Validation Methods for 3D Digitizing Precision Concerning Jet Engine BLISKs

Thomas Backhaus
Technische Universität Dresden,
Chair of Turbomachinery and Flight Propulsion,
George-Bähr-Straße 3c, 01069 Dresden,
Germany

Martin Harding
Rolls-Royce Deutschland Ltd & Co KG,
Manufacturing Engineer Metrology,
Hohemarkstraße 60-70, 61440 Oberursel,
Germany

Sven Schrape
Rolls-Royce Deutschland Ltd & Co KG,
Compressor Stress / Aeroelasticity,
Eschenweg 11, 15827 Blankenfelde-Mahlow,
Germany

Matthias Voigt, Ronald Mailach
Technische Universität Dresden,
Chair of Turbomachinery and Flight Propulsion,
George-Bähr-Straße 3c, 01069 Dresden,
Germany

ABSTRACT

The demand for higher efficiency of jet engines requires new technologies within the design and manufacturing processes. Since those methods influence the structural and aerodynamic behavior of the engine, several effects need to be considered. These effects can be estimated using different simulation techniques considering real geometry data. This can be accomplished either within a reverse engineering process, using the real digitized surface, or within a probabilistic simulation. The second method is taking a certain amount of measured parts (e.g. BLISKs or airfoils), gaining typical geometry parameters and evaluating their distributions. By using these distributions it is possible to build up digital three-dimensional models, representing the manufacturing or wear based geometry scatter. These models allow the user to evaluate not only a deterministic response of the numerical simulation, but a whole response value distribution within a probabilistic evaluation. This way it will be possible to robusten the intentional design towards the manufacturing or wear variability. For both methods it is an essential task to capture the parts geometry with high accuracy.

There are several techniques and purposes of capturing a part's geometry. This paper will concentrate on digitizing a high pressure BLISK of a jet engine by using tactile coordinate measurement machines (CMM) and optical structured blue light projection systems. With this focus it is essential to determine the purpose and the fields of application of both digitizing systems as well as their advantages and disadvantages. While the tactile CMM are commonly used by the BLISK manufacturer for tolerance checks, these methods seem not to be sufficient anymore concerning reverse engineering applications. Optical methods are able to digitize complete three-dimensional surfaces with a quality sufficient to describe all features of interest of a BLISK. Because of the different digitizing approaches of tactile and optical systems, it seems hard to deliver a quantified comparison with valid conclusions. This paper tries to give a first quantification of different error values as well as their statistical probability of occurrence.

The aim of the presented paper is to improve the understanding and estimation of the precision of structured light projection systems used within BLISK digitizing. This includes statements about the precision as well as the accuracy. The results will give a quantified statement about precision of the projects measurement setup as well as a quantified comparison between typical airfoil parameters of tactile and optical measuring systems. The work contributes towards a better acceptance of the optical measuring systems within the manufacturing tolerance checks, the parts integrity estimation during maintenance and for all kinds of reverse engineering processes.

KEYWORDS

Jet Engine, BLISK, Compressor, Uncertainty Quantification, Optical and Tactile Measurement, Accuracy and Precision

NOMENCLATURE

Symbols

$d(P_1,P_2)$	Euclidean distance between P_1 and P_2
l	length
lc, hc	low curvature, high curvature
i, j	indices
n	number
r	radius
s	span position
x, y, z	cartesian coordinates
ε	error / offset value
γ	stagger angle
μ	mean value

Subscripts and Superscripts

$(..)_{0.95}$	95% quantile value
$(..)_{0.99}$	99% quantile value
$(..)_{A,B}$	indices
$(..)_{ch}$	chord
$(..)_{comp}$	comparison
$(..)_{delta}$	difference between two comparison
$(..)_{LE,TE}$	leading edge, trailing edge
$(..)_{nodes}$	mesh nodes
$(..)_{pp}$	patch points
$(..)_{rep}$	repetition
$(..)_{s}$	section
$(..)_{sum}$	sum
$(..)_{sys}$	systematic
$(..)^{nom}$	nominal design
$(..)^{opt}$	optical
$(..)^{tac}$	tactile

Abbreviations

2D	two-dimensional
3D	three-dimensional
BLISK	blade integrated disk
CAD	computed-aided design
CFD	computational fluid dynamics
CMM	coordinate measuring machine
CRC	curvature resolution constant
FEM	finite element methods
GOM	Gesellschaft für optische Messtechnik
STL	stereo lithography

