A PARAMETRIC STUDY OF THE PARAMETERS GOVERNING FLOW INCIDENCE ANGLE TOLERANCE FOR TURBOMACHINE BLADES

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ABSTRACT

Performance metrics quantifying the efficiency of various turbomachinery blades aid in the development of an optimal blade design. In this study, a metric was created to investigate the performance of 48 different compressor blades created with Octave and MISES software. Three input parameters were varied: leading edge radius, the location of maximum blade thickness, and the number of blades in a blade row. The objective was to determine which of these parameters most strongly affects the average loss and incidence range for the blade row. After a sensitivity analysis of the three input parameters was conducted, it was found that the number of blades had the largest effect on blade performance, followed by the leading edge geometry and lastly the location of maximum thickness.

Les indicateurs de performance qui mesurent les efficacités de plusieurs pales utilisées dans les turbomachines aident le développement d'une conception optimale des pales. Dans cet article, un indicateur a été créé pour étudier la performance de 48 pales de compresseurs axiaux différents qui ont été faites avec les logiciels Octave et MISES. Trois paramètres d'entrés ont été examinés : le rayon du bord d'attaque, l'endroit de l'épaisseur maximale de la pale et le nombre de pales dans la rangée. L'objectif était de déterminer lequel parmi ces paramètres a l'effet le plus important sur la perte moyenne et la gamme de l'incidence de la rangée de pales. Après une analyse de sensibilité des trois paramètres, les résultats ont montré que le nombre de pales dans la rangée a eu l'effet le plus important sur la performance des pales, suivie par la géométrie du bord d'attaque et enfin l'endroit de l'épaisseur maximale.

KEY WORDS

Computational fluid dynamics; Compressor blades; Turbomachinery; Sensitivity analysis; Blade efficiency

INTRODUCTION

Research Objectives

Turbomachines are any machines that transfers energy to or from a fluid through the action of rotating blades, found commonly in anything from hairdryers to helicopters engines, wind turbines to dentist drills. They are classified into two main categories—turbines, through which static pressure falls throughout the machine, and compressors, through which static pressure rises (Denton, 2012). The latter is the main focus of this report—the aerodynamic design of compressor blades is intrinsically more difficult, due to the tendency of fluid boundary layers to quickly thicken and subsequently separate in conditions with rising pressure. Separating boundary layers or fluid flow cause a multitude of problems for the performance of the blade; separating flow creates eddies and vortices which then increase drag and therefore degrading blade performance (Denton, 2012).

Fluid flow velocity is determined by a combination of the inlet and outlet flow conditions. The relative inlet flow direction ideally has a very wide range; this allows a greater range of operation for the machine. At subsonic speeds, the fluid flow at the trailing edge of the blade is determined by the Kutta condition—in any blade with a sharp trailing edge, the flow will smoothly leave the trailing edge without the flow remaining attached to the body (Denton, 2012). The separation of boundary layers in supersonic speed flow results in a massive loss coefficient (ω, a measure of lost work potential), as seen in Figure 2, where a shockwave from fluid flow travelling at speeds greater than Mach 1 quadruples the loss coefficient of the same blade with a lower fluid

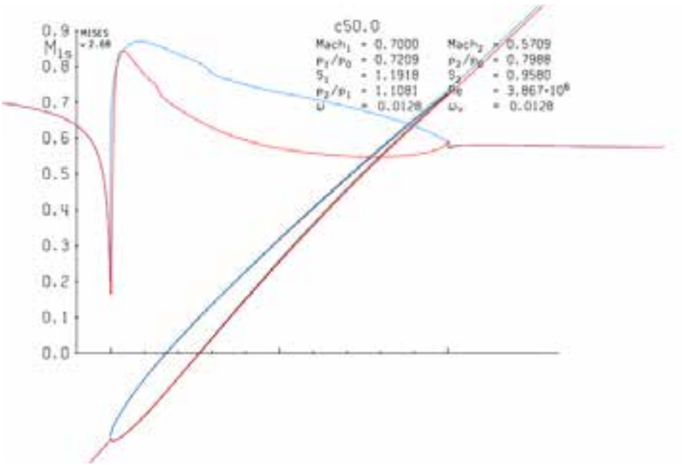

Figure 1: 0° Incidence Angle

Blade surface Mach number distribution and displacement thickness at an incidence angle of 0, showing no shockwaves.

