MULTI-POINT, MULTI-OBJECTIVE OPTIMISATION OF CENTRIFUGAL FANS BY 3D INVERSE DESIGN METHOD

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SUMMARY

In this paper we present the design and optimisation of a centrifugal fan with requirements of maximizing the pressure rise and efficiency at two operating points and the maximum torque provided by the motor power using 3D inverse design method, DOE (Design of Experiment), RSM (Response Surface Model) and MOGA (Multi-objective Genetic Algorithm). The fan geometry is parametrized using 13 design parameters and 120 different designs are generated. The fan performance of all the designs at two operating conditions are evaluated through steady-stage CFD simulations. The resulting design matrix is used to create a RSM based on Kriging method and MOGA is used to search the design space using the RSM and find the optimal designs.

INTRODUCTION

Centrifugal fans are used in many applications where relatively high pressure rise is required in the compact size. The application can vary from household appliances, industrial to air-conditioning and data center cooling applications. In many of these applications the fans are required to meet multi-point requirements in terms of both pressure rise and efficiency. In the literature, several work have been published to show the aerodynamic optimisation of centrifugal fans using both numerical and experimental methods. [1] [2] [3]

In this paper we started with the design of a baseline design which meets the pressure rise requirements at two operating points using 3D inverse design method. The fan aerodynamic performance (pressure-rise and efficiency) is evaluated through steady-state CFD simulations. The meridional geometry and blade loading parameters are then parameterized using 13 parameters and around 120 different blade geometries are generated with a wide range of variation of these 13 design parameters. Pressure rise and efficiency values of these 120 designs will be evaluated using CFD simulations. A design matrix consisting of all the design and performance parameters of these 120 designs is obtained. Kriging will be used to create a RSM using the design matrix data and

MOGA will be used to search the optimal designs in the design space based on RSM. The final optimal design is selected from the Pareto Front and its performance is validated using CFD simulations at two operating points. The flow chart of the design and optimization process is shown in Figure 1.

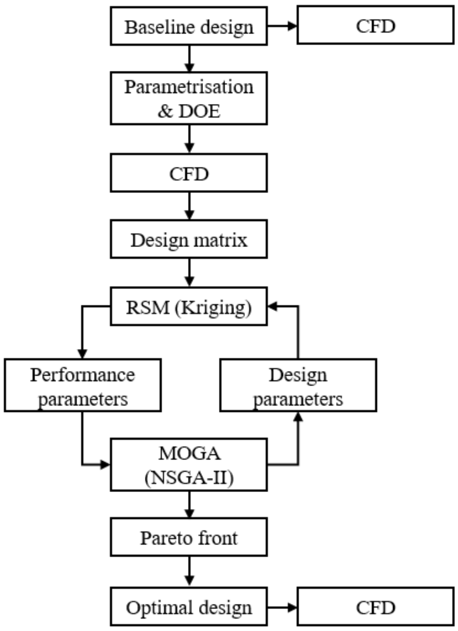

Figure 1: Flow chart of the design and optimization process

BLADE DESIGN

3D inverse design method

The 3D inverse design method, also known as Circulation Method in the literature, is described in details in [4]. It has been used in the design of all types of fans including axial fans [5] and centrifugal blowers [6]. The blade geometry is calculated iteratively based on the prescribed blade loading distribution ($\frac{\partial(r\overline{V_\theta})}{\partial m}$, the derivative of $r\overline{V_\theta}$ along the meridional direction) on the meridional geometry. $r\overline{V_\theta}$ is the circumferentially averaged bound circulation and is defined by Eq. (1) below. For incompressible potential flow, the blade loading (the pressure difference between the pressure surface and suction surface of the blade) is defined by Eq. (2).

$$r\overline{V_\theta} = \frac{N}{2\pi}\int_0^{2\pi/N} r \cdot V_\theta d\theta \tag{1}$$

$$p^+ - p^- = \frac{2\pi}{N}\rho W_{mbl}\frac{\partial(r\overline{V_\theta})}{\partial m} \tag{2}$$

Using the inverse design method, the blade meridional geometry and the blade thickness distribution need to be defined first. LE and TE $r\overline{V_\theta}$ are used as inputs which will fix the work coefficient (specific torque/power) based on Euler's Turbomachinery Equation. The streamwise blade loading distribution ($\frac{\partial(r\overline{V_\theta})}{\partial m}$) is defined using a three-segment method shown in the Figure 2. The loading distribution is defined by two curves at hub and shroud. For each curve, two points on the meridional location (NC and ND) divide the curve into three parts. The first and last curves are parabolic and the middle curve is a straight line. The slope of the middle straight line is defined by a parameter called SLOPE. The loading value at LE (m = 0) is defined by DRVT which controls the incidence at the LE.

