ParCFD'2019
31st International Conference on Parallel Computational Fluid Dynamics
May 14-17 2019, Antalya TURKEY

BEZIER CURVE-BASED S-SHAPE OPTIMIZATION FOR RAE-M2129 INLET

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Key words: RAE M2129 Intake, Bezier Curve, Optimization, Genetic Algorithm.

Summary. *In this article, intake performance was tried to enhance by optimizing s-shape of RAE-M2129 Model. Inlet geometry is important for engine performance. Geometry of S-Shape has direct effect on performance of engine, leading loss of total pressure, occurring shock, etc. Distortion coefficient (DC) and pressure recovery (PR) are important indicators of inlet efficiency and they have considerably high effect on engine performance also. The optimization for intake shape was done by using Genetic Algorithm, distortion coefficient and pressure recovery defined as objectives. The detailed numerical analysis was studied for validation[1] by setting methodology 2-equation k-epsilon turbulence model with 2nd order discretization. Multi-objective Genetic Algorithm is used to manipulate the Bezier control points so as to change intake geometry with the aiming of maximizing pressure recovery and minimizing distortion coefficient. The optimization cycle continues with importing those points representing geometry structure to CATIA V5 in order to obtain CAD model. Then, numerical elements are created for ANSYS FLUENT 19 flow solver. In addition, engine face diameter, length of the inlet duct and throat diameter are kept constant. Finally, feasible design configurations were compared and best alternative groups are examined in detail.*

1 INTRODUCTION

Inlet is a part of a jet engine, which captures air and conveys it to the following engine part. It has also responsible for slowing velocity of the flow to the desired level for upcoming part of the engine. While no work is done on the flow in inlet, the inlet performance strongly affects the net thrust. Moreover, inlet shape is an important parameter for an aircraft design. In history of aviation, several types of inlets are tried[2]. S-duct is one of the most widely used inlet type model for air-vehicle with turbojet engine. There is an increasing interest in inlet design to improve the overall performance of the engine. Due to geometry complexity of intake, design process is a stage that should be considered with high accuracy modeling for capturing real condition flow characteristics.

There are several parameters that define the efficiency of inlet such as pressure recovery and uniformity of flow that enter the inlet. Engine net thrust highly depends on the incoming flow characteristics. The lack of total pressure at the engine inlet leads loss of net thrust in the system and ratio of total pressure (PR) is a key design parameter that should be maximized. The uniformity of flow at the engine inlet is another important sign for high inlet performance. Accurate prediction of flow characteristic for intake has become a critical topic of interest in CFD authorities recently. Widely used numerical method[7] is Reynold Average Navier-Stokes approach, has good trade-off for computational effort and accuracy of results.

2 METHODOLOGY

In Computational Fluid Dynamics analysis, Navier-Stokes equations are used to find conservative derivatives such as pressure, velocity and density, etc. The choice of numerical algorithm influences the stability of numerical solution. Navier Stokes equations are set of coupled differential equations and describe how moving fluid are related with conservative derivatives difficult to solve analytically.

The mathematical model and underlying assumption for CFD analysis are explained as follows.

2.1 Conservative equations

The most general form of the Navier-Stokes equation,

$$\rho \frac{D\vec{v}}{Dt} = -\nabla p + \nabla \cdot T + \vec{f} \tag{1}$$

where ∇p, $\nabla \cdot T$, $\vec{f}$ represent volumetric stress tensor, stress term due to friction and shear stress and force term acting every single fluid particle respectively.

The effect of turbulence comes from the additional terms in the general form of Navier-Stokes equation.

$$-\rho\overline{u_i' u_j'} = \mu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\left(pk + \mu_t \frac{\partial u_k}{\partial x_k}\right)\delta_{ij}\frac{\partial y}{\partial x} \tag{2}$$

The realizable k-epsilon turbulence was used to calculate Reynolds stress tensor ($-\boldsymbol{\rho\overline{u_i' u_j'}}$). That model contains new formulation for the turbulent viscosity and a new transport equation for the dissipation rate ε.

