

Axial Flow Turbine Aerodynamic Shape Design optimization

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1 Abstract

This paper presents an axial turbine blade metamodeling (surrogate modeling) process performing the axial turbine blade aerodynamic shape design optimization, based on the axial turbine design parameters. This modeling technique is applied on the rotor blade of the axial flow turbine stage, working through the small turbojet engine JETCAT P 200. This metamodel consists of 140 turbine stage CFD models, generated by varying the inlet and exit meanline airfoil cone angles of the rotor blade within certain range using the integrated random sampling function in the commercial program MATLAB. The flow field of these models is solved numerically by the commercial CFD code ANSYS CFX. The objective of these optimization process is to study the effect of blade profile shape change on the different aerothermodynamic performance parameters of the axial turbine stage. A special code is designed on MATLAB to collect the resultant data of great concern from the pre-solved CFD models. The CFD generated data is interpolated and presented in graphs using the integrated curve fitting APPS in MATLAB to study the relationship between the turbine blade profile change and the axial turbine stage working conditions, which is the Surrogate Modeling. The presented parameters are the total-total isentropic efficiency, exit stage total pressure, turbine work, engine thrust, mass flow rate through the turbine stage. A multi objective optimization using the Surrogate Model generated data to determine the optimum working point according to the requirements of the present case study.

2 Introduction

At the end of the design cycle, it becomes essential to optimize the design according to the requirements of the working application. In the field of axial flow turbine shape design optimization, there is no direct relationship between the turbine shape design parameters and the flow working conditions (cannot be represented by a direct equation). The mass, momentum and energy transfer of the flow through the axial flow turbine are governed by a non-linear 2nd order partial differential equations (could not be solved analytically), so, the flow field around the axial turbine blades needs to be evaluated numerically using the CFD techniques. In the present case, there is no direct relationship between i.e. turbine total-total efficiency and the blade profile shape parameters, so, using the conventional optimization algorithms like Genetic Algorithm (GA) are so difficult to be applied. The optimization process using the conventional GA needs designing of special codes of high-level language which is out of scope of most of the turbomachinery designers and takes much time to be achieved. Surrogate model or metamodel will be efficient to be used here, which is called the Aerodynamic design optimization (ADO). The first step of performing this technique is to design a CFD model representing the studied axial turbine stage using its dimensions and working conditions. The flow parameters (objective) are obtained numerically by solving the turbine stage flow-field over the real case working domain using the commercial CFD code ANSYS CFX. After validating the results of the designed CFD model, it becomes the High-Fidelity Model. The domain of the experiment should be designed with a fair number of CFD models, and the response surface is generated for the flow parameters of great concern separately. The response surface is a three axes graph, in which, the independent parameters are represented on the x and y axes, while the z axis represents the resultant data from the CFD code for the objective parameter. The response surface becomes the direct mathematical relationship between the independent variable and flow parameters. The mathematical equation of the response surface is now easy to be obtained using the modern programs like i.e. MATLAB or EXCEL. A check step here is essential by solving more number of high-fidelity models and comparing its results with those are predicted using the generated response surface. A new phase of the optimization process is ready to be achieved, the role of the high-fidelity model (the CFD work) is finished. The response surface becomes the main model to predict the needed turbine performance parameters data for any proposed model over the designed domain of experiment and for any further optimization work [1].

The Aerodynamic Design Optimization is recently increased due to the increasing demands for optimizing complicated geometries like studying the different turbomachinery blade profiles, achieving improved operating conditions, and satisfying several design and market requirements. Since the aerodynamic design works mainly depend on numerical simulation computer codes, the use of ADO is now strongly preferred because of the increasing capabilities of modern super computers.

3 Surrogate construction methodology

Fig. 1 shows a flow chart for the whole process of turbine rotor profile shape optimization including the metamodel construction steps which is described in further sections.

