INTRODUCTION OF AN IMPROVED AXIAL COMPRESSOR PROFILE SHAPE MODELLING APPROACH FOR INCREASED FLEXIBILITY IN TRANSONIC PROFILE DESIGN

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ABSTRACT

With the goal to reduce carbon emissions of future aircraft engines the concept of shape adaptive rotor blading for transonic fan and compressor applications is researched within the Excellence Cluster SE²A. As the aerodynamic design point is shifted by the morphing of the blade shape, the transonic profile design plays a major role in keeping the respective operation point efficiency close to the initial design point efficiency. To increase flexibility and accuracy in transonic profile design, an improved profile modelling approach is presented. To keep the number of modelling parameters to a minimum, a superposition of a generalized parabolic arc camber with a CSM (Class Function / Shape Function) thickness distribution is applied. As the CSM methodology offers an extension of the modelling parameters, the number of parameters is successively increased within this research to enable a better representation of transonic profile shapes. Additionally, the impact of leading edge design and suction side curvature on the blade-shock interaction is explored by specifically manipulating the CSM thickness distribution in the leading edge area. The proposed modelling approach is then applied to a redesign of the tip area of the NASA rotor 67 and evaluated through Q3D RANS simulations in Ansys CFX.

INTRODUCTION

Within the Cluster of Excellency SE²A, shape morphing rotor blades are investigated. To increase the jet engine efficiency over the whole flight mission, the shape of transonic compressor rotors is adapted to ideally match varying operating conditions with different inflow as well as flow deflection requirements. As demonstrated by Krone et al. (2017) the deformation is realized by applying piezoceramic actuators onto the rotor pressure and suction sides to adapt the spanwise blade turning and twist. This concept however has a major impact on the applicability of existing design methodologies, because the aerodynamic design space is increasingly limited by structural design requirements and the blade deformation feasibility. For a preliminary feasibility study the transonic NASA rotor 67, described and analysed in Hathaway (1986) is redesigned and transformed into a shape adaptive system. With a relative inflow Mach number of 1.38 at the blade tip, the rotor is supersonic in the tip region and compression shocks are inevitable. A major challenge in the design of the shape adaptive rotor is therefore the reduction of shock losses and the management of the blade shock interaction, which becomes even more important, as the highest deformations are achievable in the tip region of the rotor (Seidler et al., 2021). In the aerodynamic design process a high flexibility in profile design is advantageous in order to find an optimal blade design for the existing flow situation. With the introduction of transonic fan and high pressure compressor rotors, flexibility becomes even more important, as profile shape and curvature are critical for the occurrence of compression shocks and the magnitude of additional shock related losses. As stated by Bennini (2004), it is the goal of transonic profile design to control the shock location and strength rather than avoiding it to increase the overall profile performance. By reducing the peak profile Mach number and the flow acceleration between leading edge and shock position, the shock losses can be reduced significantly. To achieve that, improved transonic profile shapes have been developed and investigated, ranging from wedge shaped profiles (Joos, 2020) to inverse profile designs for a controlled diffusion and therefore a shock free deceleration for peak Mach numbers up to 1.3 (Hobbs and Weingold, 1984). An early modelling suggestion for transonic profiles was given by Fottner and Lichtfuss (1983), who separated transonic profile shapes in a wedge shaped front in order to control the flow acceleration towards the compression shock and an aft end with a NACA65 thickness distribution.
deflecting the subsonic flow downstream of the shock. Calvert and Ginder (1999) summarized the influence of selected geometrical characteristics, like camber distribution or leading edge shape and thickness on the transonic flow behaviour, also including the concept of a concave suction side surface to further reduce the Mach number preliminary to the shock. With the increase in accessible computational power, the flexibility in transonic blade modelling was increased, leading to automated profile optimization routines with an increased number of design parameters. Oyama et al. (2002) and Bennini (2004) used b-spline based modelling approaches of higher order to remodel and optimize the NASA rotor 67 and rotor 37, respectively, offering a high modelling flexibility with a total number of modelling parameters higher than 10.