2.2 Bézier curve

A parametric Bézier curve piece of degree n is defined as

$$Q(t) = \sum_{i=0}^{n} V_i B_i^n(t), \quad 0 \le t \le 1 \tag{3}$$

where the V_i are the control points and B_i^n are the Bernstein polynomial[4].

$$B_i^n(t) = \binom{n}{i} t^i (1-t)^{n-i}, \qquad i = 0, \dots, n. \tag{4}$$

2.3 Genetic algorithm

Recently, optimization methods became popular with the advance of highly accurate, reliable, cost effective algorithms. There are many algorithms some of which are more suitable for searching a complex and nonlinear design space as such in the field of aerodynamics, such as Genetic Algorithms (GAs). GAs are population based searching algorithms that use inspired mechanisms of evolution[6]. Since it includes many random processes inside, by its nature, it can jump out of local optimum and find the global optimum.

In GAs, each design parameter represented by chromosomes and optimization starts with the initial population created randomly which evolves through generations with the Darwinian's theory of survival of the fittest. For every design, the fitness function is calculated and parents are chosen in the selection step of the algorithm based upon the fitness values of the designs. During breeding the child, crossovers and mutations occur randomly. In the end, the last population has the best design alternatives.

3 DISCUSSION AND RESULTS

3.1 Numerical validation

In this article, RAE M2129 intake Model[1] was used to validate our numerical approach. Pressure recovery, distortion coefficient of inlet and static pressure ratio measured from 4-specific locations was compared with experimental results.

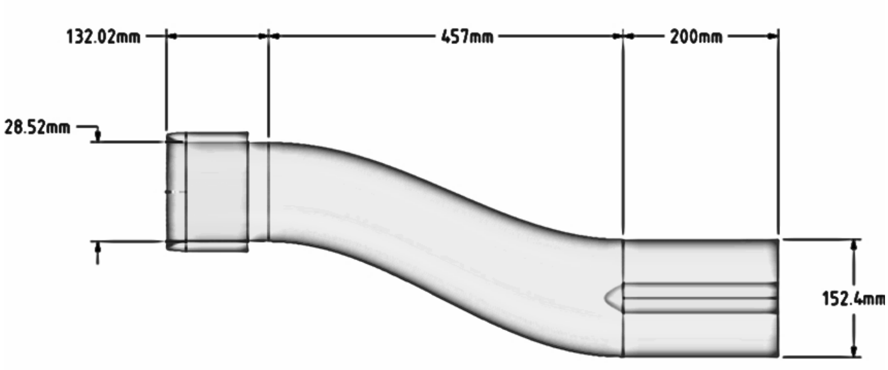


Figure 1 : RAE M2129 Intake Model Length

Freestream Flow	
Angle of Attack	0^0
Sideslip Angle	0^0
Mass Flow Rate	2.692 kg/s
Free Stream Mach Number	0.204
Free Stream Pressure	105140,2 Pa

