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BLADE - Natural Laminar Flow Flight Testing

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Abstract

Current design methods for Natural Laminar Flow (NLF) application to a large passenger aircraft wing are predominantly based on results from a combination of dedicated Wind Tunnel tests, and Flight Test campaigns with partial NLF application. Whilst both approaches are invaluable in proving the maturity of technologies, each provides unique challenges when exploiting results to inform future design decisions. Wind Tunnel testing suffers from small model scales especially when testing in high Reynolds numbers facilities to achieve relevant Reynolds numbers (in excess of 20 million for typical short range aircraft). With a model scale of 1:11 typical, imperfections which could cause unwanted transition on a full-scale aircraft become too small to model and contaminants in the tunnel airflow can also prove problematic. Flight Testing can be prohibitively expensive if significant modifications to aircraft structure are required, meaning that historically testing has been limited to either aircraft tail surfaces, or lightweight manufactured gloves affixed to the wing surface to alter the aerodynamic profile. These have limited span and are constrained by the geometry of the underlying wing.

In order to address this, and obtain a clear understanding of the feasibility of an NLF wing on a passenger aircraft, the “Breakthrough Laminar Demonstrator in Europe” (BLADE) aircraft was conceived under the Smart Fixed Wing Aircraft project framework of the Clean Sky consortium. The aim of the BLADE aircraft is not only to provide aerodynamic data for NLF on a near full-scale section, but importantly to do so with a realistic internal structure. The basis for the experimental aircraft is an A340-300 Flight Test aircraft from which the outer wings were replaced with carefully designed NLF panels of lower sweep and nine metres span. The right-hand panel uses a current industry standard approach of separate leading edge and upper cover panels, whereas the left-hand wing – of identical aerodynamic design - features a single piece leading edge and upper cover. It is worth noting that whilst Airbus have provided the airframe for the project, the design, manufacture and integration of the various parts of the demonstrator have been the result of considerable work undertaken by a large number of the Clean Sky partners.

The aircraft has undergone an extensive flight test programme aimed at assessing both the feasibility, and industrialisation, of NLF technology on a representative platform. The considerable instrumentation installed and quality of the data received not only allows evaluation of the laminar extent across a range of flight conditions but also how the specific structural response influences the stability of the laminar boundary layer.

Correlation of data from a range of different test instrumentation is providing a comprehensive analysis of the sensitivities of NLF, demonstrating the effectiveness of the BLADE platform. For example, by correlating any features identified in pressure distributions with both global and local deformation measurements relating to the in-flight surface, an unprecedented assessment of the attainability of NLF on an industrially representative design can be performed. As a result, the BLADE demonstrator is not simply a tool for assessing the performance benefits of NLF but also the influence of shape and manufacturing techniques on the resulting surface.

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Keywords: Laminar Flow, Wing Design, Testing.

1. Background

Laminar and turbulent boundary-layers are fundamental aspects of attached fluid flow around bodies. Subject to freestream and attachment line turbulence levels, the boundary-layer on the wetted surface will start off laminar, implying a favourably thin boundary-layer with low surface skin friction, so long as the laminarity remains stable. However, in the Natural Laminar Flow (NLF) case with no external interventions such as surface suction or cooling to prolong the stability of the laminar boundary-layer, the laminar state cannot be maintained indefinitely. After a given distance - dependent on the flow Reynolds number but potentially much shortened by surface imperfections or adverse pressure gradients - the flow will transition to turbulent over a short distance with accompanying significant increases in the boundary-layer thickness and skin friction level.

1.1 Interest in Natural Laminar Flow for Aircraft Applications

Modern transport aircraft have typically been designed assuming turbulent flow in the boundary-layers over the majority of their wetted surfaces. This is particularly the case for airliner wings, where a combination of high chord-based Reynolds numbers and high leading edge sweeps – selected to manage compressibility drag – creates an adverse environment for delaying the transition of the boundary-layer from laminar to turbulent such that the flow can easily be turbulent right from the leading edge attachment line.

On this basis, a very high level of aerodynamic efficiency has been achieved in the latest transonic transports thanks to a combination of factors including evolutions of supercritical aerofoil design technology, significantly improved complex configuration simulation methods, and resulting improvements in the integration of junctions, fairings and latest generation turbofan technology.

However, in order to take the next steps in fuel and environmental efficiency as targeted by Airbus and the European Commission’s Flightpath 2050 Vision for Aviation, further improvements in the aerodynamic design standard will be required – along with, of course, improvements across the engineering and manufacture of the aircraft through to how it is used in service. Considering lift dependent drag, various avenues have been and continue to be studied from camber optimization, through tip devices (wing tip fences and sharklets) and onwards to span extensions enabled by new structural and load control technologies. However, reducing lift independent drag for a turbulent aircraft is challenging, especially once the payload and high lift requirements have constrained the extent to which wetted area can be reduced.

In this context, designing wings capable of operating with substantial areas of laminar boundary-layer flow is a key aircraft level opportunity, providing significant skin friction and hence lift independent drag reductions; for an aerofoil surface where the transition to turbulent flow can be delayed beyond approximately 60% chord, the reduction in the local friction may be up to 50%. This in turn offers the opportunity for fuel burn reductions in the order of 5% at aircraft level for long runs of laminar flow on the wing upper surfaces, with still further benefits if other areas of the aircraft (e.g. the nacelle inlets and horizontal and vertical tails) can also achieve useful runs of Natural Laminar Flow (NLF).

It is reminded at this point that NLF aerofoils are not a new phenomenon – they were first developed in the 1930s – nor is the role of NLF in the wing design process unknown – laminar boundary-layers may often be encountered in sub-scale wind tunnel testing. However, the constraints they impose on the design of the aircraft and its pressure distributions and manufacture, combined with their potential sensitivity to in-service contamination, have so far limited the commercial exploitation of NLF.

1.2 Laminar to Turbulent Transition Mechanisms

Three key transition mechanisms are of primary interest in the preliminary aerodynamic design of a wing – Attachment Line Transition (ALT), Crossflow transition (CF), and Tollmien-Schlichting transition (TS).

- Attachment Line Transition is typically associated with wings of relatively high sweep, to some extent compounded by the leading edge shape and pressure distribution. These factors result in a turbulent attachment line along the wing span removing any realistic prospect of achieving NLF further aft on the aerofoil profile. Avoiding these factors typically constrains wing sweep – with implications for aircraft design Mach number – and leading-edge shaping with potential implications for low speed behaviour.

