Optimization of High Pressure Ratio Compressor Blade Section

Nilesh P. Salunke, S. A. Channiwala

Abstract Optimization of airfoil shape utilizing developmental calculations is turning into a pattern in plan of cutting edges for turbomachines and flying machine. Transformative calculations work with parameterization of airfoil shape for example portrayal of an airfoil with the assistance of some shape administering parameters. Along these lines one of the difficulties in this field is to portray the airfoil with reasonable parameters and unequivocal or verifiable scientific capacities. In this work, the airfoil cutting edges are effectively improved utilizing hereditary calculation. Airfoil is parameterized utilizing Bezier-PARSEC parameterization plan and same is numerically broke down utilizing Gambit and FLUENT. A base CDA airfoil is improved for different weight proportions running from 1.1 to 2.2. The sharp edge segments so streamlined are tried for low constrain proportion to approve the calculation in low speed course wind burrow. Further the calculation is approved with distributed exploratory information of Rotor37 which approves value of the optimization technique.

Keywords:** *Compressor blade,* **Bezier-PARSEC parameterization,** *CDA,* **Parameterization.

I. INTRODUCTION

Optimized blades have been increasing in popularity in the recent times. Turbomachinery blades are optimized based on multiobjective function [1][4]. Algos based on principles of genetics for the search of optimum solution are proving to be excellent. These evolutionary algorithms coupled with CFD softwares are potential tools of optimization[2]. The main hurdle in the optimization process of airfoil blades was to define the geometry of airfoil with the help of few controlling parameters[3]. Defining the airfoil blade with few governing parameters is called as parameterization. Various techniques have been developed to carry out the parameterization. Parameterization techniques normally include Bezier parameterization, PARSEC method, Sobeiczky method, B-spline parameterization and Bezier-PARSEC parameterization. Bezier-PARSEC parameterization is found to fit for parameterize a wide range of existing airfoilsand is used in the present work.

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Once an airfoil is represented with its parameters, these parameters could be changed in the set range so as to obtain a pool of airfoils. Each of the airfoil of this pool can be tested for its performance and the best airfoil which satisfies the objective function could be obtained over the specified number of generations.

In the present work a base CDA airfoil is parameterized using Bezier-PARSEC parameterization. A pool of airfoils is generated using genetic algorithm and a numerical study conducted on every airfoil using GAMBIT and FLUENT software.

The stream attributes at transonic velocities are exceptionally touchy to the geometry of the aerofoil. This makes the parameterization system a key factor in the opposite structure issues. The significance of shape parameterization in reverse plan isn't just to effectively discover the geometry that relates to target stream circulation, yet additionally to expand the combination pace of the optimization procedure to the objective aerofoil. The parameterization of the cutting edge shape is of essential significance. Identified with it is the all out number of free parameters that ought to be kept as low as feasible for most extreme computational productivity. Then again by permitting a wide quest space for each plan parameter the model gets adaptable enough to adapt to an assortment of Turbomachinery sharp edge shapes. Albeit much research has been done on streamlined shape optimization, just a couple have considered the impact of shape parameterization in the immediate and backwards configuration forms

The desired requirements from a parameterization method are:

- To have expanded adaptability in order to cover the hunt space to the most elevated degree, permitting in this manner improved arrangements with "non-customary" shapes to appear,
- To keep the quantity of structure parameters as low as could reasonably be expected,
- To maintain a strategic distance from incline or arch discontinuities at the intersections of bends or surfaces worked through nearby guess or addition modes,
- To reject plan factors which influence unimportantly the streamlined presentation of the shape, generally the relationship shifts with the wellness or cost capacity will be uproarious and this variable may postpone assembly to the ideal arrangement.

- To ideally incorporate structure factors connected straightforwardly to the limitations, in order to forgo any important handling.

Ava Shahrokhi et al [2] researched the impact of airfoil shape parameterization on ideal structure and its effect on the intermingling of the optimization procedure are explored utilizing a Genetic Algorithm by an unstructured matrix Navier–Stokes stream solver with a two-condition K−ε choppiness model is utilized to assess the wellness work. Lars Sommer et al [4] presents another ebb and flow based structure parameterization of two-dimensional high weight blower sharp edge segments to be utilized in a multi-criteria streamlined plan optimization process by USING a B-spline bend. The subsequent blower sharp edge segment is advanced w.r.t.

