Analysis of jet engine compressor deterioration and capturing correlations between geometric parameters

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Abstract

The increasing pressure on costs forces the MRO-Companies (Maintenance, Repair and Overhaul) to improve their repair processes. Currently, an evolution in jet engine maintenance philosohpy can be noticed: The change from a time-based overhaul to an engine based overhaul. So, each engine gets tailored maintenance actions to fulfill customer specifications like EGT (Exhaust Gas Temperature) and TSFC (Thrust Specific Fuel Consumption). Representing a high influence on engine performance, the HPC (High Pressure Compressor) was chosen for the following investigations. To ensure an effective HPC-maintenance, a detailed knowledge of its blade geometry is necessary. Therefore, each blade has to be analyzed on different blade heights for its stagger angle, chord length, thicknesses, etc.. Because of the plurality of the required measurement variables, the needed measuring time increases to an uneconomic level. So, correlations between geometric parameters could reduce the measuring time to a profitable level. This paper will present such correlations for rotor blades and stator vanes for different stages. Furthermore, the found correlations will be explained by compressor aerodynamics.

Keywords

Compressor aerodynamics — Airfoil deterioration — Erosion

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INTRODUCTION

During on-wing time of a jet engine, the engine performance constantly reduces due to deterioration effects. Deterioration leads to decreasing component efficiencies which increase EGT and TSFC. The engine typically has to be overhauled when a specified EGT limit is reached. This does not imply to restore the engine to the new condition which would mean to replace every component with a new one or repair the parts to new condition. Rather the executing MRO company and its customer which is considering the most efficient use of its financial maintenance reserves agree by contract to restore the engine performance to a sufficient margin. The contract contains the engine performance requirements for the individual operation and on-wing time. Hence specific deterioration mechanisms are accouted for which have to be attended during maintenance.

To conduct such customized maintenance within strict cost limits, the MRO installs a mix of used, repaired and new parts to restore the engine performance to the desired margin. The used parts are inspected to determine their serviceability and repair demands. However, especially the standard inspection of aerodynamic parts gives typically little clue to the condition of the part regarding its performance in the engine, especially in case of multiple parts usage e.g. airfoils. To evaluate the performance of aerodynamic parts a much more detailed inspection of the parts would be required, due to the diversity in deterioration patterns and the resulting amount of parameters to describe them.

Research on the deterioration of a Turbofan HPC has been conducted, since the HPC performance (efficiency, pressure rise, mass flow rate and stall margin) is critical to overall engine performance. The HPC performance mainly depends on the condition of its compressor airfoils. These are subjected to a variety of deterioration effects. The geometric diversion of an abitrary blade to a respective new part is equally versatile, but blades of the same stage which have been subjected to the same operation should be similar. Therefore, not every parameter required to describe the entity of deterioration patterns is needed to determine the performance of the compressor blades in a certain stages. Still to reach a conclusion about a blades performance a multitude of parameter has to be measured. To reduce the amount of measurements required, correlations between certain parameters have been researched.

The research is based on the measurements of Marx et al. [1], who analyzed the geometries of 1200 HPC-blades of two jet engines of the same type with similar operational area. The on wing-time is approx. 3200 and 5000 CSLSV. To improve the data basis, further blades have been measured and analyzed by the authors. Additionally, 300 stator vanes have been digitized to compare them with the rotor results. The airfoils have been digitized by a structured light 3D scanner. The data is analyzed with an in-house programmed software [2] to determine the geometric properties. The determined geometric variances are examined for correlations among themselves.

1. METHODS

A correlation between two or more parameters is a functional relationship based on empirical evidence, rather than a physical theorem. To describe the magnitude of the functional relationship a correlation coefficient is used. For this research the correlation coefficient of Bravais and Pearson [3] [4] has been chosen. The coefficient is calculated by the covariance of the coupled parameters s_{xy} and the covariance of the single parameters s_x and s_y.

$$r = \frac{s_{xy}}{s_x \cdot s_y} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}} \quad (1)$$

This normalized coefficient is in the domain of $\{-1 \leq r \leq 1\}$. To interprete the results Tab. 1 is used. It states that values of $\{0 \leq |r| \leq 0.3\}$ indicate a stochastical distribution. Only absolut values of $\{1 \leq |r| \leq 0.3\}$ could be considered as viable correlation between two parameters. Still a viable absolut value of $|r|$ might still indicate a spurious correlation [5]. These are correlations which occur if in a chosen general sample two parameters are examined which are independent of one anonther but yield a correlation due to a common third parameter.

