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Multidisciplinary Optimization of Axial Turbine Blade Based on CFD Modelling and FEA Analysis

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ABSTRACT

The turbine blade is designed to achieve expansion at high efficiency levels. For improving the turbine efficiency, different aerodynamic design optimisations are performed. On the other hand, the aerodynamic design must be enhanced to match the mechanical design. This research proposes a novel design optimisation method for both aerodynamic and mechanical requirements. A multidisciplinary optimisation approach is used to improve the reliability of the turbine design, which included the use of Computational Fluid Dynamics (CFD) models and Finite Element Analysis (FEA). The primary objective is to guarantee that the aerodynamically optimised blade profile could efficiently withstand mechanical stress. The multidisciplinary optimisation approach is successful in reducing total equivalent pressures from 49.72 MPa to 41.73 MPa while keeping the turbine's overall efficiency at an impressive level of 80.95%. These Results highlight the effectiveness of using a multidisciplinary optimization method to successfully improve the efficiency of a turbine blade profile while simultaneously ensuring its ability to withstand the needed mechanical loads. Using a multidisciplinary optimisation method, the turbine maintains an impressively high efficiency of approximately 83%, with only a marginal reduction of 1.8% compared to the efficiency achieved solely through aerodynamic blade optimisation.

Keywords:
Axial turbine; multidisciplinary design; optimization

1. Introduction

For numerous years, researchers have been actively investigating the enhancement of axial turbine blades as it plays a vital role in improving the efficiency and reliability of turbines. Computational Fluid Dynamics (CFD) is applied across a range of industries and research areas where a thorough comprehension of fluid flow characteristics is essential [1-3]. Recent studies have primarily concentrated on employing multidisciplinary optimization methods that integrate CFD modeling and FEA to assess and enhance blade efficiency. Various optimization algorithms, including genetic algorithms, particle swarm optimization, and multi-objective optimization, have been utilized by researchers to discover the most suitable blade designs that achieve a balance between

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aerodynamic and structural performance. Designers of turbine blades modify the turbine blade from a predetermined starting shape to guarantee that the shape satisfies the specifications and enhances performance [4]. In recent years, the growth of computer technology has led to a significant increase in the application of three-dimensional numerical simulation methods and numerical optimization methodologies in the aerodynamic optimization design of rotor blades [5]. Many researchers have studied multidisciplinary optimization of compressor blade aerodynamics and structure [6,7].

Blade shapes are frequently designed using an optimization method. Multidisciplinary design optimization is an important tool widely used in designing and optimizing components of turbo machinery [8,9]. The effective and reliable FEM and CFD methods have substantially aided the design process [10]. A high-pressure turbine disc was subjected to an aero-thermal-structural study by Xiaodong and Xiuli, [11], which optimized both the height and width of the disc bore as design factors. The weight of the disc was reduced as a result of this multidisciplinary design optimization, which also greatly reduced the design and research time.

Balje and Binsley, [12] used simplified loss prediction correlations together with a mean line method to optimize axial turbine designs. The turbine efficiency was improved by 5% through modifying the blade profile geometry parameters. Rao and Gupta, [13] extended their approach by applying multi-objective optimization to maximise efficiency while minimizing turbine mass. This method decreased turbine mass by 18% while increasing efficiency by 2.48%. Massardo and Satta, [14] improved the optimization method further by combining a multi-objective optimization technique with a mean line design code, yielding a 1.7% efficiency gain through blade shape change.

Dennis *et al.*, [15] used a flow analysis algorithm to build a multi-objective optimisation strategy in the context of 2D and 3D blade profile optimisation. The optimization sought to reduce losses and the number of blades, using 18 design factors parameterized. This research suggested that a multi-objective genetic algorithm be used as an effective and adaptable optimisation technique for 2D and 3D blade design optimisation. Several studies focused on the modelling and optimisation of radial turbines [16-18]. Surrogate model-based optimisation replaced aerodynamic simulation analysis with mathematical functions to increase optimisation efficiency [19,20]. CFD has recently emerged as a valuable tool for turbine optimisation, notably via viscous 2D and 3D simulations. Modern CFD systems include form aerodynamic optimisation capabilities, allowing turbines to be optimised for minimal losses [21].

