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Aeromechanical Optimization of First Row Compressor Test Stand Blades

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ABSTRACT

In this study, an optimization of the first blade in new test rig presented. Blade tuning is conducted using 3D geometrical parameters. Sweep and dihedral play an essential role in this study. Compressor characteristics and blades vibrational behavior are the main objective of the evaluation. Here, the attachments are designed to isolate blade dynamics from Disk. So, the Vibrational behaviors of the one's blade are tuned based on the self-excited and forced vibration phenomenon. Using a semi analytical MATLAB code instability conditions are satisfied. The code takes advantages of whitehead and force response theory to predict classically and stall flutter speeds. Beside, Forced vibrations instability is controlled using a theory presented by Campbell. Aerodynamics of new blade geometry determined using multistage simulations Computational fluid dynamics (CFD) software. Numerical results show increasing performance near the surge line and working interval along with increasing mass flow.

Keywords: design optimization; axial compressor blade, Sweep angle, Taper, Dihedral angles, Aero elasticity, multidisciplinary design optimization, Computational fluid dynamics

INTRODUCTION

Aeromechanical considerations are the major issues in developing advanced turbomachinery blades. Flutter, Forced response, and asynchronous vibration are the main critical aero-elastic phenomena which affect the design criteria's of the blades. Forced response and asynchronous vibrations originated from the aerodynamic sources; however, flutter instability caused by the interaction of the blades motions and the aerodynamics forces. Flutter instabilities which appear as limit cycle oscillation in practice can cause the failure of the turbomachinery blades, especially in the high aspect ratio ones. Oscillatory aerodynamic loading is another design factor. The stress induced by these excitations maintained at a minimum level. At resonance condition, the vibration amplitude remarkably increases which can lead to high cycle fatigue failure.

The early research studies of the turbomachinery blades flutter concentrated on the developing of the simple aero-elastic models for the cascades exposed in a subsonic airflow. In 1960 Whitehead [8], with using vortex panel theory and non-penetrating flow boundary conditions, extracted the analytical solution for lift and moment of a cascade in flexural and torsional oscillating modes. His theory established based on the Theodorsen aerodynamic

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model predicts classical flutter for a single oscillating airfoil. The incompressibility of flow, inviscid, and low angle of attack for prescribe vibration properties of flat airfoils are fundamental assumptions of the Whitehead model. Later Mikolajczak[7], Srinivasan[8], Kielb [9],Lubomski[10], and Kurkov[11], suggested a different limit for classical and stall flutter instability.

Besides Shrouds, clappers or damper which are usually designed to postpone flutter speed, geometrical parameters likes sweep angle, dihedral angle, and taper ratio can play positive role in aero structural modifications of the blades [4]. Indeed, they can change the elastic axis position and influence on behavior of the structure.

Using this parameter as well as multidisciplinary design optimization technique (MDO), the best shape of the blades extracted. Wang Jingchao [1] took advantages of MDO approach to create best shape of the disk and blades turbine components. Shen et al. [3] using MDO and Thermo-Elastic-Plastic Analysis presented the algorithm to extract best shape of the disk and blades Integration and multidisciplinary design optimization of a simplified gas turbine model are carried out by Jasmin[2].

In this paper, Design and modification of the first rotary blades in a new axial compressor test stand is presented. The compressor has five stages with 3.5 pressure ratio and operates in the speed range of 8500-16500 RPM Fig(1). Using multidisciplinary design optimization technique and based on CFD and Finite Element Method the aeromechanical optimization is carried out. Sweep and dihedral angles are the main geometrical parameters in the optimizations process. Flutter Speed preventing and blades forced response considerations are our structural constraint.Also, Compressor characteristics and evaluation of its performance which extracted by CFD method consist the aerodynamics constraints.