all out weight misfortune coefficient as a target capacity and working reach utilizing process combination and a hereditary calculation. K.M. Pandey et al [5] broke down the stream conduct through a blower course with the assistance of Computational Fluid Dynamics utilizing the FLUENT programming. S Obayashi et al [1] determined a multi objective hereditary calculation (GA) in light of Fonseca–Fleming's Pareto-based positioning and wellness sharing procedures for streamlined shape optimization of course airfoil structure. The present multiobjective structure looks for high weight rise, high stream turning edge, and low absolute weight misfortune at a low Mach number. The best Pareto arrangement gives 40% decrease of misfortune contrasted with CDA and the weight misfortune coefficient esteem acquired on enhanced cutting edge segment ranges from 0.0189 to 0.0337. Athar Kharal et al [10] portrays the usage of counterfeit neural nets for the airfoil geometry assurance. Rather than utilizing full facilitates of the airfoil, Bezier–PARSEC 3434 parameters have been utilized to portray an airfoil by utilization of Genetic Algorithms for calibrating of certain BP3434 parameters. Dennis et al[12] utilized a mix of GA and compelled based technique utilized for advancing two dimensional sharp edge geometry regarding complete weight misfortune. The creators utilized a higher complex N-S stream solver with an incorporated choppiness model for better stream assessment where the cutting edge geometry is parameterized utilizing B-splines. A noteworthy decrease of the all out weight misfortune is watched. Syam et al [8] proposed the Bezier-PARSEC technique for camber and thickness appropriation of CDA aerofoil and Genetic Algorithm for optimization. Bezier bends have favorable circumstances of geometric parameters and PARSEC techniques have points of interest of streamlined parameters and by consolidating both they discovered upgrades in aerofoil parameterization. Coupling of Bezier-PARSEC parameterization with GA and CFD together, offers an ideal course profile with an absolute weight misfortune co productive decrease of 0.0394 with proficient stream design over the course. Brian H Dennis et al [12], acquainted a streamlined shape structure with limit all out weight misfortune over the two-dimensional direct airfoil course push while fulfilling various imperatives. For the investigation of the exhibition of halfway course shapes they utilized an unstructured-framework based compressible Navier-Stokes stream field examination code with k-epsilon choppiness model. Group Falla et al [21], utilized k-epsilon model to represent the tempestuous conduct of the stream and a limited volume technique was utilized to illuminate the stream overseeing conditions on NACA 65 and CDA utilizing the solver FLUENT. The geometry of the two profiles that accommodate the couple sharp edge is browsed the open writing, which is bolstered by test results. Since the course geometry is fairly mind boggling the work for every setup is produced utilizing a parametric calculation created in GAMBIT.

Naixing Chen et al [50], presented the cutting edge parameterization technique (BPM) and Rotor 37 was parameterized by BPM utilizing set of polynomials, Also it empowers to change the sharp edge from arrange communicated information to parameter communicated ones. Reaction surface technique and inclination based parameterization examining (GPAM) were joined with a fast 3D cutting edge generator and matrix generator (RAPID3DGRID), a N-S solver utilized in the optimization mechanized circle. The stream example and stun structure of the advanced blower Rotor are sensible. The expanding of adiabatic proficiency of the Rotor by the optimization are about 1.73%. The all out weight proportion and stream rate likewise expanded a smidgen. The Relative Mach number forms at 5%, 50 and 95% range statures are appeared in Figure 2.14.

Pierluigi Della Vecchia et al [59], presented an inventive optimization process for airfoil geometry configuration is presented. This system depends on the coupling of a PARSEC parameterization for airfoil shape and a hereditary calculations (GA) optimization strategy to discover Nash equilibria (NE) as in Figure 2.20. While the PARSEC airfoil parameterization technique has the capacity to reliably depict an airfoil geometry utilizing regular building parameters, then again the Nash game hypothetical methodology enables every player to choose, with a progressively physical correspondence between geometric parameters and target work, in which course the airfoil shape ought to be changed. Indeed the optimization under NE arrangements would be progressively appealing to utilize when a very much presented differentiation between players factors exists.

Georgia N. Koini et al [61], presents a product instrument for the calculated structure of turbomachinery blading's named "T4T" (Tools for Turbomachinery). It gives the capacity to intuitively develop parametric 3D edge lines of different kinds, including for multistage machines. The plan strategy is parametric and a wide range of pivoting hardware segments might be delivered. The structure parameters utilized for the cutting edges just as the center and cover surfaces development compare to 2D segments. Be that as it may, the subsequent geometries are displayed as NURBS 3D surfaces and can be imported to other CAD or investigation programming through standard trade conventions. The geometry definition is enabled by the item arranged structure of the product and a simple to-utilize graphical interface, which makes the plan stage a clear methodology.

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The product's structure and geometric calculations, the blading plan methodology, alongside test plans which exhibit the capacities of the product, are additionally introduced.

