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RISK ANALYSIS FOR FLUTTER OF LAMINAR WINGS

Lorenz Tichy[1], Holger Mai[1], Michael Fehrs[1], Jens Nitzsche[1] and Anne Hebler[1]

[1] German Aerospace Center (DLR) – Institute of Aeroelasticity
Bunsenstraße 10, 37199 Goettingen, Germany
lorenz.tichy@dlr.de

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Abstract: The effect of transition from laminar to turbulent flow on the flutter behaviour is discussed on basis of classical and new wind-tunnel tests. Requirements are defined for numerical methods in order to predict the risk of transition effects on the flutter behavior of transport aircraft with laminar wings. Due to the lack of validation data and reliable transition modelling, the accuracy of flutter predictions for aircraft with laminar wing is expected to be lower than for conventional aircraft. Instead of managing late the risk in an engineering way with possible loss of performance, the authors propose to develop early enough adequate transition models and to prepare a wind-tunnel test at high Reynolds and Mach number conditions with a laminar wing in forced motion.

1 INTRODUCTION

Since decades and due to its enormous potential for the reduction of friction drag, laminarization of the flow around wings is an important research topic in the aerodynamic community, see e.g. Green [1]. It is the objective to keep the boundary layer flow laminar on a maximum of the wing surface by shifting the transition from the laminar to the turbulent state to the rear. There are different transition mechanisms on a swept wing under operating conditions, Tollmien-Schlichting instability (TSI), cross flow (CF) instability and attachment line transition (ALT). In principle, laminarization can be reached passively (natural laminar flow, NLF) by keeping the wing sweep angle moderate and by using *laminar* wing airfoils with a backward thickness maximum, actively with a boundary layer suction system or by a combination of both technologies (hybrid laminar flow control, HLFC). On aircraft wings there will be in any case a transition of the laminar boundary layer flow to turbulence. In contrary to conventional (turbulent) airfoils, laminar airfoils show a *laminar bucket* in the drag polar, because the flow can be kept laminar only for moderate angles of attack, see figure 1(right). The transition has also a nonlinear effect on local lift (see fig. 1(left)), which can be ascribed to the different increases of the displacement thickness of a laminar and a turbulent boundary layer.

In contrary to aerodynamics, the influence of laminar flow on the aeroelastic behavior is nearly no research topic at all. Historically, transition effects are mainly known as wind tunnel artefacts, if no transition tripping was applied. Oscillations occurred for subsonic attached flow with free transition and in several tests for transonic flow conditions, see Houwink [2] and Mabey [3]. Mabey made a quasi-steady approximation for the transition on an airfoil in plunging motion (see below) to explain the principal physical mechanism of the vibrations observed in several wind tunnel tests. He drew conclusions for pitch oscillations, which were strongly criticized by Ericsson [4]. Ericsson reasoned later by analogy to dynamic stall effects

[5], that pressure gradients and unsteady effects of accelerated flow and moving wall effects (*Magnus effect*) delay or promote transition on a pitching or plunging airfoil. A public discussion between both authors followed [6].

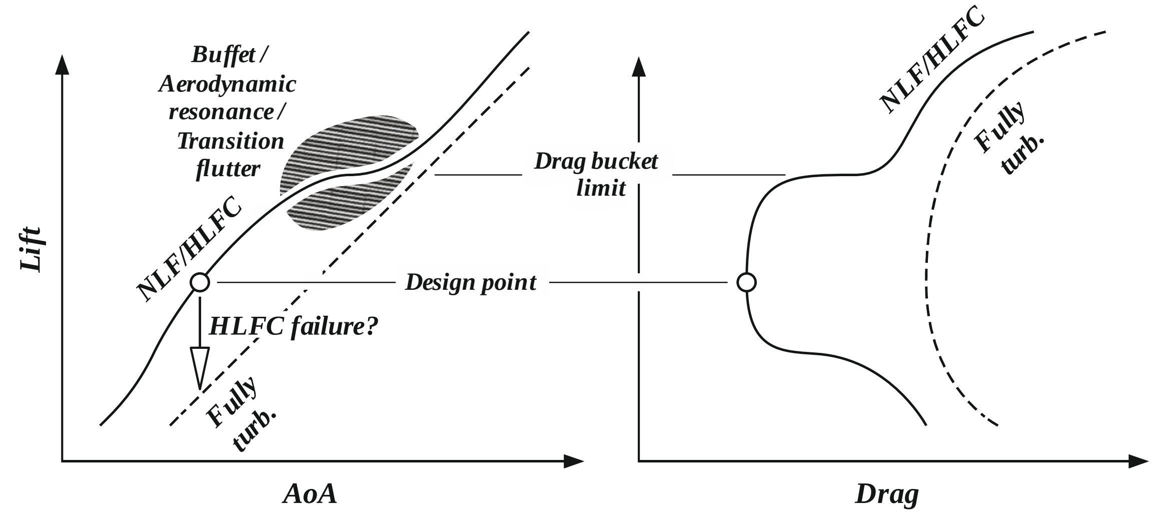

Figure 1: Relationship between lift nonlinearity (left) and drag polar (right).
Source: J. Nitzsche and M. Fehrs, DLR