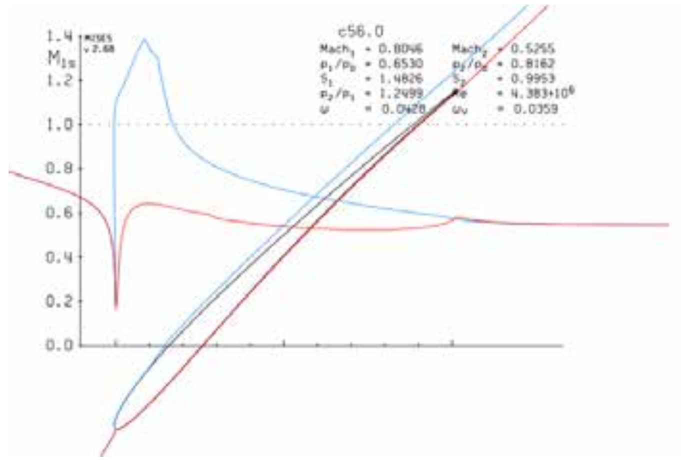

Figure 2: 6° Incidence Angle

Blade surface Mach number distribution and displacement thickness at an incidence angle of +6° for the same blade, showing supersonic flow and shock on the upper surface. The loss coefficient has increased by a factor of 3.5.

flow speed (Figure 1). Study conducted on blades was limited to subsonic incoming fluid flow, although some blades at an extreme incidence angle experienced shockwaves.

Research Topic and Goal

Throughout the course of this study, a metric was created to investigate the overall performance of a compressor blade, and was subsequently assessed to determine its sensitivity to changes in inputs of an input parameter. This is calculated by $\frac{\text{average loss coefficient}}{\text{range of incidence angles}}$[1], with a larger figure indicating worse performance. Only the average loss coefficient and range of incidence angles for up to 150% of the minimum loss were used to calculate the metric—any loss larger than 150% essentially renders the blade unusable. To simplify the display of results and reduce the need for decimals, the resulting number was multiplied by 10^6.

The overall goal of this study was to develop the metric, and subsequently identify the relative sensitivities of the three input parameters considered through an analysis of the metric.

The sensitivity of this metric in response to various inputs allows one to judge which input results in the most significant change. This will provide a basis in the future for analysis of different compressor blades— if it is the size of the leading edge that has the biggest impact on efficiency, the metric will determine at which levels the width of the leading edge will create the most efficient blade, relative to any other factors.

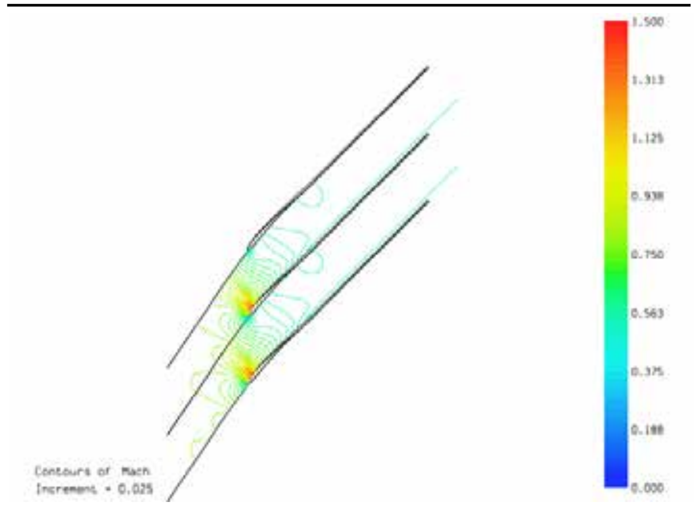

Figure 3: Fluid Flow Speed at a 6° Incidence Angle

Contour plot of the Mach number of fluid flow surrounding the blade in Figure 2, showing shocks on the top surface of the blade near the leading edge.