The last input parameter required is the stacking condition which is a spanwise wrap angle distribution at a fixed streamwise location. For fans, it is common to stack at the TE. Most of the centrifugal fans are made from sheet metal and the blade has to be 2D and axial filament. However, development in additive manufacturing can make it easier to design centrifugal fan blades with 3D geometry. The 3D inverse design method used in this study makes it quite easy to design either in 3D or in 2D. In this paper, a 2D geometry is used for the blade optimization and a zero stacking at TE has been used for all the designs. Once all the inputs are specified, the 3D inverse design method computes the blade shape for a given specified blade loading.

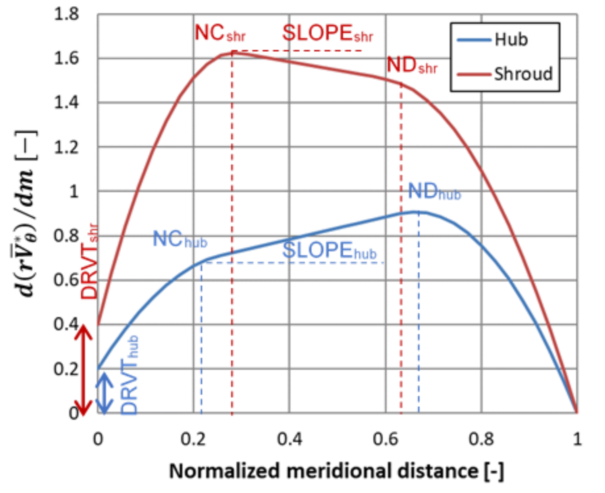

Figure 2: Streamwise blade loading defined using three-segment method

Design specifications and baseline blade generation

The design specifications are shown in Table 1. The fan is required to meet the minimum pressure rise requirements at two operating points (OP_1 and OP_2). The maximum torque is set by the motor provided and the main target is to maximize the efficiency at two operating points. The geometrical constraints are that the fan diameter cannot exceed the maximum value provided and the blade has to be 2D and axial-filament.

Table 1: Design specifications and constraints

RPM	$\leq RPM_{max}$
Volume flow rate @ OP_1	Q_1
Pressure rise @ OP_1	$\geq \Delta P_1$
Volume flow rate @ OP_2	Q_2 = 117 % Q_1
Pressure rise @ OP_2	$\geq \Delta P_2$
Torque	$\leq \tau_{max}$
Efficiency @ OP_1	Maximize
Efficiency @ OP_2	Maximize
Impeller diameter	$\leq D_{max}$
Blade	2D & axial-filament

The meridional geometry of the baseline design is shown in Figure 3. The blade thickness distribution is defined as 5 mm and the No. of blades is 10. The LE/TE $r\overline{V_\theta}$ and streamwise blade loading are shown in Figure 4. It is noted that LE/TE $r\overline{V_\theta}$ is normalized by the blade tip radius and tip speed. Once the solver is converged, the 3D blade from the inverse design method will be converted to a 2D/axial-filament blade using axial filament modification which axially maps the wrap angle distribution of the hub to all the other spanwise layers.