- Crossflow transition is driven by the amplification of crossflow instabilities encountered in particular on swept wings. The instabilities can be managed by suitable tuning of the wing pressure distribution especially in the leading edge region – or, alternatively and where this is possible, by minimizing wing sweep potentially at a cost in wave drag.
- Tollmien-Schlichting transition is driven by instabilities resulting in particular from the chordwise pressure distribution, with regions of adverse pressure gradient tending to rapidly destabilize the boundary-layer and drive transition to turbulent flow. As with CF, this results in constraints on the type of pressure distribution which can be defined for an NLF wing – and indeed a tendency to strong shockwaves and hence undesirable wave drag characteristics given the need to manage CF and TS instabilities simultaneously.

Having mentioned these three instabilities of concern in the conceptual aerodynamic design of a wing, it should also be noted that instabilities can occur due to surface imperfections coming from the detailed design of a laminar wing or its contamination in service. Large imperfections may cause immediate transition of the boundary-layer – referred to as bypass transition. For smaller imperfections, bypass transition may be avoided but only at the cost of amplifications of CF and TS instabilities, with the result that a shorter NLF run hence less drag benefit will be seen than potentially achievable for the 'ideal' profile.

1.3 A Very Brief Review of Past Large Scale Natural Laminar Flow Investigations

Following research work in particular by the National Advisory Committee for Aeronautics (NACA) in the United States in the 1930s, the first mass-manufactured aircraft with nominally laminar flow wings were the North American P51 Mustang and Bell P63 King Cobra; however, studies of the former by the NACA and the latter by the British Royal Aeronautical Establishment indicated that neither would in fact achieve significant performance benefit in 'as delivered' condition due to surface irregularities such as surface waviness. Subsequently the RAE was able to demonstrate long run laminarity beyond 50% chord on a King Cobra, but only after substantially rebuilding its wing to an exacting and effectively impractical finish standard. Similar observation around the need for exacting surface quality emerged from tests around the same time on a Hawker Hurricane fitted with a laminar wing and indeed during the development of the Supermarine Spiteful [1] – which exhibited performance degradations for surface imperfections as small as 50 microns. On this basis and given the manufacturing technology of the time, NLF research assumed a lower profile for a period after the 1940s as the focus of the aerospace industry moved to the exploitation of jet propulsion.

Only in the 1980s did major flight testing of NLF wing solutions resume. In the United States, activities included the testing of NLF gloves on the F111 TACT aircraft, a Boeing 757 and the F14 VSTFE, while glove experiments were completed in Europe on DLR's VFW614 "ATTAS" and a Fokker 100 in 1992 [2,3,4,5]. These activities have served to provide useful data up to high Reynolds numbers and high wing sweeps for the calibration of NLF prediction methods in free air under flight conditions – but only for specially manufactured test items of limited spanwise extent.

The 1980s also saw the first flights of a number of executive jet sized aircraft with wing designs targeting extents of laminar flow in operation – marking the first step forward in major NLF wing operations since the 1940s and the high water mark of the potential of NLF to date.

Further information on several of the tests mentioned above is given in [6].

2. Basis for the BLADE program

Following on from work on NLF in the 1990s at Airbus, which accompanied the DLR "ATTAS" and Fokker 100 flight tests, a renewed program of research began in 2006 to review the feasibility of NLF for future Airbus large passenger aircraft wing designs as one contribution to achieving the ACARE Vision 2020 Environment goals for European Aviation. The work began relatively traditionally in aerodynamic design terms, with numerical studies supported by wind tunnel testing.

2.1 Numerical capabilities

The core aerodynamic tools used were the same as those used for turbulent wing design - strongly based on the DLR Tau Reynolds Averaged Navier-Stokes (RANS) Computational Fluid Dynamics (CFD) code coupled to a transition prediction capability developed principally by Schrauf [7].

The transition prediction capability consists of a boundary-layer code Coco which computes a local boundary-layer development based on the local pressure distribution provided by the RANS code, and a linear stability code Lilo which computes CF and TS amplification 'N' factors along the chord for a range of disturbance frequencies – with transition predicted at the point where the combined CF and TS N-factors cross a CF/TS envelope inferred from the earlier ATTAS and Fokker 100 flight tests at multiple flight points of differing pressure distributions. Since the envelope represents a conservative interpretation of the flight tests, the overall capability should ensure designs capable of at least the predicted degree of NLF in general in the absence of surface imperfections or contamination.

2.2 Experimental capabilities

The design studies were accompanied by high Reynolds number tests in the KRG research wind tunnel and in particular in the European Transonic Windtunnel (ETW) near Cologne in Germany. As with the numerical capabilities, the latter represented the use of a simulation means familiar and in standard usage for the development of turbulent wings but with additional means - in the experimental case, Temperature Sensitive Paint [8] - to allow the detection of the transition position on the wing.

Key steps in the testing have included the calibration of the ETW N-factors thanks to a calibration wing tested as part of the Telfona research project [9,10], subsequent tests on a small number of clean wing designs confirming recurring good agreement between numerical and experimental simulations, and a number of tests where mechanically- or hydraulically-generated shape deformations have been tested to assess the sensitivity of NLF to surface imperfections. A recurring challenge in the testing, however, has come from model contamination caused by tiny particles in the highly controlled tunnel flow – limiting the useful Reynolds number range and serving again to emphasise the importance of mastering surface quality in order to unlock the benefits of NLF.

2.3 BLADE objectives

Early in the wing design research, based on the findings of the wind tunnel testing program but also to achieve Technology Readiness Level 6, the need was identified to take NLF into full scale flight. Specifically:

- To demonstrate the viability of the Natural Laminar Flow wing concept at operational conditions and large scale to contribute to proving technical and industrial maturity for TRL6
- …"De-risking" NLF technology via full scale manufacturing & flight testing
- … Underpinning the prediction of the Natural Laminar Flow benefit potential at aircraft level

These became the overall objectives of the BLADE program, with implied requirements that the resulting flight test program should:

- Deliver a Reynolds number as close as possible to that of a realistically-sized short-medium range NLF passenger aircraft
- Consider a representative 3D wing shape including incorporating sweep, taper and twist
- Be of industrially representative and viable construction from an aerospace industry perspective
- Carry extensive aerodynamic instrumentation and support extensive and detailed shape measurements both on the ground and in flight
- Provide data based on real atmospheric conditions
- Enable a sustained program of flights

With reference to section 1.3, it may be noted that these requirements represent a level of ambition in the NLF area not seen since the 1940s – but now for significantly larger and faster aircraft.