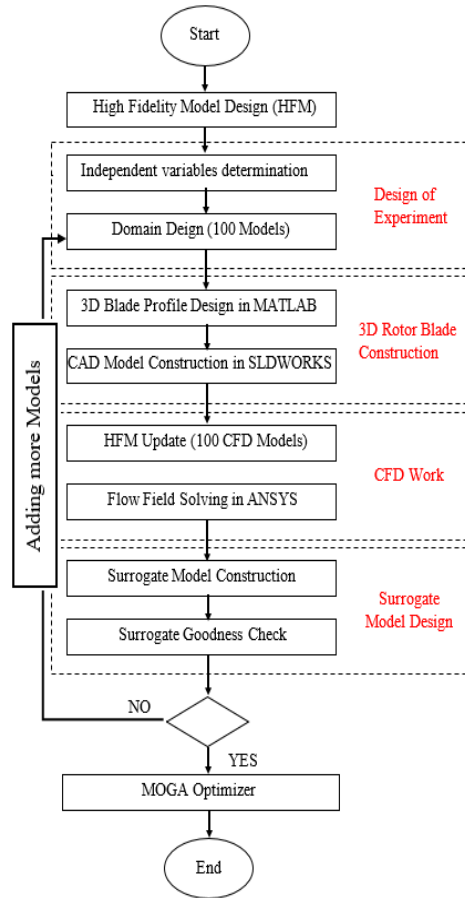


Fig. 1 Metamodel construction methodology flow chart

3.1 High-Fidelity Model design

A CFD model is designed for the axial turbine stage of the turbojet engine JETCAT P200 and the flow field is solved numerically. The results of the CFD work are verified compared with the real dimensions and working conditions of the real case [2]. This CFD model is called now the High-fidelity Model.

3.2 Design of experiment (DoE)

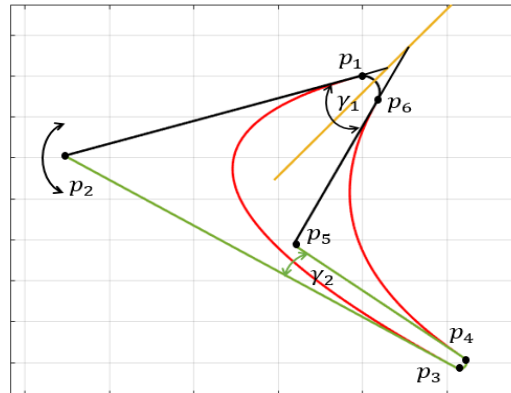


Fig. 2 2D turbine rotor blade airfoil parametrization

To investigate the effect of rotor blade profile change on the turbine stage aerothermodynamic performance, the geometric variables that control the blade profile shape would be determined as the independent variables.

The blade three-dimensional shape construction depends mainly on the two-dimensional construction and parametrization of the airfoils at different radii. The airfoil two-dimensional parametrization is based on the proposed inlet and exit blade cone angles γ_1 & γ_2 through the airfoil graphical design method Fig. 2. The used graphical method to design the airfoil, enables the designer to construct 3 control points for each side (pressure side and suction side) to generate a parabolic spline fit curve [3] representing the pressure and suction side of the airfoil [4].

These three points for each arc, are formed by the intersection of the two lines constructing the governing cone angles γ_1 & γ_2 . For the suction side, the points p_1 & p_2 & p_3 are the control points and p_4 & p_5 & p_6 are the control points of the pressure side as shown in Fig. 2.

In the proposed methodology, the nominal values of γ_1 is 45° at the root section and 15° at the tip section with linear change along the blade span, while the nominal values of γ_2 is 5° at the root section and 3° at the tip section with linear change along the blade span.

The target of this work is to investigate the effect of changing the nominal values of γ_1 & γ_2 within certain range on the different performance parameters of the axial flow turbine stage to recommend new nominal values for these angles according to the requirements of the recent application.

The proposed ranges of γ_1 & γ_2 values change are $[40^\circ - 50^\circ]$ and $[3^\circ - 8^\circ]$ respectively at the root section and $[12^\circ - 18^\circ]$ and $[1.5^\circ - 4.5^\circ]$ respectively at the tip section with linear change along the blade span.

3.3 Domain design

The pre-mentioned ranges of γ_1 & γ_2 are sampled to design the working domain. Random sampling is used to perform the step of Design Of Experiment, because the random design is the simplest domain design technique while the other techniques need more complications to be applied. The major disadvantage of the random technique is that the generated points are not of uniform distribution over the working domain which harms the smoothness of the Response Surface. The Random Sampling step is done using the integrated random sampling function in MATLAB.