Daabo *et al.,* [22] employed computational fluid dynamics (CFD) visualization to examine the three-dimensional flow pattern within the turbine and created a model for evaluating losses in radial flow turbines. Their investigation revealed that, under identical operating conditions, the single-stage radial flow turbine yielded greater power output. Daabo *et al.,* [23] studied the structural performance of a Small-Scale Radial Turbine (SSRT) using Finite Element Methods (FEM) and Computational Fluid Dynamics (CFD), employing 3D printing with RGD 525 plastic. Their analysis focused on mechanical stresses under varied loads, highlighting the impact of rotor speed and blade shapes. Results showed that stress levels were influenced by both rotor speed and fluid temperature, with notable deflection observed in the tip shroud region, reaching 21% of the blade tip width.

This study introduces a design optimization method that addresses both aerodynamic and mechanical considerations. Employing a multidisciplinary optimization approach, it enhances turbine design reliability by integrating Computational Fluid Dynamics (CFD) models and Finite Element Analysis (FEA). The main aim is to ensure that the aerodynamically optimized blade profile remains structurally robust enough to withstand mechanical stresses effectively.

2. Methodology

Design optimization can employ various optimization techniques to identify the most appropriate solution. However, the feasibility and applicability of these techniques may vary across different disciplines. In the context of axial turbines, the design process consists of two main steps. First, aerodynamic design focuses on analysing the complex flow through the turbine blades using CFD to achieve the desired performance. Secondly, mechanical design uses FEA to assess the maximum stress levels caused by aerodynamic loads. The goal of improving the design of turbines is to increase their efficiency while ensuring mechanical reliability by predicting stress levels. Thus, achieving an effective turbine design poses a difficult task involving multiple goals and disciplines [24].

The Multidisciplinary optimization approach combines computational fluid dynamics modelling with finite element analysis simultaneously to optimize the aerodynamic blade profile while ensuring that it meets mechanical requirements based on FEA for total deformation and maximum stress on turbine blades and all the conflicts in the design illustrated in Figure 1 could possibly be avoided [25]. By employing a Genetic Algorithm (GA) optimization approach with input data from both Navier Stokes (NS) calculations and FEA, multidisciplinary optimization can avoid design conflicts and guarantee the optimal blade profile as shown in Figure 2. Multidisciplinary optimization determines a global objective function for all design aspects using a high number of iterations, which saves time of the design and resources. Another advantage is that parallel calculations can be conducted in independent disciplines, further reducing the overall optimization time. Overall, multidisciplinary optimization is an efficient method for optimizing the aerodynamic blade profile while ensuring mechanical reliability.