Laminar wings are applied for small aircraft, e.g. gliders. But as far as known to the authors, there is no published information available concerning a specific flutter behavior of these aircraft. For laminar wings with relevance for large transport aircraft at typical flight Reynolds numbers of $\sim 10^7$ and in transonic flow, not even experimental data for flutter stability or motion induced unsteady airloads are available. For completeness it should be remarked, that at lower Reynolds numbers of $\sim 10^5$, Studer [7] measured the unsteady transition in oscillating boundary layers and Poirel [8] investigated a specific flutter mechanism, which he reduced to laminar flow separation and therefore called *laminar separation flutter*.

The DLR Institute of Aeroelasticity follows a long term strategy from lower to higher Reynolds and Mach numbers to fill these gaps on the experimental as well as on the numerical side. As a starting point at moderate Reynolds numbers of about $2 \cdot 10^6$, an oscillating CAST10-2 wing airfoil was tested in the transonic wind tunnel in Goettingen (DNW-TWG) in subsonic and transonic flow conditions with natural transition and with transition tripping as reference. This model was excited in pitch [9], [10] to obtain unsteady aerodynamic data for forced motion oscillations. For small angles of attack, the flow was attached, for lower and higher angles laminar separation bubbles occurred at transonic flow conditions [10]. These tests have been extended by a flutter test at transonic conditions [11]. Very recently a high Re experiment for a wing in forced pitching motion was performed in the low speed cryogenic wind tunnel in Cologne (DNW-KKK).

Numerical aeroelastic simulation methods become more and more an alternative to experiments and could be seen as a means for risk analysis in this respect. Before doing so, it has to be ensured that the envisaged CFD methods have really all the necessary capabilities for this task. There is generally a lack of validated transition and turbulence models for transonic, unsteady, transitional flows. Transition models can be seen as suitable candidates for the flutter prediction of a laminar wing only, if at least the laminar buckets for steady flow conditions and at flight Reynolds numbers can be predicted accurately [12]. Beyond, it has to be ensured that the dynamic behavior of the transition for a wing oscillating in its elastic modes can be described by an adequate, experimentally validated aerodynamic model. Or

vice versa, if the dynamic behavior of transition is not properly represented, the CFD model has to be seen as inappropriate. Numerical simulations with such a model might not show any or no reliable sensitivity of flutter to effects of laminar flow and a resulting risk might not be assessed correctly.
Summarizing the situation, today it is therefore not known, if a laminar wing has to be seen as more critical than a fully turbulent one and moreover, there is no comprehensive basis for a proper flutter risk assessment as neither adequate experimental data nor reliable numerical models exist.
The assessment of the risk of a laminar wing on flutter in this paper can be based therefore only on the available bricks of knowledge. Moreover, it is the intention of the authors to sensitize the aeroelastic and the aerodynamic (!) communities for this topic, to identify and realize the research needs on the experimental and numerical side in order to do a more robust risk assessment in the future and so to contribute to the realization of the laminar wing for commercial transport aircraft.

2 SUBSCALE EXPERIMENTAL APPROACH

In this paper it is assumed, that TSI is the relevant transition mechanism, because CF instability and ALT are prevented by a moderate sweep angle or by a suction system in the leading edge region. The Reynolds number Re with the chord length is one of the decisive parameters for all the aerodynamic and aeroelastic effects, which will be discussed in this paper.

