About Subsonic Compressor Tandem Aerodynamics - A Fundamental Study

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ISROMAC 2016

International Symposium on Transport Phenomena and Dynamics of Rotating Machinery

Hawaii, Honolulu

April 10-15, 2016

Abstract

This paper deals with the description of the fundamental operation principles of a modern high efficient subsonic compressor tandem cascade. Design recommendations are developed by considering these principles and based on an optimization database with more than 1900 tandem geometries. Therefore, one essential part of the investigation presented is the definition of a highly loaded outlet guide vane application and the design of subsonic tandem cascades by means of an advanced optimization procedure. As boundary conditions for the optimization an inlet Mach number of 0.5 as well as three operating points are defined in order to ensure a maximum working range of 15 deg. Furthermore, three objective functions are used, which are focused on the minimization of the losses at the three operating points and the enhancement of the cascade performance in terms of pressure rise. Afterwards, the optimization database was analyzed in detail with respect to the correlation between the aerodynamic performance parameters and the geometrical parameters of the subsonic tandem cascade. This analysis shows, that there is only a small range of optimal subsonic tandem geometries for a wide range of performance requirements.

Keywords

subsonic compressor, tandem, cascade, design principles, optimization

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INTRODUCTION

The development of modern axial compressors has already reached a high level. Therefore an enlargement of the design space by means of new or advanced aerodynamic methods is necessary in order to achieve further enhancements of performance and efficiency. The tandem arrangement of profiles as an outlet guide vane in a compressor is such a method, because the stage matching becomes more flexible. Furthermore, tandem configurations are well known for increased deflection and static pressure ratio in an axial compressor stage at a constant loss level [1, 2, 3, 4]. However, for an efficient industrial application the knowledge of the fundamental design principles is needed.

In this context, a lot of investigations can be found in the literature how to arrange the blades. Ohashi [5] investigated the interference effect of the blades by a comparision of the losses of the singe blades and the tandem configuration. It was shown that the loss behaviour depends on pitchwise shift because a loss reduction of 10 percent was found at a relative pitchwise position of blade 2 of 0.8 for an axial position which varies between 0.15 and 0.5 of the chord length. Linnemann [3] experimentaly investigated the arrangement of tandem blades at an one stage low pressure compressor. He found, that the tandem cofiguration shows higher efficiency at the same presssure rise compared to a single blade configuration. The results of this study show, that an optimal tandem blade configuration is characterized by a small axial overlap and a pitchwise shift of the blades in the range from 15% up to 20% of the pitch. Within the cascade study carried out by Pal [6] the results show the same tendency. He also suggested a small axial overlap and a pitchwise shift of the baldes by 20% pitch. In addition to that Sieverding [4] stated that the dimension of the slot/nozzle between the blades influences the flow behavior on the blade surfaces. The influence of the slot dimension was also described by Railly et al. [7]. The outcome of this investigation was a pitchwise gap in the range from 5% up to 12% of the pitch in order to achieve the highest deflection and pressure rise. An extensive design study on the optimal blade arrangement for a transonic compressor tandem cascade was performed by Hergt and Siller [8]. This study shows that at transonic conditions the optimal blade arrangement is represented by a pitchwise shift in the range from 15% up to 30% of the pitch and a small axial overlap up to 5% axial chord. In summary it can be extracted from the literature, that the preferable pitchwise position should be in the range between to 0.7 and 0.9 of the relative pitch [9, 10, 11, 12, 13, 14, 15, 8]. Furthermore, it can be found in the literature that a good tandem performance can be achieved with a zero or very small axial overlap for different tandem applications [14, 15, 16, 8].

In the work of Weber and Steinert [17] the development and experimental investigation of a transonic tandem cascade with a deflection of 60 deg is presented. This cascade concept is characterized by a blade ratio of 1:2, without axial overlap of the blades. The study of Hoeger and Müller et al. [18, 19] about a transonic tandem cascade shows that with a tandem configuration of 19 percent chordwise blade overlap a 10 percent increase of turning and a loss reduction by

30 percent was achieved, compared to a wide chord single blade. Additionally, Hertel et al. [20] investigated the loading limit of a subsonic cascade tandem and found a dependency between the incidence angle and the loading distribution of the blades. An increase of the incidence angle leads to an increase in loading of the first blade and a decrease of the incidence angle leads to higher loading of the second blade. The investigation of the secondary flow behavior within a further study [21] shows a significant impact on cascade performance. A more detailed 3D design of a tandem cascade seems to be necessary to achieve further improvements. In the study of McGlumphy et al. [16] a tandem blade arrangement for a rotor application was numericaly investigated. It is shown that such a configuration could enable more rotor work and should replace three conventional rotors. They used NACA 65 blades with a chord length ratio of 1 without axial overlap and only a small pitchwise shift between the blades.

It becomes apparent, that the design of a tandem cascade is specific and depends on the application and the used design philosophy. In this context, the question is: is it possible to define fundamental design recommendations for the arrangement of a compressor tandem cascade using modern design procedures? Hence, the current study is focused on the development of such recommendations for a subsonic compressor tandem cascade using an optimization process.