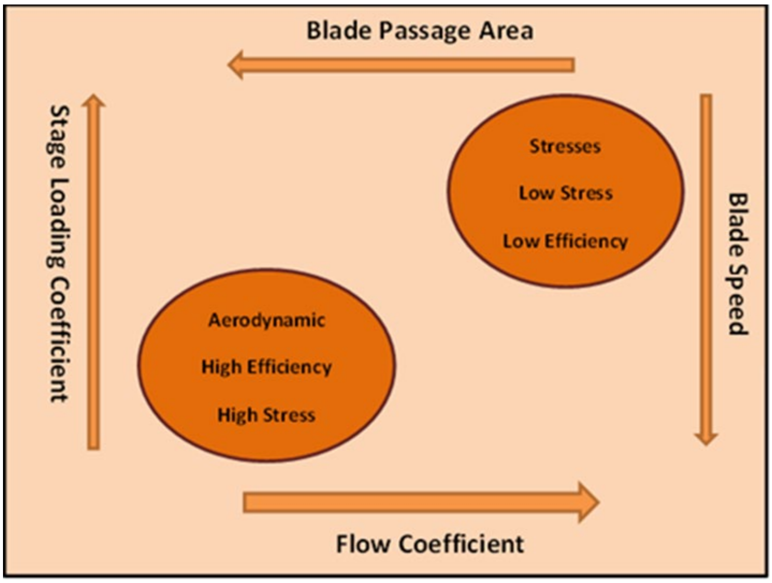


Fig. 1. Interactions of aerodynamic and mechanical designs

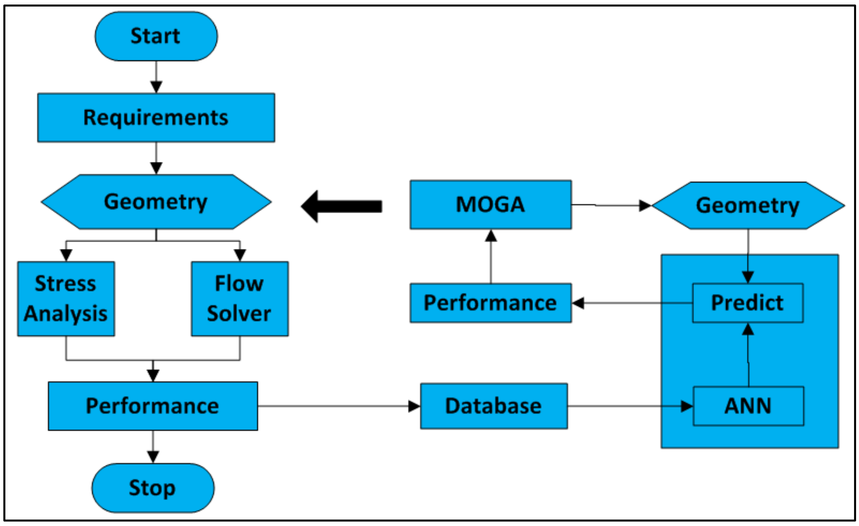


Fig. 2. Flowchart for multidisciplinary optimization [25]

3. Results

The aerodynamic features of the turbine blade profile have a significant impact on the performance of axial turbines. Individual blade geometry factors significantly influence the overall pressure losses inside the turbine stage. There is an optimal value for each parameter that minimises these losses. To achieve optimum turbine efficiency and satisfy the specified power output, all parameters are optimised simultaneously, and an efficient blade profile are created. To design efficient aerodynamic turbines and accurately predict flow features within turbine passages, a combination of 3D CFD modeling and optimization techniques is effective in enhancing turbine performance. In this study, researchers used the Multi-Objective Genetic Algorithm (MOGA) technique to optimize the aerodynamic blade profile for on and off-design conditions, as seen in Figure 3.

