NUMERICAL STUDIES ON HIGH PRESSURE RATIO AIRFOILS FOR AXIAL FLOW COMPRESSORS

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Abstract— The gas turbine engine manufacturers are looking for the efficient engines which can produce higher thrust, and having higher thrust to weight ratio. To achieve these goals, improvement in compressor blade design is essential. Therefore, the goal of the blade design is to achieve the desired flow turning with minimum losses, within the constraint of the blade rows. The new airfoil design include various parameterization, meshing, solving N-S computation and optimization techniques. A CDA airfoil section has been used as base airfoil and then parameterized by Bezier Parsec parameterization method. The optimization of parametric CDA cascade model is carried out by Genetic algorithm coupled with CFD. Parameterization and generation of new airfoil coordinates are made using the programme code prepared in Matlab. Numerical simulation have been carried out by CFD software GAMBIT and FLUENT. Matlab evaluates the airfoil and optimizes the airfoil using Genetic algorithms and checks the objective function in each iteration. The main objective is to get lower value of total pressure loss coefficient at higher pressure ratio without any flow separation. This would indicates that the airfoil section is capable of producing that pressure ratio without flow separation. This process is repeated till an optimum solution reached. The maximum pressure ratio attained by base airfoil was found out to be 1.4. The process was carried out for finding solutions for higher pressure ratios. The optimal solutions are obtained for higher pressure ratios up to 3.0.

Index Terms— Numerical Simulation, High Pressure Ratio Airfoils.

NOMENCLATURES

b	Bezier Parameter
c	Chord
y	Camber/Thickness
k	Curvature
p	Static Pressure
T	Static Temperature
Po	Stagnation Pressure
To	Stagnation Temperature
V	Velocity
U	Peripheral Velocity
C_D	Coefficient of Drag
ΔPo	Total Pressure Loss
r	Radius
β	Blade angle
θ	Camber angle

ω	Total Pressure Loss Coefficient
X_{cg} ,Y_{cg}	Center of Gravity of airfoil
Cp	Coefficient of Pressure
γ	Stagger angle

I. INTRODUCTION

The study of turbomachinery has gone through several historical stages from the 1940s till now. The study in this period has moved from one-dimensional to two-dimensional and three-dimensional flows, from inviscid to viscous flows, and from steady to unsteady flows [1]. The principal type of compressor being used nowadays, in majority of the gas turbine and power plants and especially in aircraft applications, is the axial flow compressor. This dominance is mainly due to the ability of the axial flow compressor to satisfy the basic requirements of the aircraft gas turbine. Transonic axial flow compressors are today widely used in aircraft engines to obtain maximum pressure ratios per single stage. High stage pressure ratios are important because they make it possible to reduce the engine weight and size and, therefore investment and operational costs. Performance of transonic compressors has today reached a high level but engine manufacturers are oriented towards increasing it further [2]. A small increment in efficiency, for instance, can result in huge savings in fuel costs. The increase in gas turbine efficiency mainly dependent on Increase in Pressure Ratio. So in the present work CDA airfoil is parameterized and optimized for higher pressure ratios up to 3.0 with reduction of overall total pressure loss.

