Design and Optimization of Compressor Airfoils by Using Class-Function / Shape-Function Methodology

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Long Abstract

Introduction

Modern industrial axial flow compressors are operating in different climate conditions in which several requirements have to be ensured. Depending on the power demand the gas turbine has to work efficiently at wide operating range. To ensure a reliable energy supply, sufficient surge and choke margin are required. A changing power demand can be achieved by a change in mass flow. Hence, the blade sections of each compressor stage experience a different incidence variations which it has to cope with.

In the beginning of airfoil design, extensive experimental studies were performed to develop families for aero- and land-based engines. The outcome of these experiments were the well-know NACA 65-series [1] which were subsequently used in gas turbine applications. Following in profile generation methods, controlled diffusion airfoils were developed and widely used in compressor design, [2]. This results in parameterization of blade section geometry based on spline functions and an additional coupling with optimization algorithm such as genetic methods, [3] and [4].

The paper applies a method for designing blade profiles by superposing a generalized parabolic arc mean line and the class function / shape function thickness distribution. The objective is to develop a fast and analytical design tool for compressor airfoils used in land-based engines. The method has been tested on four compressor cascades available in open literature which differ in inflow velocity and flow turning.

1. Methods

In the current study a generalized parabolic arc mean line superimposed by a thickness distribution generated with the CST methodology has been used to provide blade airfoil geometry, [5]. In accordance to Schlichting and Truckenbrodt [6] the parabolic mean arc line is defined dimensionless as follows

$$Y_c(X) = a \cdot \frac{X(1-X)}{1+bX} \tag{1}$$

with the parameters a and b including the position of the maximum camber

$$a = \frac{f}{X_f^2 l} \text{ and } b = \frac{1-2X}{X_f^2}. \tag{2}$$

Kulfan and Bussoletti [7] presented the CST methodology in order to provide a general geometry generation for aircraft wings, nacelles and fuselages. It is given as

$$Y_t(X) = C(X) \cdot S(X) + X \cdot \Delta Y_{TE}. \tag{3}$$

For a given trailing edge thickness ΔY_{TE}, the class-function $C(X)$ and shape-function $S(X)$ is defined as

$$C(X) = X^{N1} \cdot (1-X)^{N2} \text{ and } S(X) = KR \cdot (1-X) + \frac{1}{KR} \cdot X, \tag{4}$$

respectively. Thereby, the class-function characterizes the principle type controlled by the factors $N1$ and $N2$. Aircraft wings as well as compressor profiles are illustrated by $N1 = 0.5$ and $N2 = 1$ showing a leading and a trailing edge which is rounded and sharp, respectively. The shape-function, however, influences the profile contour in more detail. By chosing a higher value for KR the leading edge radius increases and the trailing edge angle decreases. This results in a more frontloaded profile which is required for land-based engines.

Referring to Sonoda and Schreiber [8] subsonic compressor cascades can be categorized in its application and Reynolds number. According to the much lower density at higher altitude aeroengines operate in Reynolds number up to $2x10^6$ whereas compressor airfoils of land-based engines usually work at Reynolds number higher than the afore-mentioned value.

Within the developed design methodology the profile generation was coupled with DAKOTA [9] and the aerodynamic performance were automatically calculated by using the two-dimensional blade-to-blade solver MISES [10]. DAKOTA applies a genetic optimization algorithm to estimate the design variables KR from eq. (4) as well as the maximum camber and its position. For assessing the aerodynamic performance a fitness function has been defined with the objective of a wider operating range and low loss coefficient.

In the study four profiles with different Reynolds number have been taken from literature ([1] and [11]) as a reference. Figure 1 shows the change in geometry from one initial NACA 65-profile to its optimized profile which is less curved with a more frontloaded profile shape. An increase of 30 % in operating ranges with 15 % larger distance to the surge margin have been achieved for that profile, cf. Fig. 2. A higher surge margin distance has been accomplished for all four profiles.