3. Laminar Panel Concept and Design

3.1 Flight Test Concept

The approach selected to meet the BLADE objectives involved identifying one of the NLF wings developed during the NLF wing design studies at Airbus and then a host aircraft capable of carrying such a wing and demonstrating its cruise aerodynamic characteristics at matched flight conditions, acceptable cost and with as few compromises as possible.

A number of potential vehicles were considered to provide the basis for the testing, including the idea of 're-winging' either a large drone or military trainer, or replacing a large part of the outer wing of an Airbus A320 Family aircraft. However, the selection converged rather quickly on the use of an existing Airbus A340-300 flight test aircraft (MSN 1) with laminar panels replacing the outer wing panels and offering advantages as follows:

- The presence of spar joints just outboard of the outer engines, easing the substitution of alternative panels over an appreciable outboard spanwise extent

- The ability to carry a physically (dimensionally) large outer panel but with the panel only representing a small proportion of the overall flight test aircraft – allowing the minimization of modifications to the aircraft high lift, fuel, propulsion systems and landing gear
- The existing knowledge and instrumentation of the flight test aircraft, including the scope provided by the aircraft size to add additional instrumentation if needed
- A flight envelope covering the full range of typical short-medium range aircraft operations in terms of Mach number and altitude, and an endurance capability allowing long duration flights if required
- The ability to operate the aircraft on a 'permit to fly' basis.

The overall aircraft arrangement is shown in Figure 1.

Figure 1 – BLADE aircraft, with the NLF panels apparent outboard of the outer engines.

3.2 Aerodynamic Sizing, Design and Integration of the Flight Test Panel

As might be expected, it was wished to use the BLADE test to test as much of the parent NLF wing design as possible, with the exception of those regions of the parent wing dominated by wing root and tip effects; that is, effectively, to graft the aerodynamic intent from the parent directly across onto the flight test vehicle. However, it was immediately clear that the simplistic approach of carrying across the parent wing geometry one-for-one onto the A340 outer wing would not be viable. This would have led to:

- A chord mismatch at the junction between the NLF and host A340 wings, requiring fairings and locally dis-adapting the aerodynamic behaviours of both wing portions
- Significant loads increases at the structural joint, exceeding the local structural capability, due to the larger area of the NLF wing compared to the original A340 outer wing and the reduction in sweep affecting torsional loading
- A general dis-adaptation of the NLF panel pressure distributions and hence laminar characteristics even without changing the local aerofoil shapes at all due to tip induced incidence and 3D transonic effects

The aerodynamic design of the panel and its integration on the A340 outer wing join therefore involved a series of careful shape design and trade-off activities all aimed at maximizing the upper surface area over which pressure distributions and laminarity representative of the parent wing would be observed. In particular:

- The spanwise portion of the parent wing which was to be flown was adapted, including the adoption of an 85% scaling factor, to manage the loads due to panel planform area
- In addition, the aerofoil profiles were adapted by careful thickening to reduce their inherent lifting capability while maintaining unchanged upper surface pressure distributions
- The induced incidence effects of the tip were compensated out by adaptation of the panel twist and aerofoils
- A large 'Wing Aerodynamic Fairing' was developed to separate and reduce the aerodynamic interference in particular from the A340 wing onto the NLF panel, to enable NLF as far inboard on the panel as possible (with help from local aerofoil adaptations), to cover structural attachment fittings, and to provide space for some of the NLF panel instrumentation. The fairing included detailed shaping on both its inboard and outboard sides for local flow treatment purposes
- A diffusion zone to fill in the triangle between the spar joint (oriented normal to sweep) and the Wing Aerodynamic Fairing (oriented line of flight)
- A tip pod was provided primarily to allow NLF to be developed as close to the wing tip as possible – as with the Wing Aerodynamic Fairing, supported by careful local adjustments to the local aerofoils

The resulting shapes – shown in Figure 2 - went on to be manufactured by a range of separate partner organisations, with their eventual and successful integration on the aircraft representing a significant milestone.

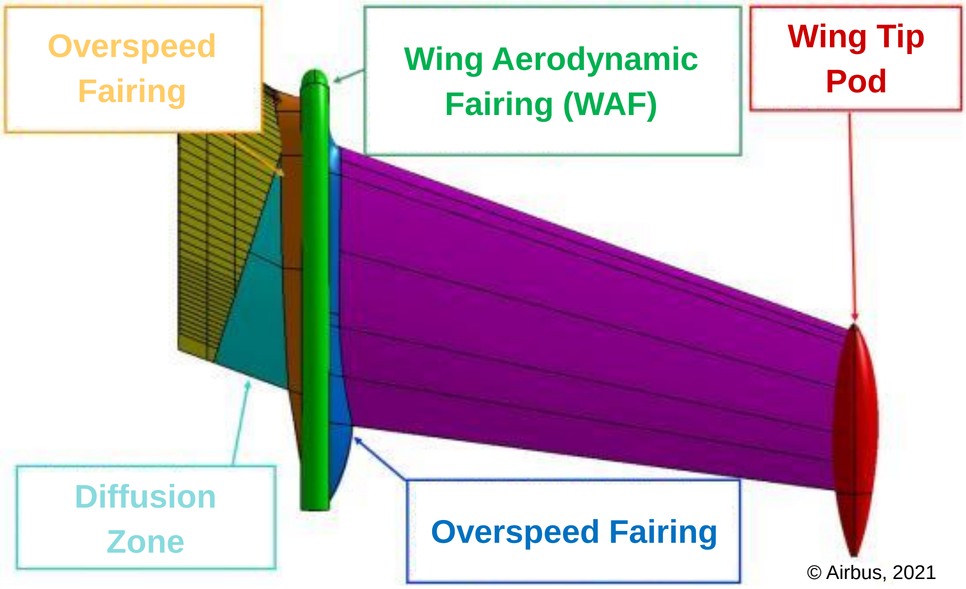

Figure 2 – BLADE NLF panel arrangement fitted to A340 outer wing

3.3 Panel Manufacture Concepts

The aerodynamic design work described in the preceding section was performed entirely symmetrically – that is to say, with identical design intent port and starboard. However, the project had already decided to adopt quite different manufacture approaches on each side for research reasons but also offering some risk mitigation in the event of significant underperformance (which was not eventually observed) on either side. The arrangements are shown schematically in Figure 3.

