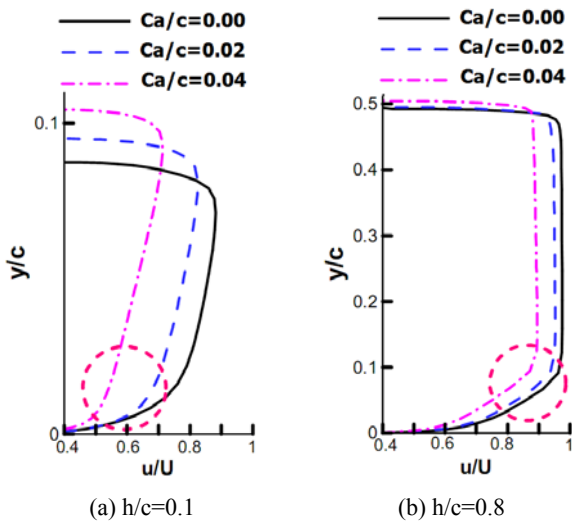


Figure 10. Velocity profile in the area between the airfoil and ground surfaces for different camber values and AOA=5°.

Hence, pressure coefficient distributions along the upper and lower surfaces of airfoils are illustrated in Fig.11 with various cambers, in both low and high ground clearances. The difference of pressure between the upper and lower surfaces is increased. Nevertheless, it is noteworthy that the pressure differences between the two surfaces are enormously changed in the lower ground clearance, as can be found by the comparison between Figs. 11(a) and (b). Consequently, the lift coefficients in low h/c are significantly greater than in high h/c. In contrast, the drag coefficients have the reverse trend and they are slightly reduced while the moving airfoil approaches the ground. On the other hand, the lift and drag coefficients have a noticeable growth by the increasing camber; but the percentage of their growth is various. As a result, the behavior of L/D is not simplistic and easily predictable when other parameters (camber, thickness, AOA, h/c) are changed.

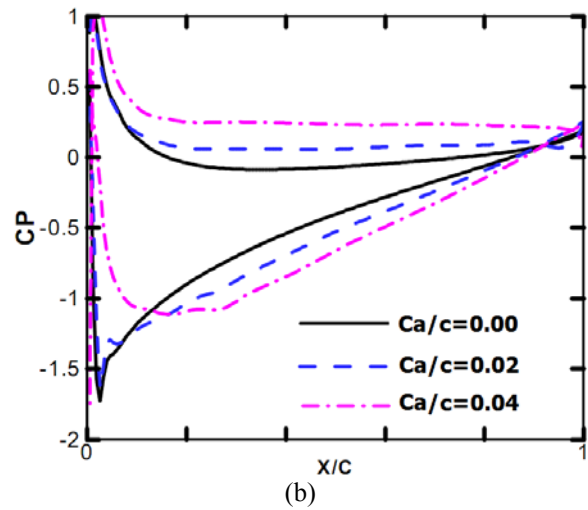
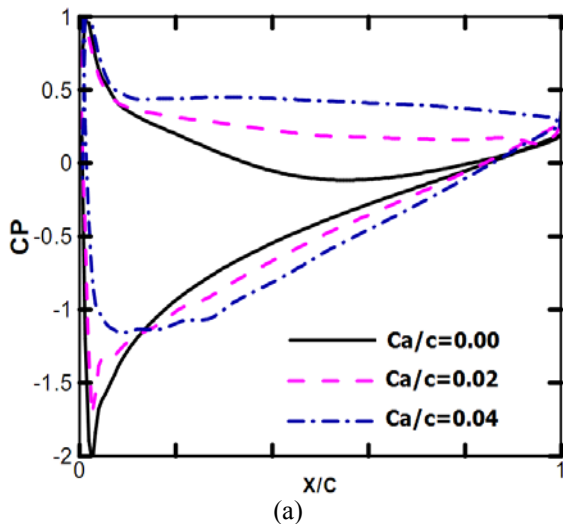


Figure 11. Pressure coefficient distribution on the surface of the airfoils for different cambers at AOA 5° (a) h/c=0.1, (b) h/c=0.8

As a result of the numerical simulations and above discussions, the combination of the wing shape and static conditions compounds the matter of improving the performance. Actually, their relationship is nonlinear and unpredictable; this also sets out some powerful arguments that both wing shape and static conditions should be simultaneously deliberated in the WIG studies, especially in the optimization process. This is a clear illustration of the importance of using a strong and accurate optimization method.

Optimization results

High L/D provides a net gain in economic efficiency; hence, this is one of the principal design parameters of the WIG craft. Numerical simulation makes a case for general influences of four parameters (camber, thickness, AOA, h/c) on the objective function (L/D); therefore, to find the optimum shape and condition, it is needed to go into great details. In this paper, RSM method is applied and response surface is achieved according to the numerical simulation. The data in table 2 is used to build initial response surfaces in terms of the aerodynamic coefficients and the ANFIS approach sets out some powerful rules, which will form the searching space accurately [30].