Hypothesis and Questions

We hypothesized that the number of blades in a blade row will have the largest effect on blade performance, because the increase in lost work potential compounds as fluid flow leaves each blade in a cascade. The radius of the leading edge is also hypothesized to show a very significant effect in the performance of the blade, as a very narrow or wide leading edge tends to narrow the operating range of the blade. Lastly, the location of maximum thickness will likely have the least effect on the performance of the blade, as it only minimally changes the shape of the blade.

Rationale

Much research relating to the design of aerodynamic turbomachinery has been conducted in order to create blades which prevent or delay flow separation for as long as possible. As with any machine, it is important to maximize the efficiency of compressor blades, to minimise the required energy for their operation. Recent work includes the Silent Aircraft Initiative, which aims to develop a near-silent airplane using principles of fluid dynamics to design blades which operate in a wide range of incidence angles in distorted flows. Unlike conventional planes, the silent aircraft project embeds the engines into the airframe, which results in less lost work potential. It also incorporates a boundary layer-ingesting (BLI) propulsion system, which improves fuel efficiency by taking the boundary layers from the body of an aircraft through a propulsor (Plas et al, 2007). The metric created in this study is similar to the one used to measure efficiency in the BLI propulsion configuration, which investigates the sensitivity of propulsive efficiency to input parameters such as engine mass flow, fan efficiency, and duct losses (Plas et al, 2007).

Measuring the performance of a blade row based on varying inputs of different parameters is important for future research and development of compressor blades. This study in particular provides a basis for optimal blade design by analyzing three different factors and their effects on the overall performance of a blade.

MATERIALS AND METHODS

The main instruments used for blade analysis were MISES, a set of software programs used for cascade flow analysis, and Octave, a program which creates different blade files that can be run through MISES. Developed by Mark Drela and Harold Youngren at the MIT Aerospace Computation Design Laboratory, MISES includes 3 main programs: ISET, ISES, and IPLOT. ISET is used to create the initial blade geometry file (called a state file) given the shape of the blade. This completed state file is then run through ISES, which sets up the fluid flow conditions around the blade, running iterations of the blade until it is converged on tolerance. It typically takes less than 50 iterations in order to converge the blade, though blades with a higher loss coefficient tend to need more iterations until the residuals become small enough for the blade to converge. Finally, IPLOT uses the flow and geometry information created by the state file to create a blade surface plot. This plot produces a calculation of various factors, from the speed of the fluid flow to the specific heat capacity. The most important calculation produced by the blade surface plot is the loss coefficient, which effectively summarizes the efficiency of the blade and gives insight into the velocity of the surrounding fluid flow. Put into simpler terms, the loss coefficient equates to the lost work potential, and a smaller number means a better-performing blade.

Written by Jeff Defoe, Martin Goodhand, and Lucas Lonni, the code running in Octave was used in this study to modify blade geometry as needed by inputting different values into parameters. Blade geometry is established mostly through its 3 space shape parameters. The first space-shape parameter, SSP1, determines the geometry of the blade's leading edge, by changing the leading edge radius. The second space shape parameter, SSP2 determines the width of the middle of the blade, and the third, SSP3,determines the shape of the trailing edge. If the SSP1 has a value of 0.6 (quantities are unitless and relative on MISES), then the leading edge is much thicker and more blunt. If it has a value of 0.1, the leading edge is very thin. This holds true for SSP2 and SSP3- generally, the smaller the values, the thinner the blade is.

3 main parameters are the focus of this study—the first shape-space parameter which determines the shape of the leading edge (SSP1), the location the second space shape parameter is applied (X2), and the number of blades in a blade row. An initial fluid flow speed of 0.7 Mach, a zero-incidence angle of 50°, a SSP2 of 0.2 and an SSP3 of 0.1 were kept constant for all blades. In total, 48 different blades were produced using Octave and then run through MISES, with every combination of 4 different SSP1s, 3 different X2s, and 4 different blade numbers being used

RESULTS

Table 1: The loss metric values at an X_2 value of 0.3, with varying SSP1s and blade numbers.

