Optimization of Gas Turbine Compressor Blade Parameters for Gas-dynamic Efficiency under Strength Constraints

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Abstract: This article describes an approach for optimization of gas turbine compressor blade based on one-way fluid-structure interaction (FSI) analysis coupled with evolutionary optimization algorithm. Commercial CFD and FE code ANSYS was used for the simulations. Paper gives detailed description of developed geometric model, CFD and FE models, as well as description of employed optimization technique. Obtained results indicate that adiabatic efficiency and pressure rate of compressor can be increased up to 23% and 7% correspondingly by rational selection of relative positions of compressor blade cross-sections.

1 PROBLEM

Gas turbine power plants (gas turbines) are increasingly used as power sources in a variety of military and civilian applications. This includes propulsion for air, land, overwater and even underwater applications, as well as electric power plants, pumping stations, etc. Gas turbine power plants, in comparison with the piston engines, have greater body-weight capacity, more favorable traction performance and longer service life. They do not need any cooling system and thus have no problems associated with it. In addition, they are unpretentious in operation, being easy to run at lower temperatures, not requiring fine air purification and having high environmental performance, as well as relatively low emissions and low consumption of oil.

Major disadvantage of gas turbine engines is complexity of their design. This results in the high cost of their life cycle *(*Kuzmenko et al., 2007*)*. In turn, complexity of design results from the mutual influence of different physical processes simultaneously occurring in gas turbine. Reduction of life-cycle costs of a gas turbine requires its optimization with regard to different efficiency parameters (e.g., adiabatic efficiency and pressure rate of compressor, weight) and taking into account multiple constraints (e.g., strength, stiffness, natural frequencies etc.)

A number of examples of such analyses have been described in the literature. In *(*Lian and Liou, 2005*)* multi-objective optimization was performed to maximize stage pressure ratio and minimize weight of NASA rotor67 compressor blade. It was conducted over 32 design variables controlling geometry of 4 cross-sections along the blade span. Optimization resulted in 1.8% and 5.4% improvement of baseline design for pressure ratio and weight, correspondingly. Simulations used TRAF3D CFD code combined with response surface generator and genetic algorithm. In (Lee and Kim, 2000) and, more recently in (Samad and Kim, 2008), optimization was carried out for two conflicting objectives, such as total pressure ratio and adiabatic efficiency, using only 3 design variables controlling geometry of stacking line of compressor blade. As in the previous case, genetic algorithm was used in (Samad and Kim, 2008) as optimization technique. In (Chen et al, 2007) blade parameterization technique was developed to reduce number of design variables in optimization. Optimization was performed using combination of gradient-based algorithm with response surface approximations. 1.73% of increase in adiabatic efficiency for NASA rotor37 was reported. Another example of parameterization of compressor blades for multi-objective optimization is given in (Sommer and Bestle, 2011). The parameterization technique is based on the use of B-splines. Presented simulations were two-dimensional.

This short review allows determining two main

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distinctive features of existing approaches to optimization of compressor blades. First, they consider the problem as multi-objective. Second, rational techniques for decreasing of a number of design variables are continuously been sought.

In this paper we present an approach for optimal design of compressor blades aiming to maximize such conflicting parameters as adiabatic efficiency and pressure rate of compressor. All simulations in our study are full scale and three-dimensional. As compared to results presented in the literature, our approach is different in taking into account strength constraints due to coupled CFD-FE simulations and in use of formalized procedure for choosing design variables based on parameters correlation study. Described optimal design procedure, instead of being based on an in-house code, utilizes commercial widely used software ANSYS, which makes it reproducible and ready-to-use by engineering practitioners.

2 NUMERICAL SIMULATIONS

All simulations were done in the ANSYS Workbench environment using the following set of modeling applications (Figure 1):

- ANSYS Design Modeler for geometric modeling (DesignModeler User Guide, 2011);
- ANSYS TurboGrid for high-quality hexagonal meshing of inter-blade channel (ANSYS TurboSystem User Guide, 2011);
- ANSYS CFX for gas dynamics simulations (ANSYS CFX-Solver Modeling Guide, 2011);
- ANSYS Static Structural for strength analysis (ANSYS Mechanical Application User's Guide, 2011);
- Parameters Correlation and Response Surface Optimization toolboxes for identification of most influencing design variables, calculation of response surfaces and optimization (Design Exploration User Guide, 2011).