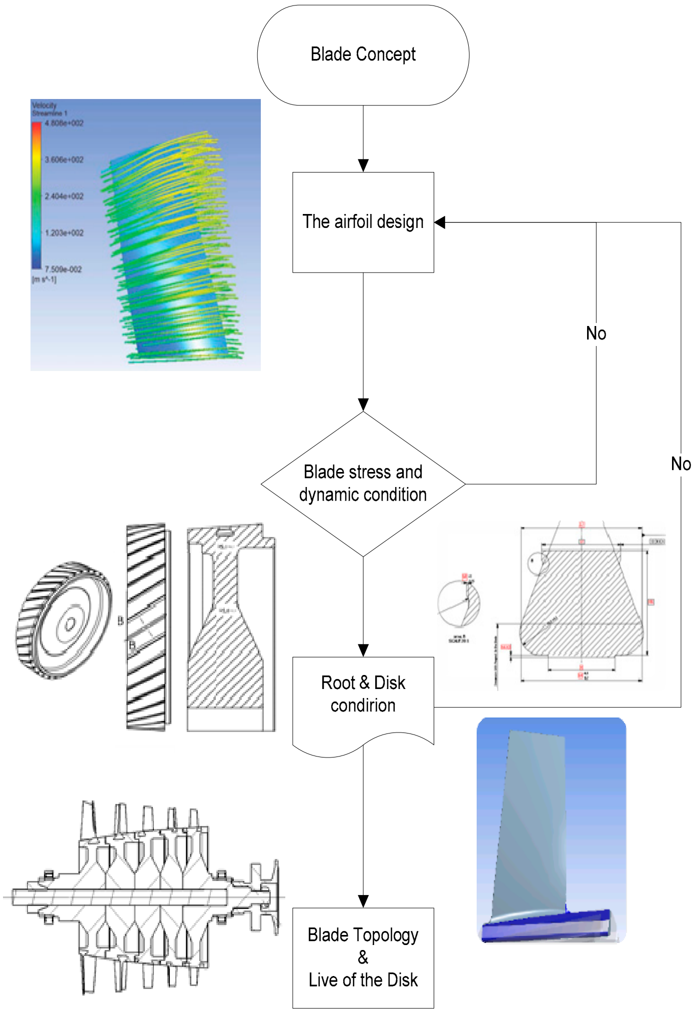


Fig 1.Classical design flow of the blade

GEOMETRICAL PARAMETER (SWEEP AND TAPER EFFECTS)

Usually, turbomachinery blades create with variable cross-section airfoils which stack on each other. Different position of the airfoil cross sections on a row can change the aeromechanical properties of the whole compressor. Sweep angle which creates with dislocating of the cross section of the airfoil along the chord. They play an essential role in the performance of the axial turbomachinery. Generally, three dimensional influences of the Swept blades enhance the amount of the efficiency and range of the operation. In the mechanical aspect of the view swept blade because of changing elastic axis position have different frequency value than the un-swept blade. Aerodynamics study also proof that this parameter can increase the pressure ratio value limits the secondary loss effects and decreasing the loading near leading edge and blockage in the vicinity of blades tip. The Sweep angle can also change the shock waves structures and improve the loss effects in transonic regimes. The advantages of the forward sweep blades are the alleviation of leading edge loading, incidence angle effects, and leakage [4].

Taper and dihedral [4] can also effect on the performance of the turbomachinery. From mechanical aspect, especially vibrational view tapering can increase the frequency of the blades but aerodynamic shown the negative effect of this parameter in the whole of our compressor Fig [2]