X2=0.3	Blade #			
SSP1	16	20	25	30
0.15	1558	2368	3538	2659
0.3	1042	2305	1535	2190
0.45	1283	1607	2080	2497
0.6	1857	2392	3511	4806

Table 2: The loss metric values at an X_2 value of 0.5.

X2=0.3	Blade #			
SSP1	16	20	25	30
0.15	1530	1720	2510	2596
0.3	971	1249	1580	2193
0.45	1051	1398	1910	2644
0.6	1505	1931	2902	5164

Table 3: The loss metric values at an X_2 value of 0.7.

X2=0.3	Blade #			
SSP1	16	20	25	30
0.15	1974	2380	3160	2653
0.3	1109	1242	1519	2123
0.45	1243	1297	1928	3190
0.6	1249	1753	2974	5776

Table 4: The normalized output and input values, corresponding to Table 1.

X2=0.3	Blade #			
SSP1	1	1.25	1.563	1.875
0.5	1.605	2.439	3.644	2.738
1	1.073	2.374	1.581	2.255
1.5	1.321	1.655	2.142	2.572
2	1.912	2.463	3.616	4.950

Table 5: The normalized output and input values corresponding to Table 2.

X2=0.3	Blade #			
SSP1	1	1.25	1.563	1.875
0.5	1.576	1.771	2.585	2.674
1	1.000	1.286	1.627	2.258
1.5	1.082	1.440	1.967	2.723
2	1.550	1.989	2.989	5.318

Table 6: The normalized output and input values corresponding to Table 3.

X2=0.3	Blade #			
SSP1	1	1.25	1.563	1.875
0.5	2.033	2.451	2.491	2.732
1	1.142	1.279	1.564	2.186
1.5	1.280	1.336	1.986	3.285
2	1.286	1.805	3.063	5.949

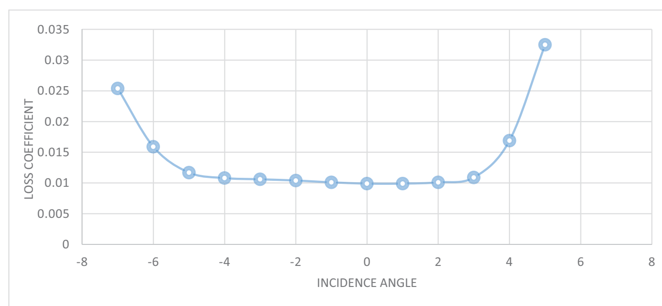

Figure 4: Incidence angle versus loss coefficient for a blade with an SSP1 of 0.45, X_2 of 0.7, and a blade number of 20

As with almost all the blades in this study, loss values increase dramatically as incidence angles stray away from the minimum.

Table 7: The normalized output and input values corresponding to Table 3.

	Fractional Change					Average	Average Relative Change
SSP1	1.152	0.97	2.049	1.854	2.198	1.645	$\frac{\text{Blade Number}}{\text{SSP1}}$ = 1.131
X2	0.355	0.722	0.435	0.158	0.18	0.37	$\frac{\text{SSP1}}{\text{X2}}$ = 4.446
Blade #	1.472	1.555	2.42	1.9935	2.02	1.86	$\frac{\text{Blade Number}}{\text{X2}}$ = 5.0229

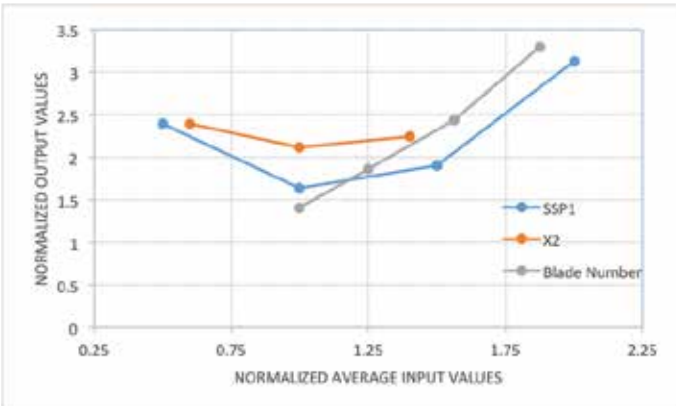

Figure 5: Normalized average input values versus normalized output values, showing rate of change for the three input parameters

As expected, the rate of change for variations in blade number is much higher than for X2, and slightly higher than for SSP1.