Modern compressor design is based on advanced CFD and optimization methods [22]. But such a methodology is not rife in the design process of tandem cascades. Only in the last years the studies of Ju and Zhang [23], Schalps et al. [24] as well as Hergt and Siller [8] show the possibility of using modern optimization procedures for the tandem design. Hence, in this study the following approach is used. In the first step an application of a subsonic tandem cascade is defined. An optimization is carried out in order to create a database of more than 1900 subsonic tandem configurations, which is the basis of the analysis. Within this process, the parametrization of the tandem arrangement takes the fundamental aerodynamic effects into account. The second step includes the analysis of the optimization database and the development of design recommendations.

NOMENCLATURE

Latin

c	profile chord length
h	blade span, height
i	incidence angle = β_1-$\beta_{1,OP0}$
M	Mach number
p	pressure
r	radius
Re	Reynolds number based on chord length
t	pitch
v	mean-flow velocity
w	cross-flow velocity
x, y, z	cartesian coordinates

Greek

β	flow angle with respect to cascade front
ϵ	cascade deflection angle = β_1-β_2
ω	total pressure loss coefficient = $\frac{p_{t,1}-p_{t,2}}{p_{t,1}-p_1}$
Θ	relative pitch shift

Subscripts

0	reference state
1	inlet plane
2	exit plane
ax	axial
B1	blade 1
B2	blade 2
is	isentropic
LE	leading edge
s	stagger
t	total, stagnation value
TE	trailing edge

Abbreviations

ADP	aerodynamic design point
AVDR	axial velocity density ratio = $\frac{\rho_2 \cdot v_2 sin\beta_2}{\rho_1 \cdot v_1 sin\beta_1}$
CP	control point
F	objective function
RANS	Reynolds-averaged Navier-Stokes
OGV	outlet guide vane
OP 0	operating point 0
OP 1	operating point 1 (ADP)
OP 2	operating point 2

TANDEM DESIGN APPROACH

The use of an optimization process provides not only the possibility to find an optimal configuration for a single application but also offers the chance to understand the aerodynamic behavior by a detailed evaluation of the database generated. The database enables the assessment of defined geometry parameters due to their direct link to the aerodynamic and performance parameter of each cascade configuration. The boundary conditions for the optimization in the current study are based on the requirements for a compressor outlet guide vane (OGV).

Subsonic Tandem Definition

The design boundary conditions for the cascade optimization are based on the definition of three operating points (OP) of the subsonic tandem configuration. An overview of these three OP is given in Tab.1. The outflow angle is 90 deg (OGV application) and it becomes apparent that within the incidence range of 15 deg between β_1 = 138 (OP 0) and β_1 = 153 (OP 2) a cascade deflection up to 63 deg should be achieved. Furthermore, a variation of the AVDR in the range of 1.0 up to 1.3 is allowed during the opimization in order to consider the influence of different aerodynamic loading levels on the tandem arrangement.

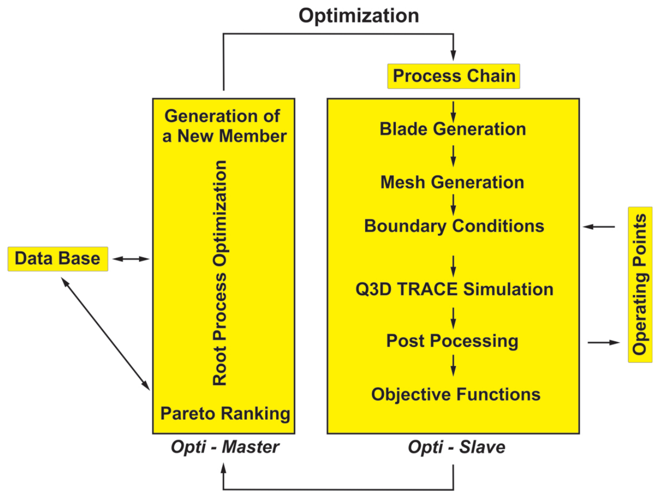

Figure 1. OPTIMIZATION PROCESS CHAIN

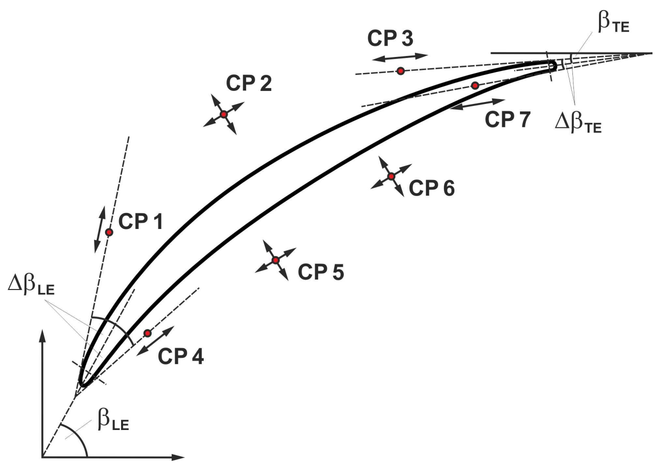

Figure 2. PARAMETRIZATION OF BLADE 1

Optimization and Numerical Setup

The optimization process was conducted using the optimization tool "AutoOpti" [25], [26] which has been developed at the DLR Institute of Propulsion Technology. The optimizer is based on an asynchronous multi-objective genetic algorithm, which here uses the 3D RANS flow solver TRACE [27]. Figure 1 shows the process chain of the optimization.