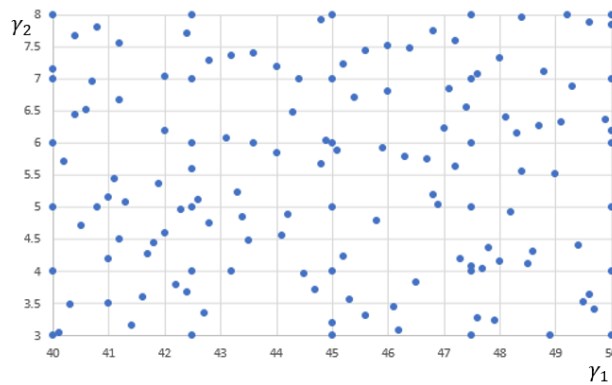


Fig. 3 Data sampling covering the domain of study

As a start, the working domain contains 100 points Fig. 3, which in turn means 100 CDF models.

3.4 CAD model construction

The generated sampling data is used as an input matrix to the designed MATLAB code to generate the three-dimensional point cloud constructing the blade shape profile in the form of text file. The text file is imported into the program SOLIDWORKS to generate the CAD model for the 100-sampling data using the integrated MACROS. Fig. 4 shows a graph generated in the MATLAB program for the rotor blade 2D airfoil hub section profile change covering the domain of the experiment.

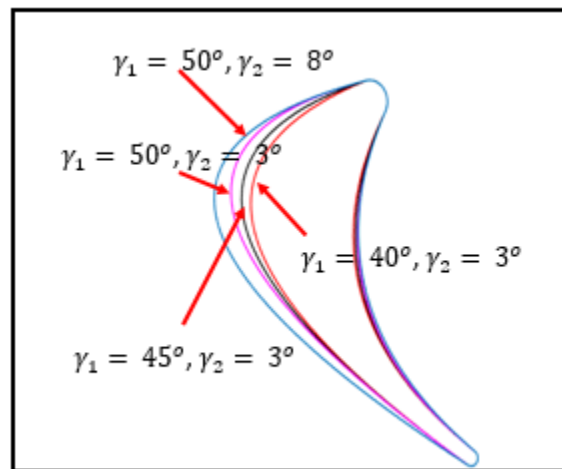


Fig. 4 2D airfoil shape variation with the rotor blade cone angles change

3.5 Numerical procedure

The process of generating 100 CFD models is done according to a certain semi-automated methodology. The generated CAD model (described in section 3.3) is saved (overwritten) in the ANSYS imported files of the high-fidelity model which is considered as the base model of the CFD work. The geometry of the new blade model is updated in the DESIGNMODELER using a special PAYTHON program. The whole CFD model is updated and the run over the same domain and boundary conditions of the base model. This process is repeated for the 100 CFD models and a MATLAB code is designed to extract the flow parameters to be discussed.

3.5.1 Parameters of great concern

At the end of the CFD work, CFX gives a full picture for the flow parameters. The main function of the gas turbine stage in the JETCAT P200 turbojet engine is to drive the centrifugal compressor and to

deliver the flow to the exhaust nozzle in good conditions (high total pressure and complete axial flow direction) to generate the maximum available thrust.

The turbine function directs the designer to the parameters that should be shown and analyzed. The work delivered to the compressor and the turbine exit flow parameters that affect the thrust are shown and discussed over the range of the study. For fixed exhaust nozzle characteristics, the engine thrust could be calculated by knowing the turbine exit total pressure and the mass flow rate as follows:

$$F = F_s m$$

Such that F_s is the engine specific thrust, m is the engine mass flow rate.

For fixed exhaust nozzle characteristics [5],

$$F_s = \sqrt{2 \bar{c}_p T_{tet} \eta_{EN} \left(1 - \frac{P_{tit}}{P_{tet}} \right)^{\frac{\gamma-1}{\gamma}}}$$

Where P_{tit} is the turbine inlet total pressure and T_{tet} , P_{tet} are the turbine exit total temperature and pressure respectively. The mass flow rate and the turbine stage exit total pressure are obtained from the CFD calculations.