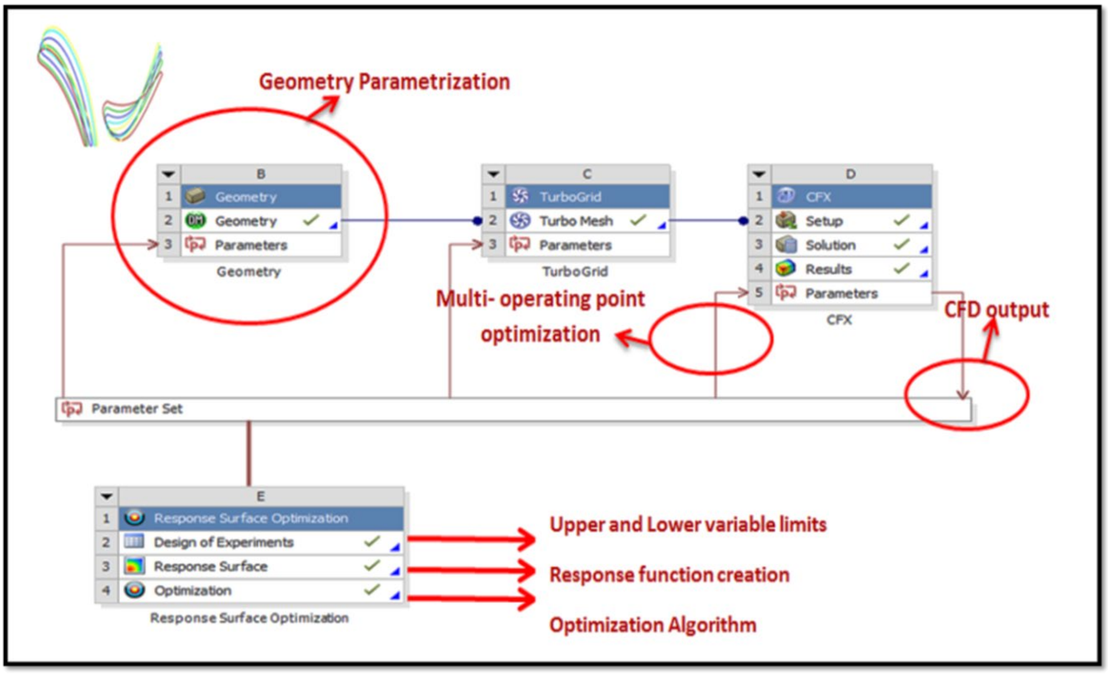


Fig. 3. Single and multi-operating point

The primary objective of aerodynamic design optimization for turbine blades is to enhance turbine efficiency by exploring various geometric variations. However, optimizing the aerodynamic design alone may lead to conflicts with structural requirements, posing challenges in achieving a compatible design that satisfies both aerodynamic and mechanical considerations. To solve this, ANSYS Workbench was used to perform a multidisciplinary automated optimisation technique, simultaneously optimising both the aerodynamic and mechanical aspects of the blade design, as illustrated in Figure 4. This method required coupling the CFD solver with the mechanical structure solver, allowing loads to be transferred to the finite element model from the CFX fluid solver.

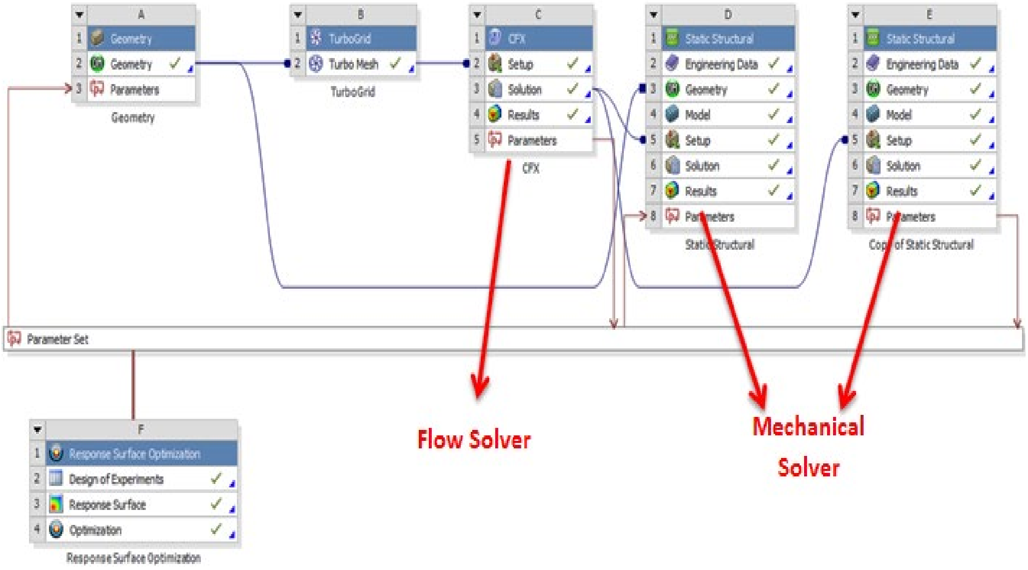


Fig. 4. Multidisciplinary optimization

By considering the total deformation and Von Mises stress as objective functions, the optimization was formulated with multi-objective functions, aiming to maximize turbine efficiency while minimizing Von Mises stress and total deformation. Sensitivity analysis of rotor blade stresses to blade geometry variations (shown in Figure 5) revealed that Von Mises stress is highly influenced by changes in both the Leading Edge (L.E) and Trailing Edge (T.E) geometries.