1 INTRODUCTION

Motivation

Modern jet engines demand an always increasing expectation in a high efficiency combined with low costs. These factors stay relevant throughout the whole lifetime, referring to costs during manufacturing, operation and maintenance.
There are many aspects for keeping the costs low and the efficiency high, like new design strategies, manufacturing technologies or material improvements. Within these aspects a main objective is keeping the part's geometry always as close as possible to the nominal design intend. Of course it won't be possible to keep the geometry identical to the nominal design throughout the manufacturing process due to the limitations of the manufacturing technologies and manufacturing cost. Later, during operation, wear changes the geometry continuously because of limitations of the material properties. Consequently, it won't be possible to avoid the geometry variation. But it is necessary to ensure that the geometry variations stays within defined tolerances and to ensure that geometry deviations are quantified correctly. The quantification of geometric deviations are mainly realized today by using tactile measuring systems. These tactile measuring systems, also known by the synonym coordinate measuring machine (CMM), are well known and approved in the manufacturing and maintenance context.
Opposing geometric measuring systems to the tactile systems are non-contact optical measuring systems. These systems seem to be an upcoming topic because of their improved ratio of measured surface (quantitative) to measuring time compared to conventional tactile systems. The main problem in increasing the acceptance of optical measuring techniques throughout the industry is the uncertainty concerning the measurement accuracy and precision. The measurement quality, accuracy and precision is mainly depending on the surface condition of the measured part. Because of these individual influences it isn't possible to give a uncertainty statement for an optical measurement system without relating it to a certain object.
This paper will reveal possibilities in evaluating the precision and the accuracy aspects for optical measurement system and tries to improve the acceptance of using these method within the geometrical digitizing. Different aspects and considerations in evaluating the digitized geometry will be discussed and analyzed. Furthermore, individual accuracies for an optical measurement of a jet engines high pressure compressor BLISK are presented and evaluated.

Geometric Airfoil Measurement Methods

In building turbomachinery parts, there are different options in using digitized airfoil information. A main field and a conventional purpose of a 3D geometric measurement is the use within production to check whether a produced part stays within the given tolerances or not. These tolerances can be given as a band of total offset deltas from a nominal surface as well as a certain, often typical geometric parameter. Examples of typical parameters of a turbomachinery airfoil can be the sections chord length (l_{ch}), the stagger angle (γ) of the airfoil or leading and trailing edge radii ($r_{LE/TE}$). Typical profile parametrization methods can be found in BACKHAUS et al.[1] for compressor airfoils or in HEINZE et al.[2] for turbine blades. Evaluating both tolerance characteristics, it is necessary to measure a sufficient number of surface points with an adequate quality in order to generate a certain amount of measuring sections. Doing this, it is either enough to check those section outline points against a nominal design with its tolerances, or an additional step need to be ensured: the calculation of the section airfoil parameters based upon the measured section outline. Tactile coordinate measuring machines (CMM), as shown in Figure 1, are able to get just the information needed for those section based tolerance analyses. The method of tactile CMM is well known in industry. But also this technique is limited and there are methods gaining more information out of a measurement for further inspections.
An alternative method is the optical geometric measurement. This paper will address the method of the triangulation for structured light projections, as described by HOLTZHAUSEN [3]. Of course the advantage of a tactile method of actually touching the investigation part can never be refused. But within the context of further investigation, like reverse engineering processes, FEM-, CFD- or probabilistic simulations, a non-contact optical measuring method deploys an essential advantage. The main advantage is the digitizing of a full 3D surface. With an appropriate post processing this will lead to a highly detailed surface mesh (STL) for the measured part of investigation.

Optical Geometry Measurement

An optical 3D geometry measurement system uses different camera positions with several viewing angles for all points on the airfoils surface. The different measurements are combined to one single result. This way ensures that each surface point is measured several times with different pixel characteristics, such as illumination, viewing angle or shading. This method is also a reliable method to calculate the digitized mesh for surfaces with a low curvature. For surfaces with a very high curvature, more camera positions are needed to round out optimal viewing angles. All of these camera positions also need to be fit together in order to generate the result surface mesh, [4],[5]. As already mentioned for tactile CMM, the precision of the digitized surface mesh will also be lower for highly curved surfaces than for less curved surfaces, using optical measurement methods. This

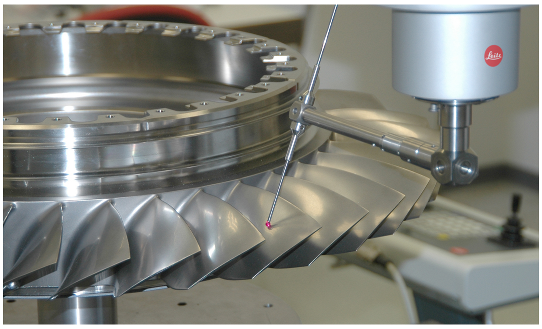

Figure 1: tactile CMM measurement system with a jet engine BLISK, [7]

paper will not give a statement about the quantity of these absolute errors, but tries to discuss and quantify the precision and to address the advantage of the full 3D measurement in respect to the upcoming evaluation methods. An estimation of a partial precision error of the used optical measurement system for surfaces with high curvature and with low curvature will be presented in the following section.
For the generation of this papers results, a measurement setup as shown in Figure 2 was used. The setup includes an uncoupled photogrammetry of coded and uncoded reference markers and the BLISKs surface scan related to those reference points. The reference markers were placed on a separate reference frame in order to capture 100 percent of the airfoils surface and not cover surface area by reference points. A 29 megapixel photogrammetry camera was used to teach the system the position of all reference points and the systems length scale on a digital cartesian coordinate system. Afterwards a sensor with a structured blue light projector and a doubled 16 megapixel camera system is used to measure the surface, including the surface curvature, out of several sensor positions by using the relation to the previous calculated reference system. The used photogrammetry system as well as the sensor system is linked to an industrial 6 axis robot system and an additional rotation table, [6]. This optical scan system is built by the company *'GOM GmbH'*.

