Australian Journal of Basic and Applied Sciences, 8(17) November 2014, Pages: 476-482

AENSI Journals

Australian Journal of Basic and Applied Sciences

ISSN:1991-8178

Journal home page: www.ajbasweb.com

Design Optimization of Airfoil and Its Validation Using Wind Tunnel

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ARTICLE INFO

Article history:
Received 25 August 2014
Received in revised form
19 September 2014
Accepted 29 October 2014
Available online 16 November 2014

Keywords:
Design Optimization, Parametric Section, Panel Method, PSO, Wind Tunnel.

ABSTRACT

Background: Aerodynamic shape optimization has become a vital part of aircraft design in the recent years. Generally we have to describe the airfoil with least hundred points of x and y co-ordinates. It is really difficult to optimize airfoils with this large number of co-ordinates. Many different schemes of parameter sets are used to describe general airfoil such as B-spline, Hicks- Henne Bump function, PARSEC etc. **Objective:** The main goal of these parameterization schemes is to reduce the number of needed parameters as few as possible while controlling the important aerodynamic features effectively. The objective of this work is to introduce the knowledge of describing general airfoil using twelve parameters by representing its shape as a polynomial function by using PARSEC method. We have used the concept of Particle Swarm optimization (PSO) Algorithm to optimize the aerodynamic characteristics of a general airfoil. **Results:** This algorithm has been tested for standard NACA 2411 airfoil and optimized to improve its coefficient of lift for 5.0 deg angle of attack. Pressure distribution and co-efficient of lift for the airfoil geometry has been calculated using panel method. **Conclusion:** The optimized airfoil has the improved co-efficient of lift and it is validated using wind tunnel data.

To Cite This Article: R. Mukesh and Dr. K. Lingadurai, Design Optimization of Airfoil and Its Validation Using Wind Tunnel. ***Aust. J. Basic & Appl. Sci.,*** *8(17): 476-482, 2014*

INTRODUCTION

The computational resources and time required to solve a given problem have always been a problem for engineers for a long time though a sufficient amount of growth is achieved in the computational power in the last thirty years. This becomes more complicated to deal with when the given problem is an optimization problem which requires huge amount of computational simulations. These kinds of problems have been one of the important problems to be addressed in the context of design optimization for quite some years. When the number of result(s) influencing variables are large in a given optimization problem, the required computational time per simulation increases automatically. This will severely influence the required computational resources to solve the given design optimization problem. Due to this reason, a need arises to describe a general geometry with minimum number of design variables. This leads to a search activity of finding some of the best parameterization methods. Nowadays various parameterization methods are employed: (a) Partial differential equation approach (time consuming and not suitable for multidisciplinary design optimization), (b) discrete points approach (number of design variables becomes large) and (c) polynomial approach (number of design parameters depends on the degree of the polynomial chosen and suitable for multidisciplinary design optimization) are the three basic approaches to describe the geometry of a general airfoil. Previous research works in design optimization suggest that the polynomial approach based parameterization schemes highly influences the final optimum design which is obtained as a result of the optimization (Balu, 2009). In this work, the Parametric Section (PARSEC) parameterization scheme is employed. The Panel method is used to compute the flow field around the airfoil geometry during the design optimization process. PSO Algorithm is employed to carry out the design optimization problem. The PARSEC parameterization scheme is coupled with PSO Algorithm to achieve the goal of getting the optimum airfoil shape of NACA 2411 airfoil. The results and issues faced during the whole design process in discussed in the following sections.