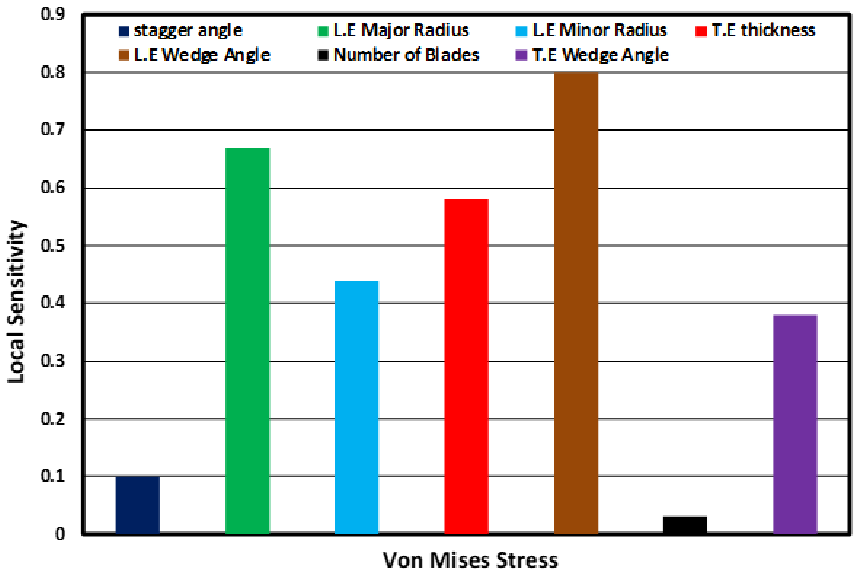
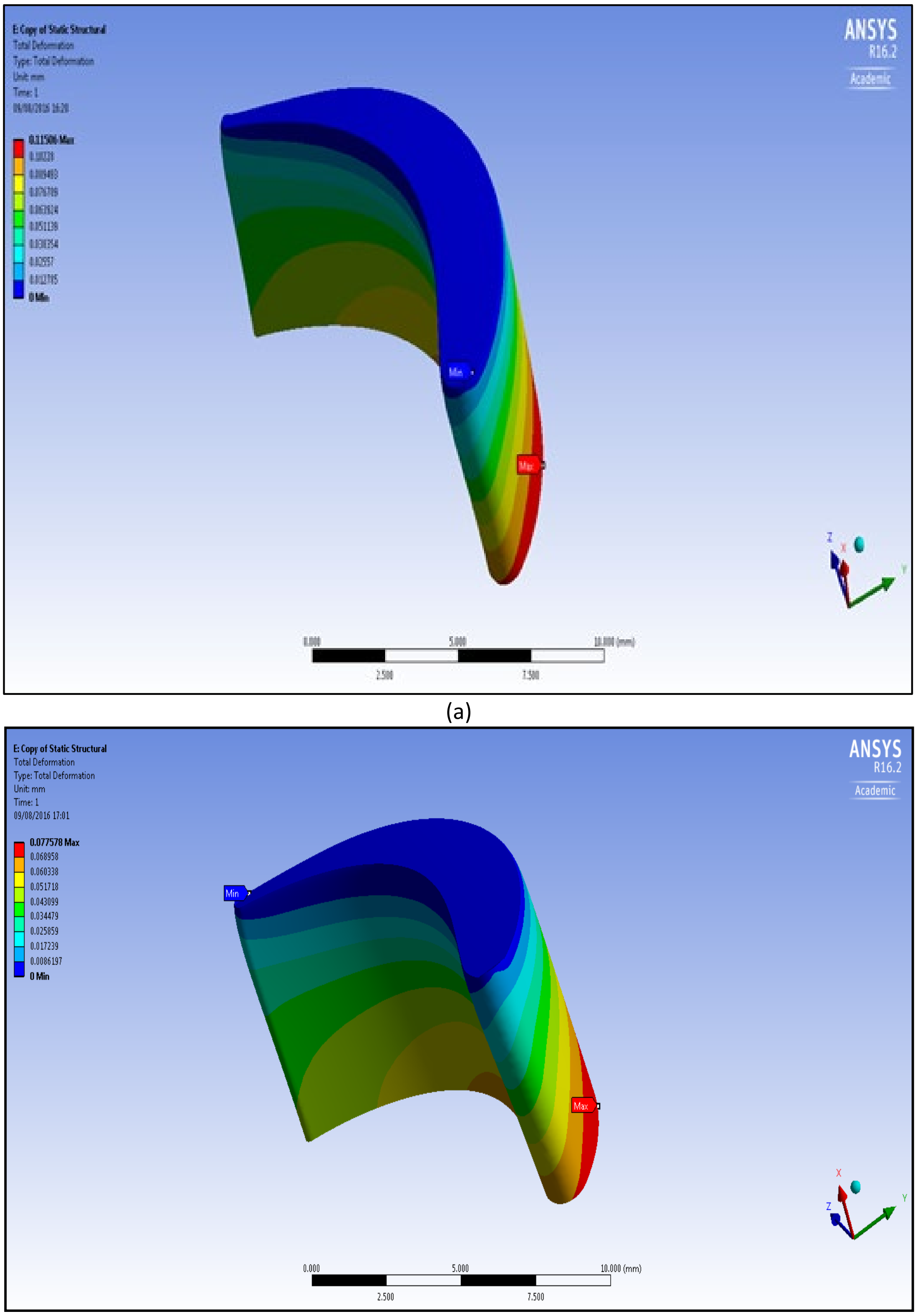