Table 1. General rules for correlation coefficients [6]

$r = 1$	perfect positive correlation
$1 \geq r \geq 0.6$	strong positive correlation
$0.6 \geq r \geq 0.3$	weak positive correlation
$0.3 \geq r \geq -0.3$	no correlation
$-0.3 \geq r \geq -0.6$	weak negative positiv
$-0.6 \geq r \geq -1$	strong negative correlation
$r = -1$	perfect negative correlation

Therefore even particularly strong coefficients r should be scrutinized. Figure 1 illustrates two distributions with a perfect correlation. Nevertheless, the parameters are completly independent from each other. As can be seen y is not influenced by x (Fig. 1, left-hand side) and vice versa (Fig. 1, right-hand side).

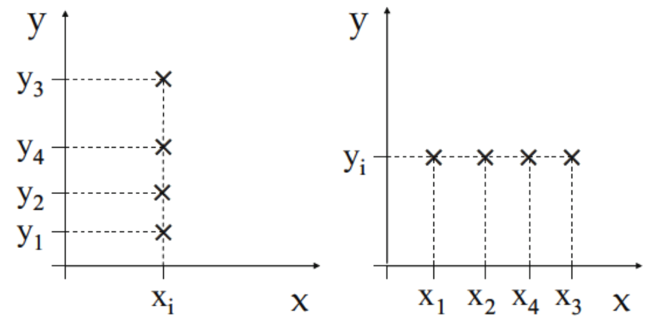

Figure 1. Perfect correlations but independent parameters [7]

2. GEOMETRIC PROPERTIES

The digitized HPC-blade point-clouds have been analyzed by an in-house programmed software [2]. This software analyzes on 19 different blade heights a multitude of associated geometric properties like chord length, stagger angle, edge geometries, etc.. To show the effect of geometric variation on compressor stage performance the leading edge geometry is used as an example. According to Giebmanns et al. [8] the leading edge geomtry of a transonic fan (or compressor) blade has a high influence on compressor performance. Giebmanns et al. [8] carried out 3D RANS simulations and compared four different leading edge types, which are commonly found during engine overhaul:

- reference blades
- blunted leading edges
- blunted leading edges and shortened chord length
- reduced chord length with reshaped leading edges

The leading edge geometry was found to be the main factor for stage performance since the behavior of a reshaped and shortened blade is similar to the behavior of the reference blade, except for a lower surge margin. Roberts et al. [9] reaches the same conclusion. Although both investigations were done for a transonic fan blade, the changed shock regions and, therefore, the changed losses, could be transferred to transonic HPC front stages.

Further investigations of geometric changes at the leading edge have been conducted by Reitz et al. [10], who investigated deterioration in a HPC mid-stage. Again 3D RANS simulations where used. The blade geometry was altered in reference to a new blade according to typical deterioration levels. For the generation of the 3D blade geometry, an in-house programmed software [2] was used, which allows an independent change of several geometric properties. Three different geometric parameters were examined independet:

- leading edge thickness
- stagger angle
- max. profile thickness

The result of this study was that the most severe changes in performance are caused by a change of the leading edge thicknes, followed by max. profile thickness and stagger angle.

Multiple other papers deal with the leading edge geometrie and its influence on compressor performance

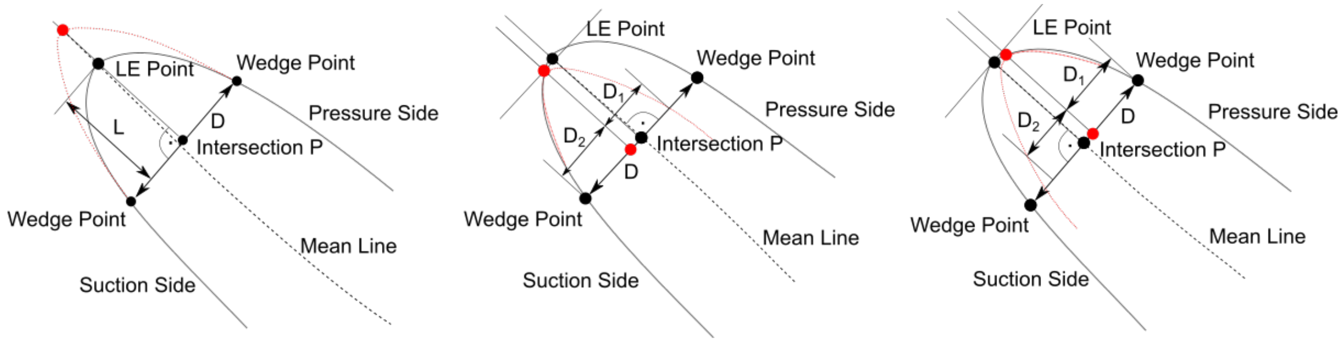

Figure 2. Definition of stretching and edge asymmetry caused by erosion on pressure and suction side

[11] [12] [13]. As shown, leading edge geometry is of great importance for compressor efficiency. So, it seems reasonable to focus on these parameters in this paper to reduce the amount of data by ensuring still convincing influences on compressor aerodynamics.