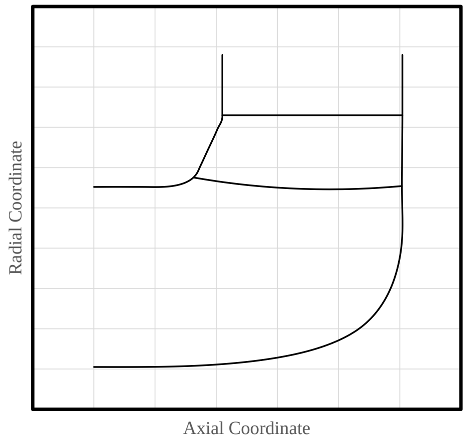

Figure 3: Baseline meridional geometry

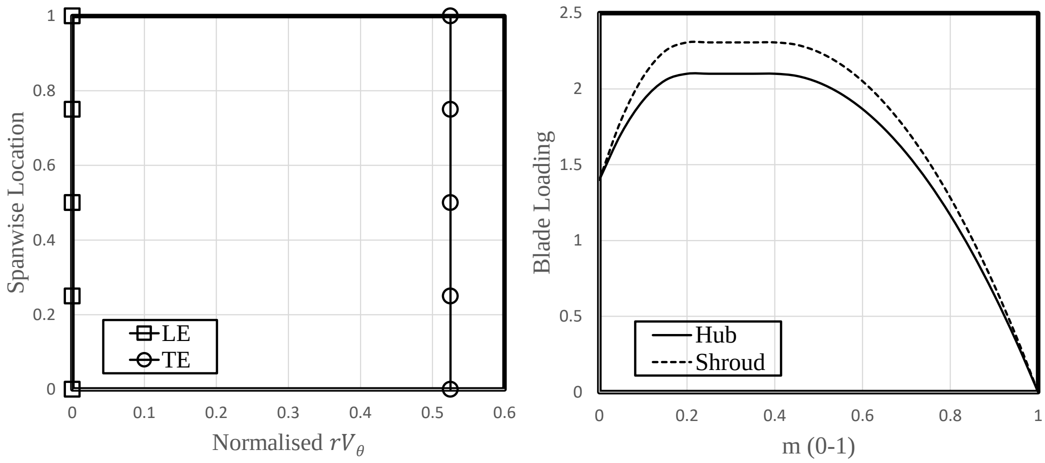

Figure 4: Baseline spanwise $r\overline{V_\theta}$ and streamwise blade loading

CFD SIMULATION

Mesh generation

The structured mesh is generated using ANSYS TurboGrid for the impeller blade (around 500,000 hexahedra elements) and unstructured mesh is generated for the inlet cone and inblock/outblock geometries (around 500,000 tetrahedra elements). The total number of elements is around 1,000,000. The near wall element size is 0.03 mm for the impeller and 0.05 mm for the inblock/outblock which result in the maximum y+ value on the walls of less than 1.0. The No. of prism layers for the inflation is 10. As it can be seen in the Figure 5, the gap between the stationary inlet cone and rotating impeller shroud casing is well resolved.

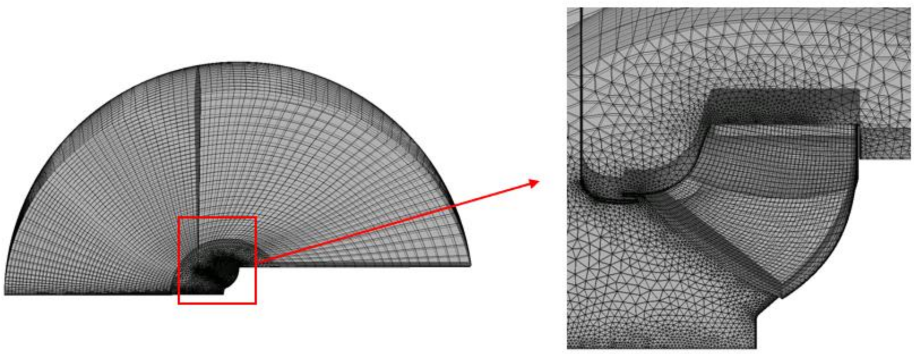

Figure 5: Computational domain

CFD setup

Steady-state CFD simulations (RANS) are performed by using commercial software ANSYS CFX. The inlet boundary condition is mass flow rate and the outlet boundary condition is opening with 1 atm static pressure. The impeller domain is rotational with the fixed RPM. Periodic boundary conditions are used for all domains to save the computational cost. The interface between the stationary domain and rotational domain is set as Frozen Rotor. The turbulence model used is SST k-ω. High resolution (2^{nd}-order) advection scheme is used. The convergence criteria for the continuity and momentum equations is set as RMS < 1.0e-04. The fan pressure rise and torque values are monitored and will reach to a constant value once the solution is converged. The complete CFD model is shown in Figure 6.