II. LITERATURE REVIEW

One of the challenging topics in optimization is the selection of the mathematical representation of airfoil design variables that provides a wide variety of possible airfoil shapes. A new method for airfoil shape parameterization is presented which takes into consideration the characteristics of viscous transonic flow particularly around the trailing edge. Typical practice is to resort to using a series of curves, such as polynomials and Bezier curves, to describe the profile. This typically reduces the number of degrees of freedom to a much smaller, manageable number. The method is then applied to airfoil shape optimization at high Reynolds number turbulent flow conditions using a Genetic Algorithm [3]. The influence of the selection of the parameterization on the optimization has received relatively little consideration to date. A new airfoil parameterization, Bezier-PARSEC, that was developed to extend and improve the typical Bezier parameterization found in use. This parameterization was found to fit the known shape of a wide range of existing airfoil profiles as well as resulting in accelerated convergence. [4], [5]. Another innovative method for airfoil geometry optimization is based on the coupling of a PARSEC parameterization for airfoil shape and a genetic algorithms (GA) optimization method to find Nash equilibria (NE). While the PARSEC airfoil parameterization method has the capability to faithfully describe an airfoil geometry using typical engineering parameters, on the other hand the Nash game theoretical approach allows each player to decide, with a more physical correspondence between geometric parameters and objective function, in which direction the airfoil shape should be modified[6]. Lars Sommer [7] introduces a new curvature based design parameterization of two-dimensional high pressure compressor blade sections to be used in a multi-criteria aerodynamic design optimization process. The suction side of the airfoil section is represented by its curvature distribution which is described by a B-spline curve. The coordinates are then derived by numerical integration. The camber line as well as pressure side are obtained by adding a thickness distribution perpendicularly to the camber line. Yongsheng Lian [8] reviewed the recent progress in design optimization using evolutionary algorithms to solve real-world aerodynamic problems. Evolutionary algorithms (EAs) are useful tools in design optimization. Due to their simplicity, ease of use, and suitability for multi-objective design optimization problems, EAs have been applied to design optimization problems from various areas. Sergey Peigin [9] suggested a new approach to the constrained design of aerodynamic shapes. The approach employs Genetic Algorithms (GAs) as an optimization tool in combination with a Reduced-Order Models (ROM) method based on linked local data bases obtained by full Navier–Stokes computations. Naixing Chen [10] describes an optimization methodology for aerodynamic design of turbomachinery combined with a rapid 3D blade and grid generator (RAPID3DGRID), a N.S. solver, a blade parameterization method (BPM), a gradient-based parameterization-analyzing method (GPAM), a response surface method (RSM) with zooming algorithm and a simple gradient method. Syam [11] suggested the Bezier-PARSEC method for camber and thickness distribution of CDA airfoil and Genetic Algorithm for optimization. T Sonoda [12] introduced two different numerical optimization methods; the evolution strategy (ES) and the multi-objective genetic algorithm (MOGA), which were adopted for the design process to minimize the total pressure loss and the deviation angle at the design point at low Reynolds number condition. Akira Oyama [13] developed a reliable and efficient aerodynamic design optimization tool using evolutionary algorithm for transonic compressor blades.

III. PARAMETERIZATION AND OPTIMIZATION

Here we are introducing the method used for the parameterization of CD Airfoil and the MATLAB Genetic Algorithm (GA) toolbox used for Optimization. The mainly used parameterization methods are briefly presented herein.

A. Bezier Curves [3]

One of the most popular methods for airfoil shape representation is the Bezier curve method that introduces control points around the geometry. These points are then used to define the airfoil shape. A Bezier curve of degree *n* is uniquely defined by *n* +1 vertex points of a polygon. These vertices are called the control points of the *n*th order Bezier curve. The general expression for an *n*th order Bezier curve is given below:

$$P(u) = \sum_{t=0}^{n} P_i \left(\frac{n!}{i!(n-1)!}\right) u^i (1u)^{n-i} \qquad (1)$$

Where Pi = i^{th} control point. The parameter u goes from 0 to 1; with 0 at the zeroth control point and unity at the *n*th control point. The Bezier parameterization is determined by its control points which are physical points in the plane. However the other control points need not be on the curve even though they determine the shape of the curve. The number of design variables is often so high that the computational time of the whole process becomes unaffordable. Fainekos and Giannakoglou [14] used the Bezier curve to define the airfoil shape in inverse design of turbomachinery blade airfoils. In their research, Fainekos and Giannakoglou [14] fixed the leading edge and trailing edge control points and also abscissas of the rest of the control points. Song and Keane [15] compared the Bezier curve method with original basis functions in generating airfoils and concluded that the Bezier curve produces better shapes in terms of accuracy but at a higher computational time. In addition, special curvature distributions that are required to achieve a desirable pressure distribution are not evident in this method.

