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AN AUTOMATED ASSESSEMENT TOOL OF NLF CRITERIA FOR AIRFRAME JOINTS

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Abstract

An ever increasing awareness of the ecological impact of air travel and associated regulatory measures demands for a cut in aircraft fuel consumption to reduce CO2 emissions and operating costs. Among improvements in engine technology or use of alternative fuels, the sustainment of laminar flow on surface areas of transport aircraft is seen as an important contribution to the solution of this challenge. The reduced friction drag of a natural laminar flow (NLF) wing can lead to a reduction in fuel consumption and thus reduction of CO2 emissions of up to 8 % on aircraft level [1].

Laminar flow‘s sensitivity to surface disturbances however requires specific shapes and high surface quality: Structural features like steps, gaps and surface waviness can cause early laminar/turbulent transition [2]. This calls for novel structural design concepts for laminar flow applications and tools to enable their practical implementation in aircraft operation.

Through the course of several national and EU-funded projects, a multi-material leading edge concept using CFRP with an integrally bonded steel foil erosion shielding is being developed by DLR [3] with a distinct focus on operability. The leading edge and an associated interchange-enabling attachment concept are realized in a 2.3 m ground based demonstrator representing an outer wing section. A test stand is designed to recreate “wing on ground” and “cruise flight” surface deformations to enable interchange trials of the leading edge [4]. To enable an assessment against NLF criteria of the achieved step at the joint between leading edge and wing cover, an automated step measurement tool is developed and verified against manual assessments. Such a tool is a necessary step not only to validate suitability to support NLF on aircraft wings of the leading edge design and attachment concept. It also serves as a key contribution to a possible closed loop system supporting the assembly of airframe structures with intended laminar flow characteristics by providing direct feedback of the surface quality and informing on necessary adjustments to be made by the technicians.

The paper will focus on the development of the assessment tool, framed by the results it delivered on the NLF leading edge installation trials.

Keywords
Natural Laminar Flow; Assembly; Measurement

1. INTRODUCTION

In a reaction to climate change, the ACARE goals demand for a cut in aircraft fuel consumption to reduce CO2 emissions. One means is to implement areas of laminar flow on surfaces of transport aircraft. With a contribution of about 18 % to the total friction drag of a typical transport aircraft [5], the wing is exceptionally suited to apply laminar flow technologies. The reduced friction drag of a natural laminar flow wing can lead to a reduction in fuel consumption and thus reduction of CO2 emissions by up to 8 % [1]. However, the laminar boundary layer is sensitive to surface disturbances. Steps, gaps and surface waviness as well as 3D disturbances, such as fastener heads, can trigger early laminar/turbulent transition [2]. To address those challenges, a novel wing leading edge design was conceived at the German Aerospace Center (DLR). The overall objective is to demonstrate the eligibility of NLF wing leading edges for real world scenarios and operation. Two major capabilities will be demonstrated:

- Interchangeability of a full-scale wing leading edge section under operational conditions of a flexible wing
- Compliance with aerodynamic NLF requirements at the leading edge/wing upper cover joint under cruise deformation.

The leading edge joint design eliminates most airflow disturbing factors, but has to be detachable to be interchangeable. Thus, a joint with an interface between both parts exists, that can be characterized by as a gap that will be filled in a real world application. However, by lack of a universally applicable criterion for filled gaps from aerodynamics, the interface will be characterized by a virtual step between both components

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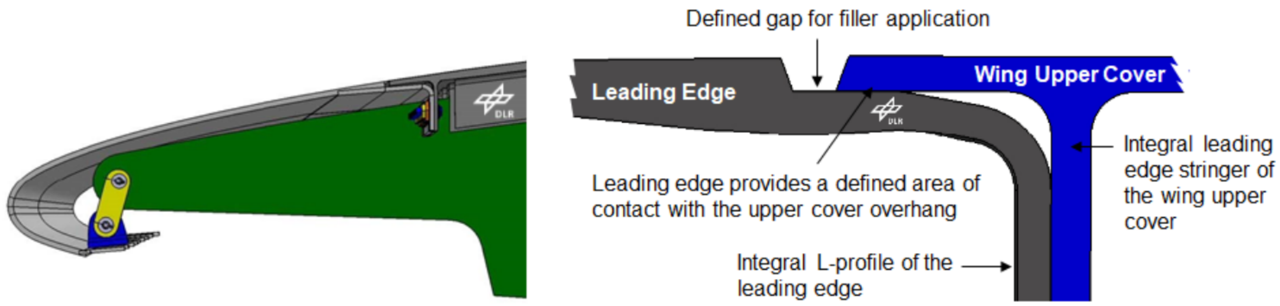

FIG 1. leading edge wing box interface with aerodynamic step

following the airflow from the leading edge over the gap. This can be considered a conservative method of assessment.