38 optimization parameters are used in the optimization. The blade shape is defined by 16 parameters for blade 1 and 15 parameters for blade 2. Figure 2 shows the definition of

Table 1. CASCADE DESIGN PARAMETERS

Near Choke (OP 0)	M_1	= 0.50
	β_1	= 138.0 deg
Aerodynamic Design Point (OP 1)	M_1	= 0.50
	β_1	= 143.0 deg
Near Surge (OP 2)	M_1	= 0.50
	β_1	= 153.0 deg

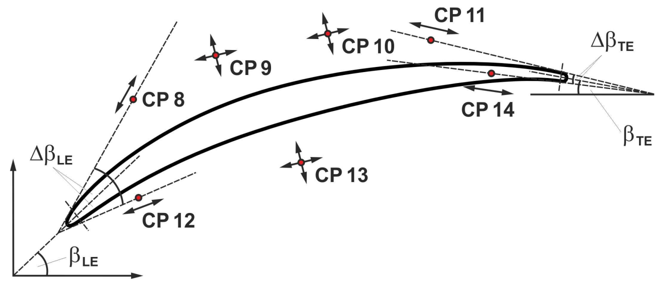

Figure 3. PARAMETRIZATION OF BLADE 2

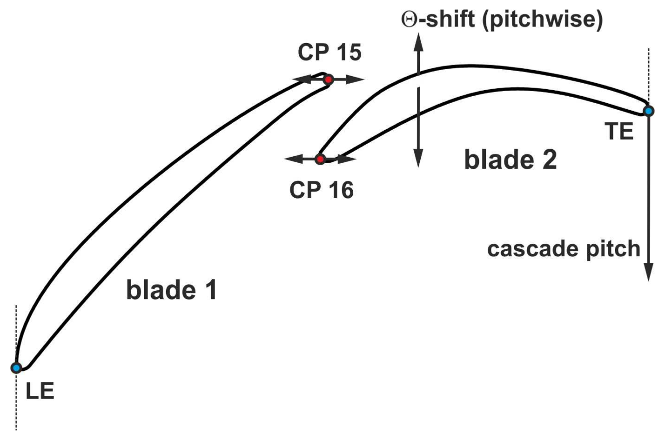

Figure 4. TANDEM ARRANGEMENT PARAMETRIZATION

the optimization parameters of blade 1 where two angles at the leading edge and two angles at the trailing edge are used. In addition to that, seven control points (CP 1 ... CP 7) comprising ten parameters are distributed over the chord length. At the pressure side of the first blade four control points are applied in order to enable positive and negative curvatures. Thus, a wider design space for the overlapping/nozzle area is possible. For the same reason, four control points are applied at the suction side of the second blade as shown in Fig. 3. For the parametrization of blade 2 also seven control points (CP 8 ... CP 14) comprising ten parameters, two leading edge and two trailing edge angles are used. Furthermore, 2 parameters are necessary for the blade stagger angles. In total 30 parameters for the blade shape are defined. One remaining parameter finalizes the parametrization, which is the first blade leading edge radius. This parameter is applied since the achievable incidence angle range of the entire tandem cascade strong depends on the leading edge shape of the first blade. Finally, a geometric restriction was set for the leading edge radius in order to avoid radii less than a critical level. In addition to that, the blade thickness is also constrained by a minimum level, which is based on a recommendation by MTU Aero Engines AG. The outflow angle of the subsonic cascade should be 90 deg +/- 0.5 deg and this was set as a further restriction for the optimization.

In addition to the 31 blade parameters the positions of the blades are defined as shown in Fig. 4. The axial length

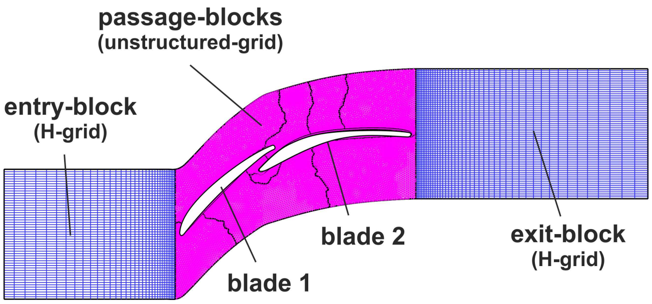

Figure 5. HYBRID STRUCTURED-UNSTRUCTURED GRID TOPOLOGY

of the cascade is 90 mm, so that the leading edge of blade 1 and the trailing edge of blade 2 are at fixed axial positions. An adjustments of the chord length of both blades and the axial overlap are enabled using the axial shift of the control points 15 and 16 (Fig. 4). For the arrangement of the blades in pitchwise direction the Θ-shift is used. In addition to that, the pitch is used as a parameter to take the loading into account, because an increase of the pitch within the optimization leads to a higher cascade loading. Finally, the last three parameters are applied in order to adjust the AVDR value which also influences the cascade loading. These three parameters are used to define the contraction by spline, which ranges from the axial leading edge position of the first blade to the axial trailing edge position of the second blade.