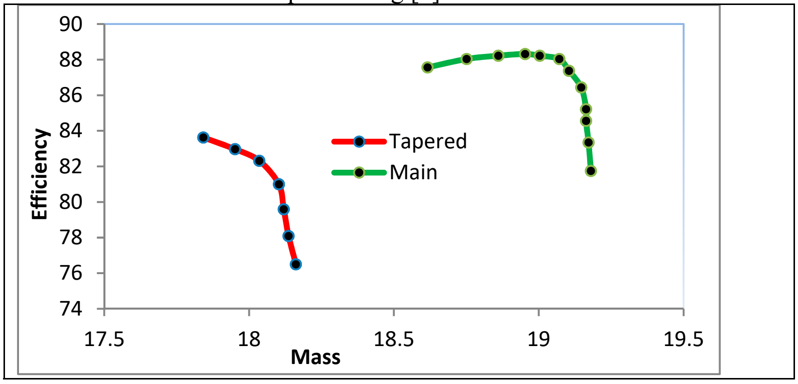
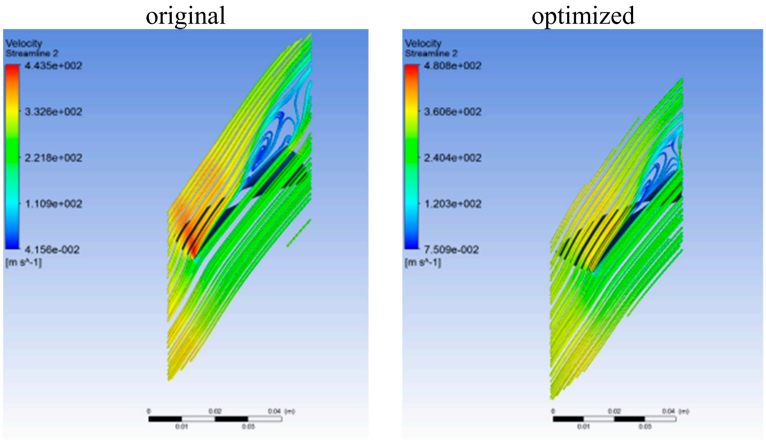


Fig 2.Aerodynamic effects of taper blade

DESIGN VARIABLE AND OBJECTIVE FUNCTION

Optimization of the axial turbomachinery as a prevalent activity in the enhancement ofthe efficiency of the blade commonly is performed in recent year. Using multi-disciplinary design optimization (MDO) [1], [2], [13-15] which found in the ANSYS Workbench as a new conventional method and other turbomachinery analysis modules, axial turbomachinery blade concept can approach to its best performance and mechanical properties. Geometrical parameters consisting of stack line position (thickness and Sweep angle) can be considered as our design variable to maximize stage characteristics. Coupled study play key role in the design process of blades. In order to prevent flutter and forced response, the frequency of the blade can be set as our objective.



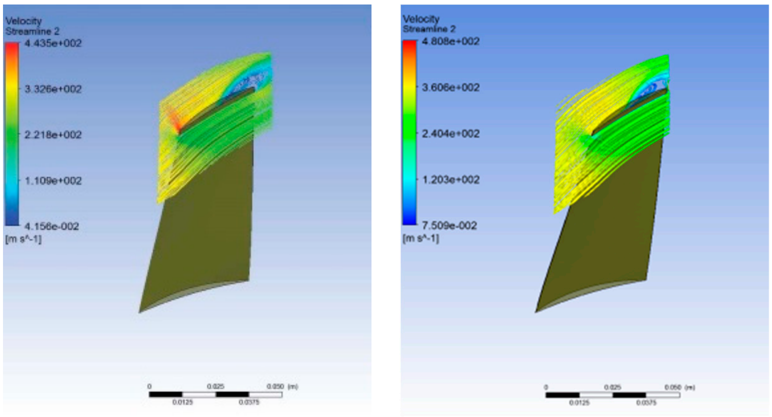


Fig 3.Aerodynamic comparison of the original and optimized blades

Parametric modeling of the airfoil section is conducted using UG software. Taper, sweep and dihedral angle is used as our design variable.

Mechanical analysis of the blade peruses by importing fluid loading on solid models. Finally, in design explore phase the optimized form of the blade is presented.