For the port wing panel, a relatively novel construction approach was adopted – consisting of an integrated (one piece) composite cover and fixed leading edge with additional internal structure elements also integrated to reduce the fastener count (but conversely, also the scope for installation adjustment) of the final panel. One clear aerodynamic advantage offered by this arrangement is the lack of any wetted joint between fixed leading edge and upper wing box cover.

For the starboard panel, the construction was more conventional and featured a composite upper cover with a metallic leading edge – the resulting assembly featuring a joint simultaneously presenting a risk from an NLF perspective but also a margin for very fine adjustment to ensure the best overall shaping of the leading edge as fitted to the aircraft.

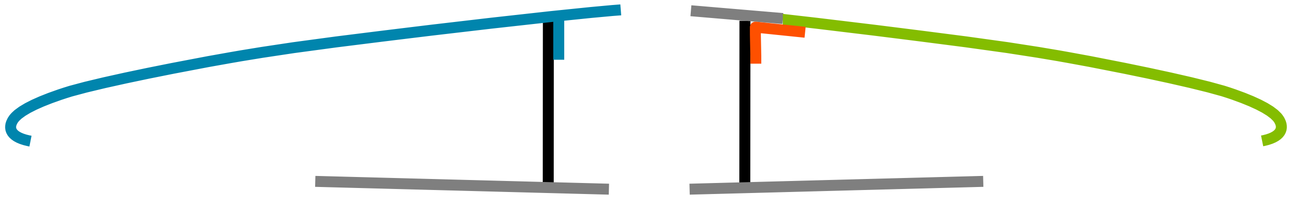

Figure 3 – Schematic of BLADE NLF panel manufacture approaches:
left - port wing (Saab), right - starboard wing (GKN Aerospace).

4. Flight Test Preparations

Once the NLF panels had been designed, the focus of the aerodynamic studies moved to ensuring the flight clearance of the BLADE aircraft and to determining the exact scope of the flight testing to be conducted. In particular, the latter involved identifying the key flight test points to be targeted for the clean wing – both as an aerodynamic entity in itself and as the reference for surface imperfection flights – and completing the definition and integration of the flight test instrumentation required to characterize the panels' NLF behaviour fully.

4.1 Development of the Flight Test Envelope

Whilst the aerodynamic design of the NLF panels ensured the panels represented the pressure and NLF behaviour of the parent wing at and around its design point, it was inevitable that the BLADE arrangement would not ensure identical pressure and NLF behaviour away from the design point. A significant and dedicated numerical investigation of the BLADE aircraft was therefore conducted ahead of the BLADE flight testing in order to assess how the stability of the laminar boundary-layer would vary across the core flight envelope of the aircraft.

Thanks to this investigation and in particular the N-factor plots provided by the Tau/Coco-Lilo CFD, it was possible to establish a number of batches of flight test points – combinations of Mach number, angle of incidence and altitude – with each batch predicted to exhibit different transition mechanisms as denoted in Figure 4. These batches would thus provide opportunities to check the validity of the CFD suite for the relevant mechanism. The associated test points would also be flown later in the flight test campaign with artificial surface imperfections installed to enable the assessment of the sensitivity of the laminar runs and transition mechanisms to imperfections of varying size.

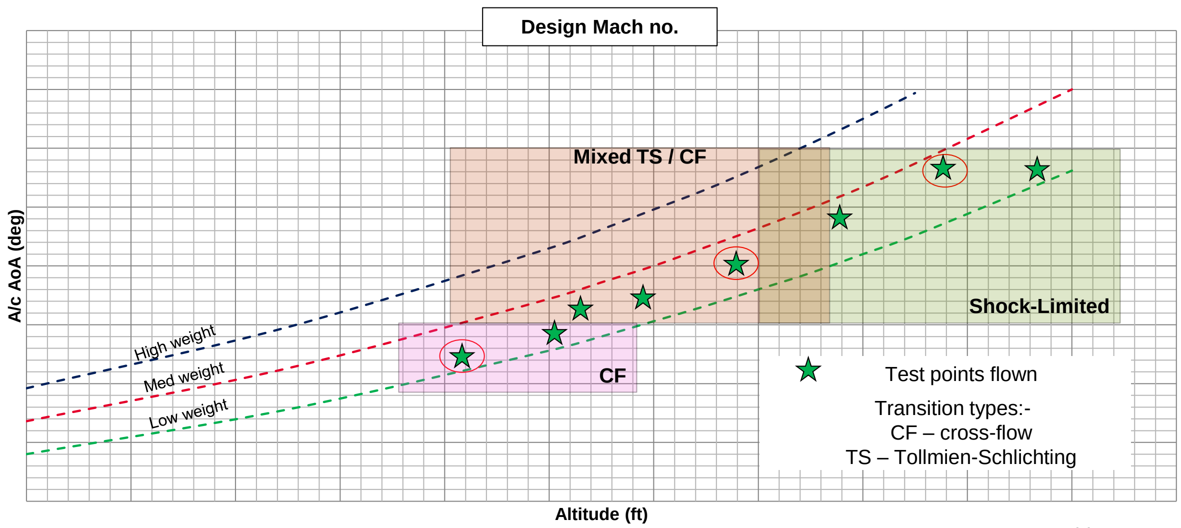

Figure 4 – Approach to design of flight test envelope and test points.

4.2 Instrumentation of the Flight Test Aircraft

Extensive instrumentation was installed on the BLADE aircraft, thanks to the lessons from previous flight test campaigns, with the aim that all data points should be fully qualified for future analysis; consideration was given here not just to standard aerodynamic measurements but also to the flight conditions, the global deformation or the wing and also the exact size of any surface imperfections that might be relevant to a particular flight. Key aspects of the instrumentation included:

- The standard and extensive instrumentation of the A340 flight test aircraft
- Infra-red cameras provided by DLR and mounted in the tip of the vertical tailplane to visualize the transition position on each of the NLF panels
- Hot films – also provided by DLR - installed at key positions on the panel surfaces to capture the local boundary-layer state
- 5 dense rows of tappings – 3 in the right hand wing and 2 in the left hand wing – to measure the local panel pressure distributions
- Internally mounted inclinometers to measure the wing twist along the span, both for the main A340 wing and the NLF panels
- Arrays of linear displacement transducers mounted within the NLF panels to analyse local surface deformations resulting in, for example, waviness
- A reflectometry system as an additional measurement system for local surface deformation

These flight measurements were complemented by ground measurements including a detailed scanning of the shape of the NLF panels and exhaustive measurements (thanks to press-on moulds inspected away from the aircraft) of all surface imperfections applied and observed during the flight testing.