To achieve this, a ground based demonstrator (GBD), including a partial wing box and leading edge, and a test rig are designed in detail. The test rig allows for measurement of the step height between leading edge and wing cover under realistic cruise flight surface deformations and to deform the wing to an on-ground deformation state, where operationally relevant data on the interchangeability of the leading edge can be gathered. The step height between leading edge and wing cover is determined based on 3D surface measurements of the GBD. Four installations are made with two different leading edges to enable a comparison between repeated installations under the same conditions or under different conditions, like installation in neutral or wing-on-ground deformation. For each installation, surface measurements are made in the neutral, wing-on-ground and cruise surface deformation states. Thus, twelve step height data sets have to be analyzed.

With the perspective of operational application in mind, where a quick way to assess the quality of the installation leading edge would be beneficial to the performing technicians, and the desire to efficiently and consistently process the data of a multitude of measurements made in different installation trials and at different deformation states of the GBD, an automated tool for the step height estimation is to be developed.

2. DEMONSTRATOR

The laminar leading edge and attachment concept are integrated in a 2.3m span GBD of a wing box section with forward wing elements attached. The wing geometry shows the full complexity of a real wing, with e.g. wing taper and decreasing profile thickness.

Fig 1 provides an overview the leading edge joint design in focus of the investigation. The laminar leading edge consists of CFRP as structural material, an electro-thermal wing ice protection system (WIPS) and a co-bonded steel foil erosion shielding. The deviating coefficients of thermal expansion of erosion shield and CFRP structure are taken into account by joining the leading edge to the leading edge ribs with a strut-assembly just at the Krueger landing (Fig 1, left). This allows for a free deformation of the leading edge in flight, reducing surface waviness over the wide range of operational temperatures. Fastener heads in the outer surface at connections to the forward wing ribs commonplace in conventional designs are hence also avoided.

As a main focus of the work, the joint between leading edge and wing upper cover (Fig 1, right), is on the inside of the structure to achieve compliance with aerodynamic NLF requirements. An integral lap joint is created, where the CFRP layup of the leading edge runs under the wing upper cover skin. The joint itself is established between a wing upper cover stringer and an L-shaped flange of the leading edge (Fig 1, right).

A controlled step height is ensured by form fit of both parts by the use of fitted fastener elements that prevent any change in the step, and by a high degree of part accuracy achieved by the selection of suitable production processes that provide a stable mould line at the mating surfaces. Thus, material thickness variations otherwise common in composites are mitigated.

To avoid resin rich buildups or critical fibre redirections at the edge of the recess in the leading edge joint area, a GFRP wedge inlay is introduced to divert the structural fibres towards the integrated L-flange. The leading edge is built out of prepreg materials in a three-parted mould in a one-shot vacuum bag autoclave production process. After assembling brackets for the rib attachment to the leading edge, it can be integrated with the GBD and the test rig.

The test rig itself, shown in Fig 2, is designed to replicate wing surface deformations obtained from full wing FE simulations on the ground based demonstrator structure. Three deformation states can be created by the test rig: neutral/CAD, cruise surface deformation and the deformation of a free cantilevered wing of an aircraft on ground. The test stand itself consists of a machine bed, a control unit and six actuators, each capable to apply of 5kN of force to the GBD. Both the GBD box and the test rig itself were designed in the same design process described in more detail in [4].

For the upper wing surface shape, and especially the leading edge joint area, is in scope of the tests, a lower wing cover is not considered in the ground based demonstrator. The deformation of a complete wing box would have required far greater loads for the same outcome. The upper wing cover used is a pre-existing component, designed and built in a German national

FIG 2. Test rig for mounted leading edge with ground and flight loads

funded project, itself designed as an NLF wing cover matching the leading edge geometry [6].
Along the wing cover and leading edge, the GBD includes a front spar, five wing box ribs behind the front spar and eight forward wing ribs, of which two are designed as end ribs to support the leading edge profile. The forward wing ribs are not optimized as part of the test stand design process. Their simple plate design matches the representation in the FE model. Wing box ribs and front spar are part of the test rig optimization process. All ribs are directly attached to integral ribcaps of the wing cover and are connected to the front spar.