DISCUSSION

Average Loss Coefficient

With every blade, the minimum value of the loss metric is located near the middle of a range of loss metric values. The values of loss coefficients at different incidence angles form a 'bucket' shape-- at opposite ends of the spectrum, the losses are the highest (at times double or even triple the minimum loss value), and in the middle, they are the lowest (Figure 4). This is due to the fact that at very low or very high incidence angles, the boundary layers of the blades separate quite easily.

SSP1

The four values for the first space shape parameter inputted into Octave were 0.15, 0.3, 0.45, and 0.6. For this parameter, the optimum value was not the smallest value—at an SSP1 of 0.3, the blades outputted an average metric value of 1588. An SSP1 of 0.45 outputted an average metric value of 1844, 0.1 outputted an average of 2205, and 0.6 outputted 2985. From these results, it can be inferred that generally neither a sharp leading edge nor a very round leading edge are desirable for optimal performance. Further research is required to test the effects of different SSP2s and SSP3s on the performance of a blade.

X2

The three values of X_2 inputted into Octave were 0.3, 0.5, and 0.7. They represent the application of the second space shape parameter $\frac{3}{10}$, $\frac{1}{2}$, and $\frac{7}{10}$ of the way into the blade. Blades with an X_2 value of 0.5 were on average much more efficient than the other X_2 values, although an X_2 value of 0.3 was more efficient than one of 0.7. Interestingly, changing the X_2 value also shifted the angle that minimum loss coefficient was most commonly found at. With an X_2 value of 0.5, the minimum loss coefficient most often occurred at or just below the incidence angle, while with an X_2 value of 0.7, the minimum loss was found at +3 degrees from the initial incidence angle. The greater the output value, the larger this variance—blades that were particularly inefficient with an X_2 value of 0.7 had a minimum loss occur at up to 5 or 6 degrees greater than the initial incidence angle, which never occurred in blades smaller X_2 values. An X_2 of 0.3 did not affect the minimum loss angle nearly to this degree, with negligible differences from an X_2 value of 0.5.

Number of Blades

The four different blade numbers used were 16, 20, 25, and 30 blades. Almost without fail, a blade with a lower number of blades, holding all else constant, had a better performance than one with a large blade number. There were two outliers in the data, both with SSP1s of 0.15 and blade numbers of 25, which had a larger metric value with than a blade with a blade number of 30. However, these blades both had a very small range of possible incidence angles due to an inability to converge at smaller incidence angles, and points more to a flaw in this particular blade shape and number rather than a trend for blade numbers in general. 16 blades resulted in an average loss metric value of 1364, 20 blades resulted in an average of 1803, 25 blades resulted in an average of 2428 (including outliers), and 30 blades resulted in an average of 3207.

However, smaller blade numbers are not without fault. At both very high and very low blade numbers, the blades would not converge on tolerance; a blade number of 15 was not used in this study for this reason. The results showed within a certain range, a smaller blade number is almost always more optimal than a large blade number. Below this range, a lower amount of blades in a blade row means that each blade does more work turning the flow, so that the force on each blade rises. Consequently, blades need to be thicker (generally meaning a higher SSP1 value) when there is a lower blade count, as seen in Tables 1-3, where thinner blades performed worse than thicker blades for the same relative change in leading edge radius. The opposite is true as well—at a higher blade number, thin blades perform better than thick blades.

Sensitivity Analysis

A sensitivity analysis was used in this study to assess changes in blade performance as a result of changes in input parameters. Essentially, this analysis calculates the 'cost' that a potential change in an input parameter has on overall blade performance, assuming all other factors remain the same.