Figure 2 presents the definition of parameters shown in this paper: Edge- asymmetry and stretching. Both parameters are formed as followed: First of all, a vertical line to the profile mean line is generated by following the profile mean line for 1% of actual mean line length from the edge points and using the local slope of the profile mean line. The points of intersections between profile and vertical line are called wedge points 1 and 2. A vertical line to the just now generated one, is placed through the edge point. Its intersection point is called intersection P. The distance between edge point and the described intersection point P is called L and the distance between the wedge points 1 and 2 is called D. The edge stretching is defined as quotient of L and D: $stretching = \frac{L}{D}$. So, a thicker airfoil would increase D and the stretching would decrease and vice versa. The distance between wedge point 2 (pressure side) to intersection point P is defined as D_1 and between wegde point 1 (suction side) and intersection point P as D_2. Their quotient defines the asymmetry: $asymmetry = \frac{D_1}{D_2}$. So, an augmented erosion on pressure side would remove material there and slightly move the edge point to the suction side (see Fig. 2, middle). Consequently, D_1 would decrease while D_2 is more or less constant. Altogether, the value of asymmetry is decreasing. So, decreasing asymmetry values indicate a moving towards suction side and increasing values a moving to pressure side (see Fig. 2, right-hand side). Please take note, that rotor blades and stator vanes are treated equally. The asymmetry is always defined as quotient of distance to pressure side and distance to suction side, even though the airfoils are mirrored.

Figure 3 illustrates the definition of leading edge thickness. The chord connects leading and trailing edge point and its length is defined as chord length. Leading edge thickness is measured at 5% actual chord length, and therefore, much deeper inside the profile compared to leading edge stretching and asymmetry. Therefore, a vertical line to chord is positioned at 5% chord length and the leading edge thickness is measured at the intersection point with profile mean line.

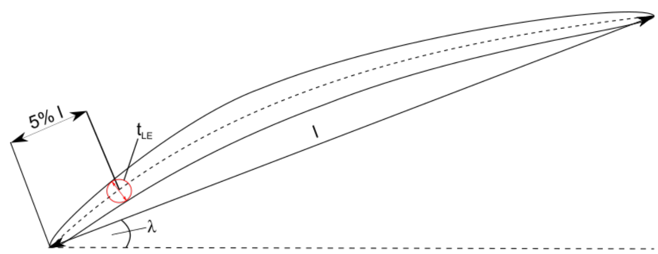

Figure 3. Definition of leading edge thickness

3. RESULTS AND DISCUSSION

Rotor Geometry

Front Stage

Figure 4 shows a scatterplot between leading edge asymmetry and its stretching for a front stage rotor. The scatterplots show all geometric values for different blade heights. In this paper, a detailed view on specific height regions is not done. The black vertical and horizontal line represent mean value of the new blades. The mean value represents manufacturing tolerances. Previous studies have shown that deviations caused by deterioration are larger than the manufacturing tolerances [1]. For example, the standard deviation in leading edge stretching caused by manufacturing tolerances is approx. 2.5%, while approx. 15% have been observed as a case of deterioration. As can be seen, in front stage the majority of parameter pairs show higher stretchings and decreasing asymmetries compared to new blades. So, a comparatively large amount of abrasion is located at blade leading edge on pressure side and the leading edge point is moving towards suction side (see Fig. 2, middle). Figure 4 also depicts the regression line through the parameter pairs. Its gradient is negative: Decreasing stretchings go ahead with increasing asymmetry values. The belonging correlation coefficient is -0.43, which is a weak correlation (see Tab. 1).