Anyway, an approximation of the optimal L/D value (η_{app}) is obtained using the active set method, which finds the global maximizer of the constructed surfaces. For the design parameters (i.e., t/c, Ca/c, h/c and AOA) yielding η_{app} , an additional numerical simulation is conducted to get η_{num} , which is compared to η_{app} . The convergence criterion in Eq. (11) decides if a new response surface is needed or not:

$$\varepsilon = \left| \frac{\eta_{num} - \eta_{app}}{\eta_{app}} \right| < 10\% \quad (11)$$

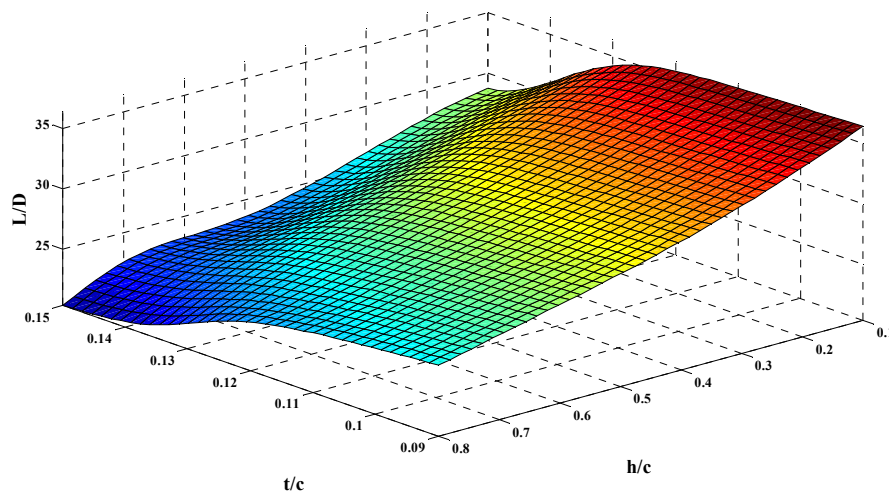
In case a new surface is required, the interest region is systematically decreased and additional experiments are considered around the latest point found for the evaluation of η_{app} (Fig. 1). In this study, only three additional surfaces have been constructed until convergence is reached. Fig. 12 demonstrates the three response surfaces attained at the last optimization level with a final interest region range. Moreover, table 4 summarizes the main numerical results obtained during the whole optimization process. Finally, the best combination of

design parameters corresponds to the aim, obtaining the maximum value of η .

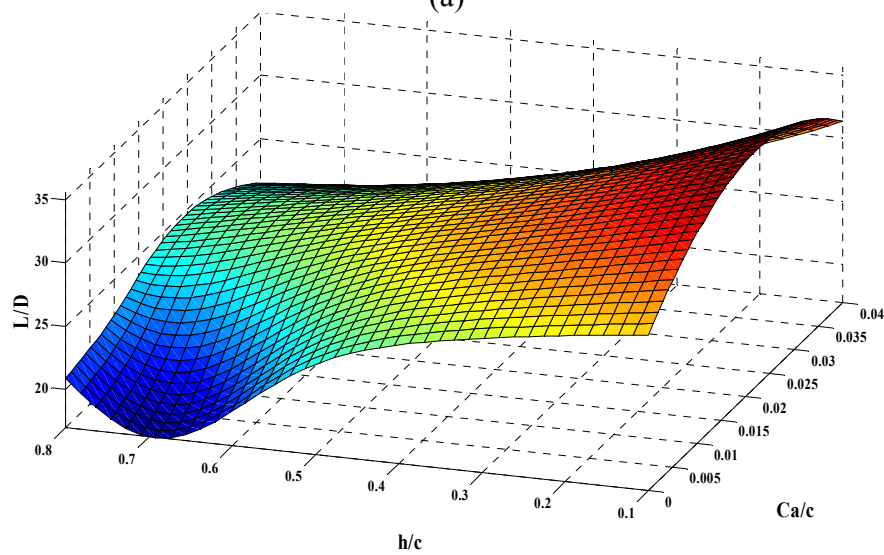
Pursuant to the following sentences, the best shape characteristics of moving airfoil and static conditions are obtained by RSM, and the optimization results are presented in Table 4. According to the results, the best moving airfoil should have 3.26% camber and 9.0% thickness; moreover, the optimum sectional wing should be also approximately 0.1 close to the ground and the best angle of attack is attained as over 7.5°.