Fig. 5 shows scattering for the obtained flow parameters from the CFD calculations

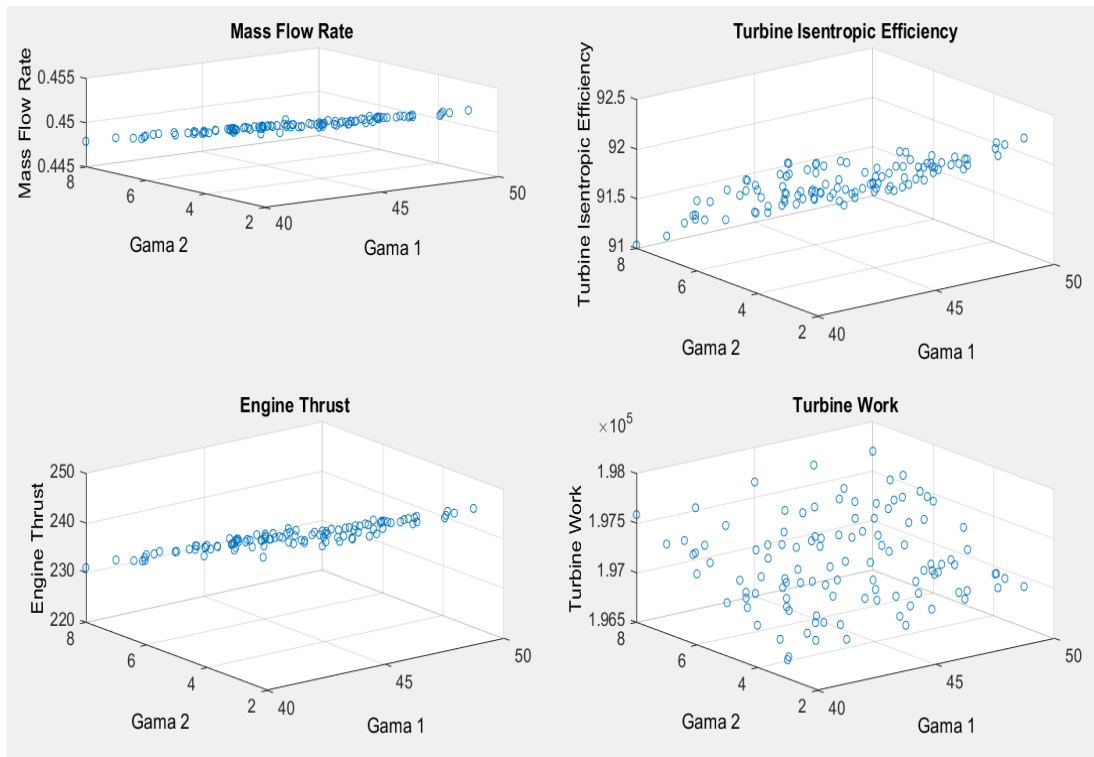


Fig. 5 Three-dimensional scattering graph for the CFD results

3.6 Fitting the scattered resulted data

The resultant CFD data is interpolated using the Polynomial regression integrated on curve fitting APPS in MATLAB to show the relationship between each of the axial turbine performance parameter with the independent parameters γ_1 & γ_2 on a Three-dimensional graph which is known as the Surrogate. The mathematical equation of each Surrogate is determined easily on MATLAB.

3.6.1 Surrogate interpolation Goodness Check

At this step, the role of CFD work has end and the Surrogate Equations become the new model to be investigated and used in further work. For this model to be trusted, a check step is done. An extra 20 CFD models are designed and evaluated numerically and then, the axial turbine performance parameters values are obtained. The same parameters data are predicted using the determined Surrogate equations and compared with those of the CFD data. The comparison gives an average deviation > 5 % which is not acceptable. These extra models are added to Surrogates to enhance its accuracy. The same process is repeated for another 10 CFD models and the results give an error value $\leq 0.005\%$ as shown in Table 1.