Given that the metric is determined by 3 variables representing different types of quantities, the parameters and the resulting output were normalized with respect to a reference value in order to compare fractional changes in each of the changing parameters. To normalize the input parameters, each input value was divided by a reference value, where $x_{ref}=x_{min}$ and x_{min} is the input value at which the lowest average output value occurs. This results in a number showing fractional change in between input values. The same process was used to normalize the output, using y_{min} as the reference value.

Tables 1, 2, and 3 show the exact values used in the Octave code; Tables 4, 5 and 6 show the corresponding normalized input and output values. The sensitivity analysis determined that the loss metric was most sensitive to the number of blades, followed by SSP1 and lastly X_2.

Metric Value

The smallest value obtained when calculating the metric was 971 (located in Table 2), meaning it had one of the smallest average loss coefficients and one of the widest ranges of incidence angles, and was thus used as the reference value (y_{ref}) to normalize the outputs. This blade had an SSP1 of 0.3, an X_2 of 0.5, and a blade number of 16. Every other output was divided by this reference in order to obtain their fractional change from the minimum. The largest change was found in a blade with an SSP1 of 0.6, an X_2 of 0.7, and a blade number of 30. This blade resulted in an output almost 600% larger than the minimum; however, most other blades stayed within 200% of the reference value.

To undergo sensitivity analysis, SSP1 values of 0.15, 0.3, 0.45, and 0.6 were normalized to 0.5, 1, 1.5, and 2 respectively—the reference value is at an SSP1 of 0.3. Similarly, the X_2 values of 0.3, 0.5, and 0.7 were normalized to 0.6, 1, and 1.4 respectively, with the reference value at X_2=0.5, and blade numbers of 16, 20, 25, and 30 were normalized to values of 1, 1.25, 1.56, and 1.875 respectively.

To calculate the sensitivity of the metric for an input variable, the fractional change for the normalized output was divided by the fractional change for the normalized input variable. In other terms, $\frac{\Delta y*}{\Delta x*}=\frac{y*-y_{ref}}{x*-x_{ref}}$ with normalized values denoted by an asterisk. The largest fractional change was taken as the sensitivity of metric to the input parameter.

Even with normalized values, each blade responded differently to the input parameters. This is due to the non-linear relationship between the loss coefficient and each input parameter. With an SSP1 of 0.6, an increase of 20% from 25 blades to 30 blades causes the output value to increase by up to 200%; however, an increase of 25% from 16 blades to 20 blades only causes the output value to rise a maximum of 50%. This difference is less pronounced at smaller SSP1s and blade numbers.

However, almost all blades showed a general trend in the difference between fractional changes in each input parameter, so the average values were taken to calculate sensitivity, as displayed in Table 7. For every blade (with the exception of the two aforementioned outliers), the output value was least sensitive to X_2, and most sensitive to the blade number. Typically, the fractional changes of SSP1 increased by a factor of approximately 4.5 from the fractional changes of X_2, and the fractional changes of the blade number increased by factor of approximately 1.1 relative to SSP1. The fractional changes of the blade number was usually around 5.0 times greater than the fractional changes of X_2.

CONCLUSION

Since the blade number has the largest effect on the performance of a compressor blade, a change of even one blade in the blade row of an optimal solution should be considered carefully—relatively, a change in this parameter is associated with a larger change in performance than a change in X2 or SSP1. This is especially important at large blade numbers, where the cost in performance for every blade added increases dramatically. The blade number found in this research with the lowest average loss coefficient is 16. Below that, the blades did not converge, so the performance of lower blade numbers could not be assessed; at higher numbers, blade performance decreased drastically. Lastly, the optimal X2 value examined in this study was at 0.5, although blades with an X2 value of 0.7 performed better at higher incidence angles. More research is necessary to assess the effect that changes in SSP2 and SSP3 would have on the blade, but the results from this research clearly shows the optimal values and clear trends for each input parameter.

ABBREVIATIONS

Abbreviation	Full Form
SSP1	Space shape parameter at leading edge of blade
SSP2	Space shape parameter in middle of blade
SSP3	Space shape parameter at trailing edge
X2	Location of maximum thickness of blade

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