Table 1: Boundary Condition for Steady-State Analysis for RAE-M2129 Intake Model

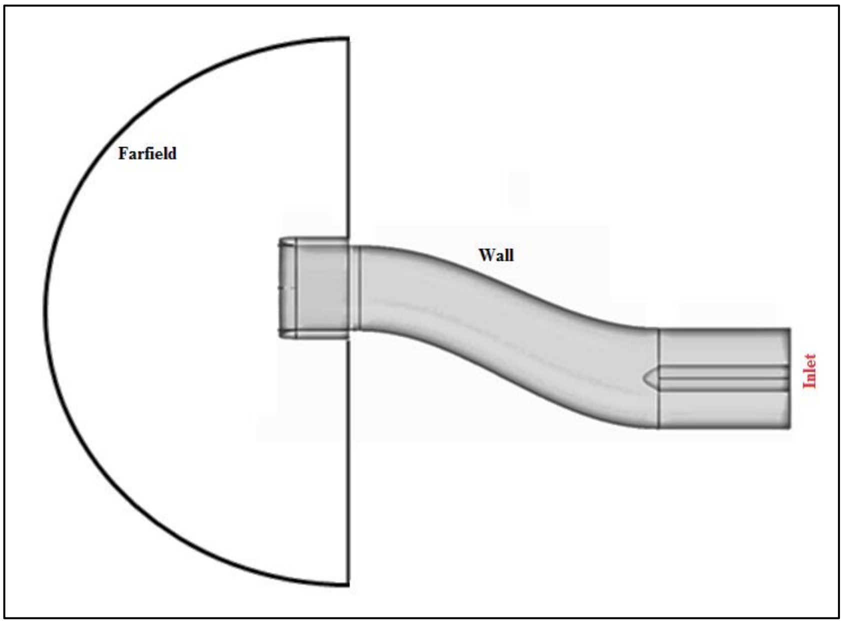


Figure 2: Boundary Conditions

To model subsonic intake flow, numerical solutions are iteratively searched for inlet back pressure to find experimental mass flow rate. Also, Mach number, Area Weighted Average Static Pressure, Distortion Coefficient (DC60) and Pressure Recovery at the AIP plane are controlled under convergence criteria.

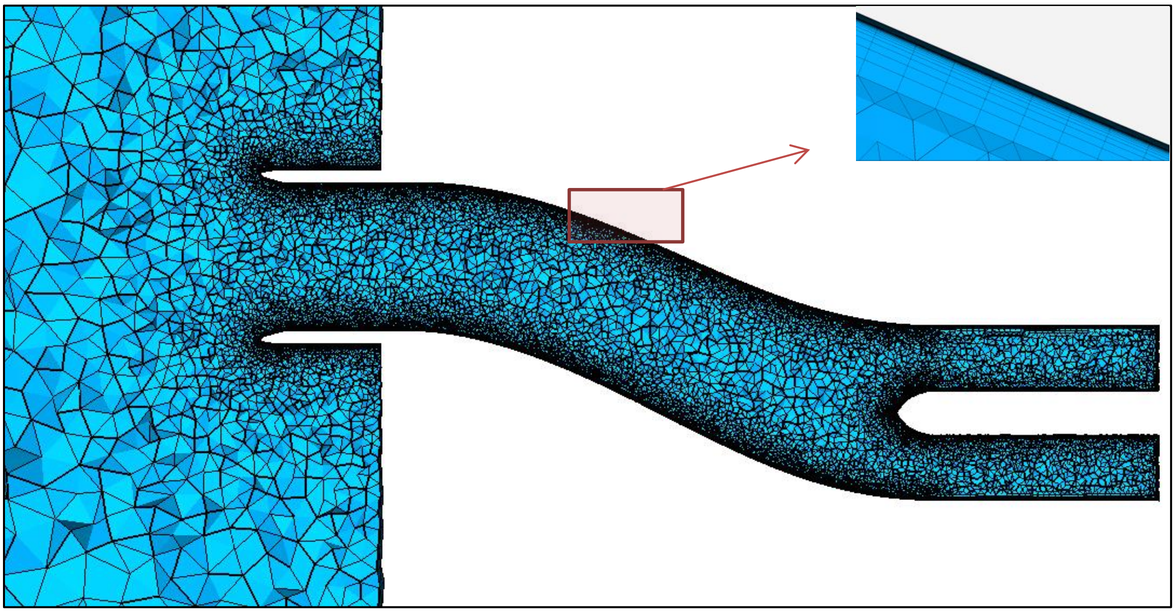


Figure 3: Triangular Mesh Cross-Section

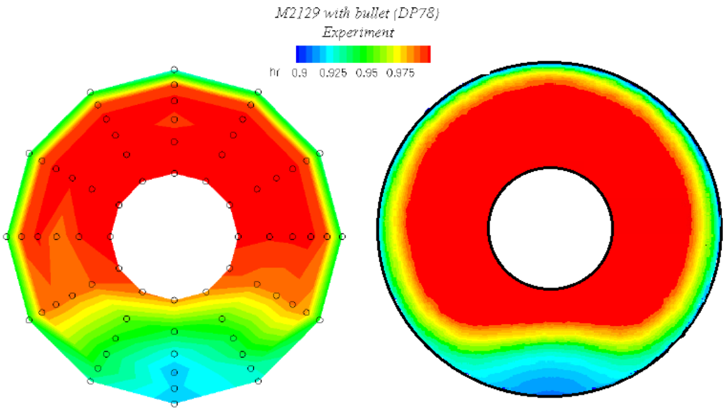


Figure 4: Experimental total pressure contours for M2129 (left) and Numerical Results total pressure contours at engine face (right)