In general, a single simulation loop can be described as follows. First, for a given set of design variables created by response surface generator, a geometric model of compressor blade is constructed. This procedure was automated by establishing parametric relationships between blade geometric elements (see section 2.1). Next, this model is discretized in Turbogrid and transferred to ANSYS CFX to perform gas-dynamics analysis. This analysis has two goals. First, it evaluates adiabatic efficiency and pressure rate of the compressor, and second, it calculates pressure field on the blade, which is then transferred to ANSYS Static Structural and used there as loading condition for strength analysis. This scheme implements so called one-way fluid-structure interaction (FSI) procedure. In Static Structural, strength is assessed by means of von Mises criterion.

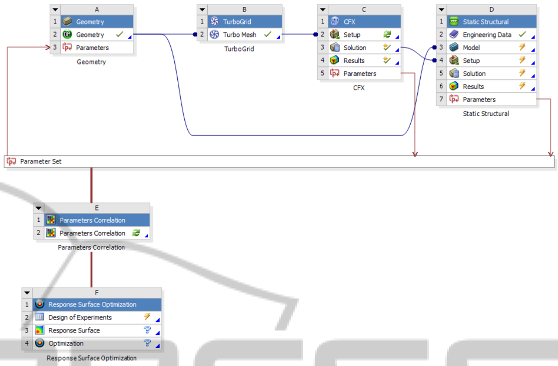

Figure 1: ANSYS Workbench project configured for optimization of compressor blade.

Such direct analyses are repeated few times to construct response surfaces for design objectives (pressure rate and adiabatic efficiency) and constraint (maximum von Mises stress in the model). Once this part is accomplished, genetic algorithm implemented in ANSYS DesignXplorer is used to solve multiobjective optimization problem.

In the next subsections, each step of this procedure is described in more details.

2.1 Geometric Model

The parametric geometry model was built in ANSYS Design Modeler and consisted of a blade and a shank. Blade was built using three cross-sections (blade profile on the hub, the middle and peripheral diameter) by Skin/Loft operator (Figure 2). Each profile was constructed according to the method of circular arcs and line segments (Figure 3) and had the following variable parameters:

- blade angles at the input (β_1) and outlet (β_2);
- chord (b);
- radius of the input (R_{in}) and output (R_{out}) edges.

Parameterization of the profile was carried out by specifying geometric and dimensional constraints. Dimensional constraints were defined by a set of equations which establish relationships between parameters of cross-sections (Figure 4). For example, the angles between blade sides and its horizontal axis (A12 and A13) can be found as inlet

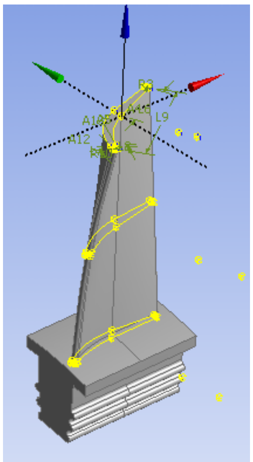

Figure 2: Blade geometry model with highlighted profiling cross-sections.

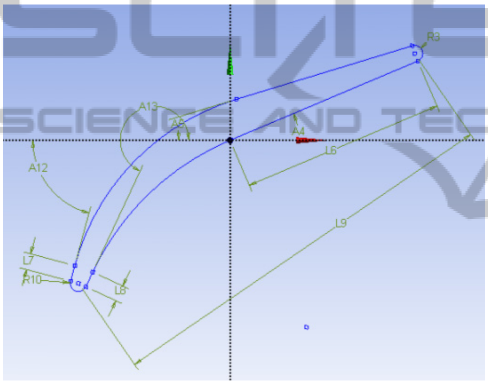

Figure 3: Blade profile sketch with imposed dimensional constraints.

vane angle plus/minus the half of inlet sharpening angle w_1:

```
Plane4.A12=@beta1 - @w1/2
Plane4.A13=@beta1 + @w1/2
```

Due to the fact that sketches of blade cross-sections were built in separate planes, each profile had two more degrees of freedom in the global coordinate system, namely the flat shift in the tangential plane. This allowed utilizing in parametric framework well-known technique of shifting blade cross-sections, which is typically used for discharging a blade from the aerodynamic forces.

Therefore blade geometry, being the most complex part of the vane, depends on a large number of parameters. Even though we used in this work relatively simple profiling technique, it resulted in more than 20 independent variables. To reduce the number of parameters in optimization, it was decided to vary only the following ones:

- inlet angles at each section (β_{1_0}, β_{1_1}, β_{1_2});
- shift of middle and peripheral sections (ΔX_1, ΔX_2);
- fillet radius at the junction of the fir-tree root and blade (R).