Parsec scheme:

PARSEC is a parameterization (Balu, 2009; Sobieczky, 1998; Mukesh, 2010) scheme which uses the unknown linear combination of base functions to express the shape of the airfoil. It uses twelve different

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geometrical characteristics of the airfoil to solve a system of linear equations by which it can express the airfoil geometry. The twelve geometrical characteristics of the airfoil serve as the design variables for the PARSEC approach. Twelve design variables are selected to have direct control over the shape of the airfoil. The twelve design variables are, Upper leading edge radius (Rleu), Lower leading edge radius (Rlel) , Upper crest point (Yup), Lower crest point (Ylo), Position of upper crest (Xup), Position of lower crest (Xlo) Upper crest curvature (YXXup), Lower crest curvature (YXXlo), Trailing edge offset (Toff), Trailing edge thickness (TTE), Trailing edge direction angle (αTE), Trailing edge wedge angle (βTE), as shown in Figure.1: Once the design variables are specified, the unknown coefficients a_i and b_i for i = 1... 6 can be obtained. Then the upper and lower surfaces of the airfoil can be expressed by the six-order polynomial Equations 1 and 2 respectively.

$$y_u = \sum_{j=1}^{6} a_i x^{i-(1/2)} \tag{1}$$

$$y_1 = \sum_{i=1}^{6} b_i\, x^{i-(1/2)} \tag{2}$$

Where y_u is the required y coordinate for the upper surface, y_l is the required y coordinate for the lower surface and a_i, b_i are the coefficients to be solved from the twelve design variables.

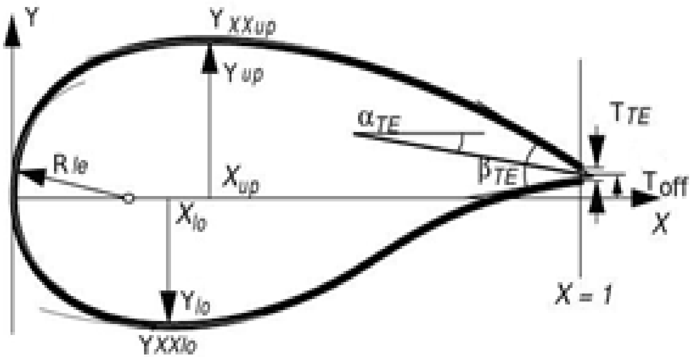

Fig. 1: Design variables for PARSEC.

Panel technique:

The Panel method is used to solve the potential equations without being computationally expensive. It provides more reasonably accurate results. These two properties make the panel method to be more suitable for design optimization problems where the number of simulations is incredibly large. Since the current problem deals with the incompressible subsonic flow region, this approach is employed in this work. The solution procedure for panel technique consists of discretizing the surface of the airfoil into straight line segments or panels and assuming the following conditions: (a) the source strength is constant over each panel but has a different value for each panel (b) the vortex strength is constant and equal over each panel [3,4,5]. The compressibility and the viscosity of air in the flow field are neglected. But it is required to satisfy the condition that the net viscosity of the flow should be such that the flow leaving the trailing edge is smooth. The curl of the velocity field is assumed to be zero. Hence,

$$\phi = \phi_\infty + \phi_s + \phi_v \tag{3}$$

Where, ø which is expressed as a summation of the free stream potential, source potential and vortex potential, is the total potential function. Except the free stream potential, the other potentials have potentially locally varying strengths. Figure.2 depicts the notations of the panel approach.

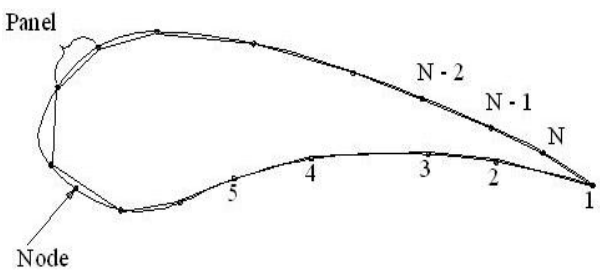

Fig. 2: Nodes and Panels.