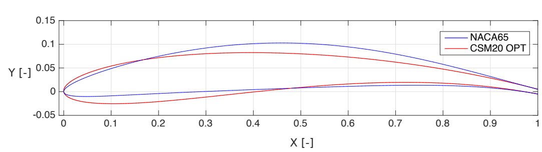

Figure 1. Profile geometry comparison

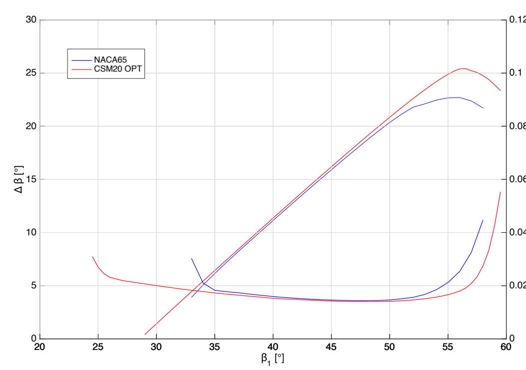

Figure 2. Flow turning and loss coefficient

References

[1] Members of Staff of Lewis Research Center. *Aerodynamic Design of Axial-Flow Compressors - NASA SP-36*. National Aeronautics and Space Administration (NASA), 1965.

[2] D. E. Hobbs and H. D. Weingold. Development of controlled diffusion airfoils for multistage compressor application. *Journal of Engineering for Gas Turbines and Power*, 106(2):271–278, April 1984.

[3] Ulf Koeller, Reinhard Moenig, Bernhard Kuesters, and Heinz-Adolf Schreiber. Development of advanced compressor airfoils for heavy-duty gas turbines: Part I: Design and optimization. *Journal of Turbomachinery*, 122(3):397–405, February 1999.

[4] Frank Sieverding, Beat Ribi, Michael Casey, and Michael Meyer. Design of industrial axial compressor blade sections for optimal range and performance. *Journal of Turbomachinery*, 122(2):323–331, April 2004.

[5] Ira H. Abbott and Albert E. von Doenhoff. *Theory of Wing Sections: Including a Summary of Airfoil Data*. Dover Books on Aeronautical Engineering. Dover Publications, 1959.

[6] Hermann Schlichting and Erich Truckenbrodt. *Aerodynamik des Flugzeuges (Band 1) - Grundlagen aus der Stroemungsmechanik, Aerodynamik des Tragfluegels (Teil 1)*. Springer-Verlag, Berlin, Deutschland, 2. edition, 1967.

[7] Brenda M. Kulfan and John E. Bussoletti. Fundamental parametric geometry representations for aircraft component shapes. *AIAA Paper 2006-6948*, pages 1–45, 2006.

[8] Toyotaka Sonoda and Heinz-Adolf Schreiber. Aerodynamic characteristics of supercritical outlet guide vanes at low reynolds number conditions. *Journal of Turbomachinery*, 129(4):694–704, August 2007.

[9] B.M. Adams, L.E. Bauman, W.J. Bohnhoff, K.R. Dalbey, M.S. Ebeida, J.P. Eddy, M.S. Eldred, P.D. Hough, K.T. Hu, J.D. Jakeman, J.A. Stephens, L.P. Swiler, D.M. Vigil, and T.M. Wildey. *Dakota, A Multilevel Parallel Object-Oriented Framework for Design Optimization, Parameter Estimation, Uncertainty Quantification, and Sensitivity Analysis: Version 6.4 User's Manual*, sandia technical report sand2014-4633 edition, Updated May 9 2014.

[10] Mark Drela and Harold Youngren. *A User's Guide to MISES 2.63*. MIT Aerospace Computational Design Laboratory, February 2008.

[11] Ulf Koeller. *Entwicklung einer fortschrittlichen Profilsystematik fuer stationaere Gasturbinenverdichter*. PhD thesis, Ruhr-Universitaet Bochum, DLR-Forschungsbericht 1999-20, 1998.