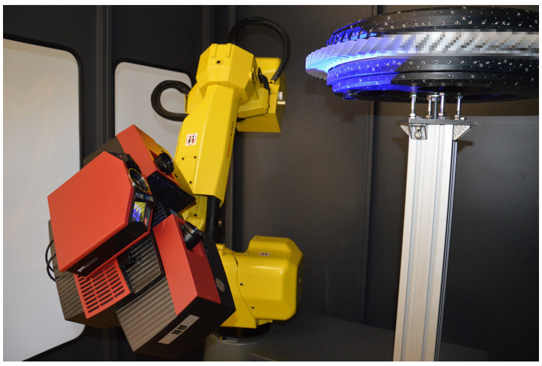

Figure 2: measuring setup with non-contact optical geometric measurement system

2 PRECISION STUDY

This section shall present a procedures to evaluate a precision for a structured blue light projection scanner and also discuss the boundary conditions of the results. For this evaluation, it is an essential foundation to define what steps of the digitizing procedure are included within the evaluation process. The digitizing setup remains the same as presented in the previous chapter. In the following, the overall procedure shall be presented and commented whether the individual step is repeated or stays constants.
For the presented application of milled from solid BLISKs the parts surface was matted to reduce the direct projector light reflection and optimized the diffuse light reflection. This process step is highly recommended for parts with a shiny surface to gain a better digitizing quality. Otherwise the effect of holes within the surface mesh at sharp edges, for example leading and trailing edge, can occur. Further more, areas with a low curvature, as suction and pressure sides, do not reflect enough light towards the camera system, that results in a bad illumination of these areas, which consequently leads to more noisy surface mesh. The matting coating consist of a Titandioxid-powder that is dissipated in liquid ethanol and spayed on the part's surface. After the application using an air brush system, the ethanol is completely vaporized and a pure powder coating remains on the parts surface.
After the matting process the BLISK is attached into an individual build reference frame, holding all photogrammetry reference markers, and mounted on the digitizing fixture as shown in Figure 2. This construction needs to be very stable to avoid excessive vibration behavior during the scanning procedure. Furthermore the individual camera position for the photogrammetry and scan procedure itself need to be defined by the user. This step is highly dependent on the experience of the user and has an high impact on the digitizing results. Still, the steps described so far are not included in the upcoming repetitive study and assigned to the status of the measurement pre-processing. The main measurement includes the three steps of running the defined photogrammetry, calibrating the sensor and executing the structured blue light scan. During the post-processing the individual scans are aligned according to the photogrammetry, a 3D surface is calculated and polygonized, resulting in a triangulated surface mesh. Finally the digitized surface mesh is aligned towards the nominal design. For this procedure, only the airfoil geometries, including the fillet areas are used for a best-fit-alignment towards the nominal CAD design. The main measurement as well as the post-processing procedures are the objectives of the presented repetitive study. Unfortunately it is not possible to separate the individual steps using the available possibilities.
For the presented precision study a $n_{rep} = 10$ time repetitive measurement campaign was realized. The results of these measurements are used for a 3D and for a 2D precision evaluation.

3D Evaluation

The first precision evaluation is based directly on the 3D surface mesh, similar to the repetitive study presented by BACKHAUS et al.[1]. In contrast to the mentioned paper, the repetitive comparisons don't consist of

$$n_{comp,[1]} = \binom{n_{rep}}{n_{delta}} = \binom{10}{2} = 45 \quad (1)$$

comparisons but of

$$n_{comp} = n_{rep} \cdot (n_{rep} - 1) = 90 \quad (2)$$

with a total number of $n_{node} = 12 \cdot 10^6$ for each comparison. The reason in this total number of comparisons is the fact, that the offset error ε_A of a '*mesh* 1' towards another '*mesh* 2' is a different than the offset error ε_B of '*mesh* 2' towards '*mesh* 1'. Figure 3 illustrates this issue visually. It can be seen, that the individual offset values $\varepsilon_A^{(i)}$, with '*mesh* 1' being the primary mesh, are different to the offset values $\varepsilon_B^{(i)}$, with '*mesh* 2' being the primary mesh. This inequality was not considered within [1] but within this study. Even if there won't be a big difference in the overall offset value, after summing up all individual offset values, the study shall be extended due to the correct scientific manner.

All $n_{comp} = 90$ surface mesh comparisons are divided into areas with low curvature (lc) and high curvature (hc). Typical low curvature areas are suction and pressure sides. Areas with high curvature are represented by the leading and trailing edges. Because of inhomogeneity of the digitizing method it is an important aspect to divide the airfoil areas into areas of different curvature.
Within this study, each surface mesh consists out of $n(lc)_{nodes} = 10.4 \cdot 10^6$ nodes for areas with a low curvature and $n(hc)_{nodes} = 1.6 \cdot 10^6$ nodes for areas with a high curvature. Figure 4 (top) shows nine overlapping frequency plots of areas with high curvatures for the first surface mesh, compared with all other $n_{rep} - 1 = 9$ repetitive measurements. All individual offset values of those nine mesh comparisons can be combined to a single frequency plot (Figure 4, bottom), representing the comparisons towards the