II. BEZIER PARSEC PARAMETERIZATION

This strategy is a mix of Bezier and PARSEC parameterization systems which joins the upsides of both the methods. The Bezier-PARSEC parameterization utilizes PARSEC factors as parameters, which are utilized to characterize four separate Bezier bends. These four bends characterize the main edge and trailing edge of the camber line and thickness circulation. The Bezier-PARSEC parameterization utilizes second request coherence to join the main and trailing edges.

Bezier-PARSEC parameterization is signified by BP ijkl where I and j speak to the request for driving and trailing edge of thickness bend and k and l speak to the request for driving and trailing edge of camber curve.[6]Obama et al. indicated that Bezier-PARSEC parameterization expanded the vigor and intermingling speed for streamlined optimization utilizing hereditary algorithms.[7]

2.1. BP 3434 Parameterization

Asthe name suggests, in BP 3434 parameterization both the leading edges have third degree curves while both the trailing edge curves have the four degree curves. The BP 3434 parameterization depends upon ten aerodynamic parameters, plus five Bezier parameterswhich are shown in Fig.1.

The parameters are:Leading edge radius – r_{le}, Trailing camber line angle – α_{te}, Trailing wedge angle – β_{te},Trailing edge vertical displacement – Z_{te}, Leading edge direction -γ_{le}, Location of the camber crest –x_c,y_c, Curvature of the camber crest – k_c, Position of the thickness crest – x_t ,y_t, Curvature of the thickness crest –k_t ,the half thickness of the trailing edge –ΔZ_{te}, and several Bezier variables, b0, b2,b8, b15 and b17.

- The parametrization and optimization of blade sections using Genetic algorithm coupled with CFD software Fluent which is a quite unique approach.

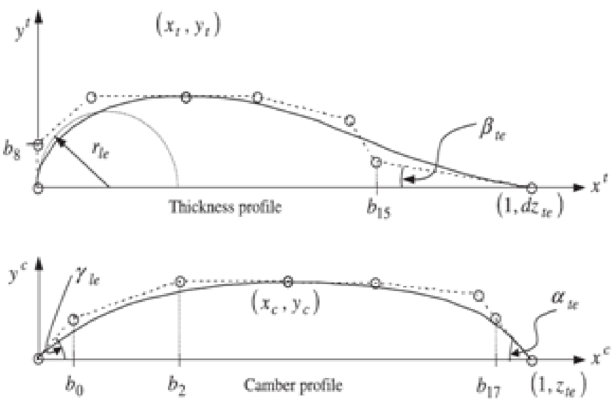

Fig.1 BP 3434 Airfoil Geometry and Bezier Control Points

III. OBJECTIVE FUNCTION

Losses in cascade airfoils are normally quantified in terms of the drop in total pressure divided by the dynamic pressure of the incoming flow. This ratio is called the total pressure loss coefficient and is defined as

$$\omega = \frac{P_{oe} - P_{oi}}{\frac{1}{2}\rho V_i^2}$$

Where P_{oe} is the total pressure at the exit, P_{oi} the total pressure at the inlet, ρ is the density of the working fluid, V_i is the velocity of the working fluid at the inlet.

IV. OBJECTIVE FUNCTION FOR OPTIMIZATION

Pressure loss coefficient can also be expressed as

$$\omega = \frac{C_d}{\left(\frac{s}{c}\right)(\cos\alpha_m)^3}$$

Mean air angle is given by,

$$\tan \alpha_m = \frac{\tan \alpha_1 + \tan \alpha_2}{2}$$

In the present case,
Inlet air angle, $\alpha_1 = 42^o$
Outlet air angle, $\alpha_2 = 1^o$
Therefore, $\alpha_m = 24.65^o$and Pitch, s = 23.33 mm. Length of blade, c = 46.1 mm.

It is obvious from the above expression that for the constant space-chord ratio and mean air angle, pressure loss coefficient is directly proportional to drag coefficient. The minimization of drag coefficient is minimization of pressure loss coefficient. Hence the objective function selected for optimization is minimization of drag coefficient.