Figure 1 Meridional view of the NASA67 stage and re-engineering of profile shapes

To reduce the modelling complexity, while maintaining a high flexibility in profile design, an alternative modelling approach is adapted within this research. The superposition of a generalized parabolic arc mean camber line with a CSM based thickness distribution is applied, which was initially introduced in Giesecke et al. (2018). Although the flexibility and the advantages of the continuous mathematical modelling were confirmed by applying the modelling approach in an optimization routine, the applicability in the development of a transonic shape adaptive NASA rotor 67 has yet to be evaluated. The rotor profile sections of the NASA rotor 67 were originally designed with a multiple circular arc methodology, while the tip sections show additional linear curvature reductions at the pressure and suction sides (see fig. 1). As a reference for the redesign, the original rotor geometry is remodelled based on the geometry data provided in Hathaway (1986). Due to the low resolution of the rotor sections at the leading and trailing edges, circles are inserted instead and resized to match the contour slope of the profile’s suction and pressure sides. As figure 1 demonstrates, the application of the CSM-based modelling methodology to transonic and supersonic rotor sections results in extremely thin leading edges, which are not feasible from a structural point of view. Additionally, the suitability of the CSM thickness modelling has to be questioned, as the remodelling accuracy of the tip section in figure 3 shows a rather high deviation between the original shape and the CSM remodelling. To improve the CSM modelling for transonic and supersonic profile shapes, a thickness modelling extension is introduced and applied to the remodelling of section 2 of the NASA rotor 67 (fig. 1). Although this research focuses on the aerodynamic applicability of the chosen modelling approach, the intensified aerostructural coupling in the profile design process due to the introduction of shape adaption has to be taken into account. To evaluate the impact of structural deformations on transonic profile designs, a complementary deformation study is conducted, also considering the suitability of the introduced modelling approach to provide target designs for the shape morphing.

METHODOLOGY

The profile modelling procedure is based on the methodology, introduced in Giesecke et al. (2018). Following the definition of Schlichting and Truckenbrodt (2001), the profile camber line is implemented as a generalized parabolic arc line with the maximum camber \( f_c \) and its chordwise position \( x_c \).

\[
Y_c(x) = a \cdot \frac{x(1-x)}{1+bx} \quad \text{with} \quad a = \frac{1}{x_c^2 f_c}, \quad b = \frac{1-2x_c}{x_c^2}
\]  
(1)

The profile pressure and suction sides are modelled by orthogonally superimposing a thickness distribution onto the camber line. The thickness distribution is implemented according to Kulfan and Bussoletti (2006) with the class function / shape function methodology, short CSM.

\[
Y_t(x) = C(x) \cdot S(x) \quad \text{with} \quad C(x) = x^{n1} \cdot (1-x)^{n2} \quad \text{and} \quad S(x) = KR(1-x) + \frac{1}{KR}x
\]  
(2)

The class function \( C(x) \) defines the basic profile shape and depends on the \( n1 \) factor for the leading edge modelling and \( n2 \) for the trailing edge shape. The class function is multiplied with the shape function \( S(x) \), where \( KR \) is a weighting factor for the thickness distribution, defining the position of the maximal thickness, as well as the leading edge radius and sharpness. Giesecke et al. (2018) predefined the \( n \)-factors as \( n1 = 0.5 \) and \( n2 = 1 \) to form a basic droplet shape for the
profile modelling. The droplet shape showed good results for the modelling of high subsonic profile shapes, such as the stator of the NASA 67 stage. When the droplet shaped thickness distribution is applied to the modelling of transonic or supersonic blade profiles, $KR$ has to be reduced significantly in order to shift the maximum thickness towards the trailing edge and to reduce suction side curvature, as it is recommended by Cumpsty (2004). Reducing the $KR$ factor however does not fully eliminate the convex curvature in the front area of the profile and additionally produces extremely thin leading edges (see fig. 2, left). In order to comply with supersonic profile design requirements, the class function is adapted in a more general form. With $n_1$ and $n_2$ as free parameters, the design flexibility is increased significantly, offering an extended range of basic form variations for the redesign (see fig. 2).