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Particle swarm optimization:

The PSO, like a Genetic Algorithm, is a population based optimization technique, but the population is now called a swarm. It is used for searching global optimum. It ties to artificial life, like fish schooling or bird flocking, and has some common features of evolutionary computation such as fitness evaluation. The technique involves simulating social behavior (Kennedy, 1995; Eberhart, 1995; Xu, 2008; Khurana1, 2009) among individuals (particles) "flying" through a multidimensional search space, each particle representing a single intersection of all search dimensions. The particles evaluate their positions relative to a goal (Cl) at every iteration, and particles in a local neighborhood share memories of their "best" positions, then use those memories to adjust their own velocities, and thus subsequent positions. Thus the particles are adjusted toward the best individual experience (PBEST) and the best social experience (GBEST). However, PSO is unlike a GA in that each potential solution, particle is ‘‘flying" through hyperspace with a velocity. Moreover, the particles and the swarm have memory; in the population of the GA memory does not exist. Let $x_{j,d}(t)$ and $v_{j,d}(t)$ denote the d^{th} dimensional value of the vector of position and velocity of j^{th} particle in the swarm, respectively, at time t. The PSO model can be expressed as

$$v_{j,d}(t) = v_{j,d}(t-1) + c_1.\varphi_1.(x^*_{j,d} - x_{j,d}(t-1)) \quad + c_2.\varphi_2.(x^\#_d - x_{j,d}(t-1)), \tag{5}$$

$$x_{j,d}(t) = x_{j,d}(t-1) + v_{j,d}(t), \tag{6}$$

where (PBEST) denotes the best position of j^{th} particle up to time t-1 and (GBEST) denotes the best position of the whole swarm up to time t-1, $\varphi 1$ and $\varphi 2$ are random numbers, and c1 and c2 represent the individuality and sociality coefficients, respectively. The population size is first determined, and the velocity and position of each particle are initialized. Each particle moves according to (5) and (6), and the fitness is then calculated. Meanwhile, the best positions of each swarm and particles are recorded. Finally, as the stopping criterion (Max Cl) is satisfied, the best position of the swarm is the final solution. The flow chart of PSO is given in Figure 3.

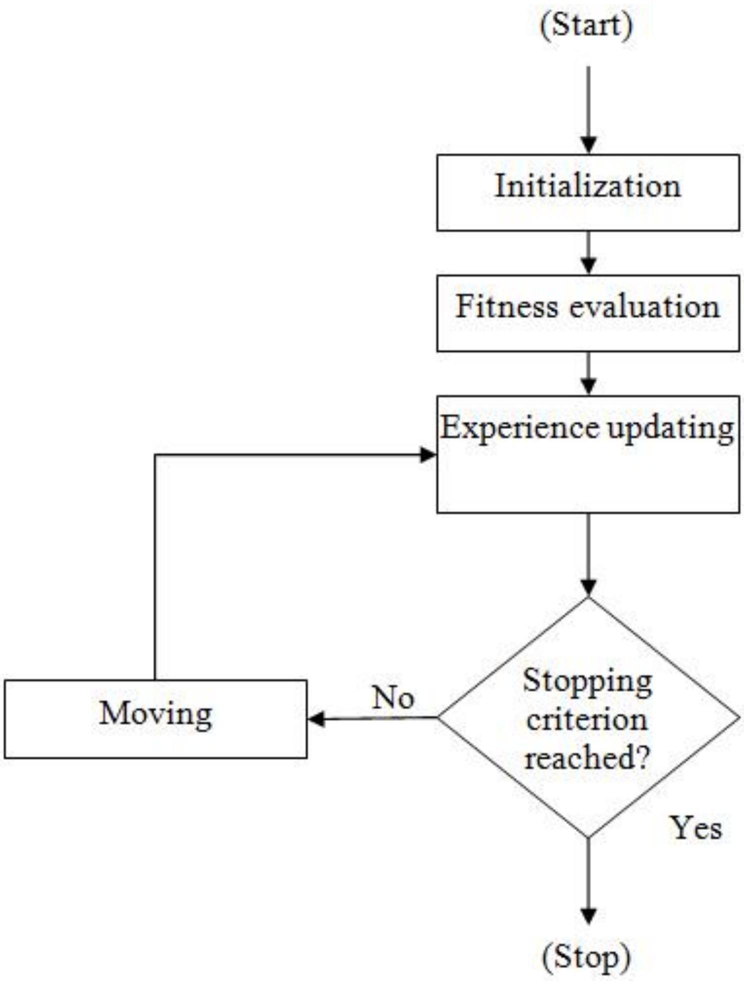

Fig. 3: Flow Chart of PSO.

