ASPECTS OF AERODYNAMIC DESIGN OF NLF WINGS

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Summary

The way towards a “green aircraft” is driving a new effort to investigate the technology of natural laminar flow for the next smaller aircraft generation. A lot of research work had been performed by research organizations and aircraft manufacturers in the 1980s and 1990s mainly in the aerodynamic field. The current activities within the Airbus internal technology project LDA (Low Drag Aircraft) are linked in a close cooperation between the major disciplines of aerodynamic, structure and manufacturing to find a common solution on aircraft level.

The aerodynamic design of a NLF wing does not only determine the performance of the wing, it also defines the wing shape with allowable space for the Krueger device integration. To achieve natural laminar flow the surface quality of this wing shape is the driving parameter for the application of a NLF wing. The surface tolerance, formulated by the aerodynamic design, has a great impact on the structural design and the manufacturing process, which at least decides if the production is possible in cost and time.

The main focus of the presentation is on showing the effect of surface imperfections like waviness and steps on the stability behaviour of the boundary layer and the definition of the allowable surface tolerances. After the study of the scale and sweep effect on stability a corresponding NLF wing design with reduced sensitivity to surface imperfections in terms of surface waviness is discussed. The design and off-design behaviour of this wing are shown with variation of lift and Mach number. In order to design a NLF wing the presentation starts with a description of the transition mechanism of a swept wing and its prediction.

1. INTRODUCTION

Natural laminar flow (NLF) over a low swept wing is a promising technology for the airframe manufacturer for the next smaller aircraft generation to reduce fuel burn and also emission besides the new engine technologies.

Laminar flow research has a long tradition. In particular in the 1980s and 1990s the basics of the numerical prediction of the instability of the boundary layer have been established, which are nowadays applied in the current wing design process.

To realize NLF on a small aircraft with low sweep a balance has to be found in the aero design process between the reduction of the viscous drag by laminar flow and the wave drag for the given cruise Mach number. Only the upper side of the wing will be investigated as the lower side houses the Krueger device as a high lift and anti-contamination device.

NLF requires a high surface quality of the wing surface. The aero design of a NLF wing is close coupled with the structural design and the manufacturing process. The prediction of the effect of surface imperfections on laminar flow at relevant boundary layer stability situation and their sensitivities is a important task.

Finding the best compromise between sweep, extent of laminar flow, Mach flexibility and robustness of the wing design against surface imperfections is the subject of the presentation.

2. TRANSITION MECHANISMS ON A SWEPT WNG AND ITS PREDICTION

On a typical swept wing of a transport aircraft, boundary – layer transition can be caused by three different mechanisms: the attachment line instability, the Tollmien-Schlichting instability and the Cross-flow instability, Fig 1

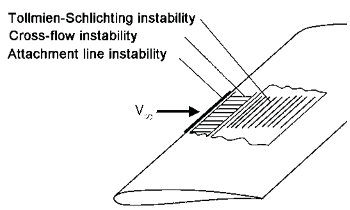

Fig 1: Transition mechanism on a swept wing

Following the description in [1], the flow direction changes rapidly from the spanwise orientated attachment line to a chordwise direction over the wing. The boundary layer becomes three-dimensional and develops a strong Cross-flow velocity component with an inflection point that causes the Cross-flow instability. Further downstream the Cross-flow component is getting weaker, the flow becomes more two-dimensional and thus unstable with respect to Tollmien-Schlichting waves.

The linear local stability theory applied in the form of the e^N method is a standard tool for the prediction of transition location. This theory considers wave-like disturbances in a laminar boundary layer and allows for the computation of the amplification rates (N-Factor) of Cross-flow (CF) and Tollmien-Schlichting (TS) modes. Laminar-turbulent transition is assumed to take place where the N-Factors of the most unstable disturbances meet an empirical 2N-boundary curve, which is determined by correlation with experiments, Fig 2. In case of flight condition the semi-empirical e^N method needs its calibration with results of flight tests [1].