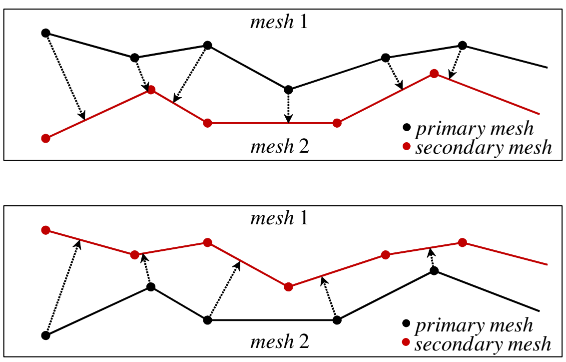

Figure 3: comparison of two exemplarily 2D surface meshes

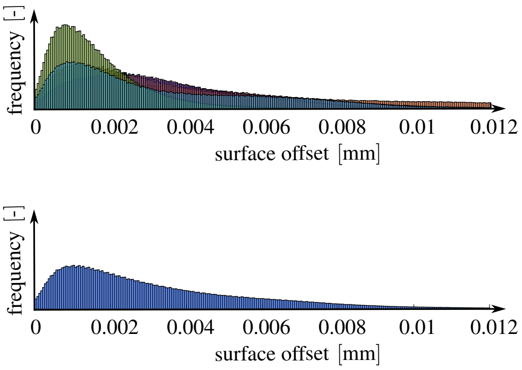

Figure 4: separated (top) and combined (bottom) comparison of one repetitive measurement

first measurement. The described procedure is applied on all $n_{rep} = 10$ repetitive measurements and all curvature areas (lc and hc). This results in the final offset ε-distribution, represented by the frequency plots as shown in Figure 5. The top plot of this figure shows a histogram for the areas with a low curvature considering about

(3) $$n(lc)_{sum} = n_{comp} \cdot n(lc)_{nodes} \approx 936 \cdot 10^6$$

surface offset values. This data set reveals that 99% of the surface error remains below $\varepsilon(lc)_{0.99} = 5.5\,\mu m$. The bottom plot of Figure 5 shows the error histogram for the areas with a high curvature considering about

(4) $$n(hc)_{sum} = n_{comp} \cdot n(hc)_{nodes} \approx 144 \cdot 10^6$$

surface offset values. This data set shows, that 99% of the offset values for areas with a high curvature are below $\varepsilon(hc)_{0.99} = 11.6\,\mu m$.

2D Evaluation

In addition to the 3D evaluation of the repetitive study, this section shall present a 2D evaluation of the same data set.

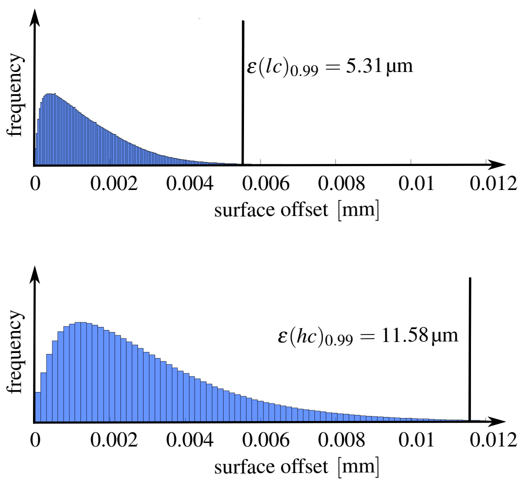

Figure 5: surface offset distribution of the repetitive 3d mesh evaluation for areas with low curvature (top) and high curvature (bottom)

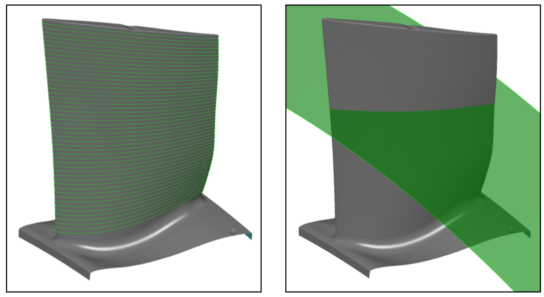

Figure 6: definition for $n = 49$ interpolated sections (left) and one streamline related area (right)

The reason of this evaluation is motivated in the unusual distribution characteristics of Figure 5. Since the distributions are showing the absolute offset values ε of the analyzed surface mesh nodes, it should be clear, that the non-absolute values should result into a normal distribution with the mean value $\mu_\varepsilon = 0$. This is not the case, instead, the modus of the distributions are located at $\varepsilon(lc)_{0.99} = 0.4\,\mu m$ and $\varepsilon(hc)_{0.99} = 1.1\,\mu m$, respectively. This speciality might not be triggered by the random characteristic of the repetitive measurement, but by a systematic error ε_{sys}. Therefor the objective of the 2D evaluation shall be the quantification of the systematic error ε_{sys} for areas with a low curvature as well as a high curvature.
For this task, all airfoils of all measurements of the BLISK were separated into $n_s = 49$ equidistant distributed sections. As introduced by LANGE et al.[8], a given hub and shroud contour is interpolated, resulting in a section distribution