4.3 Preparatory Testing

A mixture of wind tunnel and flight tests was performed to support the BLADE flight testing even before the BLADE panels were fitted and ready for flight on the A340.

A first and key concern involved ensuring appropriate behaviour of the BLADE aircraft at low speeds – at take-off and when landing. Significantly reduced performance was expected for these cases compared to the basic A340 aircraft first due to the inferior low speed properties of the NLF aerofoils themselves and second since no high-lift devices were included in the NLF panels to match the slats fitted to the basic aircraft. Wind tunnel testing of the BLADE configuration was therefore conducted as well as flight testing of the A340 with slats retracted; these tests confirmed the expected behaviour of the aircraft and led to the definition of high take-off and landing speeds for all the subsequent flight testing with slats not deployed anywhere along the span in order to ensure a stall pattern in which flow separation on the NLF panels occurs after the main wing stall. Otherwise, critical loss of roll control (with the ailerons installed on the NLF panels) or unacceptable pitch-up characteristics may have been experienced.

Other tests conducted in this preparatory phase included

- Testing of the basic A340 at the Mach numbers and angles of attack targeted for the NLF panels in order to confirm the benign behaviour of the basic aircraft at the resulting very non-standard (for A340) operating points
- Testing of specific instrumentation – for example, checking the operability of the infra-red camera system at different levels of natural illumination – making use of both A340 and also A320 flight test aircraft
- Testing on an A320 of the viability of taking off with a paper cover over the wing leading edge to protect it from insect contamination, and then using a simple system to shed the cover safely and effectively at altitude. This testing was successful such that the paper cover technique became standard for all the subsequent A340 NLF test flights.

5. Flight Test outputs and clean wing analysis

The total BLADE test database corresponds to 61 flights and a total of 184 hours of data, from which only selected data can be covered here. This paper will focus on the clean wing reference flights and provide insights into the surface imperfection flights; however the overall test program also covered flight envelope opening flights, investigations of off-design characteristics and investigations of Krueger shielding, receptivity and operational topics such as cloud encounters. The BLADE database is currently the subject of a significant collaborative data analysis amongst the CleanSky 2 partners - in particular Dassault, DLR, ONERA and Saab in addition to Airbus.

5.1 Typical Test Outputs

One of the key objectives for the clean wing reference flights was to carry out an N-factor calibration exercise for comparison with the results of the earlier DLR VFW614 “ATTAS” and Fokker 100 tests. Figure 5 shows representative data from the flight testing corresponding to the key inputs for this assessment – namely a pressure distribution on one of the NLF panels together with an infra-red picture from which an assessment of the transition position can be performed.

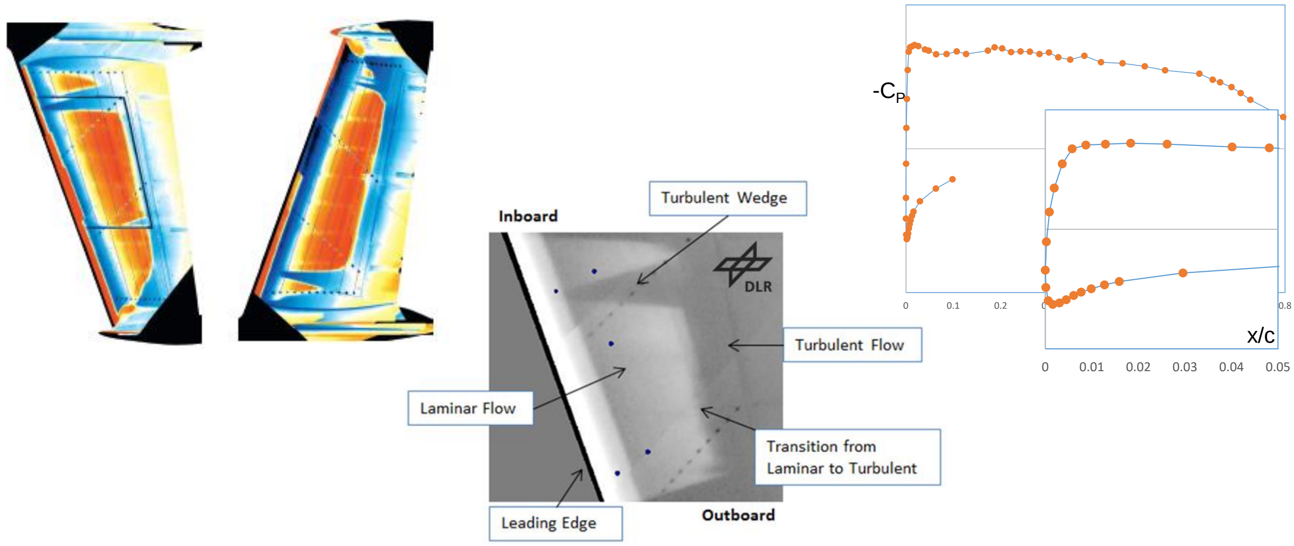

Figure 5 – Typical flight test outputs: left processed infra-red images showing transition on the NLF panels, centre an alternatively processed infra-red image courtesy of DLR and annotated with key flow features, and right representative pressure distributions

Of note is the very high density of the pressure measurements in the critical leading edge region of the aerofoil – providing a good basis for inferring the local effective sweep of the panel and a smooth pressure distribution as inputs to the transition assessment. The infra-red pictures are by themselves more qualitative, requiring the development of image processing techniques to ensure a consistent assessment of the transition position from one image to another.

Immediately apparent is the success of BLADE in delivering long runs of laminar flow on both the NLF panels – an achievement secured in the earliest flights and secured across wide ranges of operating conditions throughout the flight test program.

5.2 N Factor Calibration Process

The N factor calibration process made use of the same Coco-Lilo transition prediction capability used for laminar wing design work at Airbus and described in section 2.1. Whereas for transition prediction purposes the tools compute the development of the N-factors along the aerofoil chord and then predict the transition position according to the point where a given N-factor element is exceeded, this process is in principle simply reversed for N-factor calibration purposes.