$$F_1 = \omega_{OP1} \Rightarrow minimize \tag{1}$$

$$F_2 = \frac{1}{w_0 + w_2}(w_0\omega_{OP0} + w_2\omega_{OP2}) \Rightarrow minimize \tag{2}$$

$$F_3 = AVDR \Rightarrow minimize \tag{3}$$

The three defined objectives in the optimization are represented by three objective functions. The objective function 1 (F_1) aims at the reduction of losses at the aerodynamic design point, as shown in Equation 1. For the objective function 2 (F_2) in the the Equation 2 it becomes apparent, that the sum of losses of OP 0 and OP 2 are minimized and weighted with $w_0 = 1$ to $w_2 = 3$. Furthermore, the AVDR is minimized by objective function 3 (F_3) as shown in Equation 3. The cascade loading should be increased by this objective function which is in contrast to the loss reduction by F_1 and F_2.

Within the optimization process the steady Q3D numerical simulations were carried out with DLR's 3D-RANS flow solver TRACE, using a k-ω turbulence model. Convergence of massflow as well as the global mean residual, which had to be less than $1x10^{-6}$, were considered. In order to ensure a robust grid generation procedure within the automated optimization process a hybrid grid approach is used as shown in Fig. 5. A structured entry and exit block is combined with an unstructured passage grid. The endwall panels were defined as inviscid walls and represent the optimized AVDR by a spanwise contraction from cascade inlet to outlet for the

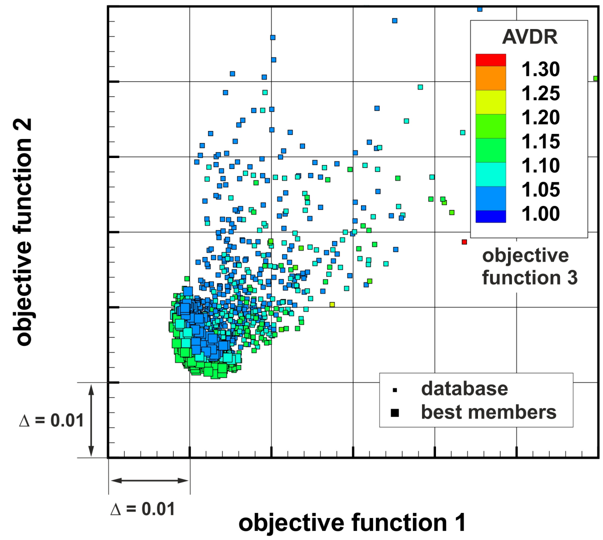

Figure 6. RESULT OF THE OPTIMIZATION (DATABASE)

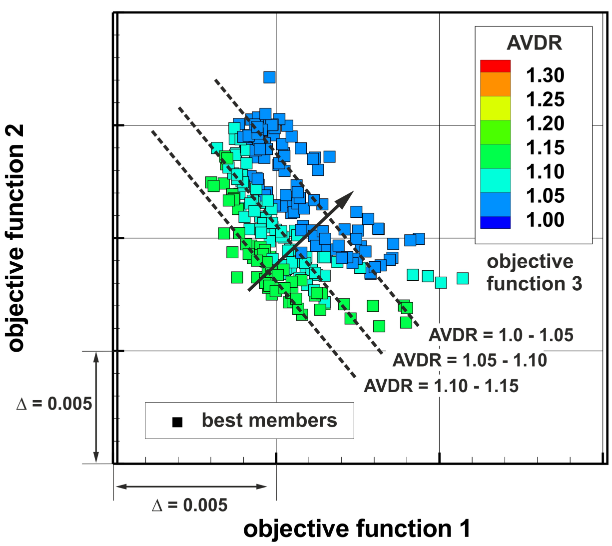

Figure 7. BEST MEMBERS OF THE DATABASE

optimized members.

For the subsonic cascade optimization a consistent specification of the aerodynamic boundary conditions are given. The inflow angle is directly set and the inflow Mach number is controlled by the back pressure P_2. The optimization sequence starts at OP 2. In case that the optimization member does not achieve the aerodynamic requirement (outflow angle) at OP 2 the process loop stops at this early point and unnecessary time waste within the optimization can be avoided.