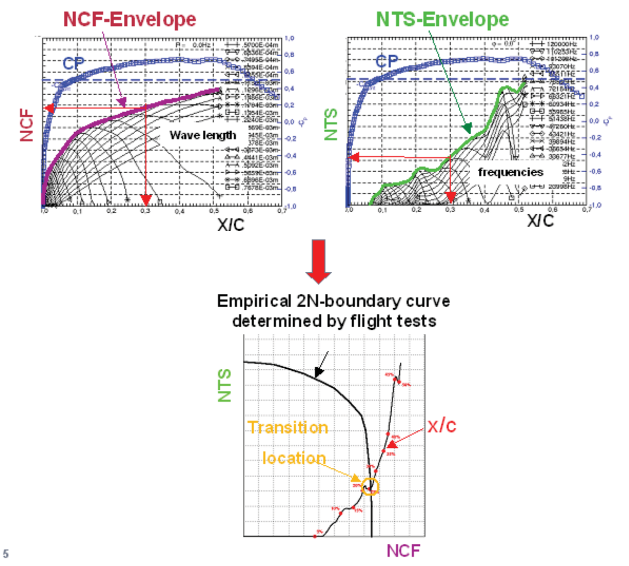

Fig 2: 2N-Factor transition prediction method

The prediction of the boundary-layer transition on a swept wing with the 2N transition method and its application as a tool for the aerodynamic design of NLF wings had been developed in the 1990s, [2,3].

Computations of the laminar-turbulent flow around NLF wings are now performed at Airbus with DLR RANS TAU code coupled with transition tool set of Geza Schrauf, [4].

3. EFFECT OF SURFACE WAVINESS AND STEPS

Surface imperfections like

- Steps (forward- & backward-facing) and gaps
- 3D disturbances (rivet heads, fasteners,…)
- Roughness as small scale disturbances (erosion,…)
- waviness as large scale disturbances

can cause premature transition of the natural laminar flow. The estimation of the effect of these surface imperfections on laminar flow is important for the definition of the surface tolerances for structure and manufacture, but has also an impact on the aerodynamic design.

3.1. Surface waviness

Stiffness of the skin with imposed loads and the overall manufacturing skin smoothness are giving the surface waviness. A surface wave could be defined by its wave length 2a with “a” as half wave length and its wave gradient b/a with “b” as wave height.

3.1.1. Effect of single wave on stability

Based on a structural concept of a leading edge with an upper cover and a joint to the front spar, Fig 3a, local deformations of three skin thicknesses had been computed under cruise loads for an outer wing section, Fig 3b.

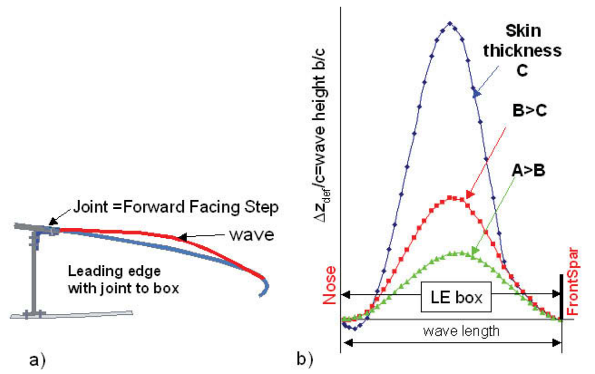

Fig 3: Example of leading edge layout and the deformations of skin under loads

To predict the pressure distribution of the swept outer wing section with waves added to shape a 2.5D prediction method is applied. The pressure distributions were post processed by the 2N transition tool leading to different increments of the NTS Envelopes, Fig 4.