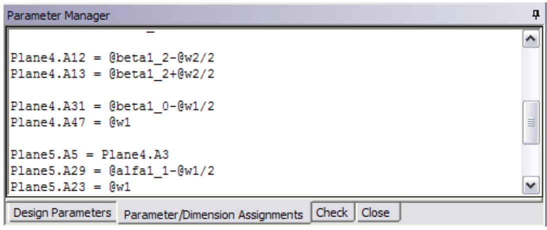

Figure 4: Design Modeler Parameter Manager Window.

ExportPoints tool from BladeEditor module of ANSYS Design Modeler was used to transfer the geometric model of inter-blade channel to TurboGrid. FlowPath operation was used to indicate the meridional sections (Figure 5). For adequate representation of fillet geometry in gas-dynamic analysis, density of sections was higher in the hub region. Position (Span) of each section was parameterized using algebraic expressions as a function of the radius of the fillet R (Figure 5).

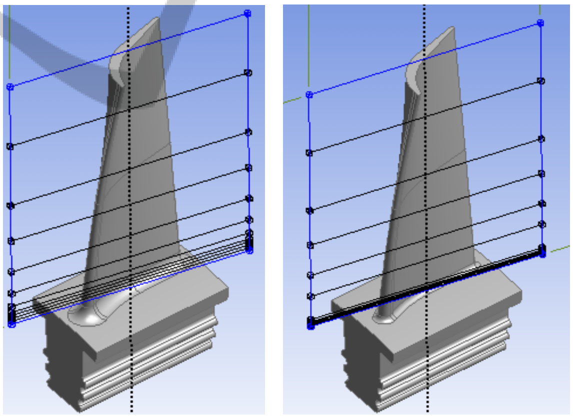

Figure 5: Parameterization of Span element using FlowPath operation: blade with large fillet radius has less layers (left) than blade with small fillet radius (right).

2.2 Gas-Dynamic Model

As it was mentioned before, TurboGrid was used to create a mesh of inter-blade channel (Figure 1). Typically, finer mesh provides higher precision of numerical simulations. However, optimal design problems require multiple analyses with different sets of design variables. Thus a compromise between simulation accuracy and computational cost should always be sought. Based on this, in the present work meshing of inter-blade channel resulted in 60 elements. This allowed maintaining sufficient accuracy in representation of physical phenomena of interest and solving the optimization problem in about 60 hours.

The gas-dynamic model was created in the CFX-Pre preprocessor using Turbo-mode tool. The air was set as working body and option of domain motion was set to the constant speed rotation. Boundary conditions were also given constant, which included absolute incident velocity of the air at the inlet and static pressure at the outlet (Figure 6).

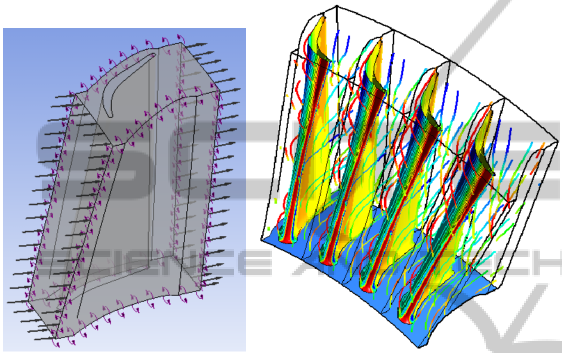

Figure 6: Model prepared for gas-dynamic simulation (left) and obtained results: streamlines and pressure contours (right).

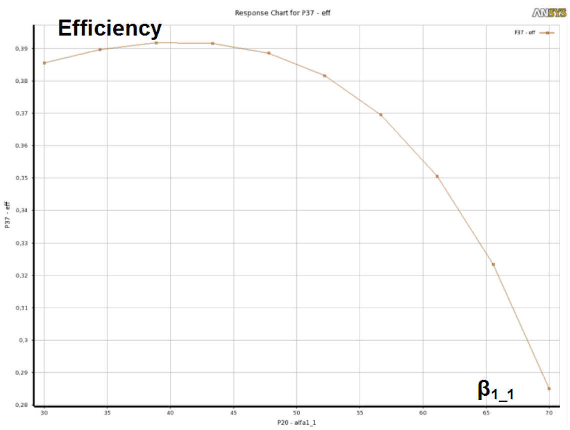

Figure 7: Dependence of efficiency on the angle of the blade inlet in the middle section.

For further reduction of computational expenses, rough convergence criteria were set, including the residual (RMS) of 0,001 and the maximum number of iterations of 150. The accuracy of the results was found to be enough for adequate representation of the physical phenomenon of interest and conducting parametric studies.