V. FLOWCHART FOR OPTIMIZATION PROCESS

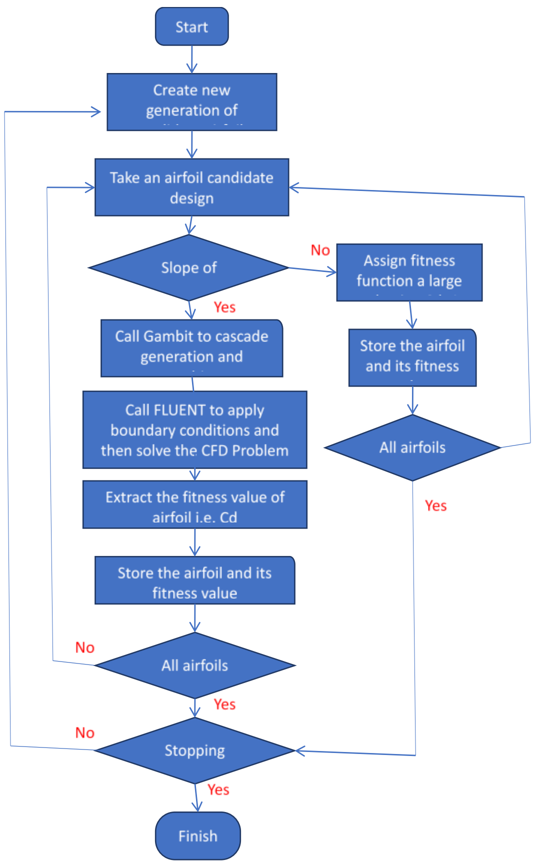

Fig. 2 Flowchart for optimization process

The Flowchart for the optimization procedure is appeared in Fig. 2. It begins with the age of a variety of airfoils utilizing hereditary calculation of optimization tool kit of MATLAB. Next, it continues towards execution (target work) testing of each airfoil.

An applicant airfoil configuration is chosen from the created pool of airfoil. Slant of this airfoil is resolved at each point on upper and lower surface of airfoil and it is guaranteed the recommended estimation of 1000:1 isn't surpassed. The estimation of slant limit is resolved from the greatest incline of standard airfoils. Care is taken to counteract the unusual shape of airfoil which whenever made to additionally strides, will disturb different parts and the optimization procedure may end. On the off chance that the created airfoil is having slant more prominent than determined, it is straightforwardly doled out a wellness (objective) estimation of 1.

This airfoil avoids the demonstrating and lattice in GAMBIT and investigation in FLUENT. In the event that the produced airfoil has an incline not exactly the recommended worth, it is a typical or worthy airfoil. It is then imported to GAMBIT where it is displayed. Stream areas are made and fit. Work record created by GAMBIT is sent out to FLUENT where after different limit conditions, issue is tackled. Familiar gives the wellness esteem for example drag coefficient comparing to that airfoil. Airfoil is spared in memory of MATLAB with its wellness esteem. Presently, the following airfoil of the age is taken and investigated in a similar way. In the wake of completing with all airfoil of the age, up and coming age of airfoils is created utilizing standards of hereditary qualities. The procedure is rehashed till halting criteria is come to.

VI. METHODOLOGY

To optimize an airfoil, a MATLAB code has been developed. This code couples various software components successfully. This makes the process automatic. Fig. 3 shows various software components and their interlinking.

As seen in above figure, MATLAB is the main component and serve as a link between other software. Using genetic algorithm solver in optimization toolbox of MATLAB, a pool (an array) of airfoils is generated. Then, by using system command, Gambit software is run in batch mode. Gambit journal file consists of various commands to import the airfoil, create the geometry of flow region and generate a mesh for it. Gambit exports the mesh file to working directory of MATLAB. After Gambit executes all the commands, it closes up and using system command, Fluent software is called in to start in batch mode.

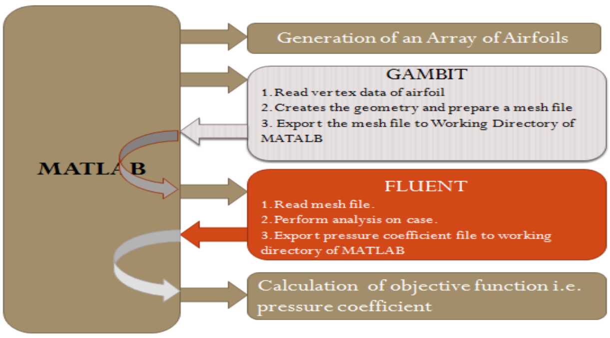

Fig.3 Components of Optimization Process

It imports the mesh file, applies various boundary conditions i.e. inlet pressure, outlet pressure etc. and performs analysis on the case and returns the objective function value i.e. drag coefficient to Matab.

The airfoil and its pressure loss coefficient value are saved in the memory of Matlab. The procedure is repeated for every candidate airfoil in each generation.

VII. CASCADE MODELLING AND MESHING

Airfoil is divided into four parts namely upper edge, lower edge, leading edge and trailing edge. In order to capture the flow parameters at leading and trailing edges, which are critical portions, a finer mesh is created near these points. Airfoil is specified as wall type boundary. Left and right edges are specified as inlet and outlet respectively. All other boundaries are specified as periodic ones. [8] The Mesh is shown in Fig. 4.