2.1 Quasi-steady Transition Effects in Subsonic Flow

The transition position depends in general on the disturbance environment (turbulence, sound, wall roughness, etc.) and in particular on pressure gradients, which are largely influenced by the angle of attack for a given airfoil. At the limits of the drag bucket, it moves rapidly forward and causes the drag increase shown schematically in fig. 1(right). In addition to the tests mentioned by Mabey [3], wind tunnel tests with hot wires [7] or hot-film sensors [9] can show the motion of the transitional area on oscillating models.
For a vertical oscillation of a symmetrical airfoil, Mabey [3] gave a quasi-steady interpretation for the effect of the transition movement on the lift force. Positive or negative damping is caused dependent on the amount of the transition position changes and the resulting boundary layer thickness variations on the upper and lower surfaces. These boundary layer thickness variations change the circulation around the airfoil resulting in a zero-lift coefficient due to transition $\Delta\alpha_t$, i.e. a shift of the lift curve. As stated by Ericsson [4], a corresponding quasi-steady approach for an airfoil in pitch oscillation would have an effect on the frequency.
To confirm that this shift of the lift curve can be reduced to different changes of the boundary layer thicknesses on the upper and lower surface, calculations for a NACA0012 airfoil with transition points fixed at positions comparable to [3] were performed with the DLR-TAU code, see fig. 2. These quasi-steady approaches imply that the airfoil shape and the resulting pressure distributions bring the transition positions from A to B or C for an upward motion $\dot{h}$ of the wing section. Aft transition locations on an airfoil require low Reynolds number flows or laminar wing airfoils. In the case of a low Reynolds number flow, a less adverse pressure gradient (decelerated flow) delays transition to a certain extent. In the case of a laminar wing section, a large nose radius and a backward thickness maximum ensure favorable pressure gradients (accelerated flow) to prevent transition close to the leading edge. The upward motion of the airfoil induces a negative incidence angle $\Delta\alpha = -\dot{h}/U_\infty$ with a transition

location further downstream on the suction side. Transition provides a negative aerodynamic damping for $\Delta\alpha_t > \Delta\alpha$.

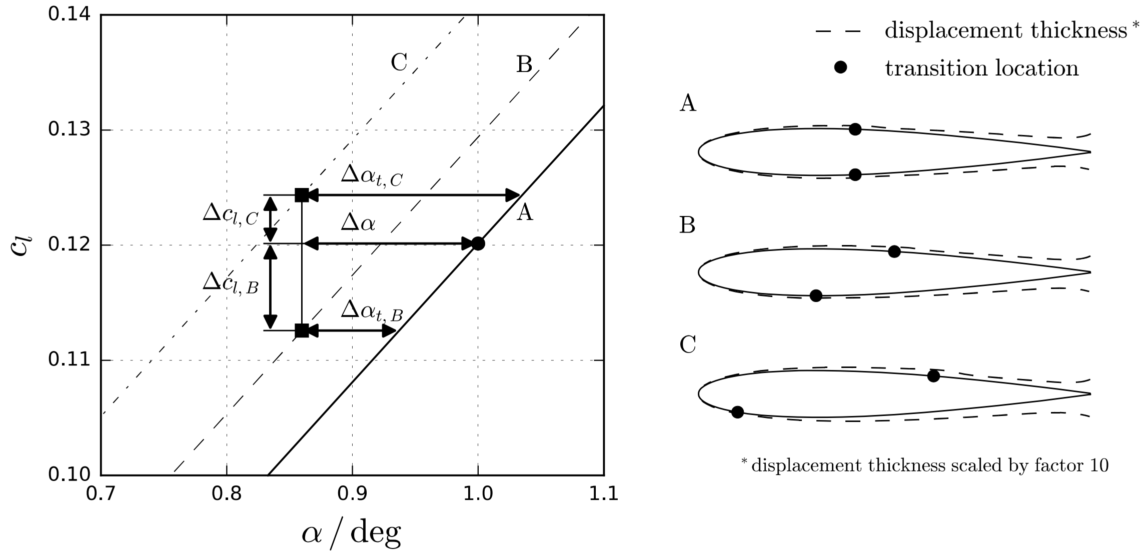

Figure 2: CFD calculations for NACA0012 with transition positions fixed at points A, B, C according to Mabey [3]

The shift of the lift curve due to the moving transition location is also the reason for the nonlinearity of the lift gradient at incidences close to the drag bucket in fig. 1(right). Hebler [10] measured the upper part of the drag bucket and of the nonlinear lift curve for the CAST10-2 airfoil at M=0.50, see fig. 3. The transitional boundary layer results in an increased lift for a given angle of attack compared to the fully turbulent boundary layer flow. For M=0.70, this shift is increased, see fig. 4. The flow was fully attached for α<1.2 degree. For α>1.2 degree, shocks and shock induced laminar separation bubbles occurred.