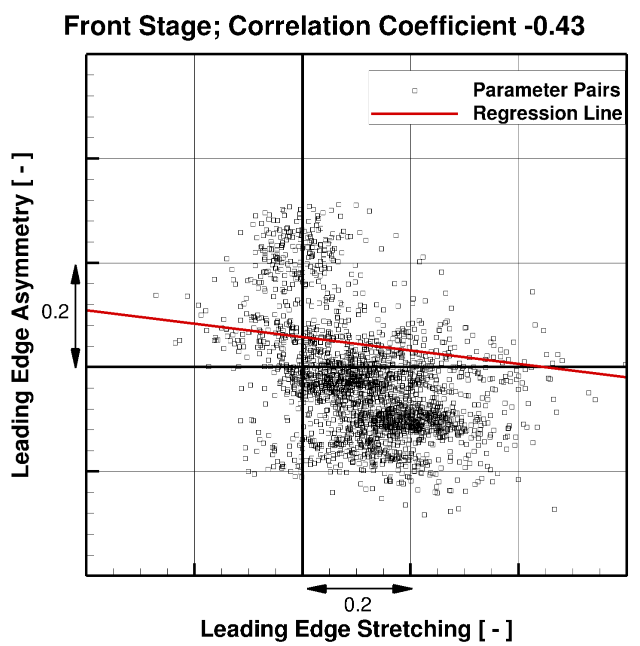

Figure 4. Correlations between leading edge stretching and asymmetry at front stage rotor

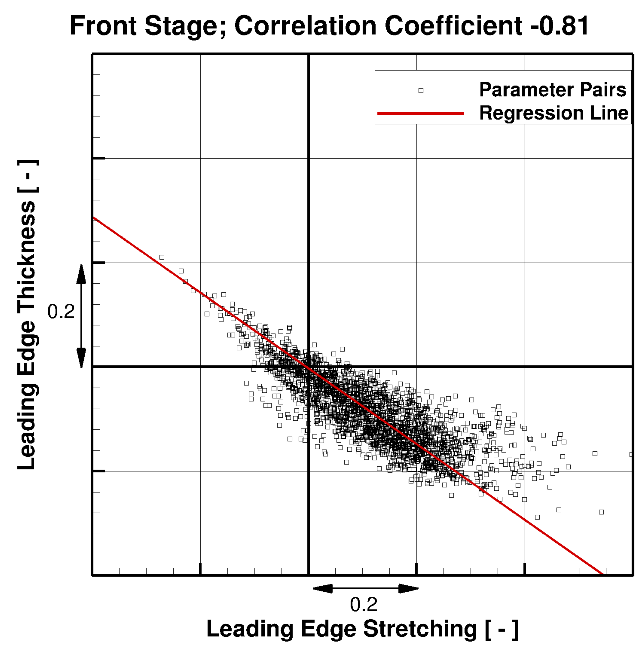

Figure 5. Correlations between leading edge stretching and thickness at front stage rotor

Figure 5 illustrates the correlation between leading edge stretching and thickness for the front stage rotor. As can be seen, a strong correlation (correlation coefficient: -0.81) between these parameters is existing. Similar to figure 4, a majority of leading edges show higher stretchings. These higher stretchings go ahead with decreasing leading edge thicknesses. Please remember, that leading edge thickness is measured at 5% chord length of the actual blade, compared to approx. 1% for stretching. So, the erosion of leading edge is localized on a larger area.

Summarized, the analyzed leading edge of the front stage rotor is thinner combined with a higher stretching and an asymmetry towards suction side.

A possible explanation for the asymmetrical erosion at front stage rotor could be given by the particle trajectory: Because the higher density of the erosive material, its endeavour to follow the air flow is quite limited. Figure 6 illustrates this behavior: It shows the velocity triangles for a compressor stage in top view. The air velocity triangles are black coloured and the particle velocity triangles are coloured in red. As can be seen, the particles have a more axial direction at rotor inlet in the absolut system W_1, and thereby, a higher circumferential speed in the relative system W_1'. This results in a steeper rotor inflow and erosion on the pressure side near the leading edge. However, the stator shows a different behavior and has erosion on suction side. An explanation could be given by accumulated erosive material at rotor pressure side. If the material is leaving the rotor passage, the increased centrifugal force would increase the deviation angle, too. Thus, the circumferential speed in relative system W_2' is increasing. Consequential, the stator inflow

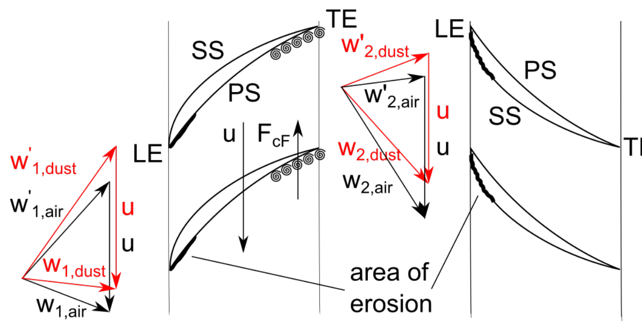

Figure 6. Velocity triangles for air and dust particles

in stationary system W_2 is flatter, which results in an increased erosion on stator suction side. In Day et al. [14] a similar observation is made while examining water injections into an axial compressor, the trajectories of water droplets changes with droplet diameter. This leads to an increased deviation angle for bigger droplets.