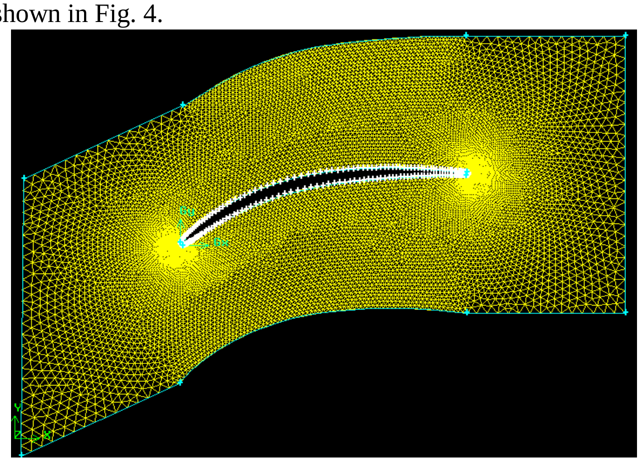

Fig.4 Mesh around the airfoil

VIII. RESULTS

The optimization of CDA airfoil for pressure ratios 1.1 to 2.2 is carried out using a cyclic process which combines the genetic algorithm, Gambit and FLUENT. The performance of base airfoil i.e. CDA airfoil is compared with the optimized airfoils. The table 1 below gives a comparison between the CDA and optimized airfoils.

It is observed from table 1that optimized airfoils for corresponding pressure ratios offer less pressure loss coefficient than that offered by the base airfoil. Simulations on the base CDA airfoil for higher pressure ratios are not run successfully i.e. a converged solution is not obtained indicating that it cannot gain pressure ratios higher than 1.4. On the other hand optimized airfoils show convergence even at higher pressure ratios up to 2.2.

The pressure distribution and Mach number distribution over optimized airfoil for pressure ratio 2.2 are shown in following figures. From Fig. 5. to Fig. 8. it is observed that the optimized aerofoil exhibits good agreement with characteristics of CDA. The optimized airfoil showed close CDA characteristics which confirm its good behavior at higher pressure ratios. The suction peak is low at higher pressure ratios as expected and uniform diffusion is present till trailing edge. The pressure on the lower surface increases uniformly till trailing edge.

Table 1 Pressure Loss Coefficients Comparison

Pressure Ratio	CDA Base Airfoil	Optimized Airfoils
	Pressure Loss Coefficient	Pressure Loss Coefficient
1.1	0.026918	0.026878
1.2	0.022034	0.021898
1.3	0.017476	0.016554
1.4	0.012587	0.012462
1.5	----	0.007903
1.6	----	0.006527
1.7	----	0.009531
1.8	----	0.005681
1.9	----	0.004332
2.0	----	0.003942
2.2	---	0.003087

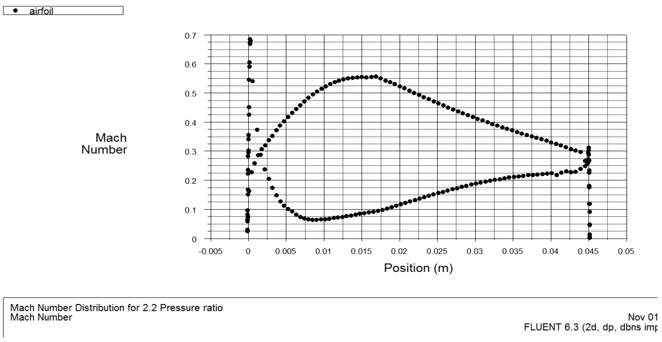

Fig.5 Mach No. Distribution of Optimized Airfoil for PR 2.2

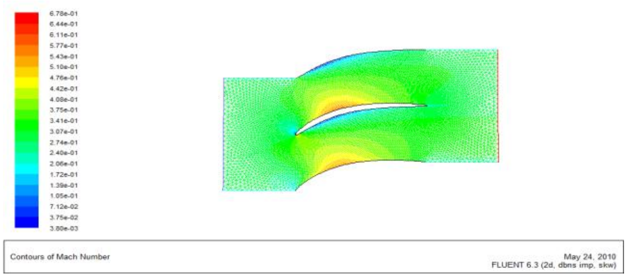

Fig.6 Contours of Mach No. over Optimized Airfoil for PR 2.2

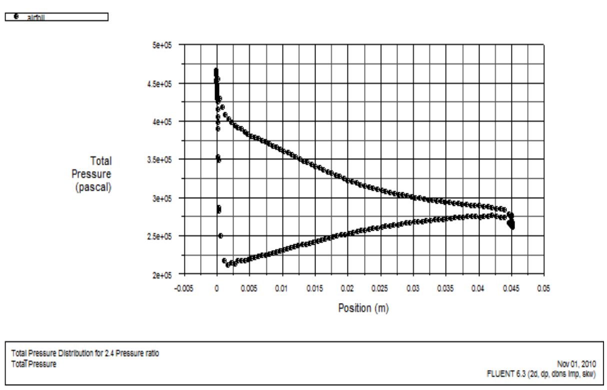

Fig.7 Total Pressure Distribution of Optimized Airfoil for PR 2.