To further adapt the basic profile form towards typical transonic blade shapes, the $n_1$ factor can be increased, leading to a sharp edged ellipse. By further reducing the $KR$ value, the maximum thickness is shifted to the rear, while the convex curvature towards the leading edge is altered. For $n_1 > 1$ the basic leading edge shape becomes concave, indicating the possibility of including pre-compression effects in the profile design. By simultaneously reducing the $n_2$ factor, the maximum thickness can be moved further to the blade rear, until the basic form is merged into a wedge shape for $n_2 = 0$. A variation of $KR$ from unity transforms the wedge shape into a more concave or convex form, allowing a specific manipulation of the supersonic expansion towards the compression shock. By transforming the original droplet form towards suitable transonic shapes, the leading edge is increasingly sharpened, which poses a conflict to structural integrity and manufacturing requirements. Therefore a further adaption of the original CSM modelling approach is required with the goal to directly design leading edge and to reduce suction side curvature, as it is recommended by Cumpsty (2004). Reducing the $s _1$ factor has to be reduced significantly in order to shift the maximum thickness towards the trailing edge and to reduce suction side curvature, as it is recommended by Cumpsty (2004). Reducing the $KR$ factor however does not fully eliminate the convex curvature in the front area of the profile and additionally produces extremely thin leading edges (see fig. 2, left). In order to comply with supersonic profile design requirements, the class function is adapted in a more general form. With $n_1$ and $n_2$ as free parameters, the design flexibility is increased significantly, offering an extended range of basic form variations for the redesign (see fig. 2).

CSM: shape extension

The first modelling approach is a simple extension of the basic CSM shape function in order to improve the leading edge area of the droplet form for transonic and supersonic inflow conditions. To avoid sharp leading edges for decreased $KR$ values and to further reduce suction side curvature, the shape function is adapted, while the class function and the $n_1$-factor remain unchanged ($n_1 = 0.5$). In the shape function an additional term is introduced, allowing a specific manipulation of the leading edge form and thickness as well as a reduction of the profile curvature beyond the leading edge.

$$Y_i(x) = C(x) \cdot \left[ S(x) + S_{LE}(x) \right] + \Delta T E \cdot x \quad \text{with} \quad S_{LE}(x) = \Delta LE \cdot (1 - x^{s_1})^2 \quad \text{(3)}$$

By introducing the $S_{LE}(x)$ function, the variable leading edge thickness parameter $\Delta LE$ provides a direct interface to adjust the leading edge thickness, according to structural as well as aerodynamic design requirements. Due to the continuous thickness modelling approach within this research, the leading edge thickness is defined as a percentage of the maximum blade thickness at 0.5% of the chord. The influence of the increased thickness towards the aft end of the profile is controlled by the leading edge shape factor $s_2$. According to Kulfan and Bussoletti (2006), $s_2 = 2$ delivers the best results for leading edge manipulations and is implemented accordingly for all profile variants. In order to directly influence the shape of the leading edge as well as the slope towards the maximum thickness, the $s_1$ parameter is introduced, leading to equation 3. For decreased $s_1$ factors, the leading edge shape becomes blunter and the slope of the thickness distribution towards the thickness maximum position is reduced. By choosing higher values ($s_1 > 0.6$) instead, a subsonic thickness distribution with increased leading edge thickness and higher curvature is regained (see fig. 3, right). As the leading edge thickness factor $\Delta LE$ directly depends on the predefined absolute leading edge thickness, the number of active modelling parameters is reduced to one for the leading edge extension and three for the full extended CSM modelling approach. The remodelling of the NASA67 rotor tip section is supported by the generalized profile composition described in Fottner and Lichtfuss (1983), where a wedge shaped blade front is combined with a NACA65 thickness distribution for the profile rear. The wedge shape and the NACA65 thickness distribution are separately depicted in figure 3 and 4 with an intersection at approximately 65% of the profile chord. For the first redesign (CSM-V1), the position of the maximum camber is therefore shifted rearwards,
while the overall blade turning and the profile orientation are adopted from the original design (see fig. 3, bottom left). To satisfy these pre-set design requirements, the maximum camber \( \omega_{\text{max}} \) is reduced and the stagger angle is adapted according to the metal angle variation at the leading edge. To gain more control over the flow acceleration towards a possible compression shock, the leading edge sharpness and suction side curvature are reduced significantly, compared to the basic CSM design, by setting \( s_1 = 0.3 \). The leading edge extension also allows the selection of a small KR, which further decreases suction side curvature, while maintaining the maximum thickness position of the original CSM design (see table 1).