The increased erosion on rotor pressure side at leading edge is in accordance with previous studies about turbofan engine deterioration: Already in 1975 Sallee et al. [15] analyzed performance deterioration of the turbofan engines JT3D and JT8D. Thereby, they proved an asymmetric erosion on front stage compressor rotors with a higher material removal on blade pressure side. Furthermore, Tabakoff et al. [16] investigated in 1987 compressor erosion and its impact on performance. Therefore, he numerically analyzed the behavior of sand (100.000 particles; 165 mircon diameter particle; 0.6 grams) ingesting a 5-stage helicopter compressor. At rotor front stage, he was able to prove that the most part of the particles are striking the blade near leading edge at pressure side. On suction side, just a few impacts could be identified. Ghenaiet et al. [17] predicted the areas of erosion on compressor blades and the resulting performance degradation, too. He also determined the area of erosion for design point near the leading edge at pressure side. However, suction side showed no significant erosion.

Rear Stage

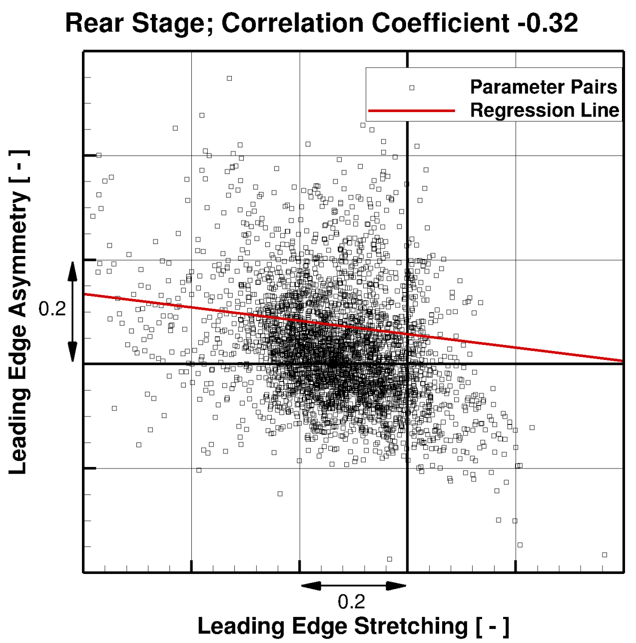

Figure 7. Correlations between leading edge stretching and asymmetry at rear stage rotor

Figure 7 illustrates the behavior of leading edge asymmetry and its stretching for a rear stage rotor. There are 6 stages between the front and the rear stage. While the front stage rotors are made of a titanium alloy, the rear stage rotors consists of a nickel-base alloy. In figure 7, the gradient of regression line and, therefore, the correlation coefficient is negative, too. Nevertheless, the parameter pairs show a different behavior: The majority of parameter pairs show lower stretchings. However, the asymmetry values are just slightly increasing. So, the leading edge point is just moving a little towards suction side, compared to the front stage. An explanation for the different behavior, compared the front stage, could be given by the reduction of particle size caused by collisions of particles with airfoils. The particles splinter and their size decreases and the particles are following the air trajectory. Furthermore, the particles were hurled towards casing [16] [17] [14] and to some extent aspirated by bleed system. So, the erosive effects decrease through the compressor. Consequential, a homogeneous material removal at rear stage rotor pressure side can be expected. The correlation coefficient of asymmetry and stretching is about -0.32, which is a weak correlation (see Tab. 1).