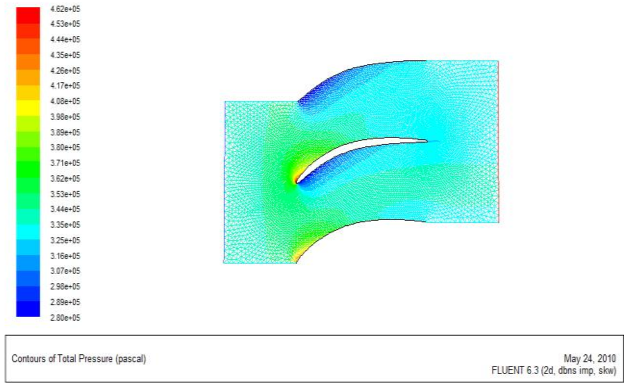

Fig.8 Contours of Total Pressure over Optimized Airfoil

8.1 Mach No. Distributions over Optimized Airfoils for Pressure Ratios 1.1 to 2.2

Mach No. dispersion for all weight proportions over upgraded airfoil is plotted at the same time. It is given underneath.

As found in Fig. 9, for all weight proportions, on upper surface, Mach No. at first increments to an estimation of pinnacle Mach No. also, from that point it diminishes constantly. On lower surface, Mach No. at first lessens and afterward increments slowly. It implies that over upper surface, liquid is quickened at first and afterward it decelerates continually to coordinate the stream conditions at the trailing edge. These are all the common qualities of a controlled dissemination airfoil. Thus the streamlined airfoils display the attributes of a CDA airfoil.

It is likewise observed that with the expansion in pressure proportion, top Mach No. is drops down. This can be defended as to pick up the bigger weight proportions, increasingly more transformation of dynamic vitality into pressure vitality for example dissemination happens, which lessens the speed of the liquid and consequently the Mach number.

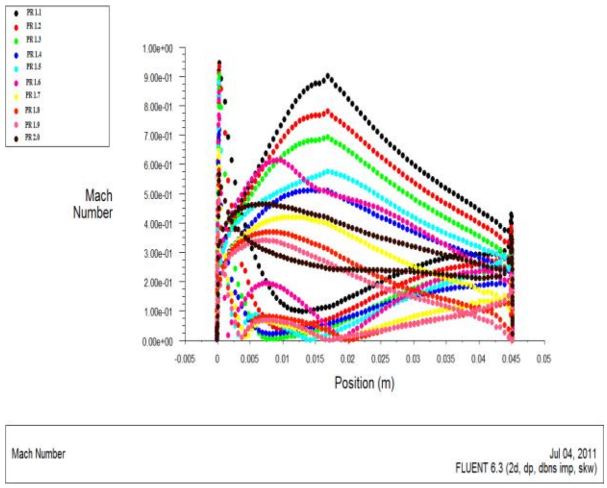

Fig.9 Mach No. Distributions over Optimized Airfoils for Various Pressure Ratios

8.2 Off-Design Performance of Optimized Airfoil

Simulations are run on optimized airfoil for pressure ratio 2.2 at different inlet Mach numbers viz. 0.6, 0.75, 0.9, 1.0, 1.1 and 1.2, as shown in fig.

10 following Mach No. distributions are obtained.Optimized airfoil exhibits the characteristics similar to those of a CDA airfoil even at different inlet Mach numbers ruling out the possibility of stalling under off-design conditions. The characteristic with respect to the Mach No. too is similar which initially accelerates to a peak point and then gradually reduces to meet the end conditions at the trailing edge.