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Optimization of naca 2411 airfoil:

The aerodynamic shape optimization (Balu, 2006; Krishnakumar, 1995) process is carried out with an intention of increasing the vertical aerodynamic force subject to aerodynamic and structural constraints. The structural constraints are implemented by fixing the values of trailing edge thickness and trailing edge offset parameters during the optimization in both the optimization schemes. These constraints are placed in order to avoid the optimizer to get converged at inefficient locations and to avoid getting unrealistic aerodynamic shapes. Since the panel method is only applicable for low speed flows, a flow constraint is placed to keep the assumptions valid throughout the whole optimization process. The flow constraint is implemented by fixing the angle of attack at 5.0 deg. For each design parameter a lower and upper bound values are defined. Each generation produced by the PSO algorithm have the best set of twelve PARSEC parameters. The corresponding airfoil profile is generated using PARSEC parameterization. Then the panel method is used to compute the flow around the airfoil at 5.0 deg angle of attack. From the pressure distribution, the lift coefficient is calculated. This new coefficient of lift is compared to the original one. The PSO algorithm in the end will lead to the best set of PARSEC parameters which will maximize the objective function within the search space. The design conditions, optimization objectives and constraints, which are used during the optimization process using PSO, are tabulated in Table 1.

Table 1: Optimization objective and constraints.

Angle of attack	5.0 deg
Geometric constraint	Max thickness must be less than 10% chord length
	Min thickness must be higher than 1% chord length
	T_{TE} and T_{off} the airfoil is zero
Aerodynamic constraint	Lift not less than original one
Objective	Maximize coefficient of lift
Population Size	24
Termination Condition	No Change in Cl for 500 iterations.

RESULTS AND DISCUSSIONS

The initial PARSEC parameters have been given approximately by specifying its lower and upper bound values. There is no need for specifying this accurately. The geometry of the airfoil expressed by the best twelve PARSEC parameters resulting from the PSO Algorithm exhibits a considerable increase in the coefficient of lift. The comparison between the original NACA 2411 airfoil and the optimized airfoils are indicated in Figure 4. The comparison of pressure distribution over the surface of the original NACA 2411 airfoil and the optimized airfoil is shown in Figure 5. Their corresponding PARSEC parameters and coefficient of lift are tabulated in Table 2 and Table 3 respectively.

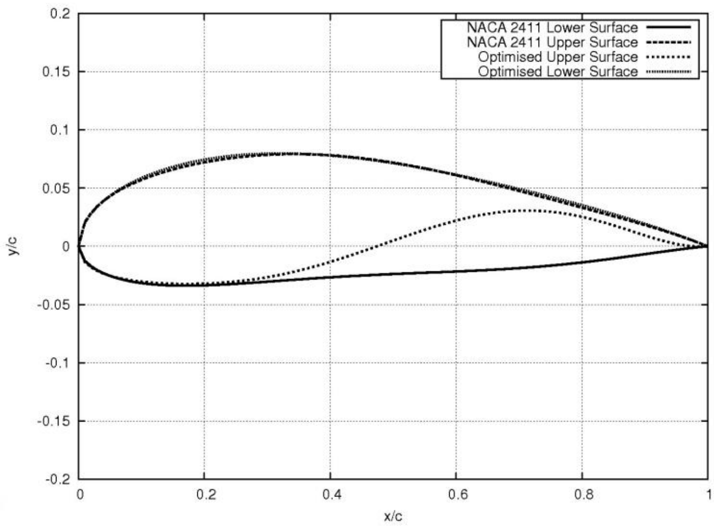

Fig.4: Original NACA 2411 airfoil Vs Optimized Airfoil.