B. PARSEC method [3]

Another common method for airfoil shape parameterization is PARSEC which has been successfully applied to many airfoil design problems. This technique has been developed to control important aerodynamic features by using the finite number of design parameters. In this method there are basic eleven parameters that are used in PARSEC method including leading edge radius (r_{LE}), upper and lower crest locations (X_{UP} , Z_{UP} , X_{LO} , Z_{LO}) and curvatures (Z_{xxUP} Z_{xxLO}), trailing edge coordinate(Z_{TE}) and direction(α_{TE}), trailing edge wedge angle(β_{TE}) and thickness(ΔZ_{TE}). A linear combination of shape functions is used to present the airfoil shape in this method.

$$Z_K = \sum_{n=1}^{6} a_{n,k} X_K^{(n-1)/2} \qquad (2)$$

The coefficients a_n are determined from defined geometric parameters. The airfoil is divided into upper and lower surfaces and the coefficients

$a_n$are determined using the information of the points in each section. The subscript k changes from 1 to 2 in order to consider the length of the upper and lower surfaces, respectively.

C. Bezier PARSEC Parameterization [4]

Derksen and Rogalsky [4] have introduced the Bezier–PARSEC parameterization. This approach will use the advantages of both the Bezier and PARSEC parameterization and avoid the disadvantages of both to represent the airfoil and provide enough flexibility over geometrical and aerodynamic parameters. Their approach is further subdivided into two parameterization methods viz. BP3333 and BP3434. In both the methods, Bezier control points are determined in terms of the PARSEC parameters of an airfoil. The camber-thickness formulation of the Bezier curves is more directly related to the flow than is the upper curve-lower curve formulation for PARSEC, while the PARSEC parameters are more aerodynamically oriented than the Bezier parameters. The BP parameterization uses the PARSEC variables as parameters, which in turn define four separate Bezier curves. These curves describe the leading and trailing portions of the camber line, and the leading and trailing portion of the thickness distributions. While the Bezier parameterization joins the leading and trailing curves with first-order continuity.

The BP parameterization uses second-order continuity. The parameters are:
Leading edge radius – rle,
Trailing camber line angle – ate,
Trailing wedge angle – bte,
Trailing edge vertical displacement – zte,
Leading edge direction -gle,
Location of the camber crest –xc, yc,
Curvature of the camber crest – kc,
Position of the thickness crest – xt, yt,
Curvature of the thickness crest –kt ,
the half thickness of the trailing edge –dzte, and several Bezier variables, b0, b2,b8, b15 and b17. This type of parameterization improves the robustness and convergence speed for aerodynamic optimization, which makes it more suitable for optimization using Genetic algorithms.

D. Optimization of Base CDA using GA [11]

Total pressure loss as objective function for optimization since it is more significant in the compressor blade efficiency. And the optimization is carried out for compressor cascade at high subsonic velocities. The optimization is meant for finding a profile section with minimal loss for the compressor blade. In this investigation we selected a CDA cascade, third stage of a compressor for the optimization. Before starting the optimization process we used to analyze the base cascade to predict the performance. The analysis is carried out numerically in CFD softwares, Gambit for modeling and meshing and Fluent for analysis. The optimization of cascade has mainly five steps as shown on the optimization flow chart. All the process is carried out using Matlab code. The design parameters are selected from the parameters obtained from the BP334. This new parameters are generated at each iteration by the GA based on the constraints and the objective function. We selected 15 parameters of BP3434 for optimizing the cascade. The first step is terminated with the generation of the new parameters by GA. The next step is to generate the airfoil section from these parameters. In the third step CFD software Gambit is called in Matlab in batch mode for the cascade modeling and meshing using reading the Gambit journal file in Matlab. After the completion and generation of the mesh file as a fourth step Fluent is called in Matlab using the system command and reads the Fluent journal file, which includes all the commands for the analysis. By the execution of the Fluent we will get all the inlet and outlet parameters such as total pressures, total temperatures, static pressures, Mach numbers, etc. Also we will get the flow parameters over the cascade i.e. Mach number, static pressure, etc. The objective function is selected as total pressure loss coefficient for this optimization which calculated from the results of Fluent analysis. At each iteration GA checks the value of the loss coefficient for the next generation of next population of parameters. The process ends when the loss coefficient is minimized. Genetic Algorithm (GA) is used as an optimization algorithm because of its global optimization nature and speed of convergence. The objective function used for GA is total pressure loss coefficient. We selected the constraint as Chord length of the Cascade and is fixed as 46.46 mm and set the number of generation as 100 with a crossover fraction of 0.8. After calculating and checking the value of loss coefficient GA generates the new population based on the crossover, selection and mutation with a constraint fixed chord length.