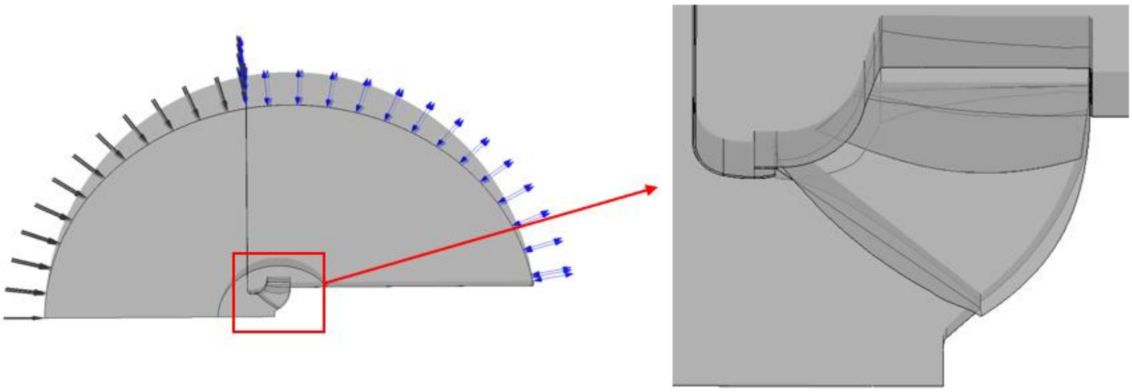

Figure 6: CFD model in ANSYS CFX

CFD results

Once the CFD simulations are converged, the pressure rise, torque and efficiency values can be obtained for both operating points (OP_1 and OP_2) and are summarized in Table 2.

Table 2: Baseline CFD results

	OP_1	OP_2
RPM	RPM_{max}	RPM_{max}
Q	Q_1	Q_2
ΔP_{ts}	$0.99\ \Delta P_1$	$0.94\ \Delta P_2$
τ	τ_{max}	$0.91\tau_{max}$
η_{ts}	57.7 %	44.2 %

It can be seen that the baseline design almost meets the pressure rise requirements at both operating points and does not exceed the maximum torque. The efficiencies for OP_1 and OP_2 are 57.7 % and 44.2 % respectively. After examining the detailed flow field, it is found that the flow behaves well at hub and mis-span locations but separates near the shroud part of the blade at OP_1 and OP_2 which can be seen in Figure 7.

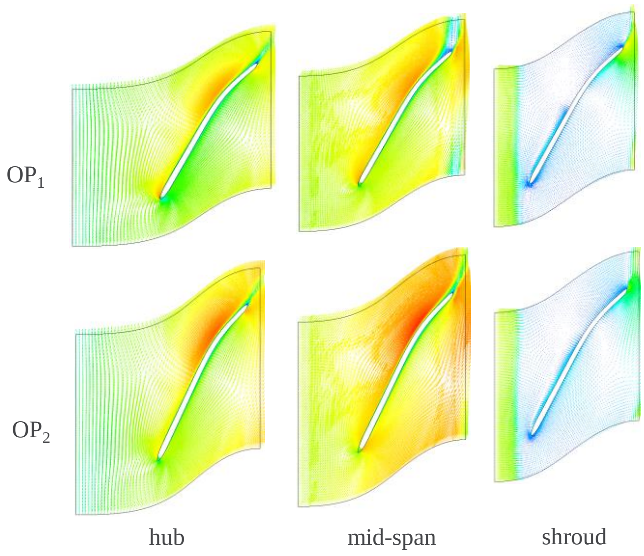

Figure 7: Baseline relative velocity vector at OP_1 and OP_2

BLADE PARAMETRISATION, DOE AND OPTIMISATION

Blade parametrisation

To improve and get the best possible fan performance, a DOE study will be performed. To begin with, the fan meridional geometry is parametrized by 8 parameters including blade tip width (L), hub radial length (dR_{hub}), shroud radial length (dR_{shr}), TE angle (α), hub angle (β_{hub}), shroud angle (β_{shr}), LE curvature and shroud curvature as shown in Figure 8. The loading parameters (NC, ND, SLOPE, DRVT and RVT_TE) will be varied in the DOE and same values are used for hub and shroud. The blade number and the blade thickness are fixed and kept same as the baseline design. In total 13 design parameters are used to parametrize the blade geometry.