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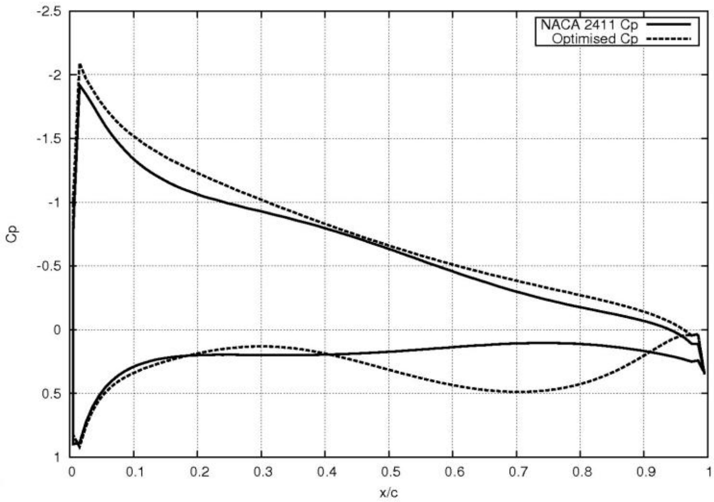

Fig. 5: Comparison of pressure distribution over the surface of original NACA 2411 airfoil and Optimized Airfoil.

Table 2: Optimized PARSEC parameters.

Parameter	Value original	Value optimized
(Rleu) Upper leading edge radius	0.0216	0.02015
(Rlel) Lower leading edge radius	0.008	0.00956
(Xup) Position of upper crest	0.3445	0.32033
(Yup) Upper crest point	0.07912	0.07973
(YXXup) Upper crest curvature	-0.6448	-0.63414
(Xlo) Position of lower crest	0.17	0.17371
(Ylo) Lower crest point	-0.033797	-0.03228
(YXXlo) Lower crest curvature	0.6748	0.67749
(TTE) Trailing edge thickness	0	0
(Toff) Trailing edge offset	0	0
(αTE) Trailing edge direction angle	-4.785	-4.7811
(βTE) Trailing edge wedge angle	15.082	15.0

Table 3: Original vs. Optimized Coefficient of Lift.

Angle of attack	$Cl_{original}$	$Cl_{optimized}$
5.0	0.8420	1.0352

Validation of optimized airfoil results using experimental method:

The optimized airfoil coordinates are given to the Ind – Lab Equipments which is an expertise in designing airfoils and wind tunnels. They manufactured the optimized airfoil and the airfoil test has been conducted in their premises itself. The newly manufactured airfoil is shown in Figure 6. The step by step procedure involved in testing the airfoil is given below.

The airfoil to be tested is placed in the test section of the wind tunnel. The test section of the wind tunnel is sealed carefully so that no atmospheric air enters in to the test section. The probes from the airfoil are connected to the respective tubes in the multitube manometer and the initial readings are taken accordingly. These denote the initial pressure acting on each point of the airfoil when the air velocity is nearly zero. Then the fan is switched on in order to activate the airflow in the wind tunnel. The thyristor is set to a particular load. The readings are taken under proper circumstances in which there are no flow disturbances or irregularities. The readings are taken from each manometer tube and the Pitot tube. The Pitot tube reading gives an insight into the dynamic and the static pressure inside the test section. The load is increased in the thyristor so as to increase the velocity of air in the wind tunnel and it is repeated for various velocities and the manometer readings are taken. Subtract each probe reading from its corresponding initial value to obtain the pressure difference in each point on the aerofoil. This gives the corrected manometer reading. The head difference is found out from the Pitot tube readings. The value of coefficient of pressure is calculated by dividing each probe value by its corresponding head difference. The probe difference value(h) is one and by numerically integrating the coefficient of pressure using the Simpson's one third rule it is possible to obtain the coefficient of lift for that particular velocity. The velocity, coefficient of Pressure and the coefficient of lift can be found out by using the equations 7, 8 and 9 respectively. The reference manometer reading at atmospheric pressure is given in Table 4. The manometer readings for different velocities are tabulated in the Table 5. The corrected manometer reading is given in the Table 6. The coefficient of pressure for the probes is provided in the Table 7. The coefficient of lift for subsonic velocity is tabulated in table 8.