Fig. 5. Von Mises stresses sensitivity analysis of geometry variations

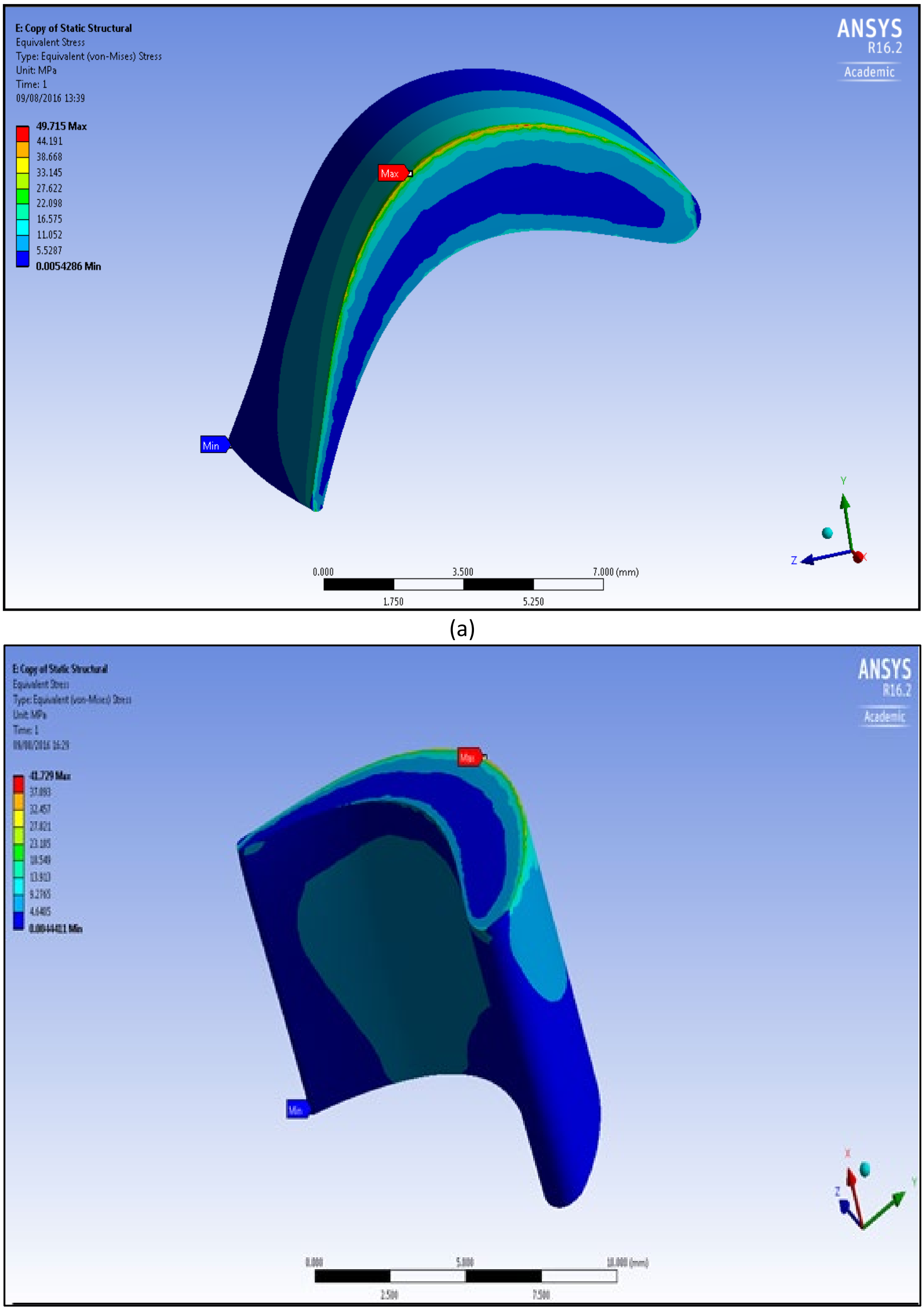
The optimization results demonstrated that the highest total blade deformation decreased from 0.115 mm to 0.0776 mm as shown in Figure 6, and the highest total equivalent Von Mises stresses decreased from 49.72 MPa to 41.73 MPa as shown in Figure 7. By employing a multidisciplinary optimization approach, the turbine's efficiency remains remarkably high at approximately 83%, with only a minor 1.8% decrease compared to the efficiency achieved through aerodynamic blade optimization alone. A detailed comparison between the results of aerodynamic-based optimization and multidisciplinary optimization is provided in Table 1. Additionally, Figure 8 illustrates the rotor blade profiles, offering a clear visual comparison between the two optimization approaches.