OPTIMIZATION RESULTS

Figure 6 shows the resulting database of the optimization with 1970 converged members. In the current case with three ob-

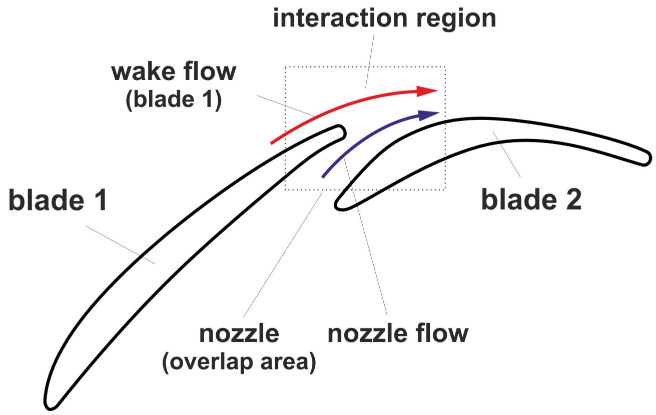

Figure 8. PRINCIPLE SKETCH OF THE TANDEM NOZZLE FLOW

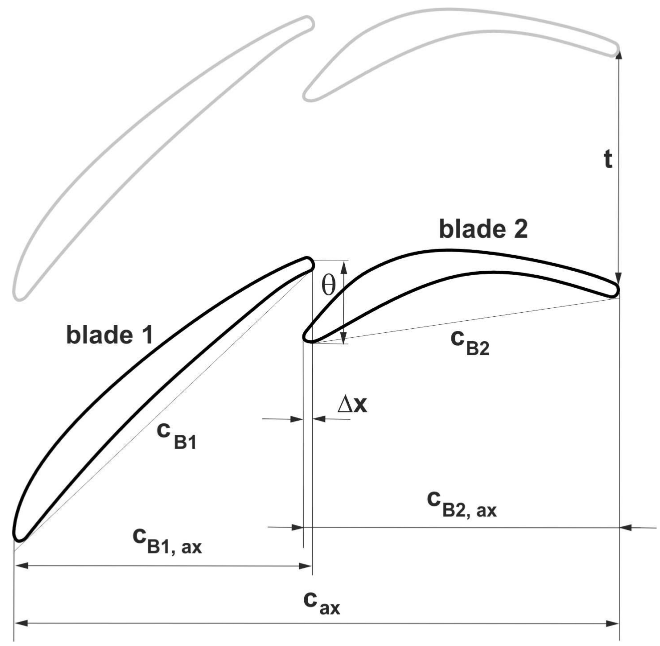

Figure 9. TANDEM CASCADE OPTIMIZATION PARAMETERS

jective functions no pareto front is visible in a 2D plot. The best members with pareto rank 1 are marked with the large symbols. Generally, the data base shows a relatively wide variation of all members in the direction of objective function 1 and 2. Additionally it is noticeable, that for the best members of the database the optimum of the objective function 3 is in the range from AVDR = 1.0 up to 1.15. Figure 7 shows the best member in more detail and it becomes apparent, that for the given objective functions a wide spectrum of optimal solutions is found.

At OP 1 the range of losses of the optimal tandem configurations is within 0.7%. This corresponds to an increase by 20%, starting from the lowest loss value. For the objective function 2, which represents the weighted loss sum of OP 0 and OP 2, the range of the F_2 value is also 20%, starting from the lowest loss value. The tendency of the objective functions 1 and 2, are negative correlated, which is symbolized by the dashed lines in Fig 7. A reduction of one objective function (F_1 or F_2) leads to an increasing of the other (F_1 or F_2). In addition to that, a further correlation with the objective function 3 becomes clear, which is illustrated by the arrow. This means, that an enhancement in objective function 3, which is equal to an increasing of the aerodynamic loading, leads to a change for the worse of the other two objective functions., if the third objective function remains constant. Based on the correlations this suggests, that there is also a wide spectrum of different optimal tandem geometries. Here the question is: can we also find these differences in the arrangement of the tandem blades concerning the pichwise shift, the axial overlap and the chord length ratio?

Analysis of the database

In order to specify the parameters which are important for the analysis of the tandem arrangement its mode of work has to be understood. There are two major mechanisms in tandem cascades. The first one is the nozzle flow which is formed between blade 1 and 2 [4, 8] as shown in Fig. 8. There is an interaction of the nozzle flow with the wake from the suction side of blade 1 and also an influence on the Mach number distribution on the suction side of the second blade. The second mechanism is the distribution of the aerodynamic load between the blades. This depends on the chord length ratio and the turning split of the blades. For the geometric characterization of the nozzle between blade 1 and 2 the Θ-shift and the axial shift Δx is significant. In addition to that, the chord length is crucial for load balancing. The definition of these geometric optimization parameters is shown in Fig. 9. Against this background and in consideration of the described correlations between the objective functions the database in Fig. 6 will be analyzed.

However it can be stated, that the chord length of the blade 1 is longer than that of the second blade. Figure 10 shows the database results where the coloring of the Members represents the chord length ratio c_{B1}/c_{B2}. It becomes apparent, that there is a wide range of the ratio between 1.1 up to 1.4 for the entire database and there is no significant correlation between the chord length ratio and the objective functions. In reference to the best members of the database it is observable, that they are located within a small range between 1.2 up to 1.3 as shown in Fig.11. It becomes apparent that for an optimal load balancing in a subsonic tandem cascade the first blade should be around 20% - 30% longer than the second blade.