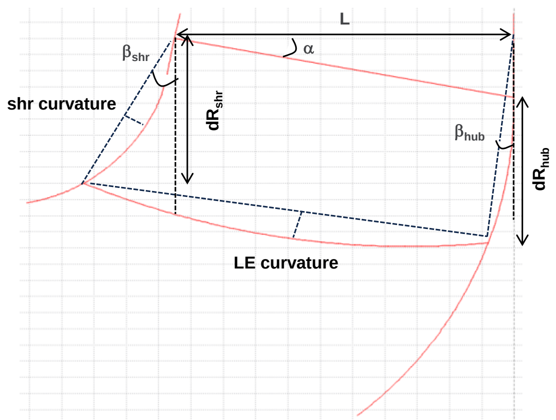

Figure 8: Meridional geometry parametrisation

DOE

For each of the 13 design parameters, a large variation of range around the baseline value is specified which allows a large design space to be explored. 120 different designs are generated using OLHS (optimal Latin hypercube sampling) method. For each design, the blade generation, meshing and CFD (two operating points) are performed automatically in ANSYS Workbench as shown in Figure 9.

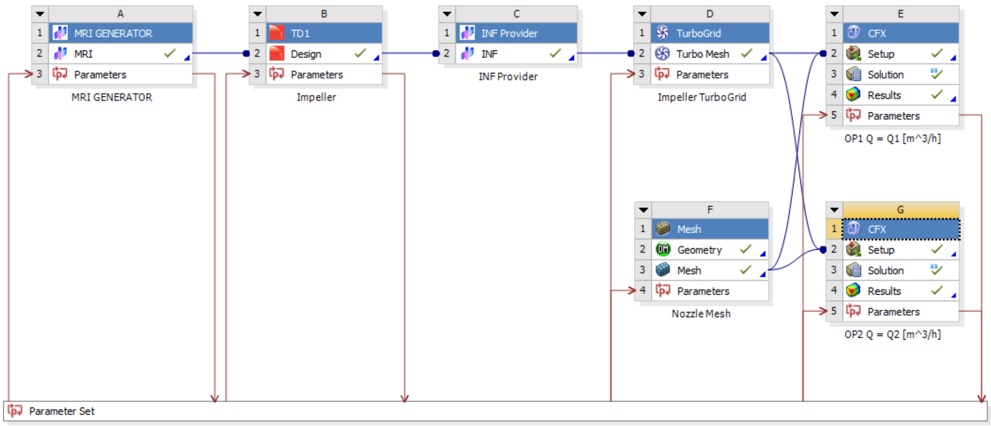

Figure 9: Automated DOE workflow in ANSYS Workbench

Once the CFD simulations are finished, a design matrix of 120 designs with all the design parameters and performance parameters are obtained. All the CFD results are shown in Figure 10. It can be seen that a number of designs in the DOE meet the minimum pressure rise requirements at both operating points with good efficiencies compared to the baseline design. The torque values of almost all the DOE designs do not exceed the maximum constraint.

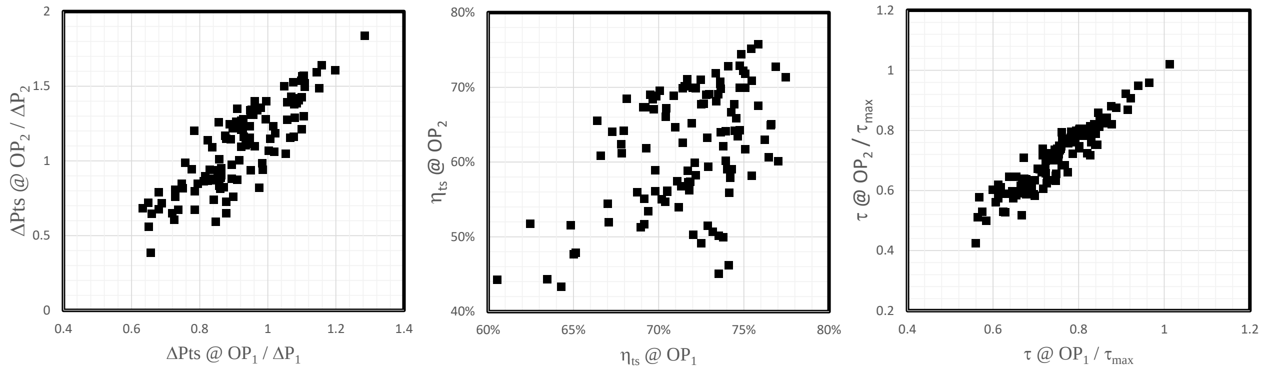

Figure 10: CFD results (pressure rise, efficiency and torque) of DOE designs

Optimisation

The terms response surface model (RSM), surrogate model, approximation model and meta model are used as synonyms in the literature. The RSM is a mathematical model and constructed based on data from known designs (usually from DOE) and provides fast approximation and evaluation of objectives for different design parameters at new design points.