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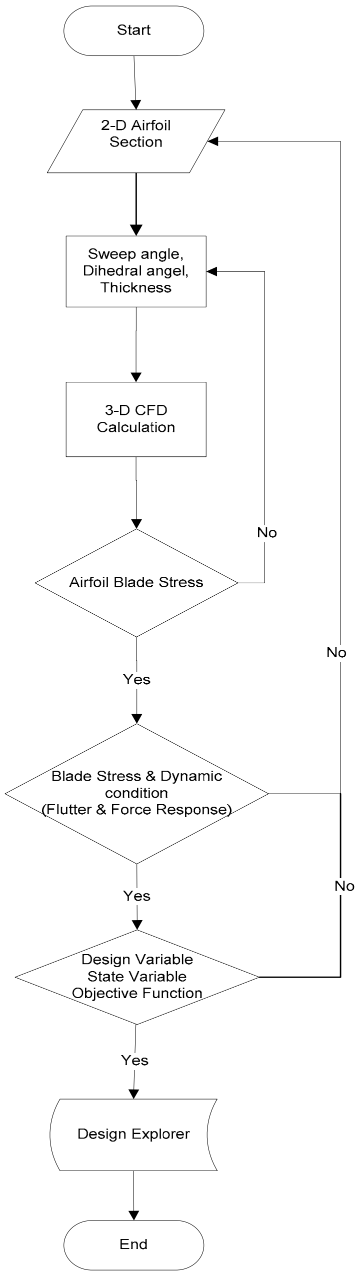


Fig 4.Optimized design flow of the blade

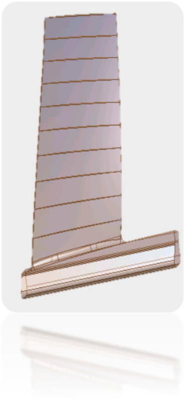
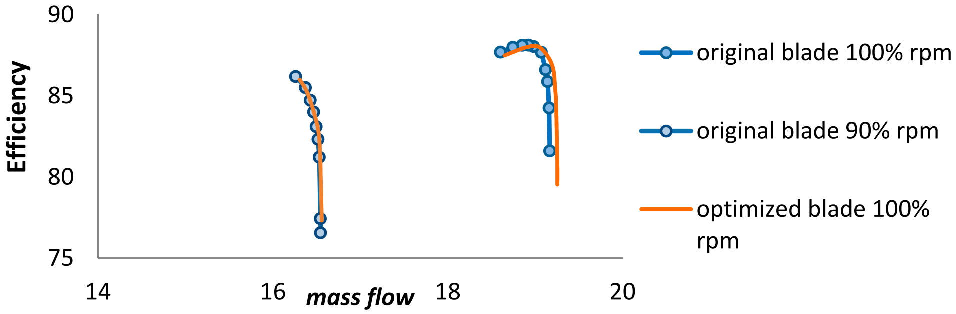
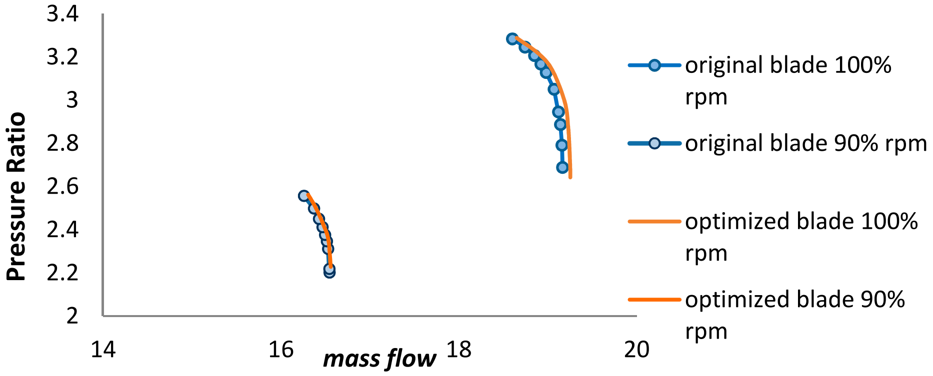