(a)

(b)

Fig. 6. Optimized profile of total deformation (a) aerodynamic (b) Multidisciplinary



(a)

(b)

Fig. 7. Optimized profile of total stress (a) aerodynamic (b) Multidisciplinary

Table 1
Optimization aerodynamic and multidisciplinary results

Seek P5 = 1000 W	Goal, Seek P5 = (Default Importance)	
Minimize P4; Pressure Loss	Goal, Minimize Mize P4	
Configuration	100 samples per iteration	
Optimization Method	Multi-Objective Genetic Algorithm method	
	Aerodynamic optimization	Multidisciplinary optimization
Number blades	18	18
Stagger angle (degree)	25.07	22.14
Leading. Minor radius (m)	0.0001133	0.0006221
Leading. Major radius (m)	0.000386	0.000944
Trailing. Minor radius (m)	0.00013	0.000707
Trailing. Major radius (m)	0.00021	0.000436
L.E Wedge Angle (degree)	17.23	22.34
Stator-Rotor Gap (mm)	3.78	3.78
Blade Solidity	1.5224	1.5224
Output Power (W)	993.48	990.27
ηts (Total-to-static)	84.457	80.95

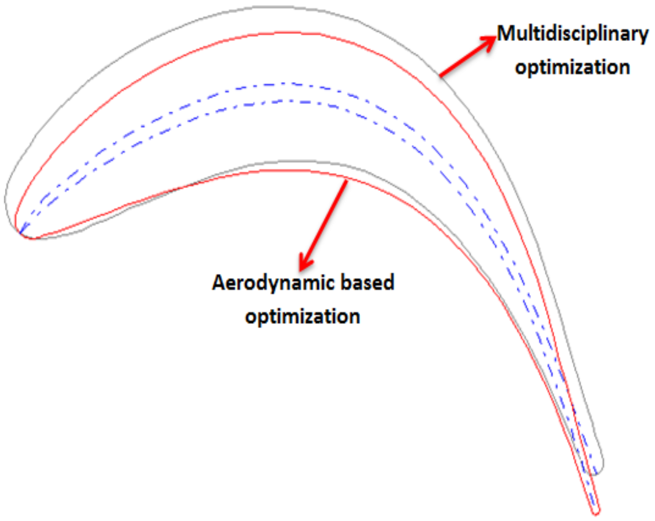


Fig. 8. Multidisciplinary and aerodynamic optimization blade profiles

4. Conclusions

Optimizing the aerodynamic design of a turbine blade profile can result in a high efficiency value but may also lead to conflicts with mechanical design constraints. The utilization of a multidisciplinary optimization strategy is employed to simultaneously optimize both the aerodynamic and mechanical aspects of the blade profile, ensuring its ability to withstand mechanical loads. This approach has demonstrated itself as an effective and innovative design tool. By employing this optimization methodology, the equivalent Von Mises Stress can be substantially diminished from 49.72 MPa to 41.73 MPa, signifying a remarkable reduction in stress levels. Additionally, the optimization maintains a high total-to-static efficiency of the turbine at 80.95%, which is 4.89% higher than the efficiency achieved through 1D mean line modeling. These results highlight the potency of multidisciplinary optimization in effectively optimizing the design of a turbine blade profile to achieve enhanced efficiency while also ensuring its ability to endure the necessary mechanical loads.

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