Figure 3 Redesign of section 2 of the NASA rotor 67 with the shape extension (left) and influence of \( s_1 \) variations on the extended CSM thickness distribution for \( n_1 = 0.5 \) and \( n_2 = 1.2 \) (right)

CSM: class-shape extension

As the NASA rotor 67 is designed with a tip speed of 429\( m/s \), high relative inflow Mach numbers occur in the blade tip area. To cope with the transonic to supersonic inflow conditions, the CSM thickness modelling approach is further refined with the goal to extend the modelling range to concave suction side contours, introducing a pre-compression capability for the profiles. Therefore, a sharp edged elliptic shape is chosen as reference form, reducing the leading edge thickness in the original CSM thickness distribution to zero (see fig. 2). In order to provide a leading edge thickness, the leading edge is modelled with a separate class function \( C_{\text{LE}}(x) \), while the main part of the profile follows the sharp edged elliptic shape, combined with the original shape function \( S(x) \).

\[
Y_{\text{c}}(x) = C(x) \cdot S(x) + C_{\text{LE}}(x) \cdot S_{\text{LE}}(x) + \Delta T E \cdot x \quad \text{with} \quad C_{\text{LE}}(x) = x^4(1-x)^2
\]  

(4)

The leading edge shape function is defined according to equation 3. For the newly introduced leading edge class function a droplet shape is chosen with \( c_1 = 0.5 \) and \( c_2 = 1.0 \). This allows to vary the \( n_1 \) and \( n_2 \) factors, without loosing the advantage of an optimized leading edge modelling. With the introduction of a variable \( n_1 \) factor, the design flexibility is further increased, compared to the shape-extension (equ. 3), as more basic forms are available for the profile design (see fig. 2). By reducing the KR factor, the thickness maximum can be shifted to the blade rear, while the \( s_1 \) factor influences leading edge shape, slope and curvature (see fig. 4).

Figure 4 Redesign of section 2 of the NASA rotor 67 with the class-shape extension (left) and influence of \( s_1 \) variations on the CSM thickness distribution for \( n_1 = 1.2 \) and \( n_2 = 1.2 \) (right)

Through the class-shape extension, the slope and curvature towards the thickness maximum can be decreased further, compared to figure 3. For the CSM-V2 design \( n_1 > 1 \) is chosen, turning the suction side curvature behind the leading edge slightly concave. With smaller KR values and higher \( n_1 \) factors, the concave curvature becomes more distinct, indicating
the potential of amplified pre-compression effects to further reduce shock losses. For the \( V1 \) and the \( V2 \) redesign, the same camber line configuration is chosen with the camber maximum located at 64\% of the chord. Due to the selected basic shapes with a concave trailing edge form \((n2 = 1.2)\), the rearward shift of the maximum thickness through a further reduction of the \( KR \) value is limited. To avoid this modelling restriction, a third profile design \((CSM-V3)\) is created with \( n1 = 1.0 \) and \( n2 \) reduced to 0.75, merging the profile thickness distribution towards a wedge shaped profile front with convex curvature towards the trailing edge. This offers a wider range of \( KR \) values for a transonic and supersonic profile thickness design, as shown in figure 4, where \( CSM-V3 \) with \( KR = 0.7 \) and \( CSM-V2 \) with \( KR = 0.1 \) result in an almost similar maximum thickness position (see table 1). Additionally, the camber maximum is shifted rearwards by another 6\%, as the first two profile designs still show a rather high pressure side curvature towards the leading edge.