This can be traced to a different working of the blades. In order to bring the aerodynamic loading of the first blade to a moderate level (prevention of stall over the entire operating range) the chord length is increased compared to the second blade. The second blade has generally a shorter chord length with a great curvature in the front part of the blade (exampl. Fig 9), because the necessary high flow turning is achievable by the interaction of the nozzle flow with the suction side boundary layer of blade 2. The ratio of the axial chord length

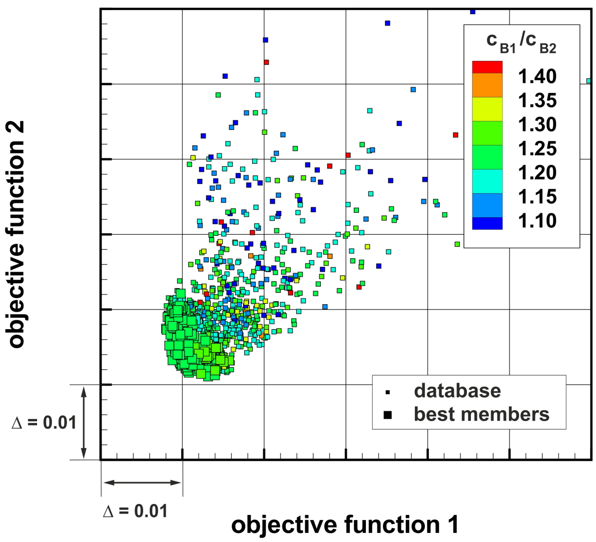

Figure 10. RELATIVE CHORD LENGTH RATIO OF THE DATABASE MEMBERS

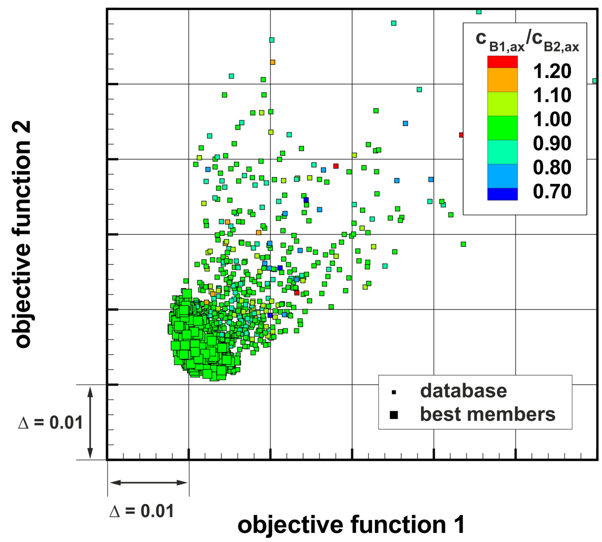

Figure 12. RELATIVE AXIAL CHORD LENGTH RATIO OF THE DATABASE MEMBERS

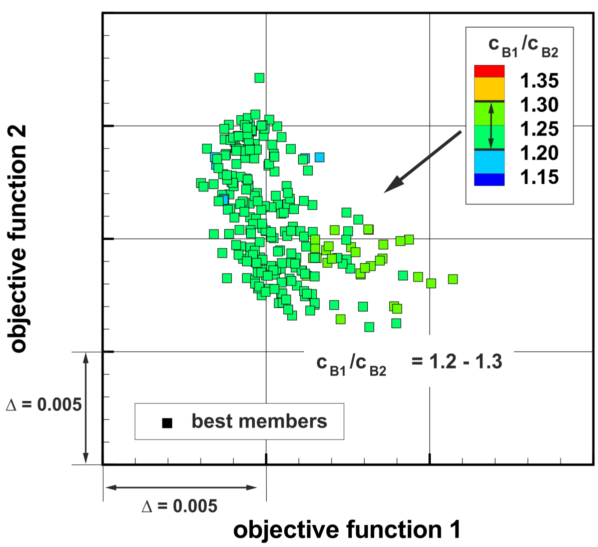

Figure 11. RELATIVE CHORD LENGTH RATIO OF THE BEST MEMBERS

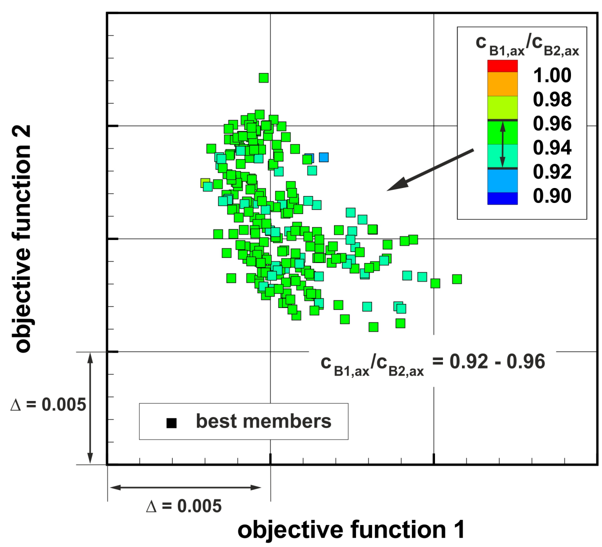

Figure 13. RELATIVE AXIAL CHORD LENGTH RATIO OF THE BEST MEMBERS

in Fig. 12 shows the nearly identical behaviour. For the best members shown in Fig. 13 the optimal range amounts a little bit smaller from $c_{B1,ax}/c_{B2,ax}$ = 0.92 up to 0.96. Based on this it can be stated that there is no significant influence of the blade staggering on the load balancing.

Concerning the cascade loading, additional information is given by the results of cascade pitch. The range of cascade pitch of all database member amounts to 0.058 m up to 0.081 m. The pitch of the best members is close to the upper bound of the entire database in the range from 0.08 m up to 0.081 m. This means a higher loading of the best members compared to all members of the database.

Figure 14 shows the entire database where the coloring of the members represents the relative axial shift $\Delta x/c_{ax}$ between both blades. If the shift amounts to 0 it means that the trailing edge of blade 1 and the leading edge of blade 2 are at the same axial position. Furthermore, a negative value means that the trailing edge of blade 1 is further downstream in the axial direction than the leading edge of blade 2. This figure depicts that members of the database include a range of the relative axial shift from -0.22 up to +0.12. Whereas the best members of the database are within a very small range between -0.01 and -0.02. It seems that a small axial overlap leads to a more optimal tandem geometry as already stated by Linnemann [3] and [6] and in addition ii is more or less independent from the loading level of the compressor cascade as shown in the results