After the convergence of the optimization algorithm for a generation of 100 we obtained the airfoil section which has minimized the objective function. The table 1 shows the newly generated profile has optimal total pressure loss coefficient compared to the base profile.

Table 1: Comparison of Base and Optimized Airfoil [11]

Airfoil Sections	Total pressure		Pressure loss coefficient
	Inlet	Outlet	
Base Airfoil	33800	335150	0.0427
Optimized Airfoil	33800	335370	0.0394

This process was repeated for various pressure ratios ranging from 1.1 to higher pressure ratios and it was found that there was a drag reversal after a pressure ratio of 1.4. The negative drag indicates the reversal of flow hence we derived a conclusion that a pressure ratio greater than 1.4 cannot be achieved from the above airfoil for the given set of conditions and there is a need to optimize the airfoil further to gain higher pressure ratios.

E. Optimization of CDA for Higher Pressure Ratios up to 2.4 [16] [17]

The following boundary conditions were applied:

Solver: Green Gauss node based, 2d, steady, implicit, density based

Model: Spalart-Allmarus

Convergence Criteria: 0.001

Fluid: Air with ideal gas density and Sutherland viscosity

Discretization: Flow: Second order upwind

Modified turbulent viscosity: Second order upwind

Inlet Total Pressure P_{O1} = 338000 Pa

Inlet Total Temperature T_{O1} = 426K

Boundary conditions:

Table 2: Boundary Conditions for Higher PR [16] [17]

Pressure Ratio	Inlet Mach No.	P_1 (Pa)	T_{02} (K)	P_2 (Pa)
1.5	0.75	232737.6	478.3231	349106.5
1.6	0.75	232737.6	487.225	372380.2
1.7	0.75	232737.6	495.7379	395654
1.8	0.75	232737.6	503.9003	418927.8
1.9	0.75	232737.6	511.7449	442201.5
2.0	0.75	232737.6	519.2998	465475.3
2.2	1.2	139383.4	533.6354	306643.62
2.4	1.4	106213.4	547.0681	254912.62

The table 3 shows the total pressure loss coefficient obtained up to 2.4 pressure ratios

Table 3: Pressure loss coefficient comparison up to 2.4 PR [17]

Pressure Ratio	CDA Base Airfoil	Optimized Airfoils
	Pressure Loss Coefficient	Pressure Loss Coefficient
1.5	----	0.007903
1.6	----	0.006527
1.7	----	0.009531
1.8	----	0.005681
1.9	----	0.004332
2.0	----	0.017324
2.2	----	0.008038
2.4	----	0.015610

IV. SIMULATION RESULTS OF HIGHER PRESSURE RATIOS MORE THAN 2.4

Further optimization of the airfoil and up to how much pressure ratio will be possible is found out in this work. We obtained a pressure ratio of 3.0 without any flow separation for a Mach number of 1.4. Beyond that further optimization is not possible with this method.

Table 4: Boundary conditions for Higher PR up to 3.1

Pressure Ratio	Inlet Mach No	P_1 (Pa)	T_{02} (K)	P_2 (Pa)
2.6	1.4	106213.4	559.7233	276154.9
2.8	1.4	106213.4	571.7011	297397.6
3.0	1.4	106213.4	583.0824	318640.2

The boundary conditions for pressure ratios up to 3.0 is as shown in table 4.

Distribution of Mach number of Optimized airfoils are given below.