Turning then to the types of flight test data as already highlighted in Figure 5: knowledge of the pressure distribution from the flight tests and the local geometry based on the aircraft inspection (corrected if necessary for measured waviness effects) allows running of the Coco-Lilo tools in standalone mode (no longer coupled to CFD). The output provided includes the values of the CF and TS N-factors as a function of the local non-dimensional chord. Based on a knowledge of the flight test measured transition position, the relevant critical N-factors can then be read off from the Coco-Lilo output. Repetition of this process for multiple flight test points can then be used to identify a critical N-factor envelope in much the same way as was done using the data from the DLR VFW614 “ATTAS” and Fokker 100 testing.

5.3 Outcomes of N-Factor Investigations

Figure 6 provides a visualization of the findings of the BLADE clean wing testing based on the ‘DV4’ pressure tapping station toward the inboard portion of the left hand NLF panel (the location will be shown later in Figure 9). The left hand depiction – indicating the transition position predicted pre-flight as a function of the Mach number and W/δ (weight divided by density ratio) – is compared with an equivalent depiction of the transition position inferred from the flight test pressure and infra-red data.

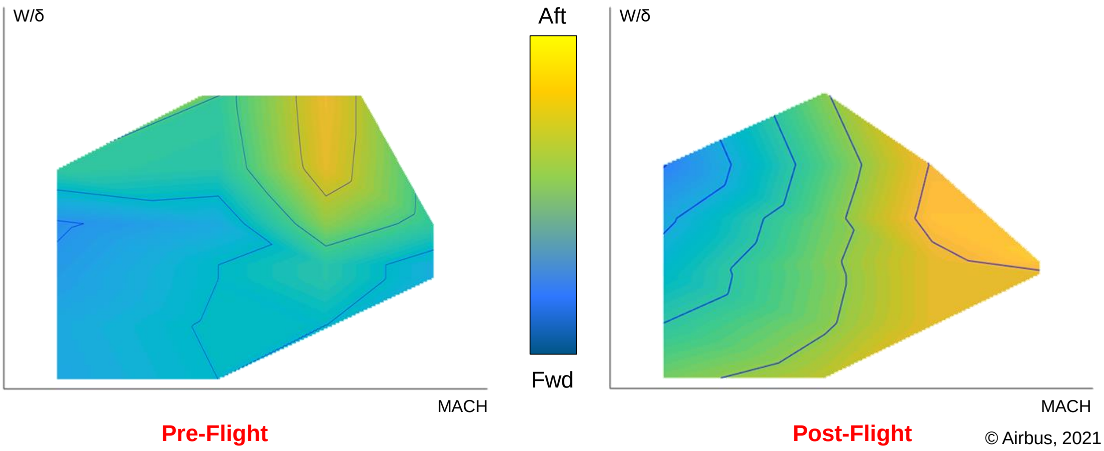

Figure 6 – Transition position at the DV4 pressure station as a function of flight conditions: left as predicted, right as observed in flight

As would be expected given the past calibrations of the prediction tool chain, the two images are qualitatively similar but with slightly further aft transition apparent in the flight test data – and indeed this aligns to the slightly conservative interpretation deliberately applied to the DLR VFW614 "ATTAS" and Fokker 100 results for the purpose of supporting robust design using Coco/Lilo.

Mapping of this information across to an N-factor calibration as described in section 5.2 yields the results shown in Figure 7. As might be expected given the favourable NLF runs observed in the BLADE flight testing, it is seen that the BLADE N-factors (colour symbols, the different colours denoting different Mach numbers) all sit outside the envelope from the previous tests (black dashed line) and indeed the data points from these tests (black crosses). In particular, BLADE suggests higher CF N-factor margins than seen in the previous testing, whereas the TS factors are much more in family with the older tests. Note that the BLADE data points are accompanied by uncertainty bands relating here to uncertainty in the assessment of the transition position – but that the richness of the BLADE database also extends to time accurate pressure distributions which provide a means to further understand the N factor uncertainty coming from the pressure measurements.

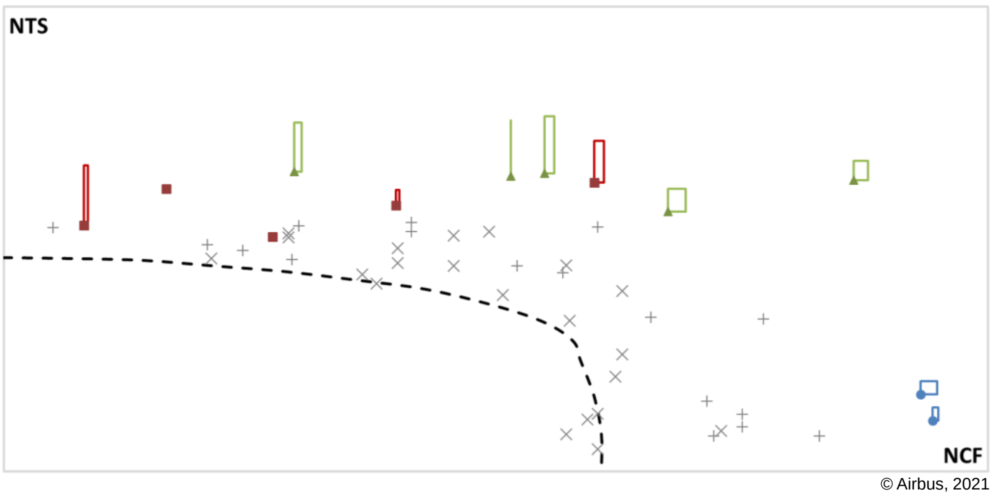

Figure 7 – N factor calibration inferred from flight test pressure and transition information recorded at the DV4 pressure tapping station

Figure 8 shows the same analysis applied to the 'DV5' pressure station, further outboard on the left hand wing. Here the results from BLADE (again in colour) are much more in family with the results from the previous tests for both CF and TS.