Results obtained in a trial calculation allowed estimating the dependence of flow parameters on the shape of the blades (**Fig. 7**).

2.3 Finite Element Model

Pressure field exported from CFX to Static structural and results of FE analysis for equivalent stresses are exemplified in Figure 8. As expected, applied loading creates a stress concentration region at the filleted area near junction of the fir-tree root and the blade.

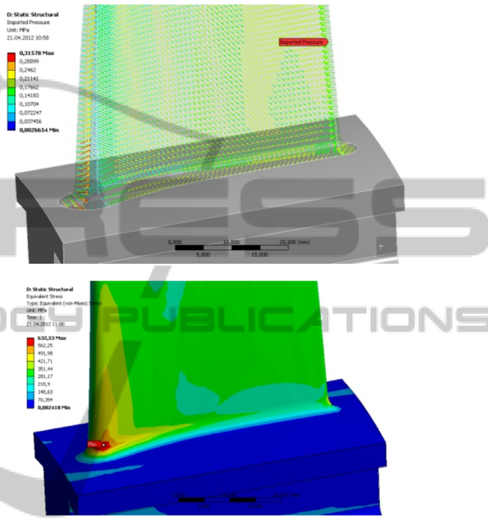

Figure 8: Blade finite element model: imposition of aerodynamic loads (upper) and equivalent stresses (lower).

The main loads acting on the blade are the aerodynamic and centrifugal forces. The aerodynamic load is transmitted to the blade as the pressure of gas flow field calculation. In such loading conditions, stress-strain state is determined by the following parameters:

- fillet radius (R), which determines the size of the stress concentration zone;
- relative position of the central and peripheral sections, which influence distance between center of gravity of the blade and its center of rotation. In turn, it influences value of the centrifugal force.

3 OPTIMIZATION PROCEDURE

3.1 Choice of Design Variables

It is obvious that the problem under consideration, in terms of optimization, refers to the class of NPcomplete problems. It means that dimension of design space exponentially depends on the number of variables. Thus, it is important to identify the most important input parameters and exclude from consideration those which have low influence on the design criteria and constraints. This can help significantly reduce complexity of the optimization problem in terms of computational time.

Global sensitivity analysis was carried out to assess dependence of adiabatic efficiency, pressure rate and maximum equivalent stress on inlet angles, shift of middle and peripheral cross-sections and fillet radius. For these calculations, Parameter Correlation tool from ANSYS DesignXplorer was used.

Results of the calculations presented in Figure 9. They allowed drawing the following conclusions:

- the value of adiabatic efficiency and pressure ratio mainly depends on blade angles at inlet, middle and far-sections, as well as (to a lesser extent) fillet radius;
- maximum equivalent stress is mainly affected by the shifts of middle and peripheral cross-sections, as well as by a fillet radius and a blade angle at the inlet.

Based on this, it was decided to use all of the above parameters as variables in optimization problem.

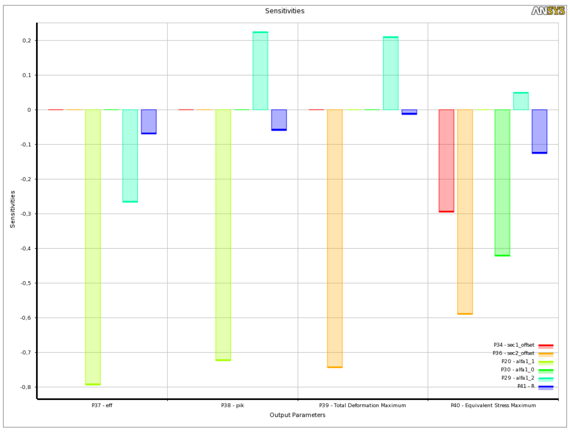

Figure 9: Dependence of the upcoming criteria optimization of variable parameters.

3.2 Optimization Formulation

As a result, the optimization problem can be formulated as follows:

$$\textit{Maximize efficiency} = f(\alpha_{1\_0}, \alpha_{1\_1}, \alpha_{1\_2}, \Delta x_0, \Delta x_1, \Delta x_2, R), \textit{ and}$$
$$\textit{Maximize } \pi_k^* = f(\alpha_{1\_0}, \alpha_{1\_1}, \alpha_{1\_2}, \Delta x_0, \Delta x_1, \Delta x_2, R)$$
$$\textit{under the constraint of } \sigma_{max} \le [\sigma],$$

where α_{1_0}, α_{1_1}, α_{1_2} – blade inlet angles to the cross sections 0…2; Δx_0, Δx_1, Δx_2 – shift of cross sections at tangential plane; R – fillet radius at the junction of the blade in fir-tree root.