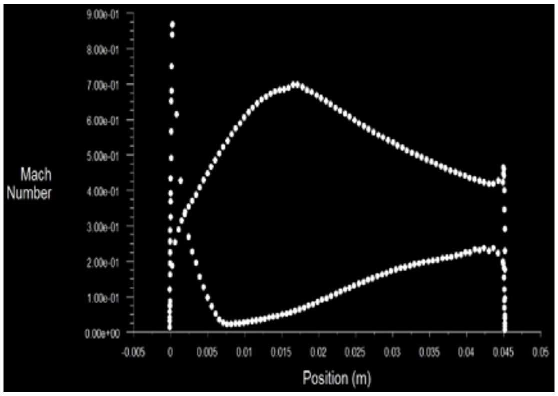

Figure 1: Mach number plot for optimized 2.6 PR airfoil

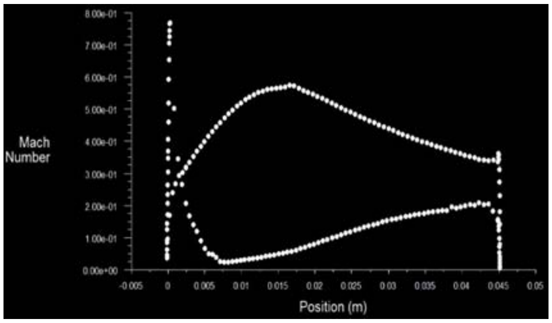

Figure 2: Mach number plot for optimized 2.8 PR airfoil

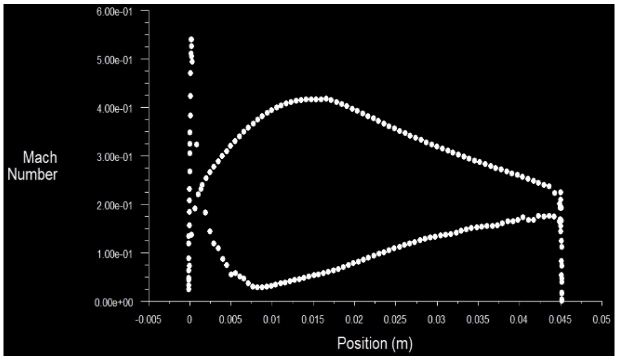

Figure 3: Mach number pot for optimized 3.0 PR airfoil

The newly optimized airfoils can perform better at higher pressure ratios up to 3.0. The optimized blades have shown perfect velocity and pressure distribution as of CDA. In the above plots we can see the exit Mach number is reducing as the pressure ratio increases.

Table 5: Pressure Loss Coefficient Comparison for PR up to 3.0

Pressure Ratio	CDA Base Airfoil	Optimized Airfoils
	Pressure Loss Coefficient	Pressure Loss Coefficient
2.6	----	0.006009
2.8	----	0.001717
3.0	----	0.007102

V. VALIDATION OF SIMULATION RESULTS

The optimized airfoil showed close CDA characteristics which confirm its good behaviour at higher pressure ratios. The suction peak is low at higher pressure ratios as expected and uniform diffusion is there till the trailing edge. The pressure on the lower surface increases uniformly till trailing edge. It is also observed that as the pressure ratio increases the peak Mach number decreases. For given pressure ratios, on upper surface, the Mach number first increases to a value of peak Mach number and thereafter it reduces continuously. On lower surface, Mach number first reduces and then increases gradually. It signifies that over upper surface, fluid is accelerated first and then it decelerates constantly to match the flow conditions at the trailing edge. These all are the typical characteristics of a controlled diffusion airfoil. Hence our optimized airfoils exhibit the characteristics of a CDA airfoil.

VI. CONCLUSION

- The parameterization and GA optimization method is capable of finding efficient and optimum airfoils in fewer number of generations.
- The development of a combined Bezier-PARSEC (BP) parameterization utilize the advantages of both the Bezier and PARSEC parameterizations.
- Coupling of Bezier-PARSEC parameterization with GA and CFD together, offers an optimal cascade profile with a reasonable total pressure loss co efficient reduction with efficient flow pattern over the cascade.
- The base CDA airfoil can offer maximum pressure ratio of 1.4, beyond which a converged solution is not obtained indicating that it cannot gain pressure ratios higher than 1.4.
- The blade optimization with Bezier PARSEC Parameterization has offered most optimized results. The newly optimized blades can perform better at higher pressure ratios up to 3.0. The optimized blades have shown perfect velocity and pressure distribution as of CDA. Up to 3.0 PR and Mach 1.4 we can use these optimized airfoils without any flow separation.