**RESULTS: EVALUATION OF MODELLING APPROACH AND REDESIGN**

For an in-depth analysis of the created profile designs, the suction side curvature is derived and depicted in figure 5. Compared to the original CSM approach, the curvature in the front third of the profile could be reduced through the redesigns. Even though, \( CSM-V1 \) and \( CSM-V2 \) achieve a significant reduction in suction side curvature in the front third of the profiles, the curvature rapidly increases towards the trailing edge. Due to the decreased \( n2 \) value, combined with a rearward shift of maximum camber within the \( CSM-V3 \) design, the curvature reduction beyond the leading edge as well as the curvature increase towards the trailing edge is damped. However, the effects of camber and thickness modelling on the suction side curvature are not clearly distinguishable beyond the leading edge area.

![Figure 5 Suction side curvature of the CSM-based profiles between \( x/c = 0.03 \) and \( x/c = 0.93 \)](image)

Characteristic profile parameters, such as maximum thickness position and stagger angle are supplemented in table 1. Additionally, a throat area criterion is derived, following the works of Wadia and Copenhaver (1996), where the throat margin is defined as the ratio of throat area \( A_T \) to inlet area \( A_I \). As the inlet passage width is defined to be perpendicular to the upstream relative inflow angle in the S1 plane, the unique incidence inflow condition is selected for the calculation of the throat area criterion.

<table>
<thead>
<tr>
<th>profile</th>
<th>( \lambda/\circ )</th>
<th>( t_{LE}/mm )</th>
<th>( t_{max}/mm )</th>
<th>( x_{t,max}/c/1 )</th>
<th>( A_T/A_I/1 )</th>
<th>( M_{a,max}/1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td>60.72</td>
<td>0.354</td>
<td>5.63</td>
<td>0.63</td>
<td>1.160</td>
<td>1.54</td>
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<td>5.63</td>
<td>0.56</td>
<td>1.165</td>
<td>1.55</td>
</tr>
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<td>5.63</td>
<td>0.55</td>
<td>1.146</td>
<td>1.50</td>
</tr>
<tr>
<td>CSM-V2</td>
<td>62.36</td>
<td>0.211</td>
<td>5.63</td>
<td>0.63</td>
<td>1.133</td>
<td>1.49</td>
</tr>
<tr>
<td>CSM-V3</td>
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<td>0.211</td>
<td>5.63</td>
<td>0.64</td>
<td>1.126</td>
<td>1.46</td>
</tr>
</tbody>
</table>

**Table 1 Summary of design parameters for the different profile designs**

In order to determine the unique incidence condition and to evaluate the profile performance of the redesigned profile sections in further detail, Q3D RANS simulations with a k-\( \omega \)-SST turbulence model are conducted in Ansys CFX. The simulation domain has a linear slope in the meridional plane, while the designed rotor tip sections are projected onto the conical design stream surfaces. In order to include 3D effects, such as channel tapering and end wall boundary layer development, the AVDR is calculated based on the original flow data in Hathaway (1986). By applying a hyperbolic AVDR modelling approach described in Stark (1987), the AVDR is remodelled and a height distribution for the calculation domain can be derived. The hub and shroud of the Q3D simulation domain is then defined as a free slip wall to avoid three-dimensional flows within the calculation domain. To prevent reflections and an interaction of the detached shock with the upstream post-processing planes beyond the spill point, the inlet length is increased until the upstream influence of the detached shock on the inflow angle is negligible. A structured mesh for the simulation domain is created in Autogrid with two cell layers in normal direction and a reduced cell size towards the blade in order to keep the \( y^+ \) at approximately 1. For
the performance line simulations the static outlet pressure is gradually increased, until the bow shock detaches and the Q3D simulations become increasingly unstable and mass flow divergence occurs.