Table 4. Optimum evolution through the optimization process

iteration	Ca/c	t/c	h/c	AOA	L/D(Numeric)	L/D(Optimized)	error
1	0.0000	0.090	0.1	5.54	32.57	37.12	0.14
2	0.0330	0.092	0.76	7.35	36.96	41.45	0.12
3	0.0326	0.090	0.1	7.5	42.01	45.82	0.09



(a)



(b)

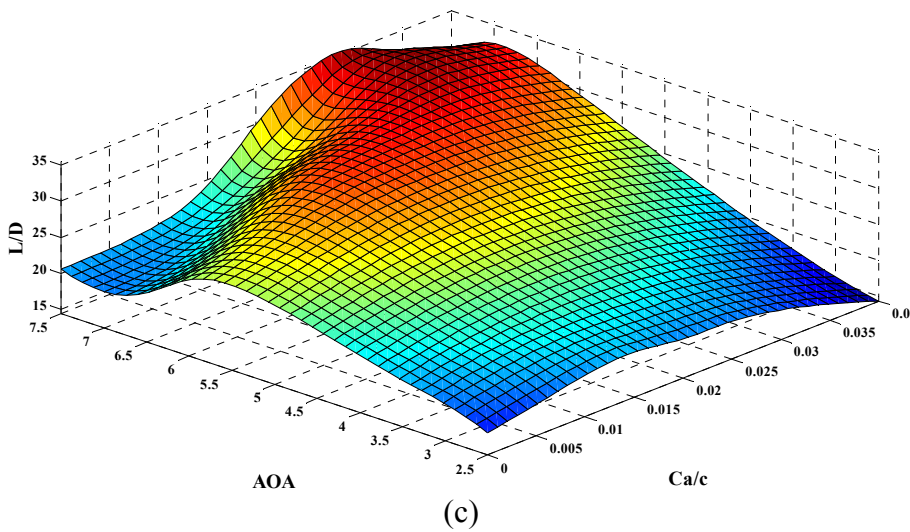


Figure 12. Approximated response surfaces at the third optimization level

Furthermore, the sensitivity of design variables is computed based on the aerodynamic forces and their amount of sensitivity is depicted in Fig.13. The comparison of them explains that the lift and drag coefficients deeply depend on the angle of attack and camber from among the static conditions and wing shape parameters, respectively. Moreover, thickness of the airfoil does not have a significant effect on the forces; but the camber can influence them, especially the lift force. As it can be seen, the angle of attack has impressed all of the aerodynamic coefficients sharply, compared with the other effective parameters; moreover, it has dramatically influenced the CD, too. On the other hand, the ground clearance has nearly the same effect on the drag and lift forces. Consequently, it can be said that some parameters are most impressive in the design of WIG wings and this analysis proves the fact that static conditions are very important in their optimization. Hence, the best optimum wing would be discovered when considering both shape parameters and static conditions.

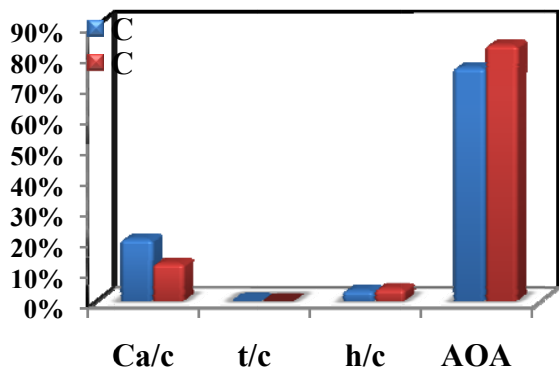


Figure 13. Amount of sensitivity of the design variables on the aerodynamic coefficients.

Conclusion

The aim of this study was to optimize the shape parameters and static conditions of a sectional wing moving close to the ground using a high order numerical procedure and response surface method (RSM). In the numerical simulation, Normalized Variable Diagram (NVD) scheme was applied in the boundedness criteria. Moreover, the lift to drag ratio (L/D) was considered as an objective function and static conditions (ground clearance and angle of attack) and shape parameters (thickness and camber of wing) were noticeable to be considered as design variables. Adaptive Neuro-Fuzzy Interface System (ANFIS) was employed to generate the surface response and the amount of sensitivity of the objective function from design variables was explored. The results demonstrated that the best moving airfoil should have 3/26% camber and 9/0% thickness; moreover, the optimum sectional wing should be also approximately 0.1 close to the ground and the best angle of attack was attained as over 7.5°. Moreover, the thickness of airfoil did not have a significant role on the forces; but the camber can influence them, especially the lift force. The angle of attack impressed all of the aerodynamic coefficients sharply, compared with other effective parameters; moreover, it dramatically influenced the CD, too. On the other hand, the ground clearance had about the same effect on the drag and lift forces. Consequently, it can be concluded that some parameters are most impressive in the design of WIG wings and this analysis proves this fact that static conditions are very important in their optimization. Hence the best optimum wing would be discovered when considering both shape parameters and static conditions.

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