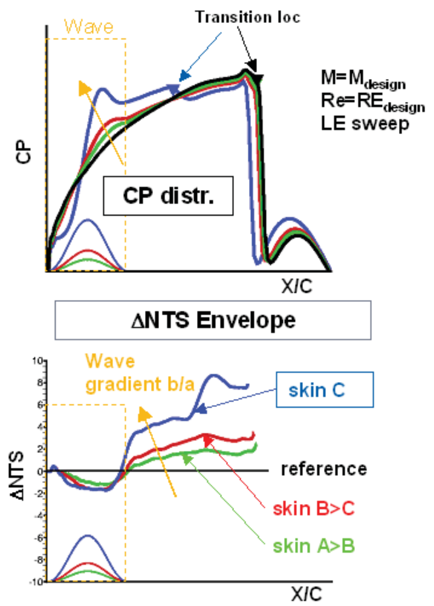

Fig 4:Effect of single wave on pressure and NTS-factor

Surface waviness mainly affects the Tollmien-Schlichting instability due to local adverse pressure gradients causing an increase of NTS-factor or local flow separation. The deformation of the thinnest skin C gives a strong change in pressure distribution with a corresponding response of the NTS-factor. First the stability is improved by a steeper favourable pressure gradient but then on the rear portion of the wave the adverse pressure gradient causes a strong increase of NTS-factor which forces the transition to move upstream of the reference. Although the increase of NTS-level of the thicker skins does not affect the transition location, it makes the stability situation more critical for further surface imperfections.

3.1.2. Allowable surface waviness

The effect of waviness on the NTS-factor depends for given local Reynolds number and sweep on

- Wave length and gradient
- Single wave or multiple waves
- Wave location (leading edge or wing box, pressure gradient)
- Wave shapes

Carmichael [5] has given a formula of an allowable wave gradient for a single wave depending on the global parameters Reynolds number, LE-sweep and wave length:

Carmichael criteria single wave
$$\frac{b}{a} = 2\left[\frac{59000 \cdot \cos^2(\varphi_{LE})}{SQRT(Re_c{}^{**}3) \cdot 2a/c}\right]^{1/2}$$

multiple wave criteria = 1/3 single wave criteria

By applying 2.5D predictions with stability analysis the surface waviness requirements could be specified by taking the boundary layer stability situation of laminar flow into account. The allowable waviness is derived by identifying a critical transition movement for a given wave length when varying the wave gradient, Fig 5.

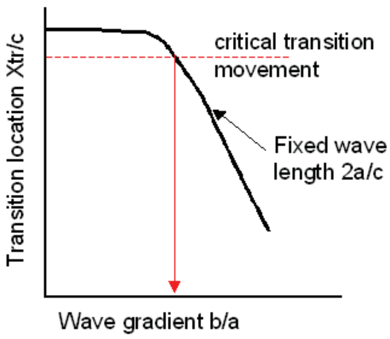

Fig 5: Allowable waviness

Good correlation between the Carmichael criteria and the 2.5D predictions was found at similar flow conditions.

3.1.3. 3D waviness by structure and manufacturing

The described process is based on the assumption that the chordwise waviness effect is dominant. But the real structure of the wing with ribs and stringers shows pattern of 3D waves under imposed loads, Fig 6.

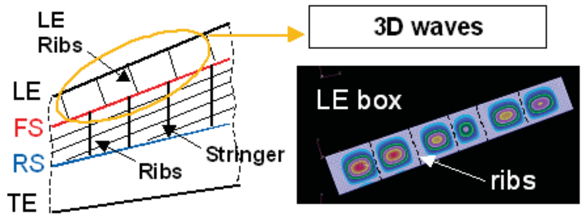

Fig 6: 3D deformation of wing structure under loads

On top of these waves caused by imposed loads, the wing surface may also be subject to additional waves or deformations caused by wing manufacturing process. A typical example is given on Fig 7 for a CFRP wing box panel. Around each stringer waviness is detected, caused by spring-in effects around stringers or other substructure.

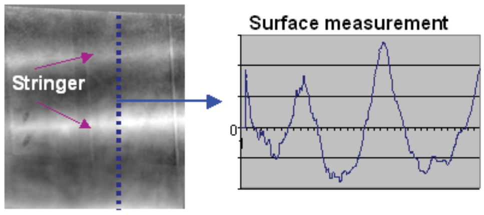

Fig 7: Skin measurements of CFRP panel with stringers

For the proof of the NLF wing design the resulting waviness which is highly three-dimensional has to be taken into account under cruise condition,. The current stability toolset applied in the RANS DLR TAU code for NLF wing design is limited to 2.5D flow approximation due to the conical boundary layer approach providing the stability code with boundary layer profile. Further progress towards an efficient 3D stability prediction is needed to access the influence of 3D waviness.

3.2. Influence of 2D steps on stability

The structural concept of the leading edge with a joint at the front spar, Fig 3a, offers some kind of advantage regarding repair and integration of systems but creates a risk of non-acceptable step height at the joint from the aerodynamic point of view.