(5) $$r_n(x) = s_n\, r^{hub}(x) + (1 - s_n)\, r^{shroud}(x)\ ,$$

with s_n defining the relative spanwise position of the airfoil height. The given discretization results in a section distance of $\mathrm{d}(s) = 0.02$. The definition of the airfoil section is illustrated on Figure 6 (left). As described in more detail by BACKHAUS et al.[1], the section contour $r_n(x)$ of each spanwise position s_n describes a solid of evolution. Figure 6 (right) visualizes this procedure exemplarily on the mid-span-section $s_n = 0.5$. Afterwards, the section outline points are transformed from the 3D Cartesian coordinate system into a 2D polar coordinate system, resulting in n_s section outline contours based on the resolution of the surface mesh, [1].
The discretization of these airfoil sections can easily be manipulated by adapting the contours by NURBS. A point resolution study was realized to evaluate the needed section outline point resolution. For this study the section outline contour is separated in four patches including leading and trailing edge as well as suction and pressure side areas. For all patches the point number is increased starting at $n_{pp} = 25$, ending at $n_{pp} = 800$ points. All $n_s = 49$ section of one airfoil were evaluated for all repetitive measurements. Finally the 99% quantile of all section outline point offset values were evaluated. Figure 7 shows the results of this resolution study. It can be seen, that the 99% quantile values converge for patch point numbers $n_{pp} \geq 100$ for suction

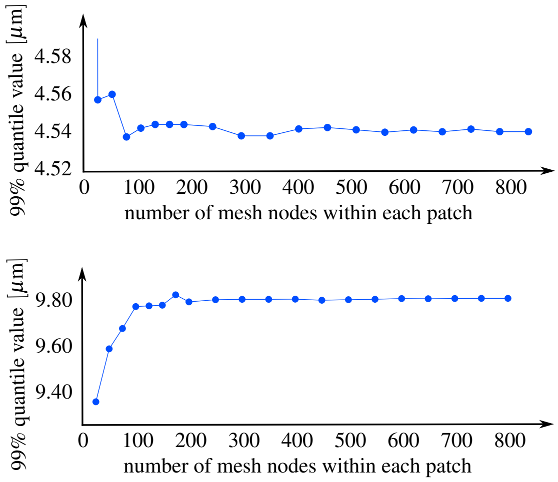

Figure 7: airfoil patch resolution study for areas with low curvature (top) and high curvature (bottom)

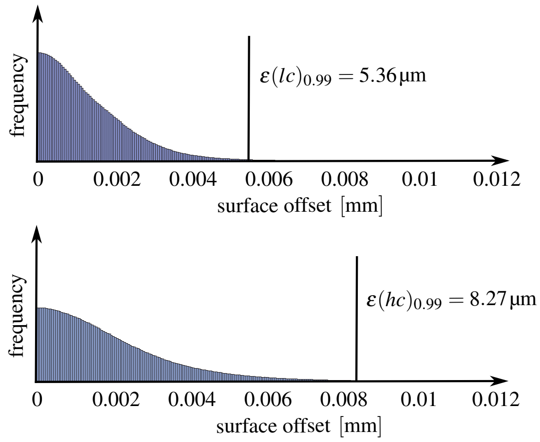

Figure 9: surface offset distribution of the repetitive 2D mesh evaluation for areas with low curvature (top) and high curvature (bottom)

and pressure side patches and $n_{pp} \geq 200$ for leading and trailing edge patches. For the upcoming evaluation, a joint patch resolution of $n_{pp} = 200$ points for each patch is chosen. This patch resolution corresponds to a dimensionless curvature-resolution-constant

(6) $$CRC = \mu_{curv} \cdot \mathrm{d}\left(P_i, P_j\right)$$

with μ_c being the average curvature and $\mathrm{d}\left(P_i, P_j\right)$ being the point distance of the equidistant point distribution of the corresponding patch. For the presented mesh resolution study the curvature-resolution-constant is

(7) $$CRC(hc)_{n_{pp}=200} = 0.010$$

for areas with high curvature and

(8) $$CRC(lc)_{n_{pp}=200} = 0.014$$

for curvature with low curvature. Figure 8 shows a leading edge with $n_{pp} = 25$ and 200 points.
Using this resolution, an equivalent study to the 3D study described in the previous section was carried out. For this 2D evaluation

(9) $$n(lc/hc)_{sum} = 2 \cdot n_{pp} \cdot n_s \cdot n_{af} \cdot n_{comp} \approx 140 \cdot 10^6$$

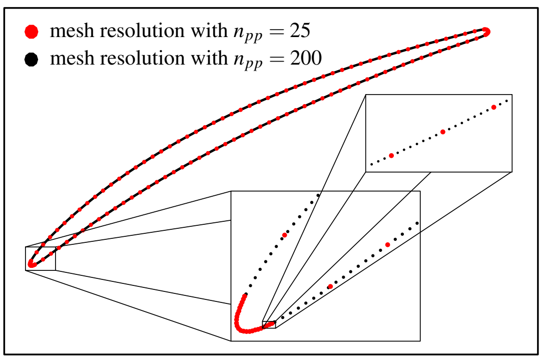

Figure 8: point resolution of a 2D airfoil section with $n_{pp} = 25$ (red) and $n_{pp} = 200$ (black) points per patch

surface offset values were calculated. 99% of these values including areas with low curvature were smaller than $\varepsilon(lc)_{0.99} = 5.36\,\mu$m. While the 99% quantile for values of areas with high curvature was at $\varepsilon(hc)_{0.99} = 8.27\,\mu$m. The corresponding frequency plot is shown in Figure 9.