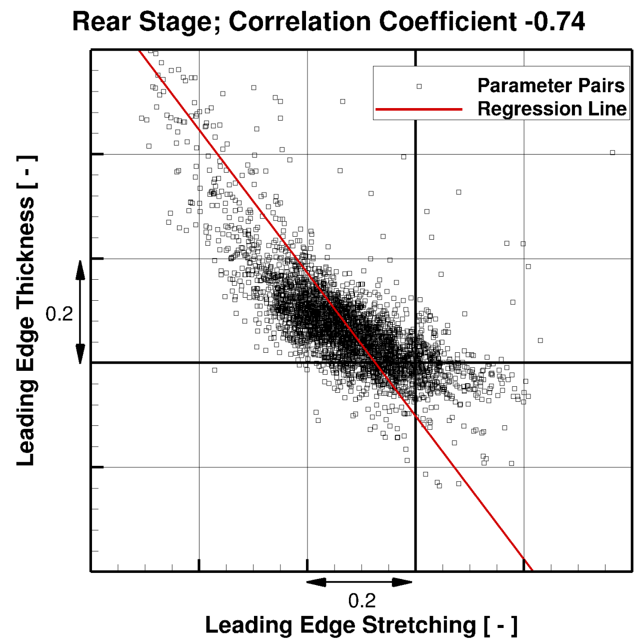

Figure 8. Correlations between leading edge stretching and thickness at rear stage rotor

Figure 8 shows a scatterplot between leading edge thickness and its stretching for a rear stage rotor. As can be seen, a strong correlation of -0.81 between both parameters is existing. Similar to figure 7, the leading edge stretching is mostly decreasing. Furthermore, the leading edge thickness is increasing. An increasing leading edge thickness can be explained by its definition: It is measured at 5% of the actual chord length. Is the chord length decreasing, the measuring position is moving inside the profile, and therefore, in a thicker area.

Summarized, the rear stage rotor blades show a nearly homogenous material removal at pressure side in conjunction with blunted leading edges.

Tabakoff et al. [16] has also shown a change of particle striking area through the compressor: While in front stage the area is located near the leading edge, the area homogenizes over chord at rear stages. The homogeneous erosion at rotor rear stage leading edges is in accordance to Sallee et al. [15], who observed the same behavior.

Stator Geometry

Front Stage

Figure 9 depicts the behavior of leading edge asymmetry and its stretching for a front stage stator. Please take note, that for stator airfoil analysis just 40 airfoils per row were available. So, the database is far smaller than for rotor analysis. Nevertheless, in contrast to front stage rotor, the front stage stators show increasing values for asymmetry. So, the leading edge seems to move towards pressure side (see Fig. 2, right-hand side). Nevertheless, the behavior for leading edge stretching seems to be similar to the rotors and the values are increasing, too.

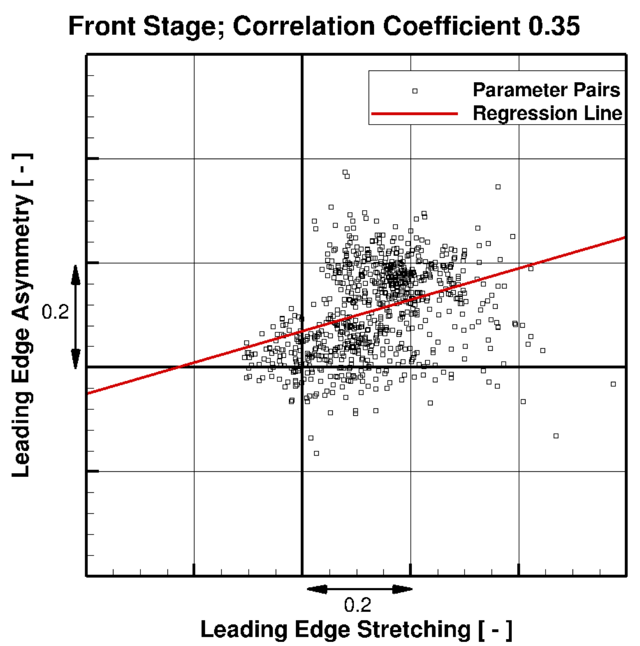

Figure 9. Correlations between leading edge stretching and asymmetry at front stage stator

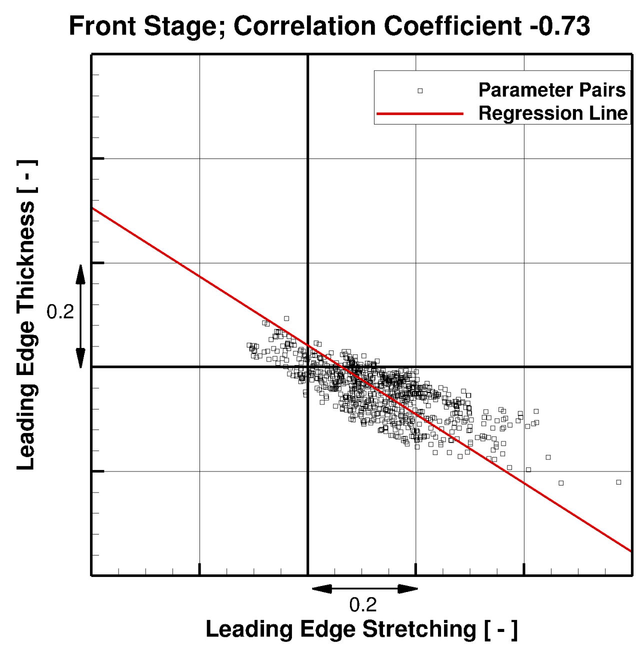

Figure 10. Correlations between leading edge stretching and thickness at front stage stator