3. MEASURMENT

To ensure the compliance with the aerodynamic NLF requirements a precise measurement in needed. As of the overall dimension and the 3D geometry the GOM ATOS 3 scanner, a contact-less 3D scanner, is used. The measuring setup is shown in (Fig 3).
To capture the complete 2.3m span of the GBD, the scanner is moved around the demonstrator, as a single scan area is only 700x700mm. The individual scans are fused to a single model using reference points ont he GBD surface.t.
After scanning the surface with the structured light projector, the software interface allows to calculate various geometric bodies or contours. During the preprocessing of the subsequent analysis some steps are important. First, a defined coordinate system is required throughout all setups to ensure comparable measurements.
Secondly, unnecessary areas (e.g. rib artefacts) should be removed. Subsequently the various evaluations can be made manually or automated and generated as a colored image or as value element reports. In here the step height along the span is the important variable. Due to the number of variations and the wish for a consistent data report structure for all measurements the evaluation was automated using Python within the GOM software. This allows for an parametric creation of the span-wise cuts and the creation of the export data file.

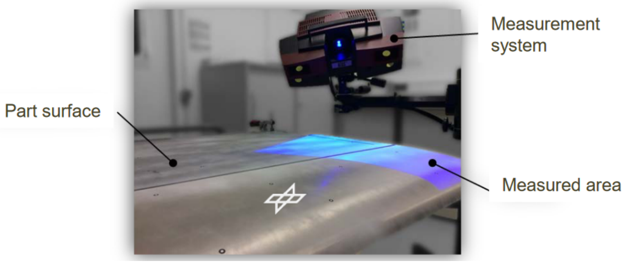

FIG 3. measurement of the leading edge on test rig

4. STEP HEIGHT ESTIMATION

The step height is measured cut wise along the span. The raw data provided by the optical measuring system are points at equally spaced cuts along the span. Each cut consists of points in the $x-y$-domain, while z is the fixed span wise position of the cut.
A large number of experiments are planned based on several combinations of assembly processes, load states and leading edges. For each measurement approximately 230 cut planes are created and have to be evaluated. In order to handle the large amount of data, an automatic and reproducible process is desired to evaluate the data.
The basis for estimating the step height is to identify the individual parts of the cut like described in Fig 1. The parts to identify are the leading edge cover, the wing box cover and the skew wall of the gap.
By extrapolating the covers a deviation of the splines of wing box and leading edge cover can be observed in the interface region. The linear extrapolation of the gap wall allows to define a virtual edge to measure the perpendicular distance of the leading edge spline to this virtual edge.
In order to validate the automatic process, a subset of the raw data are evaluated manually with engineering judgement in CATIA as a reference. Both approaches are explained hereafter.

4.1. Automatic Approach

For the automatic processing of the data, a program is written in python using common libraries for data processing. The programmatic process is structured as described in Tab. 1.

1. reading the raw data
2. identifying the sub parts: leading edge cover, wing box cover and the skew wall of the gap
3. create splines and extrapolate them
4. identify the correct splines and calculate the intersections
5. calculate the step height perpendicular to the leading edge spline