The criticality of the step depends on its orientation, forward or backward facing step (FFS, BFS). Following the Nenni criteria [6] the forward-facing step allows a twice larger step height than the backward-facing step. An example of an airfoil flow around a forward-facing step with a height of 0.2mm is shown in Fig 8.

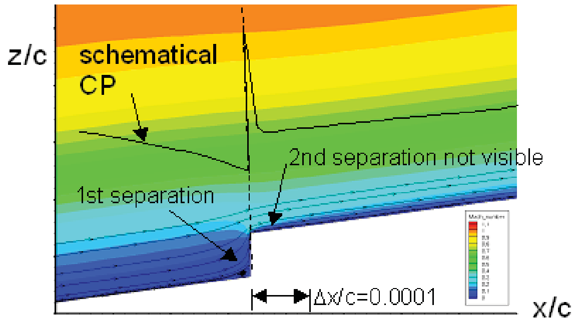

Fig 8: Airfoil flow around a forward facing step of 0.2mm

Due to the pressure rise a laminar separation bubble occurs in front of the step. Its size depends on the step height. Across the step a very strong acceleration takes place, followed by rapid pressure rise which causes at least a further increase of the N-Factor, as shown by the flat plate calculation from [7] in Fig 11.

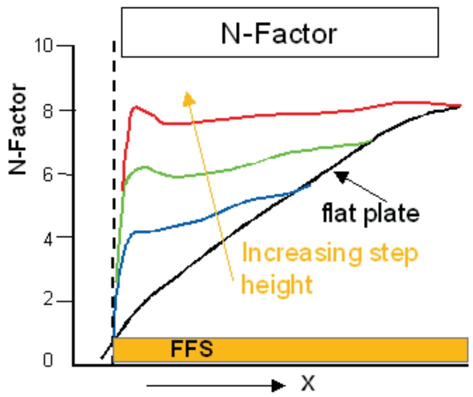

Fig 11: N-factor distribution with increasing height of forward-facing step, Ref [7].

Due to the complex local physics the prediction of the stability behaviour for flows over steps is still under development. The planned national funded project LuFo IV ATLATUS will improve our understanding and the computational capability by detailed flow measurements.

To give the structural design and manufacturing departments realistic aerodynamic requirements, in addition, experimental investigations regarding waviness and steps are being undertaken or are planned in cryogenic test facilities like DNW KRG (Kryo-Rohr-Windkanal Göttingen) for airfoils and ETW (European Transonic Wind tunnel) for half models in the frame of the national funded project LuFo IV HigherLE and of the large European research project Smart Fixed Wing Aircraft (SFWA). These wind tunnels allow testing at flight conditions. The experimental data are being used to validate and calibrate the aerodynamic computational tools for predicting the influence of the surface imperfections on the stability of NLF wings.

4. EFFECT OF SCALE AND SWEEP

Natural laminar flow over a wing under cruise conditions will also be affected by the global parameter of the planform mainly the local Reynolds number via the chord distribution and the leading edge sweep.

4.1. Local Reynolds number

Due to the distribution of the chord along the span the local Reynolds number varies by a factor of almost three between root and tip under cruise conditions, Fig 12.

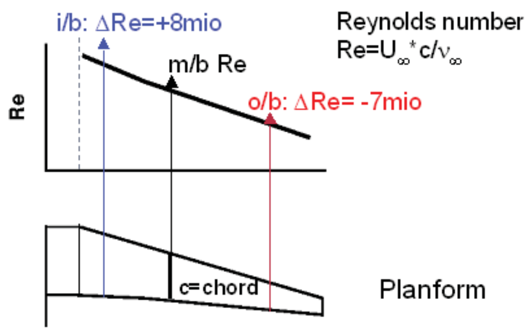

Fig 12: local Reynolds numbers versus span

Fixing the mid-board pressure distribution the effect of the higher inboard and the lower outboard Reynolds number on stability is shown as an increment of the NTS and NCF-factors, Fig 13. The Tollmien-Schlichting as well as the Cross-flow instability are influenced in the order of ΔN=2. In particular the increase of NTS&NCF level by the higher Reynolds number for the inner wing may reduce the chordwise extent of the laminar flow and/or tighten the surface tolerances.