The correlation coefficient between leading edge asymmetry and stretching is positive and has the value of 0.35, which is a weak correlation (see Tab. 1). So, increasing stretchings go ahead with increasing asymmetries.

Figure 10 shows a scatterplot between leading edge thickness and its stretching for a front stage stator. As can be seen, the correlation coefficient between leading edge thickness and stretching for front stage stator vanes is -0.73, and therefore, a strong correlation, too. Similar to figure 9, the leading edge stretching is increasing. However, leading edge thickness is decreasing.

Summarized, the front stators are getting thinner at leading edge and their leading edge point is moving towards pressure side.

This result is in contrast to Tabakoff et al. [16], who determined a similar erosion area for stators to the rotors. Nevertheless, the behavior can be explained by figure 6: As already mentioned, the deviation angle for the erosive particles at rotor exit increases [14] and goes hand-in-hand with a flatter inflow angle for the stator vane. Consequently, the particles will strike near leading edge at vane suction side which explains the local material removal.

Rear Stage

Figure 11 depicts the behavior of leading edge asymmetry and its stretching for a rear stage stator. Similar to rear stage rotor asymmetry, the rear stage stator asymmetry seems more or less homogenously distributed around the reference value. Nevertheless, the leading edge stretching shows a clear trend towards blunted edges. The correlation coefficient is -0.18, and thereby, no real correlation (see Tab. 1). So, the leading edge asymmetry is independent from the leading edge stretching.

Figure 12 illustrates the correlation between leading edge thickness and stretching for rear stage stator vanes. Here again, a strong correlation coefficient can be found with a value of -0.81. Similar to figure 11, leading edge stretching assumes lower values. Despite a high correlation coefficient between leading edge thickness and stretching, no clear trend for leading edge thickness can be found. Simliar to leading edge asymmetry, the leading edge thickness is homogenously distributed around the reference value. So the correlation coefficient should be interpreted with caution. More stator vanes would be necessary to increase the predictive significance.

Summarized, the rear stage stators have a constant leading edge asymmetry in conjunction decreased stretchings.

4. CONCLUSION

In this paper, a geometrical analysis of HPC airfoils have been done. Therefore, a front and rear-stage of a state of the art commercial jet engine have been taken under examination. To identify relationships between geometric parameters, the correlation coefficient of Bravais and Pearson [3] [4] has been chosen. To reduce the amount of data for this paper, a focusing on certain parameters was necessary. Representing a dominant factor for compressor performance, the leading edge geometry has been chosen for detailed analyzations. More precisely, leading edge stretching, asymmetry and thickness have been investigated.

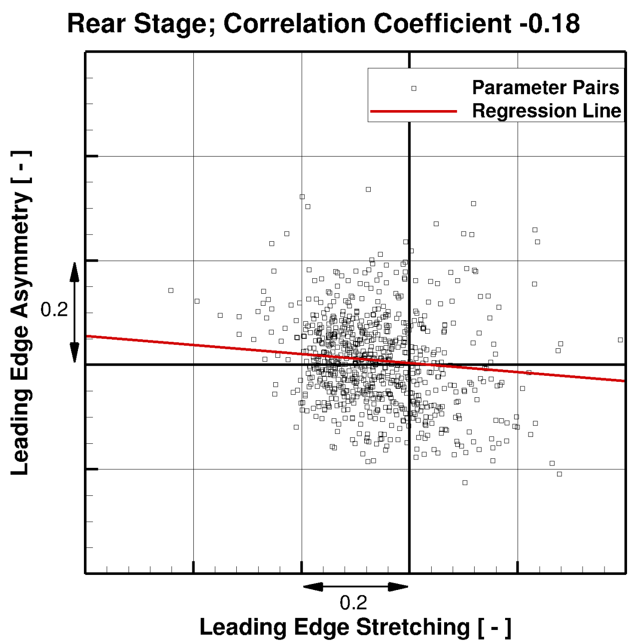

Figure 11. Correlations between leading edge stretching and asymmetry at rear stage stator