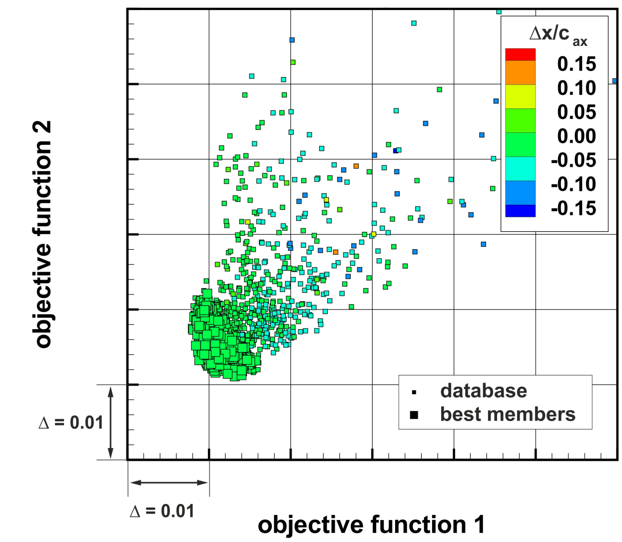

Figure 14. RELATIVE AXIAL DISPLACEMENT OF THE DATABASE MEMBERS

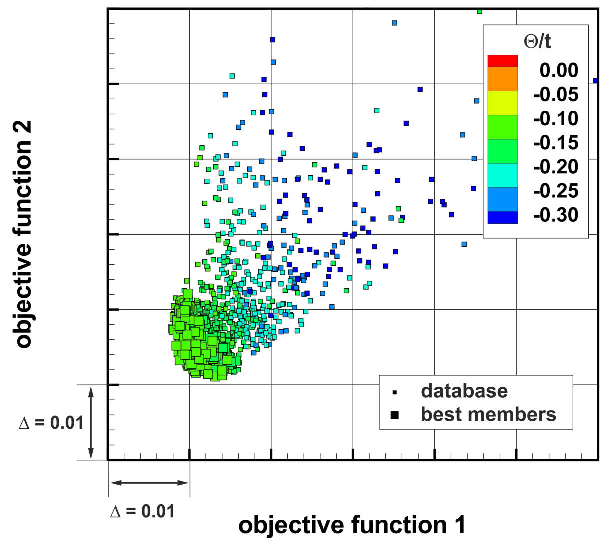

Figure 16. RELATIVE Θ-SHIFT OF THE DATABASE MEMBERS

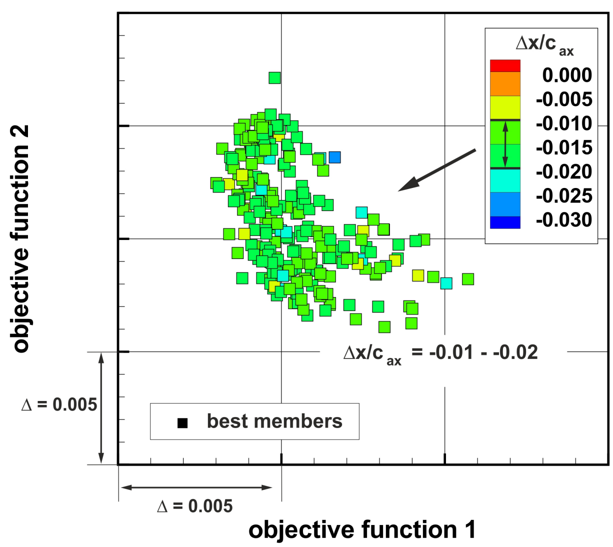

Figure 15. RELATIVE AXIAL DISPLACEMENT OF THE DATABASE BEST MEMBERS

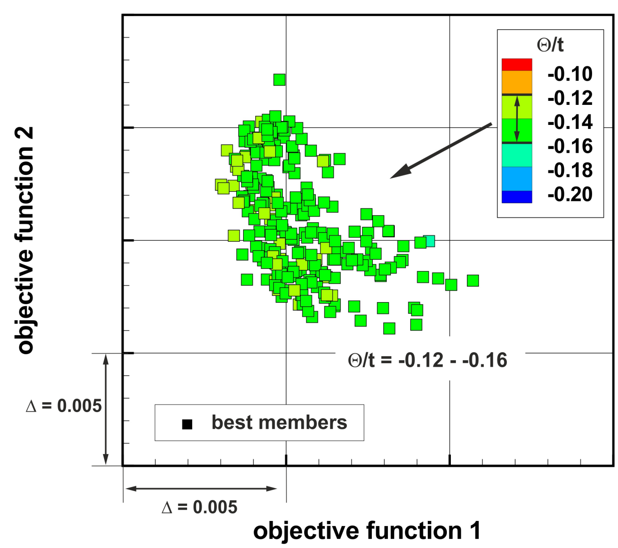

Figure 17. RELATIVE Θ-SHIFT OF THE DATABASE BEST MEMBERS

of the current study. Concerning the axial shift (overlapping), Fig. 15 shows the behavior of the best members in more detail. In this figure it becomes apparent, that the optimal members value of axial shift is nearly constant and independent of the three objective functions. Which means that for the optimal axial shift (very small parameter range) a wide performance range (aerodynamic loading) of the subsonic tandem cascade is achievable.

In Addition to that, the range of the relative Θ-shift of all database members, shown in Fig. 16, is not significantly larger. In this figure the coloring of the Members represents the relative Θ-shift. If the Θ-shift is 0 it means that the trailing edge of blade 1 and the leading edge of blade 2 are at the same pitchwise position. A negative value means that the leading edge of blade 2 is pitchwise shifted towards the pressure side of blade 1 (in Fig. 4 blade 2 is moved down). Figure 17 shows that the best subsonic tandem cascade members are very sensitive to the variation of the pitchwise position of blade 2, because the variation range is also very small. The relative Θ-shift is -0.12 up to -0.16. Furthermore it becomes apparent, that there is no correlation between the objective function 1 and the pitchwise shift. In this case it can also be stated that a wide performance range (aerodynamic loading) of the subsonic tandem cascade is achievable for an optimal pitchwise shift (very small parameter range).

Design Recommendations

Based on the optimization results the following design recommendations for a subsonic tandem cascade can be given:

I: In order to achieve an optimal load balancing between the blades, in terms of pressure rise and flow turning the first blade should be between 20% and 30 % larger than the second blade. This brings the aerodynamic loading at Blade 1 to a moderate level in order to avoid stall within the working range.