Kriging is a method of interpolation which was first proposed by a South African statistician and mining engineer Danie G. Krige and used to predict the location of unknown mineral resources. The basic idea of Kriging is that the value at an unknown point should be the average of the known values at its neighbors, weighted by the neighbor's distance to the unknown point.

MOGA (NSGA-II, Non-dominated Sorting Genetic Algorithm-II) is a multi-objective genetic algorithm which was first proposed by Deb *et al.* [7] It is well-suited for highly non-linear design spaces, each objective is treated separately and a Pareto front is constructed by selecting feasible non-dominated designs.

All the DOE results can be used to create a RSM using Kriging approximation method. The calculated CoP (Coefficient of Prognosis) of the output parameters for the Kriging RSM is around 0.85. The optimisation will be performed by searching the design space with the given constraints and objectives and the performance of different designs can be quickly evaluated through Kriging RSM model. The constraints and objectives used in the optimisation are listed in

Table 3. It is noted that '*Angle*' is defined by Eq. (3). This parameter is used to control the fan P-Q curve slope (shape) and should be kept as close as possible to the target value which is around -5°.

10,000 designs are generated using MOGA (NSGA-II) and the resulting Pareto Front and selected optimal design is shown in Figure 11. An obvious trade-off between the efficiencies at two operating points can be observed.

The CFD performance of the optimal design is compared with the baseline and shown in Figure 12. The pressure rise of the optimal design is improved significantly at both operating points compared to the target and baseline values while maintaining the desirable P-Q slope (shape). The efficiencies of the optimal design are improved by around 20 % at both operating points compared to the baseline design. The torque values are reduced and do not exceed the maximum constraint.

Table 3: Optimisation constraints and objectives

ΔP @ OP_1	$\geq \Delta P_1$
ΔP @ OP_2	$\geq \Delta P_2$
τ @ OP_1	$\leq \tau_{max}$
τ @ OP_2	$\leq \tau_{max}$
Angle	$\geq -5.5^{\circ}$ & $\leq -4.9^{\circ}$
η_{ts} @ OP_1	Maximize
η_{ts} @ OP_2	Maximize

$$Angle = \tan^{-1}\left(\frac{\Delta P_1 - \Delta P_2}{Q_1 - Q_2}\right) \quad (3)$$