Figure 6 Evaluation of the profile redesigns: isentropic Mach-number distribution (left) and loss coefficients (right)

Even though, the orientation of the profiles is kept constant, the simulated unique incidence inflow angle of the profiles varies. The highest incidence variation ($\Delta \iota = 1.07^\circ$) compared to the original profile is predicted for the CSM-V3 design. The CSM-V3 design also predicts the lowest achievable static pressure ratio, which is surprising, as the overall camber turning angle is kept constant for all profiles. For the V3 design, the predicted losses are smallest, only increasing, when the bow shock detaches from the leading edge for high static pressure ratios. The original CSM design is in good accordance with the original profile, even indicating a reduction in overall loss with increasing static pressure ratios. The simulated static pressure ratios of the alternative designs CSM-V1 and CSM-V2 are approximately at the same level as the original CSM design, but with a significant reduction of the loss coefficient over the simulated operating range. Also the maximum achievable static pressure ratios are slightly higher. Towards lower static pressure ratios, a local loss maximum is visible for the V1 and V2 redesigns, caused by a normal shock wave located near the trailing edge, which corresponds well to results reported in Tweedt et al. (1988). A further reduction of the static pressure ratio causes the loss coefficient to drop again. This behaviour, which has also been reported by Piovesan et al. (2019) occurs, when the shock travels further downstream, reducing the shock induced flow separation and therefore the overall profile loss coefficient. To define a generally applicable criteria for a further investigation of the flow around the profiles, the unique incidence condition is defined as a design point criteria. Since transonic or supersonic blades are rarely operated within the choked unique incidence condition, but merely with the leading edge bow shock detached according to Cumpsty (2004), the last unique incidence operating point before the spill point is selected for comparison. In this operating condition the leading edge bow shock overlaps with the channel shock, forming a continuous shock front, which is strongly influenced by the suction side curvature of the profile ( Bölcs and Suter, 1986). In figure 6 (left, centre) the isentropic Mach number distribution in the selected reference design points of the redesigned profiles is compared to the original designs. The original profile shape, with a circular leading edge produces a significant leading edge spike, which according to Goodhand and Miller (2011) is an indicator for leading edge separation and an increase in overall profile loss. Beyond the leading edge spike, the flow is continuously accelerated along the suction side, until a strong compression shock terminates the supersonic flow regime and induces flow separation. Even though, the continuous leading edge curvature modelling prevents the occurrence of a leading edge spike, the original CSM design indicates the highest profile curvature beyond the leading edge and therefore strong flow acceleration towards a high-magnitude compression shock (fig. 5). The peak Mach number as well as the shock magnitude is comparable to the original Hathaway design with an equally large flow separation beyond the shock in the subsonic flow regime. Through the continuous leading edge modelling with reduced suction side curvature towards the maximum profile thickness, the flow acceleration before the shock is significantly reduced for both, the CSM-V1 as well as the CSM-V2 redesign. Due to the concave suction side curvature of the CSM-V2 redesign, the flow is even decelerated after passing the leading edge (fig. 5). The strong increase in suction side curvature after the concave part however causes the flow to accelerate again towards the compression shock, leading to a marginal reduction in pre-shock Mach number compared to CSM-V1. With increasing static pressure ratios the channel shock moves further upstream towards the concave suction side segment, which reduces the suction side curvature growth towards the shock position and with that pre-shock flow acceleration as well as overall profile losses. The lowest design point peak Mach number is predicted for the CSM-V3 redesign. With the reduction of $n1$ to 1.0, chordwise curvature variations are damped and flow acceleration preliminary to the compression shock is almost prevented, shifting the shock position further downstream. This causes a local flow separation which further downstream reattaches, indicated by the local Mach number maximum near the profile trailing edge in figure 6 (centre). The relocation of the maximum camber to $x_c = 0.7$ further diminishes suction side curvature towards the leading edge, but also provokes a
camber reduction in the profile rear, limiting the profile’s pressure rise capability (fig. 6). Although the chordwise suction side curvature is a suitable indicator for the analysis of the transonic as well as supersonic profile performance, other parameters, such as blade stagger angle or throat area are known to have an influence on the flow through the cascades. However, the individual influence of isolated characteristic profile design parameters are difficult to distinguish in their exact impact. Therefore mainly the curvature has been accounted for in this analysis, as a consideration of other parameters requires a more detailed analysis with a broader number of profile design variants.