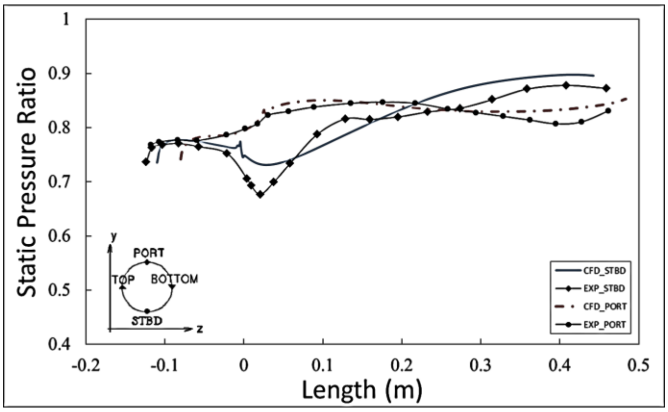


Figure 5: M2129 (DP78) wall pressure measurements and CFD results using k-epsilon turbulence model (Static pressure ratio is the ratio of averaged engine face static pressure to free-stream total pressure.)

M2129-Configuration	Static Data (ONERA)	CFD Results
Outlet Pressure (Pa)	-	91000
Engine Face Mach Number	0.4193	0.4232 (+1.40%)
Mass Flow Rate (kg/s)	2.692	2.72 (+1.00%)
Pressure Recovery (PR)	0.9744	0.9790 (+0.47%)
Distortion Coefficient	0.313	0.2971 (-5.07%)
PRA(Pstatic_engine/Ptot_inf)	0.8522	0.86 (+0.91%)

Table 2: Comparisons with Experimental Data

Wall static pressure ratios are compared at the bottom and top section of the inlet. Numerical results are close to experimental so that analysis technique can be used optimization cycle.

Performance parameters of the RAE M2129 model are tabulated in Table 2. Flow structure can be compared with engine face Mach number, mass flow rate, PRA and DC60. CFD results over predicts the experimental results for all the performance parameters except for the DC60. As indicated in Table 2, error values remain 5% error interval.

3.2 Performance optimization

First of all, the optimization algorithm decides individuals in the population, attaining each one of them binary string. In Genetic Algorithms, fitness values are evaluated for each individual in the population and new individuals are created by crossing fittest individuals and making random changes in the binary array of the newborn.

Optimization Cycle starts with the evaluations of the population. That evaluation detailed is sketched in Figure 7.

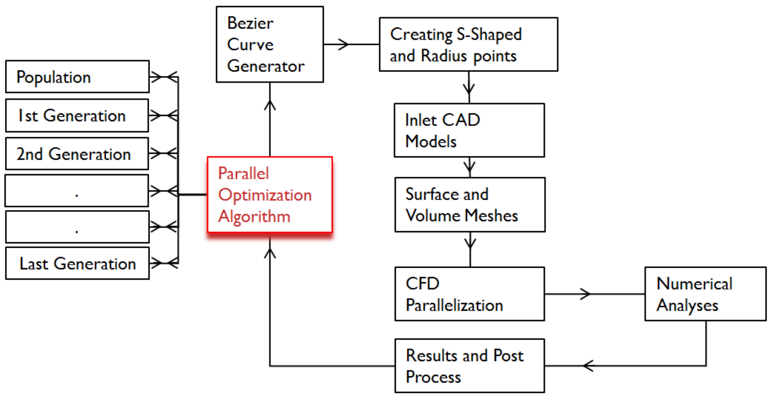


Figure 6 : Optimization Methodology Cycle

From the Figure 7, optimization algorithm sends a set of design points to analysis collaterally. The difference between sequential optimization algorithm and parallel optimization algorithm is that parallel one uses 4 Design-points with 320 CPU to have their results at the same time but sequential one uses 320 CPU for 1 Design-points and wait until it finished. Parallel Algorithm uses less CPU, quarter as in sequential algorithm but acceleration comes from faster evaluations, four times faster to evaluate whole population/generation and CPU speed up, elapsed time 2.2 hours for 80 CPU and 0.9 hours for 320 CPU.