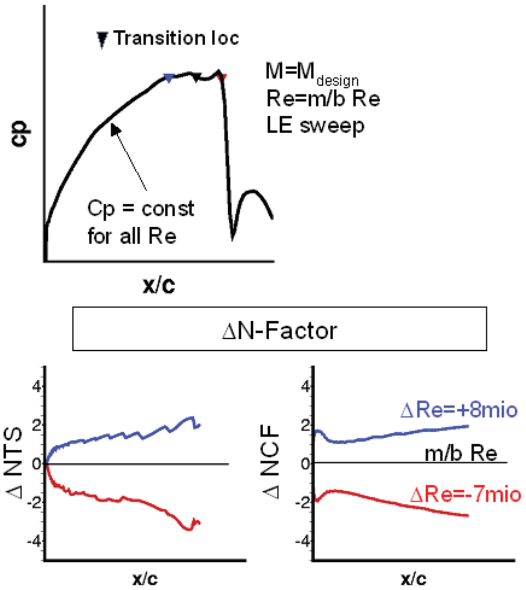

Fig 13: Effect of Reynolds number on stability

Therefore for the aero point of view a planform with a low taper ratio is preferable, which is in contradiction to lower wing weight. A compromise has to be found between the extent of laminar flow and the stability level for surface tolerances on one side and the wing weight on the other.

4.2. Leading edge (LE) sweep

The effect of sweep is investigated by shearing a planform to higher and lower LE sweep without changing the sections but adapting the twist for the same lift, Fig 14.

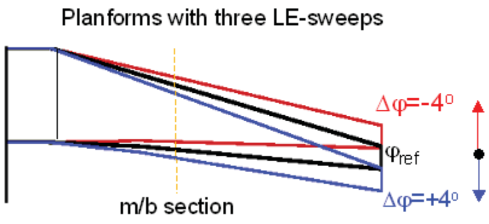

Fig 14: Variation of LE sweep

Compared to the reference LE sweep the lower LE sweep directly reduces the NCF level at the nose and the increased favourable pressure gradient reduces the NTS level, Fig 15. But the lower LE sweep leads also to a stronger shock with increase of the wave drag.

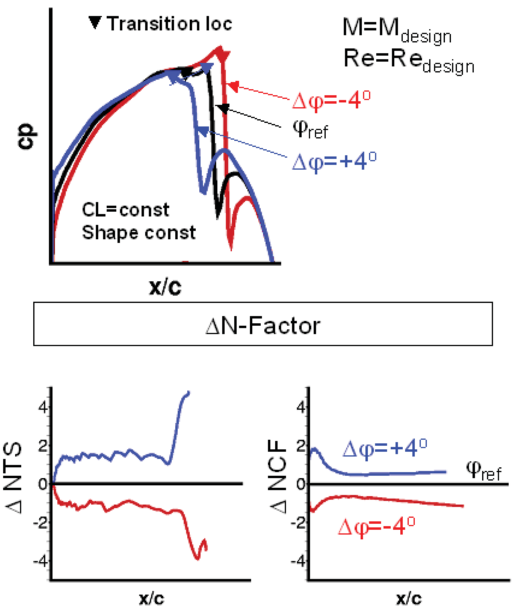

Fig 15: Effect of LE sweep on stability

The variation of LE sweeps gives the expectation that surface tolerances can be relaxed by reduced LE sweep of the wing due to lower stability level, but the increase in wave drag will restrict this approach. An optimised sweep has to be found to fulfil both requirements.

5. NLF WING DESIGN WITH REGARD TO WAVINESS

The basic problem of designing a swept NLF wing is that Cross-flow instability and the Tollmien-Schlichting instability are affected oppositely by the pressure gradient as discussed in the 1980s, [8,9], Fig 16. The design task is to find pressure distributions along the span, which are an optimum for both instabilities under the design constraints.