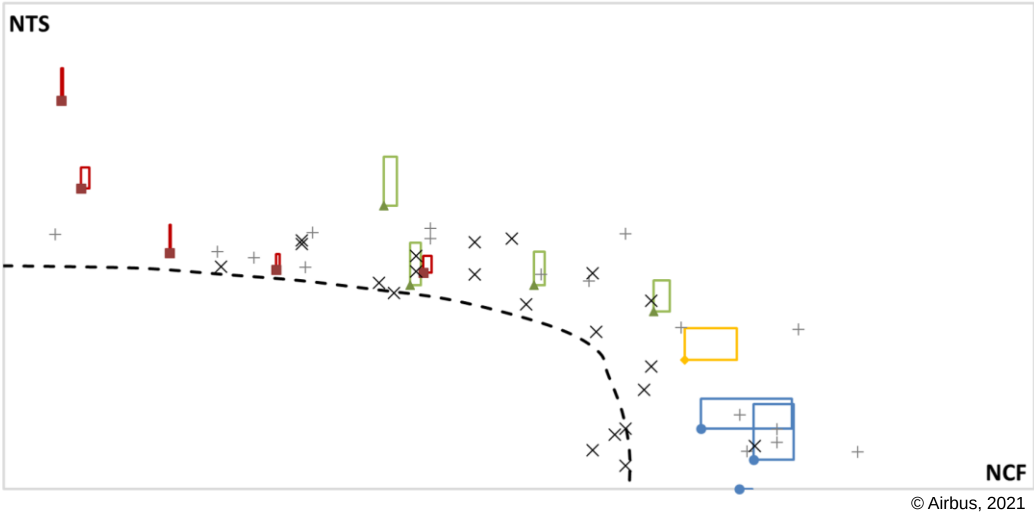

Figure 8 – N factor calibration inferred from flight test pressure and transition information recorded at the DV5 pressure tapping station

These results and many others continue to be studied amongst the BLADE partners, supported by the use of a much wider range of transition prediction tools and approaches. However, the analysis presented here tends to confirm that the key tools used at Airbus for transition prediction do indeed provide slightly cautious but not unrealistic predictions of the laminar runs achievable on a real aircraft – as intended. Both the BLADE and past flight tests provide a basis for using slightly higher N-factors to give the best but not necessarily conservative assessment of NLF benefit. However, the database analysed so far does not provide a consistent basis for adopting much higher N-factors – and in so doing, setting aside the data from the earlier flight tests.

6. Flight Test investigation of Imperfections

As discussed in section 1.2, the earliest investigations of aircraft NLF effectively came to a near halt given the challenges of manufacturing an aircraft of suitable surface quality to maintain laminarity. In spite of the progress in manufacturing capabilities since the 1940s, the ability to achieve the required standards remained a key concern with the resumption of major NLF design studies at Airbus in the mid-2000s. With an easement of the standards which might be inferred from literature essential for the efficient high rate manufacture of an NLF airliner, the detection of such easements was a key goal of the BLADE testing – BLADE offering a platform of unprecedented representativity for such studies.

6.1 Application of Surface Imperfections

For the purpose of surface imperfection testing, the BLADE panels were divided into a number of different spanwise sectors – each capable of carrying different imperfections during any one flight such that multiple imperfections could be tested at the same time as shown in Figure 9.

Surface imperfections were applied to the aircraft using a foil approach – that is, through the addition of thin layers of material whose thickness and/or edge dimensions provided the required imperfections. Recalling that the NLF behaviour was closely monitored on the panel upper surfaces only:

- Forward facing steps were produced by adding foils to the wing upper surface, starting at the desired chordwise step location and extending aft as far as necessary such that the aft facing step at the rear of the foil was positioned well aft of the expected natural transition position. Given the thickness of the foils, only minimal effects on the surface pressures were predicted away from the step locations
- Aft facing steps were achieved by applying foils around the NLF panel leading edge such that the termination of the foil on the upper surface provided the required step while the termination on the lower surface was inconsequential from an NLF perspective
- Discrete imperfections were achieved either by the direct addition of stickers to achieve positive protuberances, or of foils incorporating holes to provide negative protuberances (or dips) in the

surface

- Regions of waviness were achieved by adding foils with the required waviness integrated through variations in the foil thickness. As in the step cases, the terminations at the extremes of the resulting foils were positioned in far aft or lower surface locations of no significant consequence from an NLF perspective

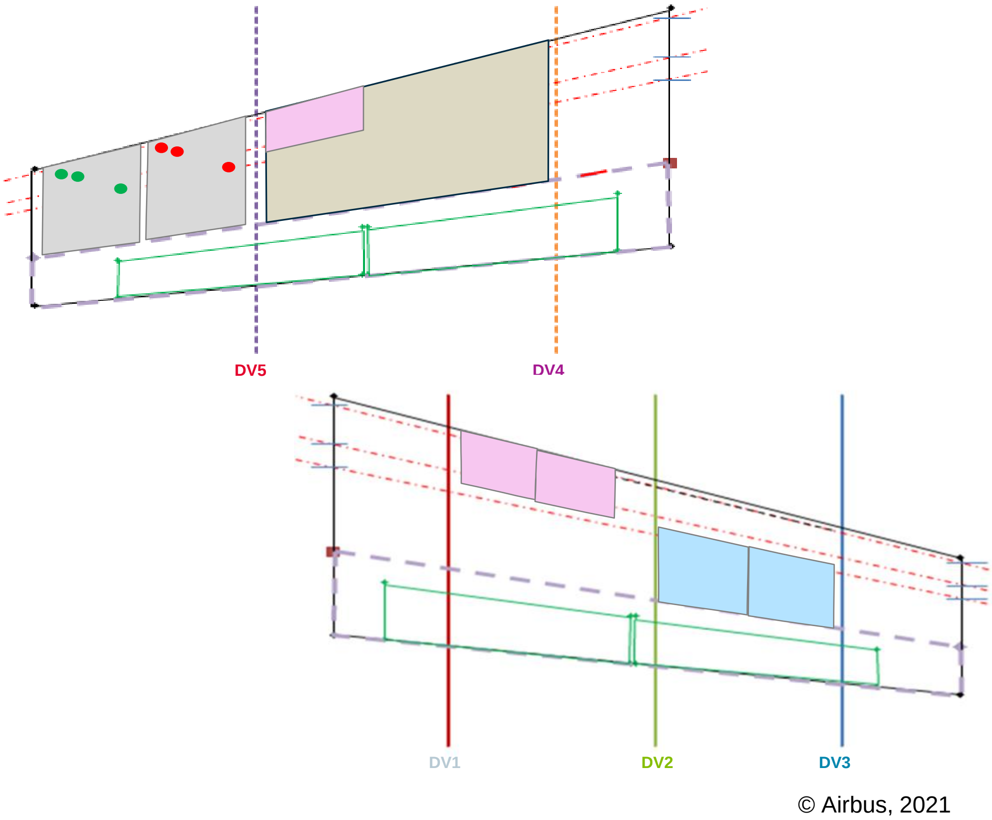

Figure 9 – Representative arrangement of imperfections and pressure tapping stations (DV1 to DV5) on the two NLF panels

In all cases, the imperfection foils were designed to achieve particular imperfection sizings but the foils were inspected in detail once installed on the aircraft such that all subsequent flight tests analysis could be based on the actual rather than nominal (designed) imperfection sizing.