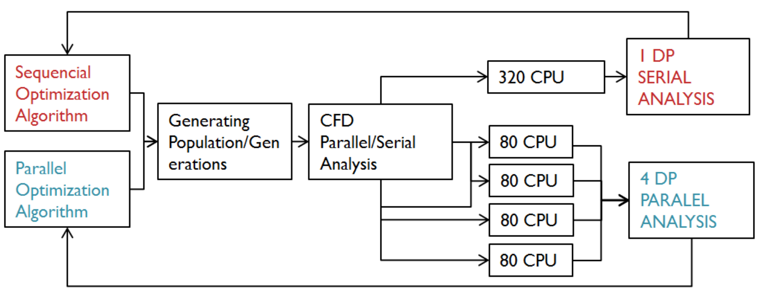


Figure 7 : The Difference between Sequential and Parallel Algorithms

	CPU per DP	Design Cycle per DP	Elapsed Time per DP(hour)	Total Elapsed Time(hour)
Sequential GA	320	1	0.9	260
Parallel GA	80	4	2.2	126,5

Table 3: Elapsed Time comparison for GAs Algorithms

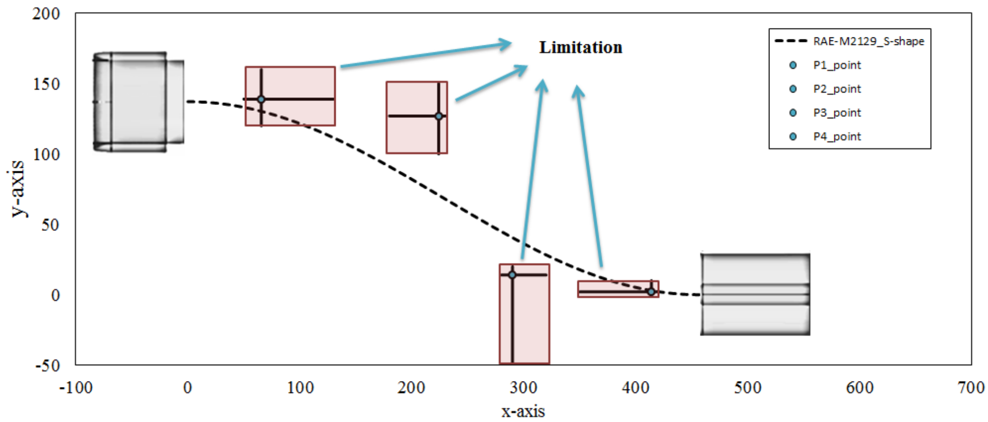


Figure 8 : Bezier Points Boundaries in Coordinates

Optimization Algorithms have 8 inputs, 4 points coordinate points. The Bezier curves are created by changing point's positions in the coordinates. Limitations come from the Bezier points defined RAE M2129 which is calculated iteratively.

Input	Lower Limit (mm)	M2129(Baseline) (mm)	Upper Limit
X1	50	65.62	130
Y1	120	139	160
X2	180	224	230
Y2	100	127	150
X3	280	290	320
Y3	-50	14	20
X4	350	414	420
Y4	0	2	10

Table 4: Input Parameters Limitation

The main object is to enhance flow quality that enters the engine. Flow has good quality when DC60 is less or PR is high.