$V = (\sqrt{2 \times \rho w \times g \times \Delta h}) / \rho a$ (7)

$Cp = H/\Delta h$ (8)

$C_L = h \{(y1 + y10) + 2 (y2 + \ldots + y9)\} / 3$ (9)

Fig. 6: Optimized Airfoil Manufactured in Ind-Lab.

Table 4: Manometer Reading at Atmospheric Pressure.

Reference Manometer Reading at Atmospheric Pressure x 10^{-2} m									
Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 6	Probe 7	Probe 8	Probe 9	Probe 10
20.2	20.5	20.5	20.6	20.6	20.7	20.8	20.8	20.8	20.9

Table 5: Velocity Vs Manometer Readings of the Probes.

S.No	Velocity m/sec	Pitot Readings			Manometer Reading x 10^{-2} m									
		h1	h2	Δh	1	2	3	4	5	6	7	8	9	10
1	25	3.6	3.1	0.5	57.9	43.0	38.2	34.0	31	20.3	26	15.6	24.2	16.2

Table 6: Corrected Manometer Readings (These readings can be formulated by subtracting the manometer readings from the values of reference manometer readings.)

S.No	Velocity m/sec	Pitot Readings			Corrected Manometer Reading x 10^{-2} m									
		h1	h2	Δh	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10
1	25	3.6	3.1	0.5	37.7	22.5	17.7	13.4	10.4	-0.4	5.2	-5.2	3.4	-4.7

Table 7: Coefficient of Pressure Readings at Various Probes.

S.No	Velocity m/sec	Pitot Readings			Coefficient of Pressure x 10^{-2} m									
		h1	h2	Δh	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10
1	25	3.6	3.1	0.5	75.4	45.0	35.4	26.8	20.8	-0.8	10.4	-10.4	6.8	-9.4

Table 8: Velocity Vs Coefficient of Lift.

Velocity in m/sec	Coefficient of Lift
25	1.113

Concluding remarks:

An aerodynamic shape optimization process is formulated and solved for NACA 2411 airfoil. The aerodynamic behavior of the optimized airfoil is validated by an experimental process. During the aerodynamic shape optimization process, the airfoil is described using the PARSEC parameterization scheme. The flow around the airfoil is solved using the linear vorticity surface panel method. The optimization is carried out using the Particle Swarm Optimization optimizer. The optimized airfoil is further manufactured and the flow around the optimized airfoil is observed experimentally in a subsonic wind tunnel.

Table 9: Computational vs. Experimental Results.

Angle of attack	$Cl_{Computational}$	$Cl_{Experimental}$
5.0	1.0352	1.113

The pressure distribution and lift-coefficient are calculated for 5.0 deg angle of attack and compared with the values obtained from the optimization process carried out by the PSO. From the calculated aerodynamic parameters, it is observed that the results produced by the PSO for the optimized airfoil during the optimization is close enough to the results obtained from the wind tunnel calculations. The computational Vs experimental results are tabulated in table 9 and from this table it is proven that the percentage of error between the computational and experimental results is in the order of 7%. It can be observed that the experimental results are quite closer to the computational results. Hence, it can be concluded that the aerodynamic shape optimization process which is followed in this paper is accurate enough to be employed during the initial phase of the aircraft design process. It can also be concluded that it can be used in further phases of the aircraft design if the panel solution algorithm is replaced by a high-fidelity solution algorithm.

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