RESULTS: EFFECT OF SHAPE ADAPTATION ON TRANSONIC BLADE PROFILE DESIGN

The comparison of profile designs with different rearward positions of the maximum camber confirms that the camber design has a major impact on transonic profile performance, incidence and the achievable compression (see fig. 3 and fig. 4). For the application of shape adaption to a transonic rotor, it is of special interest, which camber variations are most beneficial for the blade performance in order to adapt the rotor blade to varying inflow and flow deflection requirements.

With the goal to provide suitable target shapes for structural deformations, a shape adaption study is conducted based on the CSM-V3 thickness distribution. Under the precondition that the application of piezoceramic actuators onto the rotor pressure and suction sides does not structurally affect the thickness distribution of the profile sections itself, the thickness modelling parameters are assumed to be constant over the whole shape morphing process. The optimization of the thickness distribution is therefore mainly driven by aerodynamic design requirements with the full number of modelling parameters and the highest flexibility only available for the reference design point design. For the aerodynamic redesign for altering operating conditions, structural boundary conditions, such as the constant thickness distribution have to be considered, reducing the number of active design parameters to a variation of the stagger angle and an alteration of the blade camber.

The aerostructural coupling within the blade profile design for a shape morphing system is consequently mainly driven by the variation of the maximum blade camber $f_c$ and its chordwise position $x_c$ (equation 1). With the goal to evaluate the impact of external camber deformations on transonic profile performance, both parameters are systematically modified in order to adapt the blade turning of the baseline CSM-V3 redesign (fig. 7).

An increase of the maximum blade camber $f_c$ for a given maximum camber position $x_c$ leads to a linear increase in overall blade turning $\Delta \phi$, according to equation 1. By shifting the maximum camber position $x_c$ towards the trailing edge, the camber becomes increasingly asymmetric, which as well results in an increase of the blade turning. Interestingly, the effect on the blade turning is amplified with increasing $x_c$ (fig. 7). An adaption of the maximum camber therefore yields the highest variations in blade turning, when a backward position of the blade camber maximum is chosen for the reference design, which is also highly recommended for transonic and supersonic blade designs according to Fottnner and Lichtfuss (1983). With a variation of the blade camber parameters, the proportion of the ideally linear, wedge shaped front section of the profile and the rearward cambered section is altered. As the pressure rise within a transonic or supersonic blade passage is caused by the shock itself, but also by the blade turning behind the shock, where again subsonic flow occurs, an alteration of the blade camber is expected to have a major impact on profile performance and losses. Additionally, the suction side curvature is directly influenced by camber design variations, due to the initial curvature of the parabolic camber design. In order to assess the impact of camber induced suction side curvature variations, the curvature of the profile variants is derived and compared to a non-cambered reference. Figure 8 indicates that the profile cambering amplifies the suction side curvature over the profile length with increasing magnitude towards the trailing edge. By expanding the maximum camber $f_c$ or shifting the maximum camber position $x_c$ towards the profile front, the impact on leading edge curvature is further increased. This indicates an increasing uncertainty in the profile design, as the curvature introduced by the camber has to be compensated by the thickness modelling in order to effectively avoid flow acceleration towards the compression shock. Contrarily to the profile redesign study, the turning of the profiles is now defined as a design variable. In order to maintain comparability between the profiles, the orientation of all profiles is again kept constant by adapting the stagger angle.

Figure 7 Theoretical influence of camber deformations on the blade shape (left) and the camber turning (right).
according to the metal angle variation at the leading edge. This shape adaption study can therefore be related to a pressure ratio adaption scenario, where the design point mass flow is kept constant (Seidler et al., 2021). Although, it becomes apparent from figure 9 that a variation of the camber line causes flow incidence, implying a variation in mass flow for the different profile shapes. For the adaption of the blade camber, a reference profile with a maximum camber position at 70% chord length and a maximum camber of \( f_c/c = 0.0204 \) is chosen and three variations of \( x_c \) and \( f_c \) are evaluated with the preliminary described RANS set-up. Figure 9 shows the Q3D performance lines for design speed, where the back pressure was increased gradually, until the simulations showed mass flow divergence. The design point is again determined iteratively as the last design point before the bow shock detaches from the leading edge with a 0.5% accuracy in outlet back pressure variation.