Table 1 Comparison between CFD data and Surrogate data

γ_1	42.5	42.5	42.5	42.5	42.5	42.5	45	45	45	45
γ_2	3	4	5	6	7	8	3	4	5	6
Efficiency from CFD	93.78	93.79	93.83	93.85	93.85	93.87	93.79	93.81	93.83	93.84
Predicted Efficiency	93.33	94.28	93.56	93.1	93.73	93.17	93.99	93.86	93.36	93.65
Deviation	0.005	-0.005	0.0029	0.008	0.0014	0.007	-0.002	-0.0005	0.005	0.002

3.6.2 CFD data analysis

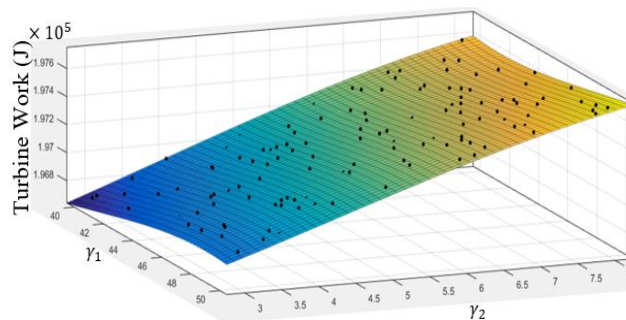


Fig. 6 Change of Turbine Work over the domain

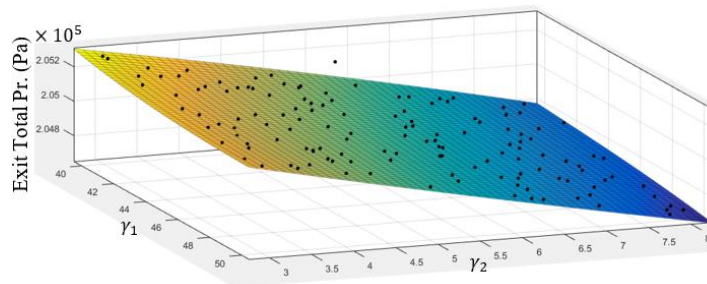


Fig. 7 Change of the turbine exit total pressure over the domain

As shown in Fig. 6, the work extracted by the turbine increases proportionally with both γ_1 & γ_2 [6]. As a result, the turbine exit total pressure behaves inversely in the same direction as shown in Fig. 7 according to Bernoulli's equation [7].

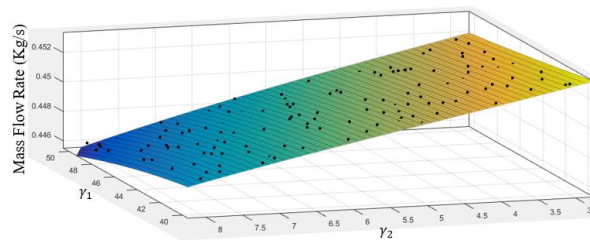


Fig. 8 Change of mass flow rate over the domain

The increase of γ_1 & γ_2 causes the increase of the rotor blade thickness, so, as shown in Fig. 8, the mass flow rate increases in the direction of decreasing both γ_1 & γ_2 due to the increasing of the flow path area (decreasing of turbine metal blockage). But the mass flow rate has no great change due to the increase of the turbine exit total pressure which decreases the mass flow velocity according Bernoulli's Eqn.

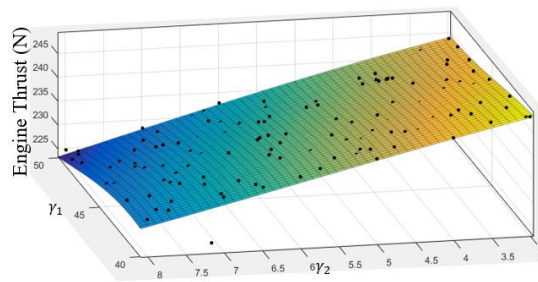


Fig. 9 Change of Engine Thrust over the domain

As the engine thrust is function of the mass flow rate and the turbine exit total pressure and has a direct proportional change with these parameters [8], the engine thrust has remarkable increase in the same direction of changing the mass flow rate, turbine exit total pressure and temperature parameters as shown in Fig. 9.