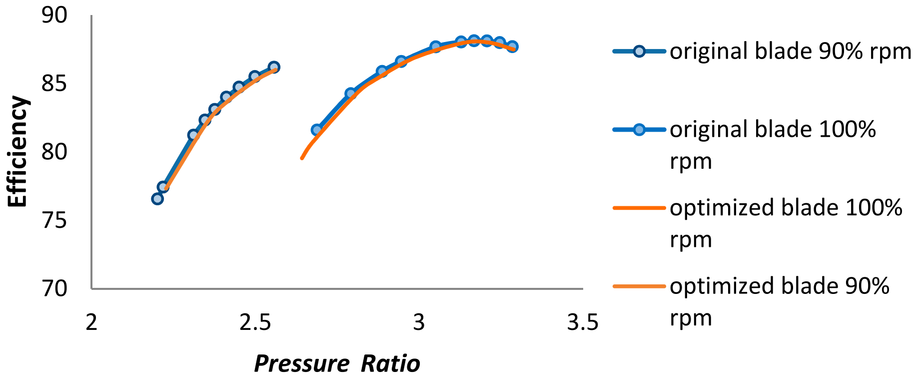
Fig 5.The optimized blade shape of the compressor test rig

AERODYNAMIC LOADING CALCULATION

Coupled Aero-Thermal analysis of the first row of the test rig was performed using the loosely coupled method. With a specific aerodynamic loading and temperature distribution of the blade obtained with the definition of wall boundary condition and fluid domain analysis. Boundary condition consists of inlet and outlet boundary, and cyclic symmetry conditions.







COUPLED MODEL

The static and dynamic structural analyses were conducted using pre-stress modal analysis [3]. In addition to safety factor strength satisfaction, the vibrational behavior tuned regard to force response and flutter speed prevention.

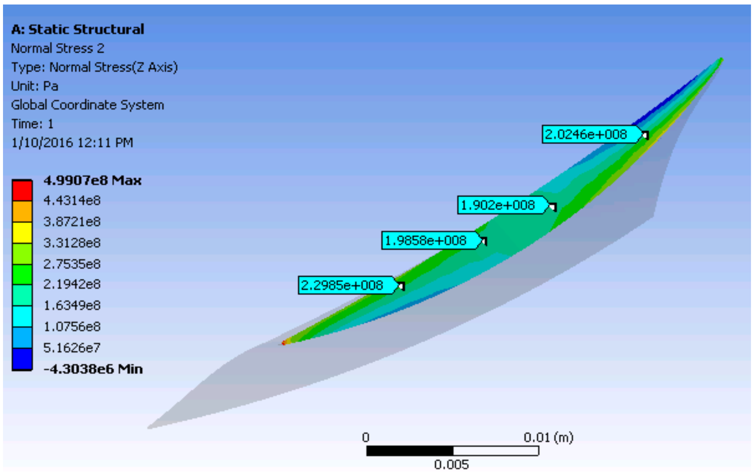


Fig 6.Blade Root and hub Stress level

Stall flutter postpones base on the literature recommendation [6-8]. Indeed, Reduced order value for torsional mode should be more than 1.5 and for flexural mode suggested the value number larger than 0.35.

Table 1.Stall Flutter investigation

Reduced Frequency	Mode	
0.527	1	**Original Blade**
1.5	2	
0.54	1	**Optimized Blade**
1.56	2	

.Semi-analytical in-house code base on the whitehead theory was developed to predict classical flutter instability. Limitation of the designed reduced frequency point for classical flutter is set between 0.4-0.75 [6-12] .Result shows that the classical flutter speed condition in the optimized blade is improved.