Objectives	Target
DC60	Minimize
Pressure Recovery	Maximize

Table 5: Optimization Objectives

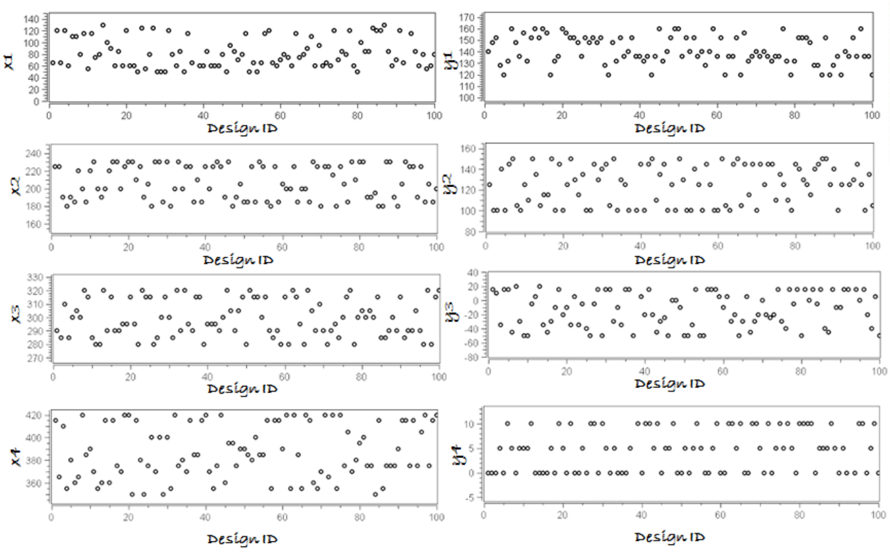


Figure 9: Individual's Bezier Points data in the coordinates for Population

GAs uses random seed for creating population individuals, searching domain randomly to understand behavior. Figure 9 shows how points disperse in the coordinates.

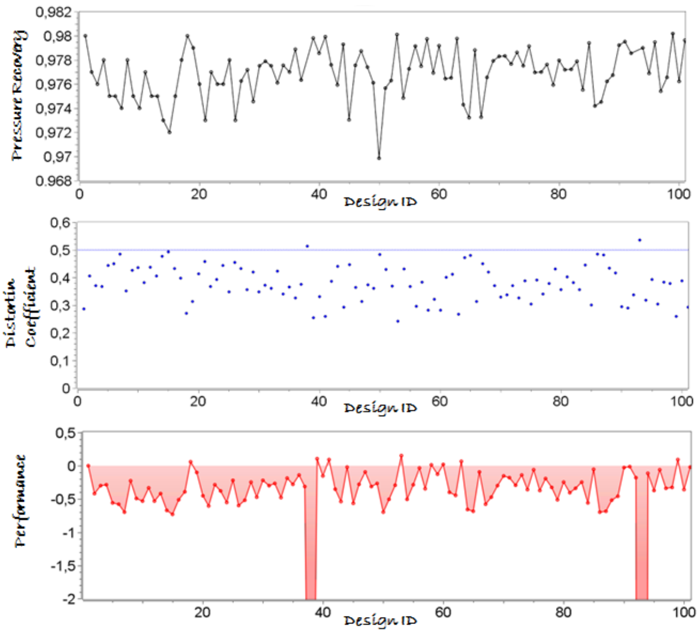


Figure 10 : Population Performance

Population has 100 Design Points (DP) at first. Performances for each individual is defined with the equal importance of how lower its distortion coefficients and how higher pressure recovery. From the Figure 10, there too few individual has positive performance, meaning better than baseline. Prominent individual's details given below.