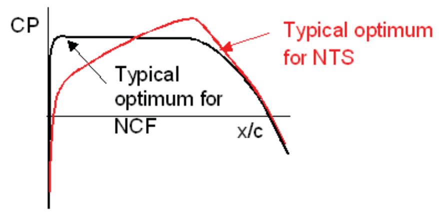

Fig 16: Optimised pressure distribution for Tollmien-Schlichting or Cross-flow instability, Ref [8]

A baseline wing of reduced LE sweep was designed to benefit from the lower sweep concerning the stability level without downgrading the wave drag. For achieving more robustness against waviness and steps from structure and manufacture the stability level was further improved. To assess both wing designs spanwise continuous waves are added to the shape related to the structural design: a single LE box wave and multiple wing box waves caused by the stringer pitch. Only the local deformations of structure under cruise loads are applied in a simplified manner, the overall twist and bend is not considered, Fig 17.

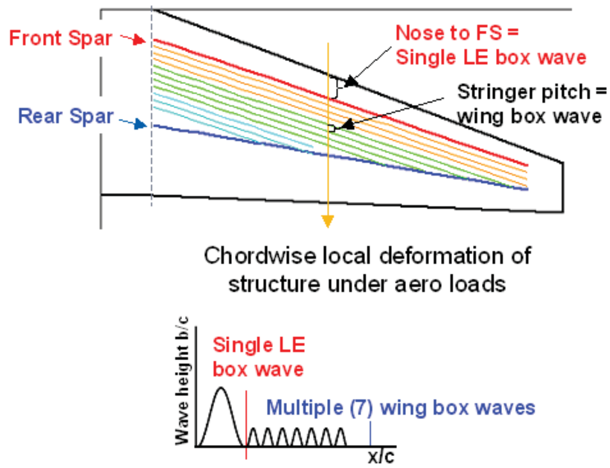

Fig 17: Wing with spanwise continuous waves

After performing computations with the RANS DLR TAU code with the embedded transition toolset the robust wing shows less movement of the transition along the whole span than the baseline wing, when the combined waviness is applied, Fig 18, and allows relaxed surface tolerances.

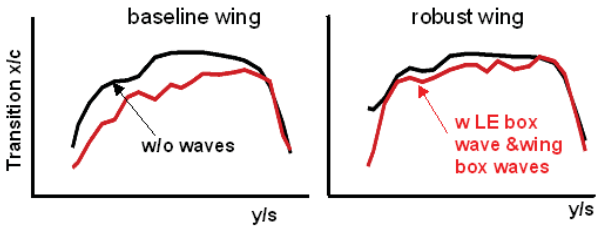

Fig 18: Transition location of baseline and robust wing

6. BEHAVIOUR OF NLF WING WITH VARIATION OF LIFT AND MACH NUMBER

The effect of lift and Mach number variation is discussed by using the previous NLF wing without surface imperfections.

6.1. Lift variation

To achieve the most benefit it is important that the laminar flow is extended up to sufficient chordwise extension from inboard up to outboard, but not only for design point, also for the design range, as shown Fig 19.

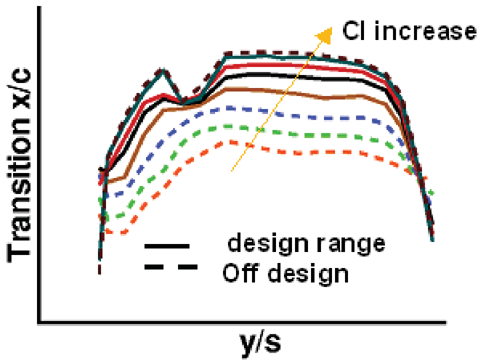

Fig 19: transition location with lift variation

With increasing lift at design Mach number the chordwise extent of laminar flow increases. For lift coefficients beyond the design range the transition location is limited by shock location and no further increase is observed. The distribution of transition with lift correlates with the increments of the total drag estimation compared to a turbulent reference wing. A large reduction of total drag is predicted of about 5% over a broad lift range, Fig 20:

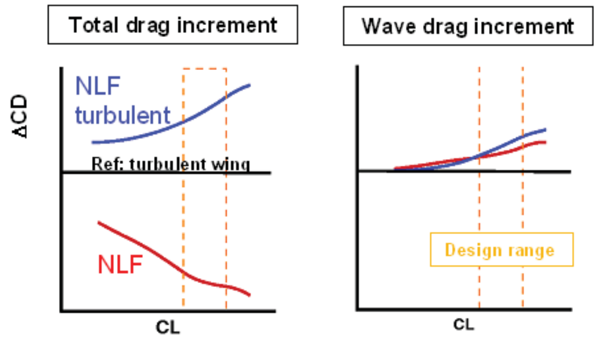

Fig 20: Drag increment with lift variation

The steep favourable pressure gradient to achieve the chordwise laminar flow extent leads to an increase of the wave drag compared to a turbulent wing. When running turbulent the NLF wing generates higher drag than the turbulent one, not only due to the higher wave drag but also due to the stronger shock boundary layer interaction that increases the viscous drag.