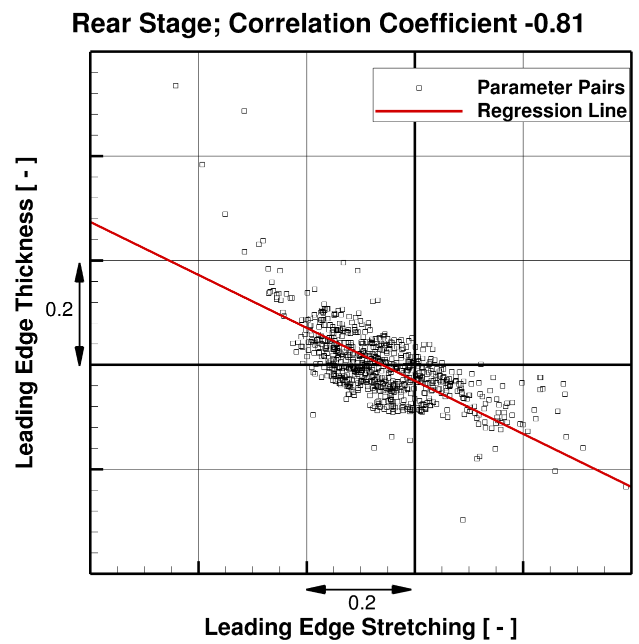

Figure 12. Correlations between leading edge stretching and thickness at rear stage stator

The results can be summarized as follows:

- Rotor front stage blades have thinner leading egdes combined with a higher stretching and an asymmetry towards suction side.
- Rotor rear stage blades show a nearly homogenous material removal at pressure side in conjunction with blunted leading edges.
- Stator front stage vanes are getting thinner at leading edge and their leading edge point is moving towards pressure side.
- Stator rear stage vanes have a constant leading edge asymmetry in conjunction with decreased stretchings.

So, erosion is not constant through the compressor or for rotor or stator airfoils. Front stages have more asymmetric leading edges, which is explained by larger particles at compressor inlet. These particles splinters during striking the airfoil and their size decreases towards compressor outlet. There, they are able to follow the air trajectories and lead to symmetric erosion on rear stage airfoils.

Furthermore, strong correlations between leading edge thickness and stretching could be found through the compressor. In the future, one parameter could be predicted by the other one. So, measuring time and the data base would decrease.

Nevertheless, further work has to be done. To underpin the given statements, more airfoils should be analyzed to enlarge the database. Additionally, it would be possible to analyze different height ranges with an increased database to eliminate the influence of the different heights to the parameters.

Additionally, an extensive Design of Experiment (DoE) could be carried out, to analyze the influence of geometric changes due to compressor deterioration on its stage performance. Thereby, the identified correlations could decrease the number of independent parameters to accelerate the process. Thus, detailed predictions of blade performance could be given to improve maintenance actions.

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ABBREVIATIONS

3D	Three-Dimensional
CSLSV	Cycle Since Last Shop Visitl
DoE	Design of Experiment
EGT	Exhaust Gas Temperature
HPC	High Pressure Compressor
LE	Leading Edge
MRO	Maintenance, Repair and Overhaul
PS	Pressure Side
RANS	Reynolds Averaged Navier Stokes
SS	Suction Side
TSFC	Thrust Specific Fuel Consumption

NOMENCLATURE

D	Distance between Wedge Points
D_1	Distance from Wedge Point on PS to Intersection Point
D_2	Distance from Wedge Point on SS to Intersection Point
F_{CF}	Centrifugal Force
i	Control Variable
l	Chord Length
L	Distance from LE to Intersection Point
n	Upper end of Control Variable
r	Correlation Coefficient of Bravais and Pearson
s_x	Covariance of Parameter x
s_{xy}	Covariance of Parameter x and y
s_y	Covariance of Parameter y
t_{LE}	Leading Edge Thickness
U	Circumferential Velocity
W_1	Absolute Flow Velocity at Rotor Entry Plane
W_1'	Relative Flow Velocity at Rotor Entry Plane
W_2	Absolute Flow Velocity at Rotor Exit Plane / Stator Entry Plane
W_2'	Relative Flow Velocity at Rotor Exit Plane / Stator Entry Plane
x	Parameter on x-Axis
$\bar{x}$	Mean Value of x
y	Parameter on y-Axis
$\bar{y}$	Mean Value of y
λ	Stagger angle