6.2 Analysis of Flight Test Data

As mentioned previously, the BLADE flight test program was planned such that a number of test points were flown repeatedly – allowing for the assessment of surface imperfection effects in principle by comparing the same flight test points flown with and without imperfections installed (after allowing for day-by-day atmospheric variations).

The effects on the NLF stability – and implicitly drag benefit - were judged according to the resulting loss of laminar run. A colour coding was adopted to categorise the losses of laminar run – with green representing no particular loss, red a significant loss, and yellow an intermediate level of loss. A set of representative data for a particular wing station and applied imperfection is shown in Figure 10; the figure serves to illustrate that the raw trends seen were sometimes not clear cut, especially without considering the robustness of the reference clean wing flow and the associated transition mechanism.

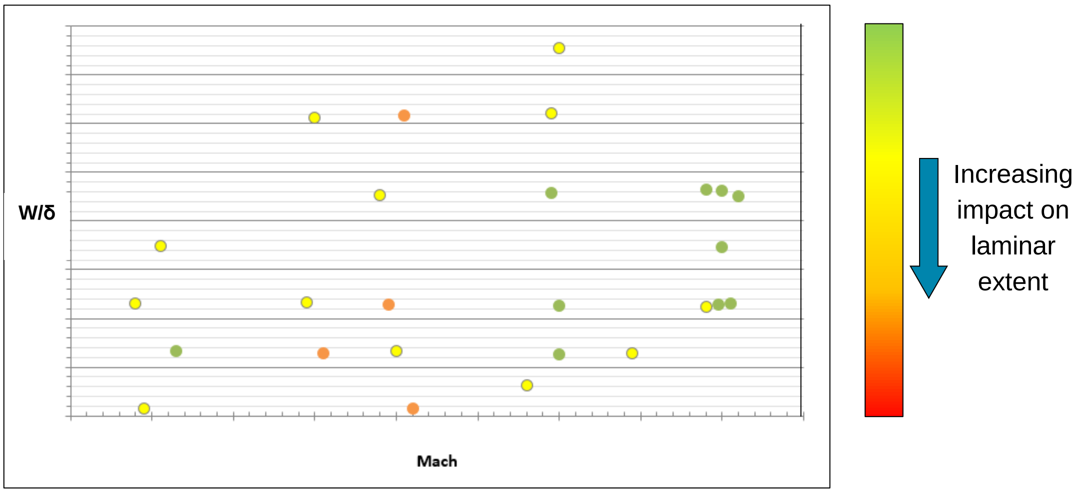

Figure 10 – Representative surface imperfection effects on NLF extent

For the purpose of avoiding the significant point by point detail involved in analyzing the complete database, a summary table for step effects is instead provided in Figure 11. The columns of the table denote different step heights; note that the actual step heights – which were selected based on preceding wind tunnel test and practicality considerations - are not presented for commercial sensitivity reasons. The cells contain green tick marks for cases where little effect on the transition position was observed, red crosses to denote cases where significant adverse effects on the laminar run were seen, and both ticks and crosses for imperfections giving a more mixed or scattered picture across the range of flight points considered. The table includes empty cells for cases which were not tested. Considering the table from left to right reveals the trend when going from large aft- to large forward-facing steps with smaller intervals considered for the aft-facing cases given their known greater criticality with respect to NLF stability. Considering the table from top to bottom shows the trend according to the positioning of the imperfections, with the top row corresponding to a forward percentage chord position and the bottom to a further aft chord station.

Position on chord	← Increasingly Aft Facing Steps					Increasingly → Forward Facing Steps								
Fwd		✗	✓✗		✓✗	✓✗			✗		✗			✗
	✗							✓✗				✓✗		✗
Aft	✗	✓✗	✓	✓	✓			✓	✓		✓	✓✗		✓✗

Figure 11 – Summary of imperfection flight findings for step imperfections

On this basis and considering first the top to bottom trends, it is seen that none of the applied imperfections proved inconsequential when positioned forward on the aerofoil profile – emphasizing the need for care when, for example, positioning erosion shielding forward on an NLF wing profile. By contrast, it is seen that the panels were able to tolerate the same imperfections much more easily when positioned further aft on the aerofoil, with no appreciable impact seen across a broad range of the imperfection heights tested. This finding is as expected given the greater thickness of the boundary-layer as a whole at the more aft step positions.
Considering the findings at the far left and right extremes of the table – corresponding to the largest step heights whether forward or aft facing – most of the cases show appreciable losses of laminarity, as might be expected. However, the results towards the centre of the table are much more favourable where the step heights are smaller. Again this finding is not surprising both from a simple physics perspective and considering the large amount of wind tunnel information which informed the selection of the flight test steps heights.
Even though it was not the aim of Blade demonstrator to collect airframe drag data (since the overall

aircraft layout was not fully representative of a production aircraft) some drag measurements were nonetheless accomplished to evidence the influence of contamination on the overall aircraft performances and complement the flow physics observations. The obtained results indeed fitted the expectations in terms of drag increase associated to loss of laminarity.

7. Conclusions

An overview of the objectives and content of the BLADE flight testing has been provided, together with an insight into some of the results secured so far from the analysis of the extensive flight test database. Key outcomes include:

- The successful achievement of long runs of NLF on a highly aircraft-representative pair of laminar panels operated at highly representative flight conditions
- The demonstration and validation of a number of flight test techniques and types of instrumentation with the potential for application to future NLF (and other) testing
- Validation of the desired behaviour of the standard Airbus laminar wing design tools
- Significantly increased confidence in our understanding of imperfection effects on NLF under operational conditions

The BLADE database represents a major asset for future NLF design and research investigations both for Airbus and amongst the BLADE partners. Key topics to be studied in greater depth include analyses to try to understand and reduce the scatter seen in the flight test analysis; the development of scaling techniques to carry the imperfection findings across onto other NLF applications; further work on insect contamination; and an improved understanding of the off-design behaviour of the aircraft including appropriate techniques to characterize this behaviour.

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9. Copyright Statement

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