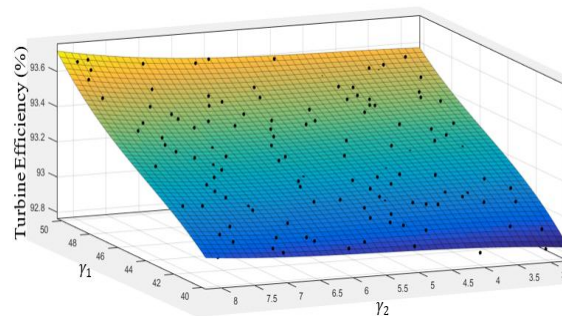


Fig. 10. Change of Turbine Total-Total Isentropic Efficiency over the domain

Fig. 10 shows the change of the turbine isentropic total-total efficiency over the domain of study with a value of 0.84 %. The minimum value is for the model of $\gamma_1 = 40^\circ$, $\gamma_2 = 3^\circ$ and the maximum value is for the model of $\gamma_1 = 50^\circ$, $\gamma_2 = 8^\circ$ which means that the turbine isentropic total-total efficiency increases in the direction of increasing the rotor blade cone metal angles.

The turbine isentropic total-total efficiency changes slightly in the direction of increasing the angle γ_1 , but the major change in the direction of increasing the angle γ_2 .

3.7 Optimization using Multi-Objective Function Genetic Algorithm

As discussed in the previous section, the axial flow turbine performance parameters behave inversely, which increase the difficulty of choosing the optimum point which will be the working point. The Multi Objective Genetic Algorithm optimization

(MOGA) is applied here using the generated surrogate models to determine the optimum working point according to designer objectives [9].

The optimization problem can be defined by the following objective functions:

$$\text{Maximize } f_1(X) = \text{Mass flow rate}$$

$$\text{Maximize } f_2(X) = \text{Engine thrust}$$

$$\text{Maximize } f_3(X) = \text{Turbine efficiency}$$

$$\text{Maximize } f_4(X) = \text{Turbine work}$$

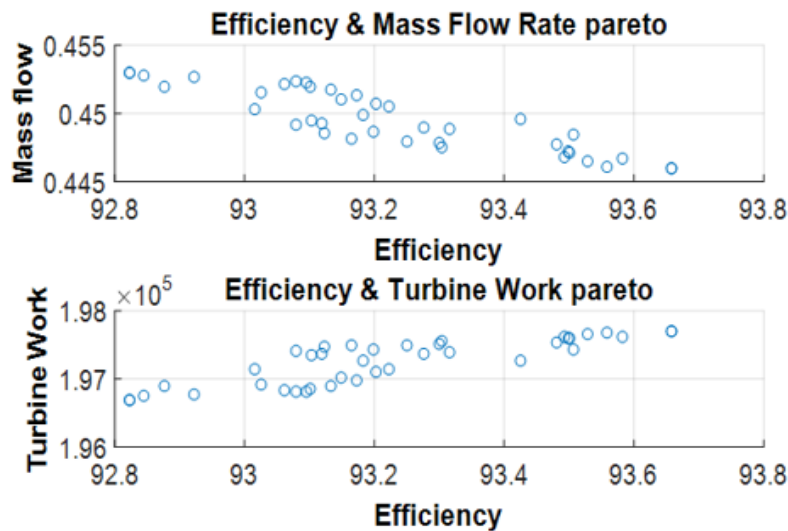
The optimization parameters vector X includes the inlet and exit cone angles γ_1 & γ_2 [10].

$$X = [\gamma_1 \quad \gamma_2]^T$$

A MATLAB code is developed to perform the Multi Objective Genetic Algorithm optimization process. The initial population size selected as 200, the design parameters lower and upper bounds are $L_B = [40, 3]^T$ and $U_B = [50, 8]^T$ respectively.