Summary

While the 99% quantile for areas with a low curvature stays consistent at a value of $\varepsilon(lc)_{0.99} \approx 5.3\,\mu$m for the 2D and 3D repetitive study, the 99% quantile for areas with a high curvature decreases from $\varepsilon(hc)_{0.99} = 11.58\,\mu$m for the 3D study to $\varepsilon(hc)_{0.99} = 8.27\,\mu$m for the 2D study. This is a reduction of 29%! This reduction is ascribed to the higher resolution of nodes at areas of high curvature. This way the systematic error of evaluating the offset value between a certain node and a corresponding surface line/plane is minimized, based on the resolution study presented in Figure 7.

Additionally it can be seen, that the surface offset distribution shape changes significantly for very small values ($\varepsilon_i < 0.002\,\mu$m). While the non-absolute offset value distribution of the 3D repetitive study does not result in a normal distribution with a zero mean value, the offset value distribution of the 3D repetitive study does. That implies, that the mesh resolution directly influences the calculated offset values for very small mesh distances. This systematic error is illustrated in Figure 10. Even if the mean value of the non-absolute offset value distribution is $\mu_\varepsilon = 0$, then only very few mesh nodes actually do have no distance towards the comparison mesh. This is only the case, if a mesh node is directly within the mesh plane of the comparison mesh (see Figure 10: node $i = 4$). While the mesh resolution increases, the averaged absolute offset values for small surface distances decreases. This effect needs to be considered within the evaluation of a precision study using surface meshes.

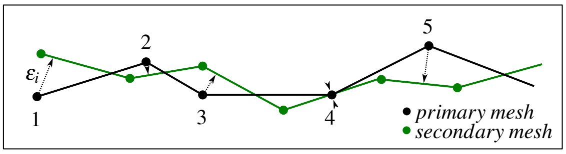

Figure 10: comparison of two exemplarily 2D surface meshes with the non-absolute offset distribution mean of $\mu_\varepsilon = 0$

3 ACCURACY EVALUATION

Measuring Setup

In order to quantify the accuracy of the presented optical measurement system, a comparison between the optical and the tactile measurement system was accomplished. For this task the BLISK was additionally measured by a CMM *'PMM-C 161210'* with an rotary table of the company *Leitz*, [9]. The used measuring routine included the digitizing of $n = 5$ section of constant radial height, as shown in Figure 11, for all airfoils of the BLISK. These section result into highly resolved 2-dimensional airfoil profiles. For each profile, different airfoil parameters can be extracted as already mentioned in Section 1. More detailed introductions to common 2D compressor airfoil parametrizations are presented in MARZOCCA [10] or BACKHAUS et al.[1]. For the presented evaluation of the measurement accuracy, the two parameters chord length (l_{ch}) and stagger angle (γ) are used for a comparison between the results of the optical and the tactile digitizing systems. The definition of those parameters are illustrated in Figure 12.

For the accuracy evaluation, both measurements were aligned identically by using the rotation axis as well as a defined reference plane of the BLISK to limit the axial shift. This way, the path of the tactile probe is defined precisely and with maximum accuracy. While the tactile CMM section data were generated live on the hardware, the optical section data were generated virtually by using the same defined measurement routine on the already optical digitized surface mesh. By using these identical measuring routines,

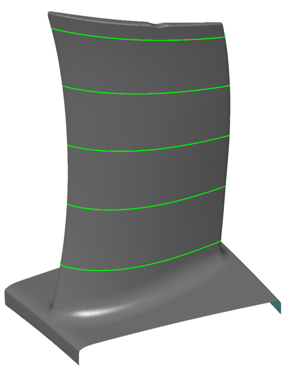

Figure 11: $n = 5$ defined sections for airfoil parameter evaluation

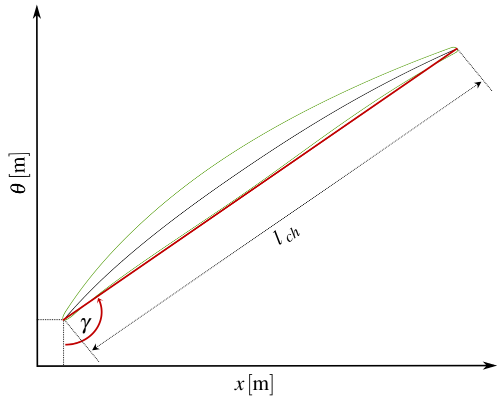

Figure 12: compressor airfoil section with definition of profile parameters l_{ch} and γ

it shall be ensured to compare identical profile sections. Furthermore, this procedure enables the identical calculation of the section parameters for both digitizing methods, due to the same parametrization algorithms. Finally the presented approach guarantees the possibility to compare the airfoil parameter results of the CMM measurement and the virtual CMM measurement of the optical digitized surface mesh.