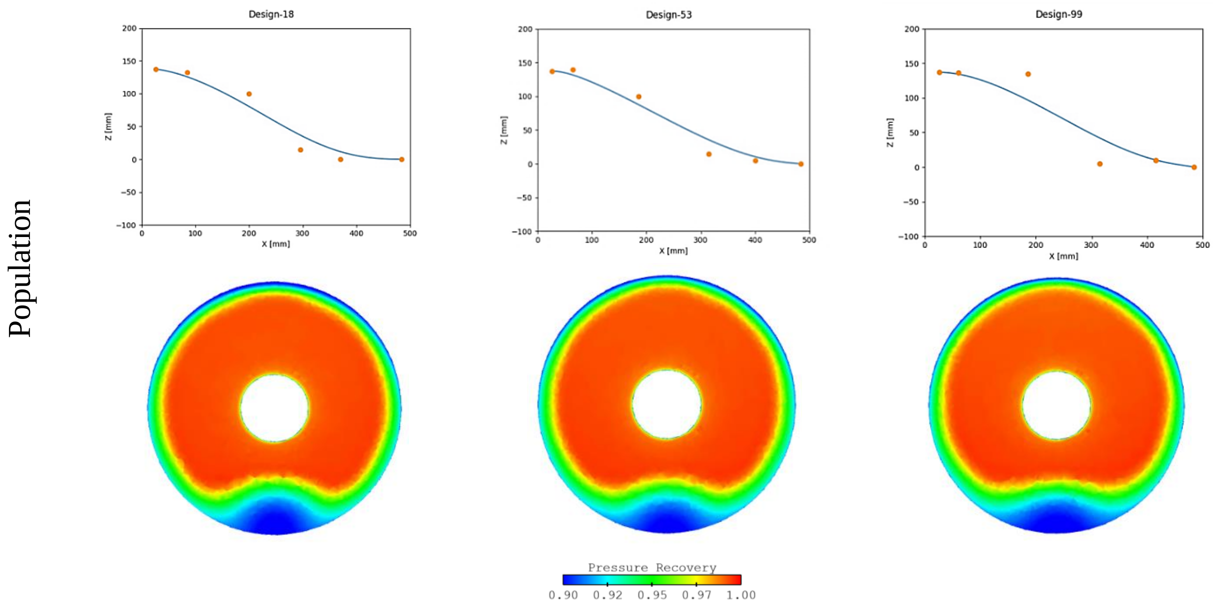


Figure 11: Outstanding Individuals in population

After having population results, GAs evaluates generations by using fittest individuals. There are 15 DP per generation cycle and Parallel GA uses 15 DP results to create new generations, include 15 DP.

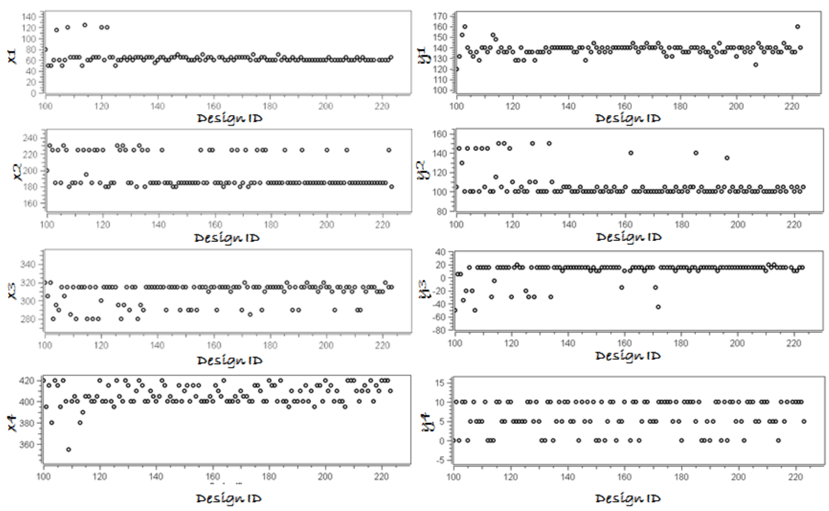


Figure 12: Individual's Bezier Points data in the coordinates for Generations

From the Figure 12, inputs have convergence along the optimization cycle. The reason why certain points have different value than convergence one is individual's mutation to avoid global minima/maxima.