By tracing the scatter points in

Fig. 11 a & b, engine thrust and the mass flow rate increase as turbine efficiency stiffness decreases, while the turbine work increases with the increasing of the turbine efficiency.



a: Pareto diagram for multiple weights of the efficiency, mass flow, engine thrust and turbine work

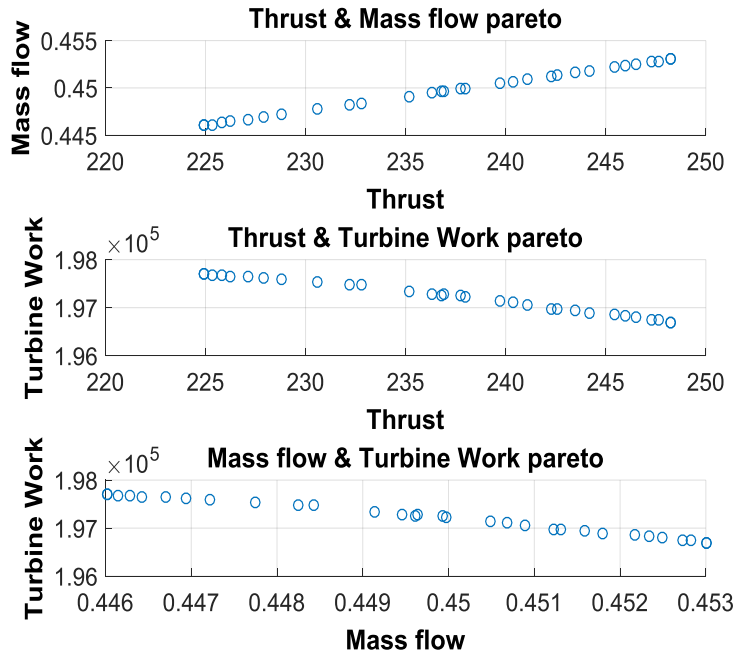


Fig. 11 b: Pareto diagram for multiple weights of the efficiency, mass flow, engine thrust and turbine work

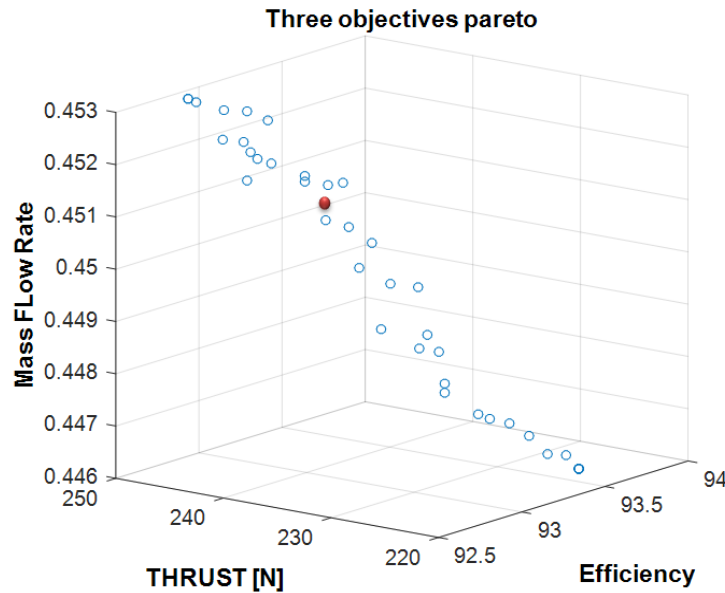


Fig. 12 Three objective Pareto diagram

As shown in Fig. 12, the red highlighted point could be the optimum point that generated by the optimum model of ($\gamma_1 = 43^\circ$ & $\gamma_2 = 4^\circ$) that it fulfils the required mass flow rate and gives good values for the other flow parameters. Table 2 shows the data of the base model and that of the final optimized one.

Table 2 Resultant values of the optimization process

Model	Mass flow rate[kg/s]	Turbine efficiency	Engine thrust [N]
High-fidelity model	0.45	93.2 %	230
Optimized model	0.451	93.12 %	242
Gain	0.2 %	-0.09 %	5.2 %

3.8 Conclusions

Aerodynamic Design Optimization is done to investigate the impact of the rotor blade profile shape change on the axial flow turbine stage flow parameters. A met model is constructed for the high-fidelity CFD turbine model showing the change of mass flow rate, turbine work, turbine exit total pressure, turbine total-total isentropic efficiency and engine thrust with the change of blade thickness.

An optimum point is clearly chosen achieving the required mass flow rate with enhancement of other flow parameters.

3.9 References

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