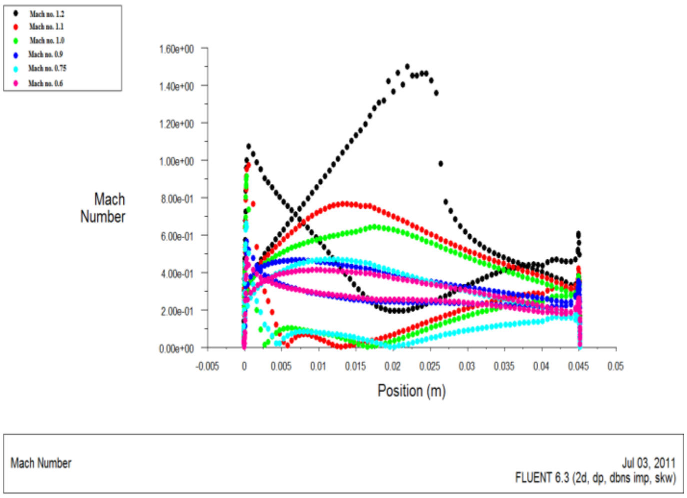

Fig. 10 Mach No. Distributions over Optimized Airfoil for Pressure Ratio 2.2 at Different Inlet Mach Numbers

IX. EXPERIMENTAL VALIDATION

For validation of algorithm a continuous blow down type cascade wind tunnel was designed and fabricated as shown in Plate 1 The various parts are test section, axial flow fan, convergent portion, screens, multilimbed manometer, Prandtl type pitot tube, frequency detector etc. The specification of the wind tunnel and test section is summarizing in table.

Plate1. Cascade Wind Tunnel Set-up

Table 2 Specification of wind tunnel

Sr No.	Parameter	Dimension
1	Total length of wind tunnel	3m
2	Type of fan used	Axial Fan
3	Maximum height	2m
4	Cross section of test section	50cmx15cm
5	Length of test section	75cm

9.1 Results

The optimization code needs to be validated but the experimental setup is not providing required Mach number so experiments are conducted for validation with a low pressure ratio airfoil of 1.02 PR for this, an optimized blade section is designed for pressure ratio of 1.02 and is tested for validation in wind tunnel.. Experimental results shows similar trend of CFD results and there by qualitatively validate the present approach of optimization. The Cp distribution results on 1.02 pressure ratio blade profile indicates a qualitative match between analytical results and experimental results which concludes that the optimization has been successful and code is validated. The optimized airfoil showed close CDA characteristics which confirm its good behavior at higher pressure ratios.

The Figure 11 represents the experimental and CFD results for the static pressure distribution coefficient (Cp) over the optimized 1.02 pressure ratio blade profile for both upper and lower surfaces of the optimized cascade profile.

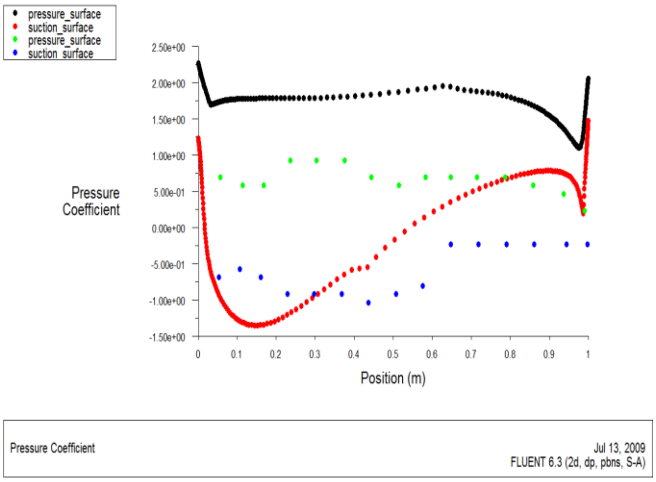

Fig. 11 Comparison of Computational and Experimental Cp Distribution on 1.02 Pressure Ratio Blade

From the graph obtained it is observing that the experimental results are showing the same trend as the CFD results. The static pressure distribution obtained by CFD seems to be more uniform compared to experimental results.

The upper surface produces suction pressure and lower surface produce positive pressure due to which lift is produced.

X. ALGORITHM VALIDATION WITH ROTOR 37

The optimization calculation is checked through a hub transonic blower NASA Rotor 37. The sharp edge is spoken to by three airfoils at various range stations, for example, center, mean and tip.

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These airfoils are then parameterized by BP3434 strategy and finding the obscure control focuses by GA Matlab tool kit and the airfoil is changed over into parametric model with set of polynomial conditions. Hereditary Algorithm optimization procedure will discover the ideal airfoil for the given limit conditions.

The enhanced airfoils are stacked for planning upgraded Rotor 37 and 3D CFD examination is completed in CFX and turbomachinery structure optimization programming AXTREAM. The stream inside pivotal stream blower is profoundly three dimensional and violent, in this way discovering immaculate disturbance model is a piece of numerical investigation of turbomachinery. There are two choppiness models, for example, Shear Stress Transport (SST) and k-ε accessible in CFX 14 were utilized and two recreations were performed under a similar limit conditions so as to make it conceivable the correlation among the models. The outcomes discovered used to contrast and test information accessible in writing. The Figure 12 shows the stagnation pressure variety with standardized range. It is conceivable to see that the qualities found by SST model stay near the test esteems up to 60% of the range than the k-ε model.