II: The axial overlapping of the tandem blades should only be within the very small range of 1% up to 2 % axial chord.

III: The second blade should be pitchwise shifted towards the pressure side of blade 1. This Θ-shift should be within a small range of 4 % of pitch. The minimum pitchwise distance between the trailing edge position of blade 1 and the leading edge position of blade 2 should be 12 % of the pitch.

Generally, it can be stated that a subsonic tandem cascade which follows the given recommendations for the blade arrangement can cover a wide performance range, in regarding the aerodynamic loading at lowest losses.

Finally, it has to be mentioned that this recommandations are the first step. In the next step they should be proved by further studies.

CONCLUSION AND OUTLOOK

Within the current study the optimization of a subsonic tandem cascade is carried out and the resulting database is used in order to develop design recommendations for an optimal arrangement of both tandem blades.

Three design recommendations are stated in the study. Blade 1 should be 20% to 30 % longer than the second blade in order to achieve an optimal load balancing between the blades. The axial overlapping of the tandem blades should only be within the small range of 1 up to 2 % axial chord. The variation of the pitchwise position of the second blade can be used to adjust the nozzle flow between the both blades. The pitchwise distance between the blades should be within a range of 12 % up to 16 % of pitch.

Based on the results of this study the validation of the design recommendations will be performed. In order to prove the efficiency of the design the application of standard NACA profiles within the tandem cascade is planned.

ACKNOWLEDGMENT

The work reported in this paper is performed under the German Aviation Research Program (LuFo IV) and is funded in part by the Federal Ministry of Economics and Technology. The authors would like to thank the colleagues from MTU Aero Engines AG for the very good cooperation and discussions within the project.

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