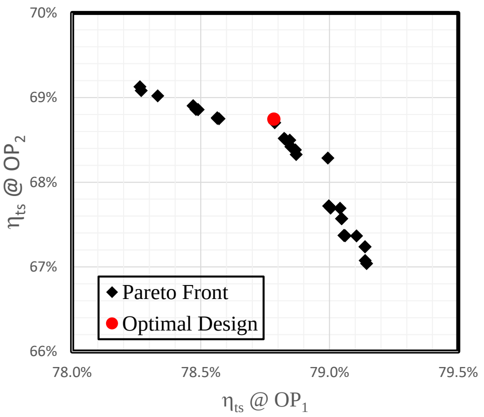

Figure 11: Pareto Front and selected optimal design

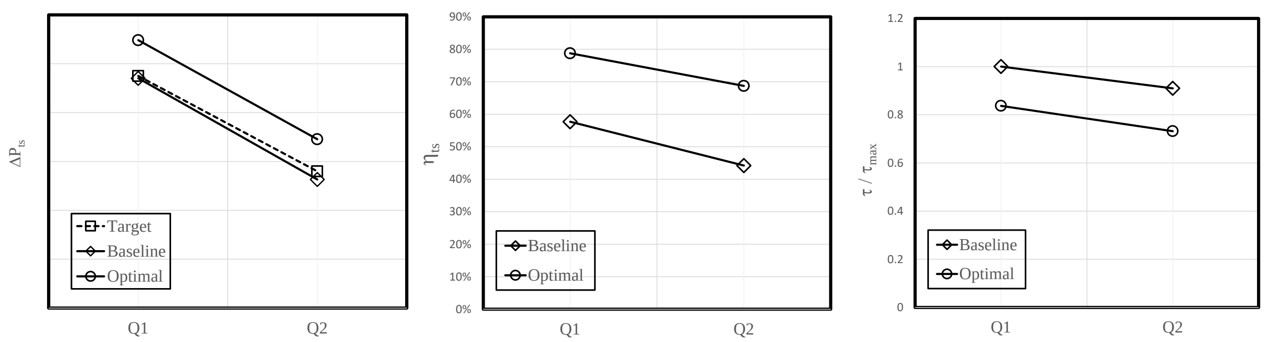

Figure 12: Comparison of CFD results for baseline and optimal design

The comparison of the meridional geometry between the optimal design and the baseline is shown in Figure 13.

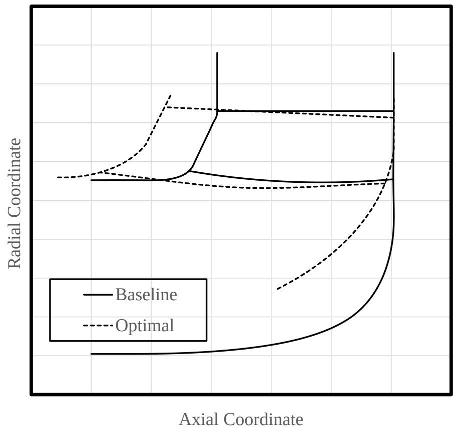

Figure 13: Comparison of meridional geometry for baseline and optimal design

The improvement in efficiencies can also be explained by comparing the flow field of two designs (Figure 7 and Figure 14). Especially the flow near the shroud of the optimal design is improved significantly and now fully attaches on the blade surface compared that of the baseline design.

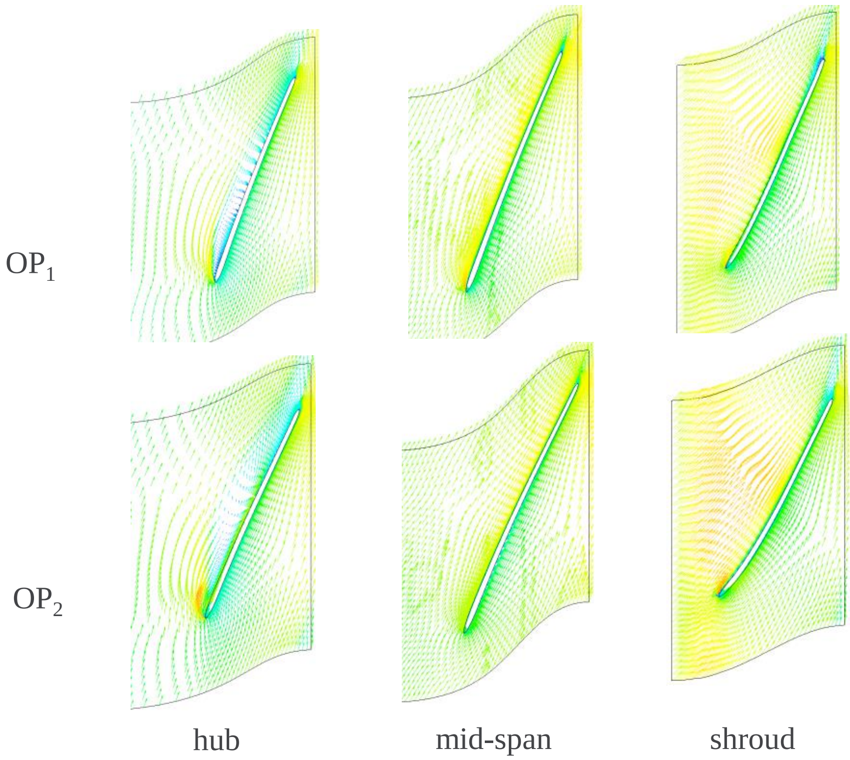

Figure 14: Optimal design relative velocity vector at OP_1 and OP_2

CONCLUSIONS

In this paper, a systematic optimisation methodology using inverse design method, DOE and MOGA has been presented and is used to optimize the aerodynamic performance of a centrifugal fan at two operating points. The pressure rise and efficiencies at two operating points are improved significantly and the improvement is validated using steady-state CFD simulations.

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