6.2. Mach number variation

When the Mach number varies from the design point, the NLF wing design has to ensure that a favourable pressure gradient is still over a large Mach number range. The pressure distributions show the flow phenomenon that occurs with variation of Mach number, Fig 21.

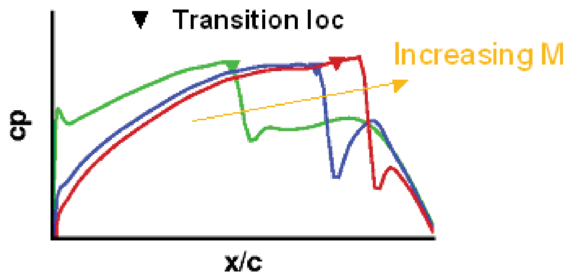

Fig 21: Variation of pressure distribution with Mach number

When the Mach number decreases from the design Mach number, the laminar flow extent is reduced by an upstream movement of the shock and the favourable pressure gradient is reduced. At least an adverse pressure gradient appears at subsonic Mach number and the pressure peak at the nose forces the transition. With increasing Mach number the shock moves downstream and the aft transition improves the viscous drag. Also the favourable pressure gradient improves which reduces the NTS level, but this leads on the other side to an increase of NCF-factor and can stop the transition moving upstream. The downstream movement of shocks raises the shock strength and therefore the wave drag, finally cancelling out the benefit coming from the laminar flow. The distribution of total drag of a NLF wing with Mach number reflects the pressure development with Mach number, Fig 22:

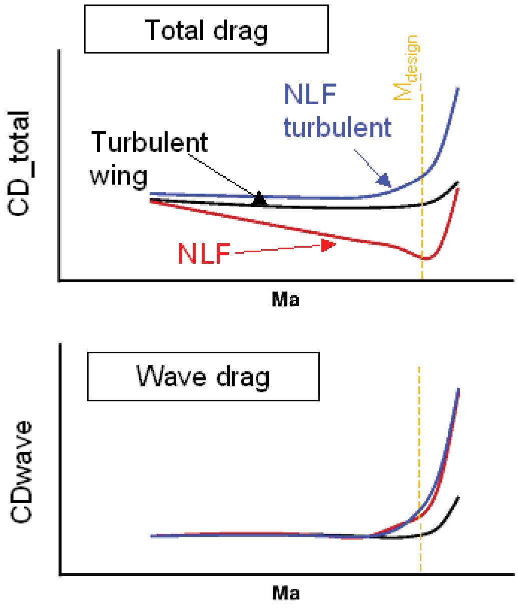

Fig 22: Drag distribution with variation of Mach number

Due to the particular pressure characteristics needed to achieve and sustain long runs of natural laminar flow the laminar wing is limited in Mach variation compared to a turbulent one.

7. CONCLUSION

The transition flow physics are generally understood and applied to NLF wing design by using transition prediction tools developed in the 1990s. Progress of the current transition methods is needed to predict the stability behaviour of the actual wing shape with 3D waviness and steps to ensure that no premature transition occurs.

Aero wing design on the one side and the structural design with the manufacturing process on the other side are closely linked by the surface tolerances. The definition of the allowable tolerances has a great impact on both sides.

The benefit of NLF depends on the scale, local Reynolds number and the sweep of the wing. Lower sweep has the advantage to use its stability potential for relaxing the surface tolerances but achieving a reasonable wave drag level is very challenging for a robust wing.

Drag reduction by a NLF wing of about 5% is computed in the design range, but the drag benefit with Mach number is limited compared to a turbulent wing.

From the aero side natural laminar flow is a promising technology to reduce drag, but the penalty of increased weight, maintenance, costs, reliability etc on aircraft level will at least decide if this is also a successful technology for the next transport aircraft generation.

8. REFERENCES

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