REFERENCES

1. Naixing Chen., Aerothermodynamics of Turbomachinery Analysis and Design, 1st Edition, John Wiley & Sons,Singapore,2010,chap.14.
2. Saravanamuttoo H.I.H, Rogers G. F. C, Henry Cohen., Gas Turbine Theory, 6th Edition, Prentice Hall, USA, 2008.chap.5
3. Ava Shahrokhi, Alireza Jahangirian, “Airfoil shape parameterization for optimum Navier–Stokes design with genetic algorithm”, Aerospace science and technology, 11(2007) 443-450
4. R.W. Derksen, Tim Rogalsky, “Bezier-PARSEC: An optimized aerofoil parameterization for design”, Advances in Engineering Software 41 (2010) 923–930.
5. Athar Kharal, Ayman Saleem, “Neural networks based airfoil generation for a given Cp using Bezier–PARSEC Parameterization”, Aerospace Science and Technology 23 (2012) 330–344.
6. Pierluigi Della Vecchia, Elia Daniele, Egidio D’Amato, “An airfoil shape optimization technique coupling PARSEC parameterization and evolutionary algorithm”, Aerospace Science and Technology 32 (2014) 103–110.
7. Lars Sommer, Dieter Bestle, “Curvature driven two-dimensional multi-objective optimization of compressor blade sections”, Aerospace Science and Technology 15 (2011) 334–342.
8. Yongsheng Lian, Akira Oyama, Meng-Sing Liou, “Progress in design optimization using evolutionary algorithms for aerodynamic problems”, Progress in Aerospace Sciences 46 (2010) 199–223
9. Sergey Peigin, Boris Epstein, “Robust optimization of 2D airfoils driven by full Navier–Stokes computations”, Computers & Fluids 33 (2004) 1175–1200.
10. Naixing Chen, Hongwu Zhang, Yanji Xu, Weiguang Huang, “Blade Parameterization and Aerodynamic Design Optimization for a 3D Transonic Compressor Rotor”, Proceedings of the 8th International Symposium on Experimental and Computational Aerothermodynamics of Internal Flows Lyon, July 2007, Paper reference: ISAIF8-0021
11. Syam, Channiwala S A, “Optimization of CDA cascade using Parameterization and Genetic Algorithm coupled with CFD”, 2nd International Conference on Mechanical, Automotive and Aerospace Engineering, ICMAAE 2013.
12. T Sonoda, Y Yamaguchi, T Arima, M Olhofer, B Senghoff and H A Schreiber, “Advanced High Turning Compressor Airfoils for Low Reynolds Number Conditions, Part 1: Design and

Optimization", Proceedings of ASME Turbo Expo 2003, GT 2003-38458.

13. Akira Oyama, Meng sing Liou, Shigeru Obayashi, "Transonic Axial Flow Blade Shape Optimization using Evolutionary Algorithm and 3D Navier Stokes Solver", AIAA Journal of Propulsion and power, 2002-5642.
14. Fainekos and Giannakoglou, Inverse Problems in Science and Engineering, 4th Edition, Taylor & Francis, UK, 2004 chap 4.
15. Song W, Keane A, A Study of Shape Parameterization Methods for Airfoil Optimisation, 10th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, 2004-4482.
16. Vilash Rajendra Shingare, A study on High Pressure Ratio Airfoils for Axial Flow compressors, Mtech Thesis, S. V. National Institute of Technology, Surat, 2012.
17. Rajesh N, High Pressure Ratio Blade Design by Parameterization and Optimization, MTech Thesis S. V. National Institute of Technology, (2014).
18. MATLAB User Guide Genetic Algorithm and Direct Search Toolbox User's Guide Copyright, Mathworks, 2004.