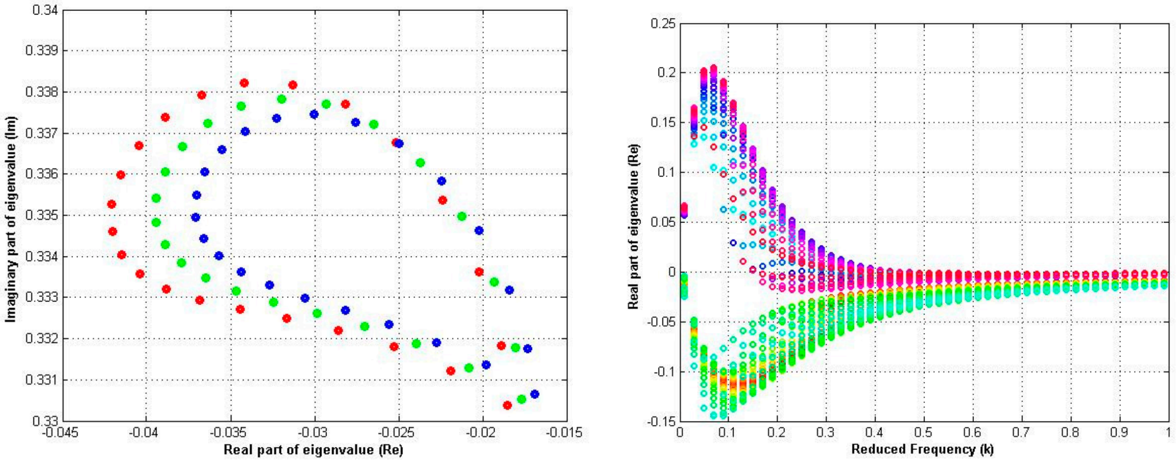


Fig7. Real and Imaginary part of the flutter speed

Table 2.Classical Flutter Results

	Matlab Code		Empirical			
Stage	Torsion		Bending		Torsion	
	Optimized	original	Optimized	original	Optimized	original
R1	0.488	0.47	0.26	0.25	0.73	0.70

Using Campbell diagram an appropriate interval speed limit can be specified. Base on the API standard [5] it can be inferred that %30 interval coincidence prevention speed is an acceptable criterion.

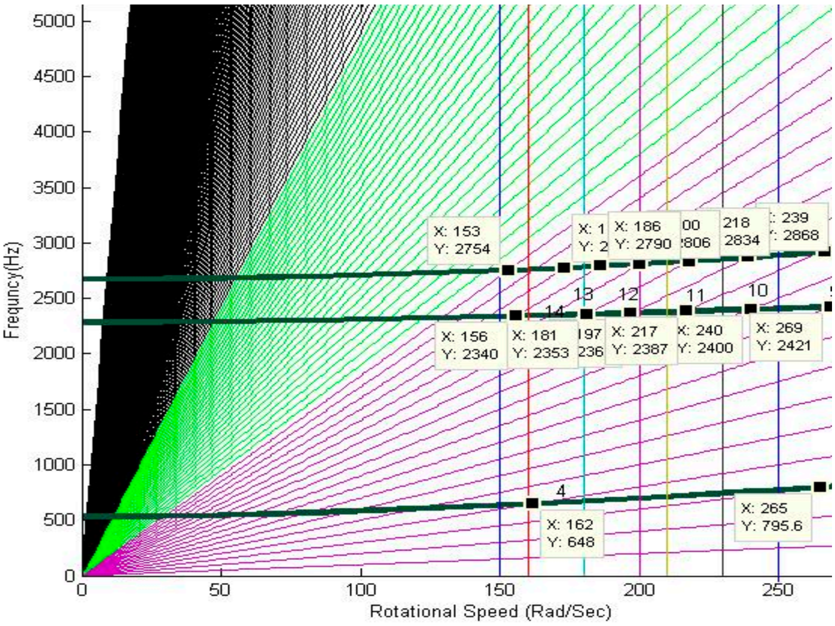


Fig 8.Campbell diagram of the blade

CONCLUSION

An optimization procedure base on the ANSYS workbench on First stages of the new compressor test rig was defined. Blade geometry was parameterized to have best aeromechanical performances. Limitation on the stacking line position or in the other word Taper, Sweep, and dihedral angle plays an important role during optimization.Using 3D simulations design explore the 3D shape of the optimized blade generated. Aerodynamic performance, stress level and aero elastic behavior of the blade set as the aeromechanical limitation. After optimization results, showed that the coupled behavior of the blade and aerodynamic performance improve about 4%.

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