Comparable to subsonic profile designs, an increase in blade turning through the variation of both camber parameters increases the overall achievable design pressure ratio. A higher maximum camber provokes an increase in profile losses, which is mainly due to the higher suction side curvature towards the profile leading edge. The shock is provoked further upstream, increasing the shock strength and thus inducing flow separations and an increase in viscous losses. Shifting the camber maximum towards the trailing edge reduces the overall profile losses, while the achievable pressure ratio is steadily increased, but not as much as through a \( f_c \) adaption. Figure 9 confirms that a maximum camber moved rearwards is beneficial for transonic profile designs, while a high camber with a camber maximum position located near the centre of the profile induces higher losses due to an increased suction side curvature. With the introduction of shape adaption capability however, some guidelines can be derived for the definition of aerodynamic target shapes for future investigations. For the reference design, a rearward camber maximum position should be chosen, as variations in maximum camber then produce lower losses and result in a higher turning variation (fig. 7). To increase blade turning and therefore the achievable pressure ratio, the maximum camber should be shifted towards the trailing edge. For a required pressure ratio reduction, a reduction of the maximum camber with a constant rearward \( x_c \) is best suited. In order to respond to mass flow variation requirements or profile incidence, an additional variation of the stagger angle has to be considered.

**Figure 8** Curvature of the CSM-V3 camber alterations between \( x/c = 0.03 \) and \( x/c = 0.93 \)

**Figure 9** Performance lines and design point loss coefficients for varied \( f_c \) (left) and \( x_c \) (right)
CONCLUSION

An extension of the CSM thickness modelling approach was introduced with the goal to provide a simple, but flexible modelling methodology for transonic and supersonic compressor profile designs. Furthermore, the application of this modelling approach to a tip near section of a shape adaptive compressor rotor was evaluated, especially focussing on the impact of camber variations on the transonic profile performance and the achievable pressure ratio. To specifically manipulate leading edge shape and suction side curvature in the front area of the profile, an additional thickness shape term is added to the shape function, offering two additional parameters for the leading edge design. By introducing a separate class function for the thickness shape term and the leading edge design, the modelling flexibility for transonic profiles was further increased, offering a higher variety of basic profile shapes. Even though, the modelling extension could not exactly reproduce the original form of the selected NASA rotor 67 tip section, the aerodynamic performance could be significantly improved with the new profile designs. With the reduction of the suction side curvature and the relocation of camber as well as maximum thickness position towards the trailing edge, the pre-shock flow acceleration and the shock induced flow separation were significantly reduced. However, the impact of AVDR on the Q3D simulation results has to be investigated in further detail. Finally, the CSM-V3 thickness distribution was selected and analysed within a shape adaption scenario.

NOMENCLATURE

\( a, b \) camber parameter
\( c \) chord
\( c_{ax} \) axial chord
\( f_c \) camber height
\( p \) static pressure
\( n1, n2 \) class parameter
\( s1, s2 \) shape parameter
\( x_c \) camber position
\( x_{t,\text{max}} \) maximum thickness position
\( y^+ \) meshing: y-plus value
\( KR \) thickness parameter
\( S(x) \) shape function
\( C(x) \) class function

\( Y_c(x) \) camber function
\( Y_t(x) \) thickness function
\( Y(x) \) profile function
\( Y'_{s}(x) \) suction side curvature
\( n_{\text{is}} \) isentropic Mach number
\( \beta_{i} \) relative inflow angle
\( i \) incidence angle
\( \lambda \) stagger angle
\( \alpha \) total pressure loss coefficient
\( \Delta \Phi \) profile turning
\( \Delta LE \) LE thickness
\( \Delta TE \) TE thickness
\( \Pi \) pressure ratio

Acronyms:
AVDR Axial Velocity Density Ratio
CSM Class function / Shape function Methodology
LE leading edge
RANS Reynolds Averaged Navier Stokes
TE trailing edge

Indices:
\( c \): camber
\( t \): thickness
\( I \): inlet
\( T \): throat

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