Method Comparison

According to the defined comparison setup

$$n_{comp} = n_{section} \cdot n_{blades} = 5 \cdot 72 = 360 \qquad (10)$$

values of the tactile and the optical measurement were compared. The absolute values for both comparison parameters (l_{ch} and γ) were transformed to offset values ε towards the nominal CAD design:

$$\varepsilon\,(l_{ch}) = (\Delta l_{ch})^{tac} - (\Delta l_{ch})^{opt} \qquad (11)$$

and

$$\varepsilon\,(\gamma) = \Delta\gamma^{tac} - \Delta\gamma^{opt} \quad . \qquad (12)$$

Figure 11 shows the offset distribution for both profile parameters. On the top graph, the offset distribution of the parameter l_{ch} reveals that the mean of the offset value is at $\varepsilon\,(l_{ch})_\mu = 0.020$ mm. By taking into account, that the parameter l_{ch} includes surface offset values for both sides of the airfoil at leading and trailing edges, this offset value stays in the same range as the precision for these areas presented in Section 2:

$$\varepsilon\,(l_{ch})_\mu \approx 2 \cdot \varepsilon(hc)_{0.99} \qquad (13)$$

Additionally it can be seen, that 95% of the offset values stay within a span of $\varepsilon\,(l_{ch})_{0.95} = 0.027$ mm. Comparing this span with the variation for all airfoils of the parameter l_{ch} itself measured by the CMM, theres a difference of

$$\frac{\varepsilon\,(l_{ch})_{0.95}}{(l_{ch})^{tac}_{0.95}} \approx \frac{1}{10} \quad . \qquad (14)$$

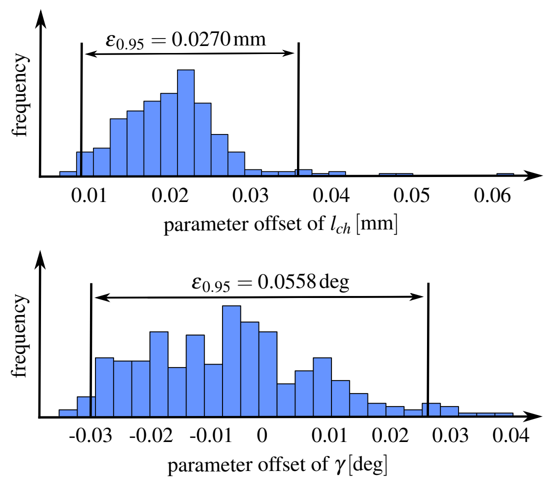

Figure 13: parameter offset distribution for the airfoil parameters l_{ch} (top) and γ (bottom)

The bottom graph of Figure 11 shows the distribution of the parameter γ. Here, the mean μ of the offset distribution between the optical and the tactile measurement differs by $\varepsilon(\gamma)_\mu = -0.005$ deg. Also the distribution variation $\gamma^{tac}_{0.95}$ itself measured by the CMM is two times higher than the variation of the offset between the two measurement methods:

$$\frac{\varepsilon(\gamma)_{0.95}}{\gamma^{tac}_{0.95}} < \frac{1}{2} \quad . \tag{15}$$

It is legit, that this deviation coefficient of the parameter γ is smaller, than the equivalent coefficient of the parameter l_{ch}, since the stagger angle is a more robust airfoil parameter with respect to geometric surface uncertainties. Nevertheless are the presented parameter comparisons a explicit result, that the optical measurement system is able to capture the section based airfoil parameter sufficient enough for manufacturing tolerance checks. Further more, the results show that the accuracy of the airfoil parameters are within the same range as the evaluated precision, presented in Section 2. That includes the expectation and the deviation value of the offset distributions.

4 CONCLUSION

Within this work, a way of evaluating the precision and the accuracy of optical measurements were presented. The precision study is based on a ten-time repetitive optical measurement and is evaluated by using a 3D mesh comparison and an additional 2D mesh comparison. All parts of the measurement routine, that were included within the repetitive study are defined and described. The 3D mesh comparison shows, that 99 percent of the surface offset of the areas with a low curvature stay below 5.3 µm and for areas with a high curvature the value resulted to 11.6 µm.
Since the non absolute offset value distribution of the 3D mesh comparison shows a bi-normal characteristics, an additional 2D mesh comparison was realized in order to change the mesh discretization and determine its influence on the precision evaluation. For this purpose, a mesh study was realized, that revealed a sufficient number of 200 2D mesh nodes per patch for the leading and trailing edge patches as well as for the suction and pressure side patches. By using these improved airfoil profile discretization with the increased number of mesh nodes, it was possible to draw a more precise offset distribution. This distributions did not show the bi-normal characteristics within its non absolute notation, but as expected a normal distribution with a mean value close to zero. The 99% quantile of the surface offset of the areas with a low curvature remained at 5.3 µm, while this value of areas with a high curvature decreased to 8.3 µm. This improved precision quantification is assigned to the improved mesh discretization at leading and trailing edge areas.
The authors are aware of the aspect, that the improved mesh discretization can also be realized within the 3D space. The shown results shall not be interpreted by the way, that the 2D mesh evaluation is more accurate than the 3D mesh evaluation, but that it is very important to use an appropriate mesh discretization at all, in order to quantify a sufficient mesh comparison.
Furthermore, a comparison of typical section based airfoil parameters was accomplished in order to quantify a accuracy of the optical measurement of the structured blue light projection relatively to a CMM. This evaluation revealed, that the optical measurement system is able to capture typical section based airfoil parameters with a sufficient accuracy in order to perform geometric tolerance checks. The presented parameter comparison also revealed, that the accuracy of the length based parameter chord length stays within the same dimension as the analyzed precision of the optical measurement system.
Eventually the evaluations of these comparisons resulted not only in quantified accuracy and precision values but also in a increased understanding of this topic. It was shown, that the optical measurement system of the structured blue light projection is able to capture the surface of a HPC jet engine BLISK with a sufficient quality in order to ensure validation tasks as parameter based tolerance checks, parts integrity estimations during maintenance and for different kinds of reverse engineering processes.