From Figure 12 it is effectively inferred that the SST disturbance model conquer the k-ε model having the qualities a lot nearer to the test information. In this way, SST model is approved and is being utilized for further optimization recreation. The SST model records for the vehicle of the violent shear pressure and gives exceptionally exact expectations of the beginning and the measure of stream detachment under unfriendly weight inclinations from above it is finished up to utilized SST model.

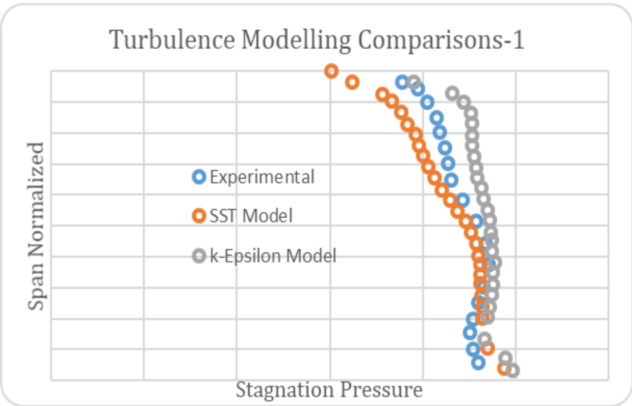
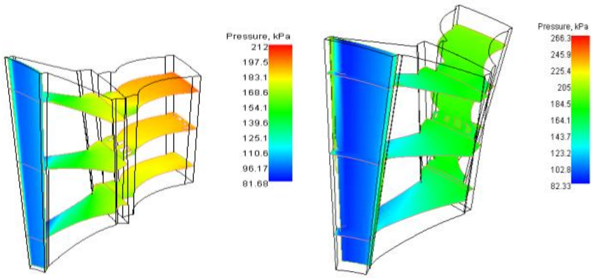


Fig.12 Stagnation Pressure Ratio Comparison

XI. STAGNATION AND STATIC PRESSURE VARIATION

Figure 13 shows the variation of stagnation and static pressure of base and optimized rotor 37. As the air enters in rotor there is transfer of energy to the air by the rotor. There is diffusion process takes place in both rotor and stator which increases total pressure and total temperature of air in rotor which is accompanied with increase in static pressure and absolute velocity of air. In compression process there will be large diffusion on the rotor surface, hence total pressure increased and also slight increment in static pressure is observed. In this there is no more total pressure loss at the exit section due to convergent duct exit. At hub mean at tip sections as it can be seen the average value of static pressure for datum Rotor 37 is 183 kPa whereas for optimized Rotor 37 it is 205 kPa.



ROTOR 37 with MCA Blade profile OPTIMISED Blade Profile

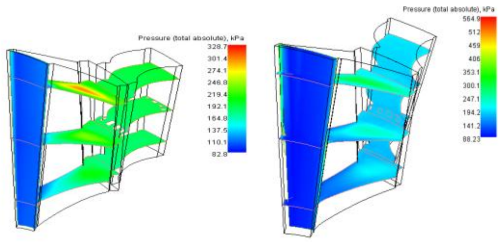


Fig. 13 Stagnation and Static Pressure Comparison

XII. CONCLUSION

It is found that CFD is an efficient tool for the optimization of an airfoil. The entire optimization process can be divided into 4 major steps namely parameterization, meshing, solving and searching for convergence. The process can be automated to make things further simple.

A method for optimization of airfoil has been successfully shown. A CDA blade taken as base airfoil is parameterized into 15 mathematical parameters which has aerodynamic and Bezier curve significance. The base airfoil is found to be capable of withstanding a pressure ratio of 1.4. With the help of Genetic algorithm, MATLAB, GAMBIT and FLUENT, the airfoil has been optimized to offer better pressure ratios. The airfoil is optimized for pressure ratios of 1.1 to 2.2. The results indicate that the optimization has been successful. The optimized airfoil showed close CDA characteristics which confirm its good behavior at higher pressure ratios. The suction peak is low at higher pressure ratio as expected and there is uniform diffusion till the trailing edge. The pressure on the lower surface increases uniformly till the trailing edge.

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Nomenclature

A_c	Cross-section area of micro-channel [m^2]	T	Local mean temperature [K]
L_x	Length of heat sink [m]	U_i	Mean velocity components (i=1, 2, 3)
R_{th}	Thermal resistance [$^oC/W$]	θ, ϕ	Design variables, W_c/H_c and W_w/H_c
Re	Reynolds number ($=U_bD_h/\nu$)	ρ	Fluid Density

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