TAB 1. Generic process steps for step height estimation

The raw data can be read directly into python using the pandas package [7]. Fig 4 a) shows the raw data. The automatic identification of the sub parts is the most challenging part of the process. This issue is tackled by using a clustering algorithm provided by scikit-learn package [8]. scikit-learn is a machine learning library in python and provides several clustering algorithms.
Multiple of the algorithms are investigated and the DBSCAN appeared to be the best algorithm for this task. DBSCAN is a Density-Based Spatial Clustering of Applications with Noise. It detects clusters with higher density features separated by areas of low density. This generic approach allows to identify areas of arbitrary shapes, which is beneficial compared to other algorithms like k-means.
Clustering is based on so called feature, which have to be provided. Such features have to be defined for each point. In addition to the vertical position (y) itself, the slope between to neighbouring points is used as an additional feature. This allows to separate the skew gap wall from the wing box. The identified clusters are exemplary shown in Fig 4 b).
For each cluster a spline is created by the SciPy package [9]. SciPy provides a class to create univariate splines of arbitrary degree. For the leading edge cover and the wing box cover splines of degree two are used, while for the gap wall a linear interpolation is used. In Fig 4 b) these splines are shown. The light purple line is the extrapolation of the gap wall, which intersects with green line from the leading edge and the red spline from the wing box cover.
Because the gap wall cluster is sometimes hard to detect, often more than one cluster is identified here, which leads to multiple splines. Here the steepest spline with respect to the leading edge spline is used. All splines based on points from the round transition between gap wall and cover, are more flat and the intersection angles is smaller with respect to the leading edge spline.
Finally the intersection point of the gap wall spline and the wing box cover spline defines the virtual edge. From this point the perpendicular distance to the leading edge spline is calculated as visualized in Fig 4 c). Positive values in this calculation means that the leading edge spline is below the edge and the airflow has a positive step, which is the desired case in terms of laminar flow.
For 229 cut section of a single measurement, the presented process took 11.2s on a basic laptop, without any optimisation of the code. Through the use of simple looping, this means 0.05s per cut.

4.2. Manual Approach for Validation

For one leading edge installation and its deformation states, the step heights are also investigated in a manual computerized approach. The section-wise point clouds of the joint area are imported into the CAD software CATIA V5R21 from Dassault Systems via the

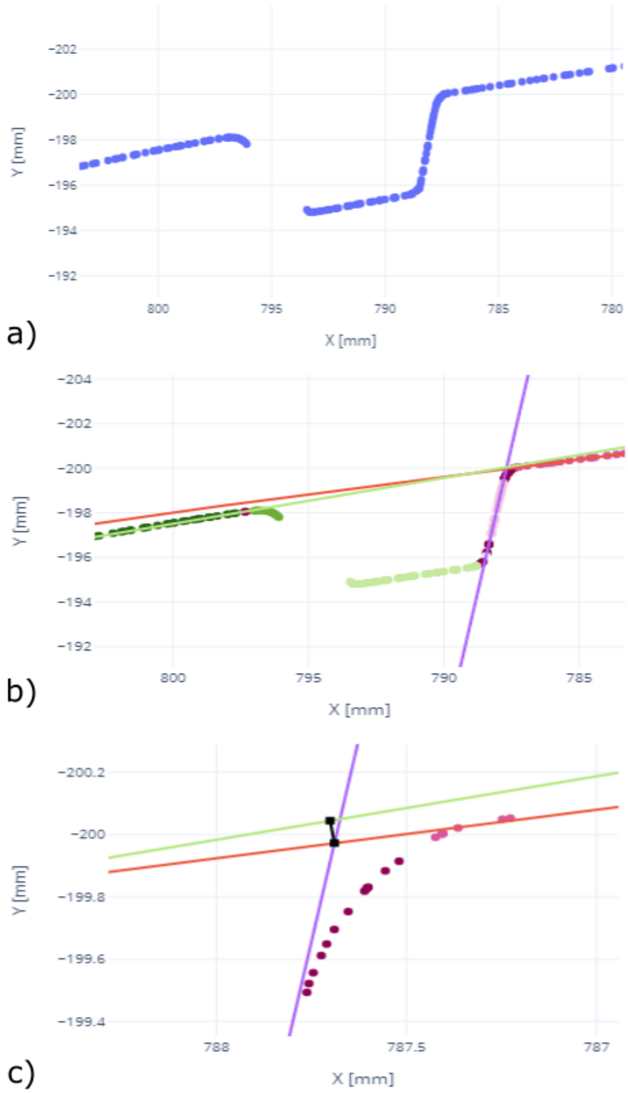

FIG 4. Data processing for example cut points.
a) raw data
b) identified features with splines
c) intersection of splines and step height

in-built point import macro. A section is investigated each 30mm over the span of the GBD.
In the same way as in the automated approach, the edge of the wing cover is reconstructed from tangentially continuous extrapolations of splines of wing upper cover points and gap skew wall points. The leading edge skin extrapolation over the gap towards the reconstructed wing cover edge is also formed using a tangentially continuous extrapolation of a spline from the leading edge surface points. The step height is measured by using the measurement tool of the CAD software as the vertical distance between leading edge tangent end reconstructed wing upper cover edge.
The points used to create all splines are chosen manually to obtain an extrapolation line that is not only tangentially continuous to the end of the spline, but also matches the imaginary tangent of the surface points using engineering judgement viewing the relevant section from different perspectives.