The first step in solving any optimization problem using ANSYS DesignXplorer is construction of response surfaces for design objectives and constraints. In the current work, response surfaces were represented using second order polynomials. Some of them are shown in Figure 10. “Central composite design” method was used to select sample points.

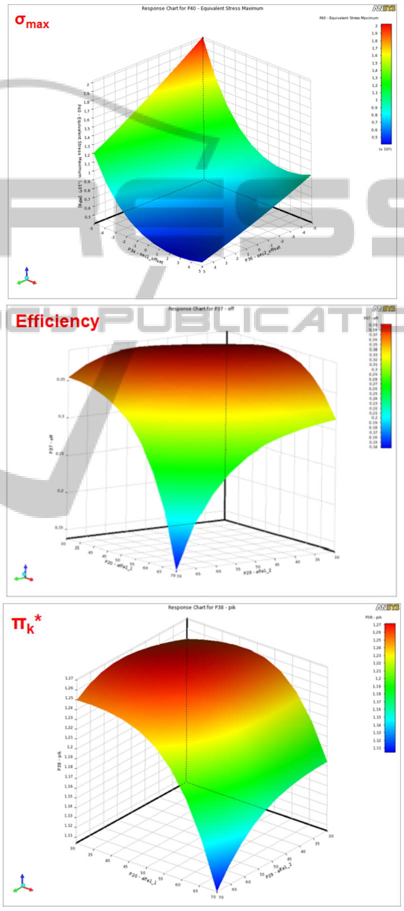

Figure 10: The constructed response surface parameters to be optimized (in the axes α1_1, α1_2): maximum equivalent stress (on the top), adiabatic efficiency (in the middle), pressure ratio (on the bottom).

The ranges of the design parameters were as follows: ±5 mm for the displacement of middle and peripheral sections; 30...70° for the angles; 2...5 mm for the fillet radius. The maximum allowable equivalent stress for the titanium blade was assumed to be 800 MPa. Equal weighting factors were used for both design criteria.

In the next stage, optimization strategy was chosen. The only method available in DesignXplorer for multiobjective optimization is so called Genetic Algorithm. This method implements mathematical model of evolutionary process.

3.3 Optimization Results

When importances of design criteria are not equal, all possible optimal solutions belong to so-called Pareto front. Calculated Pareto front for the current problem is shown in Figure 11.

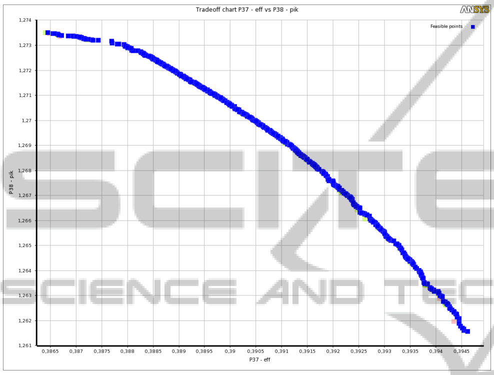

Figure 11: Pareto front.

Results obtained for the case of equal importance are presented in Table 1. Their comparison with the corresponding values for baseline design is shown in Figure 12. Increase of adiabatic efficiency and pressure ratio obtained as a result of optimization is equal to 23 and 7%, respectively.

Table 1: The values of the design parameters of the blade, obtained during optimization.

Parameter	Optimal value
$\alpha_{1\ 0}$, degrees	42.52
$\alpha_{1\ 1}$, degrees	32.11
$\alpha_{1\ 2}$, degrees	47.53
Δx_0 , mm	4.92
Δx_1 , mm	-0.83
R, mm	2.75

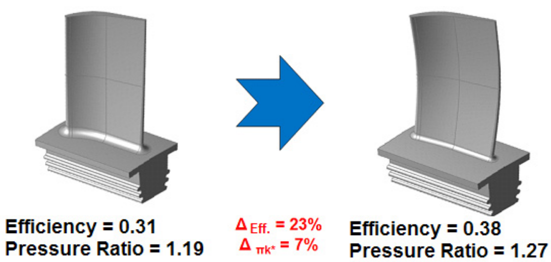

Figure 12: Comparison of the original and the optimized shape of the blade.

4 CONCLUSIONS

Multiobjective optimization of gas turbine compressor blade parameters has been performed using ANSYS software. Significant increase of gas-dynamic efficiency in terms of adiabatic efficiency and pressure ratio was achieved with strength constraints remained satisfied. Obtained results indicate that presented approach can be successfully used for the optimal design of compressor blades.

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