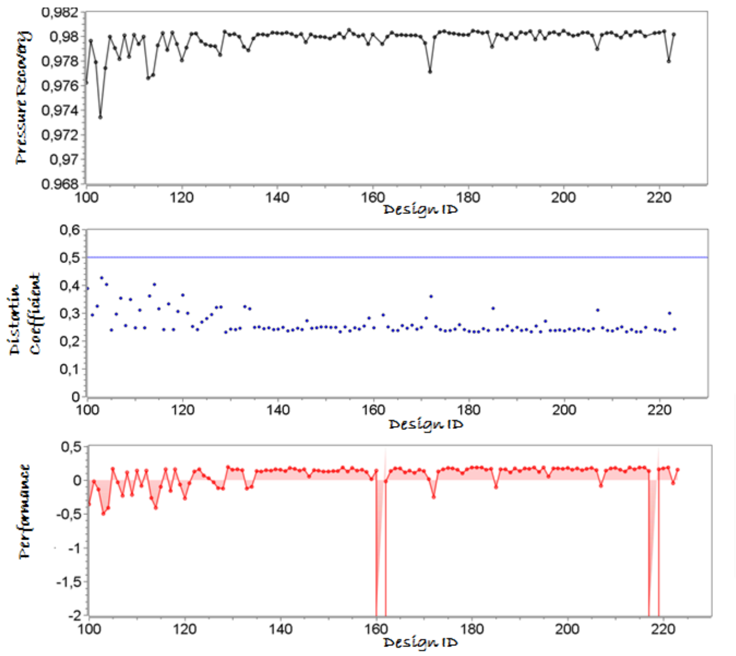
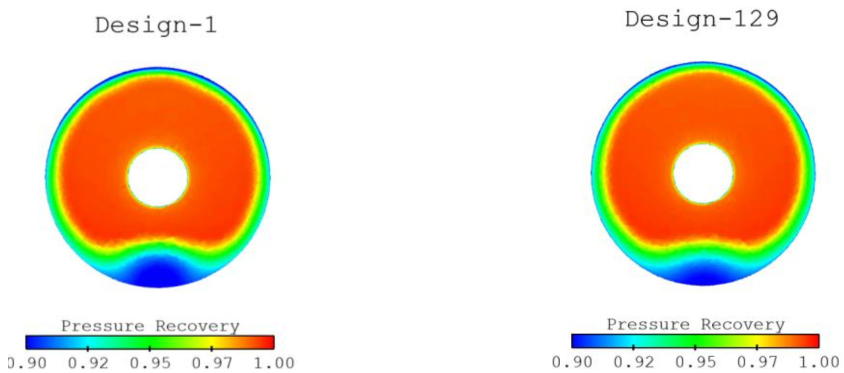


Figure 13: 9 Generations Performance (15 DP per Generation)

Performance results of generations have also steady-state. Design-129 has 26.2 and 0.5 percent improvement in distortion coefficient and pressure recovery, respectively. The reason of small improvement in pressure recovery is that the baseline already has good pressure recovery.



	Baseline (RAE M2129)	Design 129 (Best Design)
PR	0.9780	0.981
DC60	0.313	0.2318

Table 6: Performance Comparison for Baseline with Best Configuration

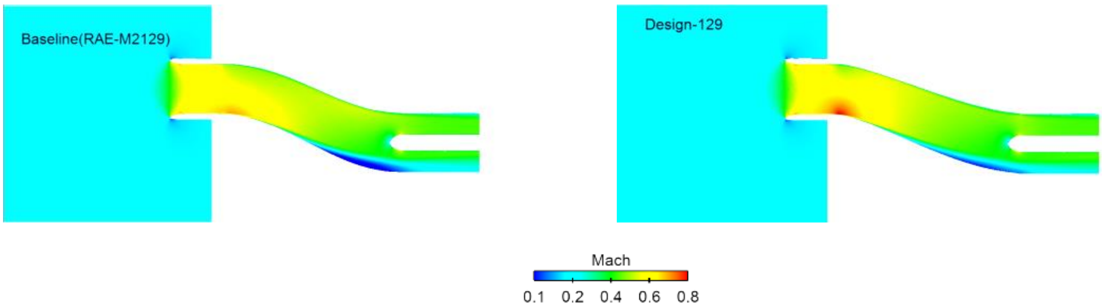


Figure 14: Mach Contours of Design-129 and RAE M2129

4 CONCLUSIONS

After having acceptable numerical results for validation case, s-shape optimization for RAE M2129 model was taken as a baseline. Optimization system uses Bezier function with controlling points to generate s-shape. To decrease the optimization cycle time, Parallel GAs Algorithm is used and it performs as half as of time elapsed in sequential algorithms. Then, best alternatives were compared with performance parameters. Baseline is enhanced at least 25 percentages less for distortion coefficient and 0.5 percentages less for pressure recovery.

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