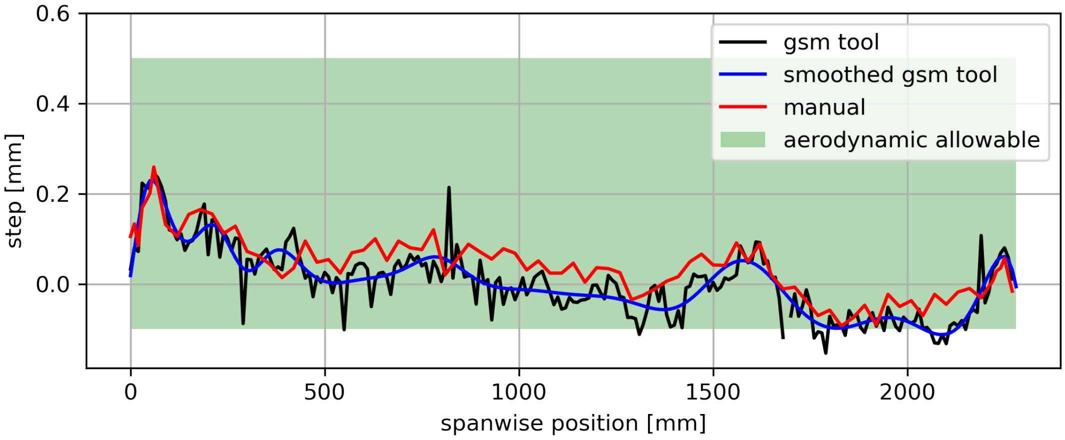

FIG 5. Results for ground loads

In case of the leading edge, this has a significant influence on the results, as the points are somewhat scattered in their plane due to measurement accuracy or may include parts of the forward facing gap wall. Combined with the distance the extrapolation line bridges over the gap and the small magnitude of the step heights that is to be measured, inclusion or exclusion of certain points can multiply the measured step height. As a means to self-check and to avoid biased spline creation, the change in the angle between the wing cover and leading edge tangent was continually observed to not make unexpected large changes while doing the spline creation section by section.
According to the generic steps described in Tab. 1, the step 2 is not applicable for the manual approach, since it is made by the user intuitively. Step 1 takes around four hours for a data set of a deformation state to be loaded in CATIA, for the macro was not capable to handle all sections' points in one import cycle. Around 10 sections have been imported at a time. Steps 3-5 can be considered one step in the manual approach, with 4 equivalent to the iterative approach of applying engineering judgement. The mean duration for the spline and tangent creation and step measurement of a single section is about eight minutes in this approach.

5. RESULTS AND DISCUSSION

To verify the automatic determined results, a comparison with the manual approach is performed. The results of the gap-step-measurement (gsm) tool and the manual evaluation of the measurements are shown in Fig 5. The results of each step height is plotted over the span wise position. At each 10 mm a cut is provided by the optical measurement software.
The green area defines the allowable region for step height in laminar flow. Besides the raw data (black), a smoothed spline (blue) shows the trend. Finally the manual evaluated results are shown in red.
Less than 1 % of the automatic determined values are omitted, because they were obviously wrong and out of a bound set to ±0.3 mm.

On the edges, there is a very good agreement with the manual evaluation. This is caused by the very high stiffness in this region due to ribs. In between this ribs a slight mean offset of 0.0342 mm exposes. The total trend is in very good agreement with the manual evaluation.
The differences are a result of different number of points used for the generation of splines. The feature detection and identification of the correct spline for a structural element is challenging, but the errors are small and negligible in mean. In the manual approach, some points at the edge are omitted, which lead to different splines and step heights. This manual tuning was done by engineering judgement but is hard to reproduce.
In summary an automated tool is presented, which allows an automated, fast and reproducible analysis of step heights over a gap. The approach is verified against a manual evaluation and increased the evaluation speed by a factor of 9600.
The reproducibility is very important for comparison of different measurements. Furthermore, fast evaluations enables the assessment of measurements on site and open the possibility of real time assessment during the assembly.

AUTHOR STATEMENT

S. Dähne: Sofware development, visualization, writing. O. Steffen: Project management and organisation, design and test application, investigation and writing. J. Kosmann: Optical measurements, providing pre-processed data, test application and writing. C. Hühne: Review & editing, Supervision, Project administration, Funding acquisition

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