Outlook

For an even better quantification of the accuracy of the presented optical measurement system a direct comparison of the detected surface points need to be evaluated. For this task, common CMM sections of constant radial and axial positions are already sufficient in order to analyze the data offset between the optical and the tactile measurement. This evaluation will eliminate the noise of the parametrization algorithms and will isolate the surface data offset. This procedure will result in a more detailed accuracy quantification

of an optical jet engine BLISK measurement.
Further more will the optical digitized BLISK geometry be used for probabilistic FE calculation in order to quantify the dependencies between geometric variations and the airfoil vibration behavior as well as BLISK mistuning effects. For this purpose the results of MAYWALD et al.[11], [12] and BACKHAUS et al.[1], as well as the results of the presented work will be combined and extended to improve the understanding on the incurrence of jet engine HPC BLISK mistuning effects. Eventually this procedure will enable a path to not only simulate the optical measured BLISK geometry within a modal analysis calculation, but also capture the complete variability of the BLISK manufacturing regarding the individual vibration characteristics.

ACKNOWLEDGEMENT

The authors would like to thank Rolls–Royce Deutschland Ltd & Co KG for encouraging and approving the publication of this work. The project is funded by Rolls–Royce Deutschland Ltd & Co KG and the Federal Ministry for Economic Affairs and Energy of the Federal Republic of Germany under the contract 03ET7021S.
A special acknowledgement goes to Martin Burk, Jörg Weigand, Thomas Stopp, Bernhard Mueck and the contributing colleagues from Rolls–Royce Deutschland Ltd & Co KG in Oberursel and Dahlewitz as well as Caetano Peng from Rolls–Royce plc for supporting this study with their individual knowledge and with organisation of capacities to generate the presented optical measurements.
We would also like to thank all colleagues at the chair of turbomachinery and flight propulsion at the TU Dresden who helped in solving technical issues within the generation data and acted supportive towards the preparation of this paper.

References

[1] Backhaus, T., Maywald, T., Schrape, S., Voigt, M., and Mailach, R., 2017. "A Parametrization Describing Blisk Airfoil Variations Referring to Modal Analysis". In Proceedings of ASME Turbo Expo 2017. GT2017-64243.

[2] Heinze, K., Meyer, M., Scharfenstein, J., Voigt, M., and Vogeler, K., 2014. "A Parametric Model for Probabilistic Analysis of Turbine Blades considering Real Geometric Effects". *CEAS Aeronautical Journal,* ***5***(1), pp. 41–51.

[3] Holtzhausen, S., 2015. "Erfassungsplanung nach dem Optimierungsprinzip am Beispiel des Streifenprojektionsverfahren". PhD Thesis, TU Dresden.

[4] Zhang, S., 2015. "High-resolution, Real-time 3-D Shape Measurement". PhD Thesis, Stony Brook University.

[5] Peng, T., and Gupta, S., 2007. "Model and algorithms for point cloud construction using digital projection patterns". *ASME Journal of Computing and Information Science in Engineering,* ***7***(4), pp. 372–381.

[6] GOM-GmbH, 2017. "ATOS ScanBox - Optical 3D Coordinate Measuring Machine".

[7] Hexagon-Metrology-Services, 2009. "Messtechnik Wetzlar wins MTU Aero Engines Competition".

[8] Lange, A., Vogeler, K., Gümmer, V., Schrapp, H., and Clemen, C., 2009. "Introduction of a Parameter Based Compressor Blade Model for Considering Measured Geometry Uncertainties in Numerical Simulation". In Proceedings of ASME Turbo Expo 2009. GT2009-59937.

[9] Hexagon-Metrology-GmbH, 2017. "Leitz PMM-C 600/700/1000 Koordinatenmessgerät".

[10] Marzocca, P., 2016. "The NACA airfoil series".

[11] Maywald, T., Kühhorn, A., and Schrape, S., 2016. "Experimental Validation of a Model Update Procedure Focusing on Small Geometric Deviations". In Proceedings of ECCOMAS Congress 2016.

[12] Maywald, T., Backhaus, T., Kühhorn, A., and Schrape, S., 2017. "Geometric Model Update of Blisks and its Experimental Validation for a Wide Frequency Range". In Proceedings of ASME Turbo Expo 2017.