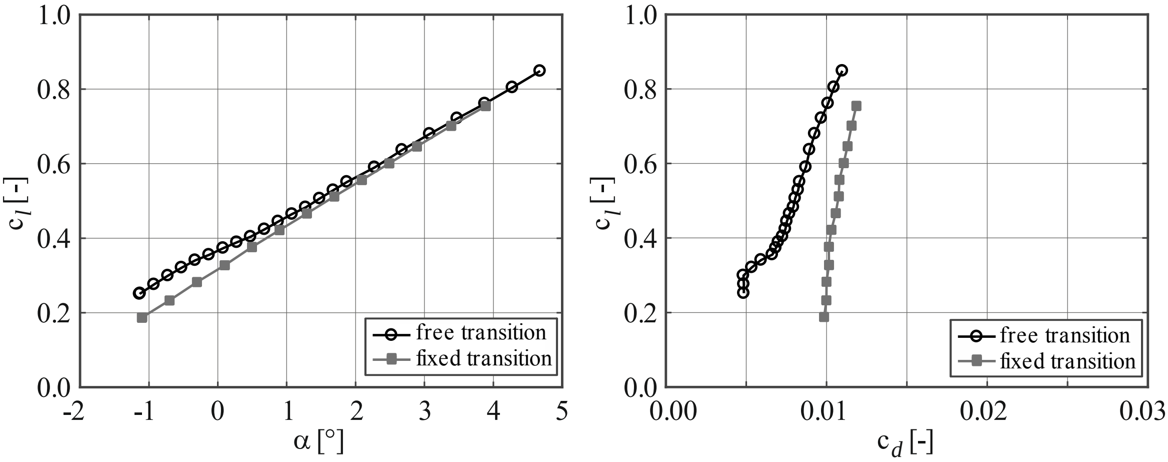

Figure 3: Lift curve (left) and drag polar (right) for transitional and fully turbulent flow at subsonic conditions, M=0.50.

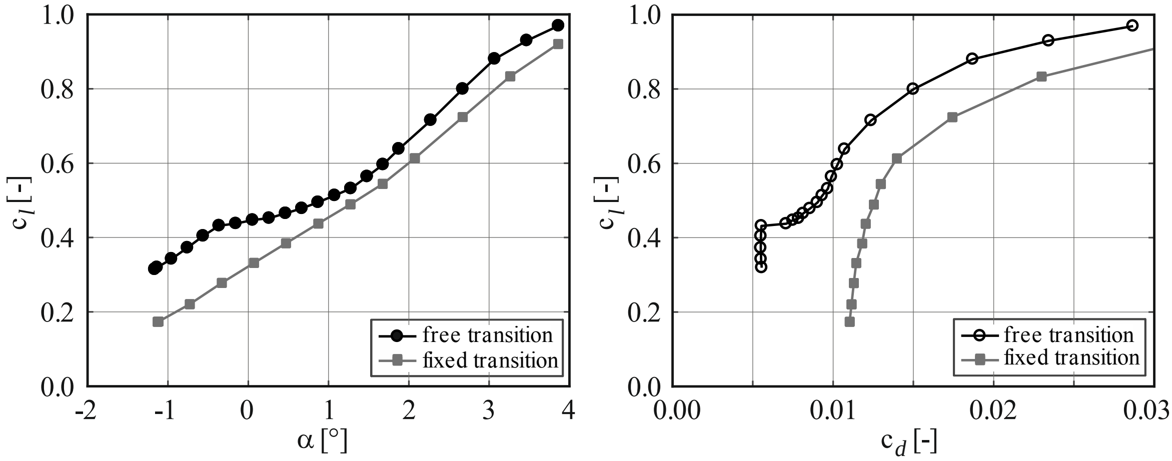

Figure 4: Lift curve (left) and drag polar (right) for transitional and fully turbulent flow at M=0.70, for subsonic to transonic conditions

The nonlinearity of the lift curve slope gives a quasi-steady indication on nonlinear (α-dependent) effects of the transition on motion induced unsteady airloads and therefore on the flutter behavior.

2.2 Quasi-steady Transition Effects in Transonic Flow

It is well-known, that the unsteady and quasi-steady airloads in transonic flow are much more dependent on the steady flow field than in subsonic flow. For a given Mach number and 2d conditions the flow field is defined by airfoil geometry and angle of attack, because these parameters determine the strength and position of shocks and the resulting peaks in unsteady and quasi-steady pressure distributions.

As a consequence, two effects will occur in transonic flow for natural transition. The first one is the above described boundary layer displacement thickness effect, which changes the effective airfoil camber and therefore the lift. The second effect is the shock wave/boundary layer interaction; the boundary layer influences position and strength of the shock due to its high sensitivity of the airfoil shape and vice versa. Additionally, if transition does not take place in front of the shock, the shock will cause transition. For high flight Reynolds numbers, the flow remains attached for moderate α and the shock can have a higher strength and be located more downstream for laminar flow in comparison to fully turbulent flow, see the numerical result for a fixed Mach/lift condition in fig. 5a (left). The resulting quasi-steady pressure distribution and the shock peak in fig. 5b (right) indicate an increasing criticality concerning flutter. Ideally this shock / boundary layer interaction at high Re conditions will be validated in a dedicated wind tunnel test.

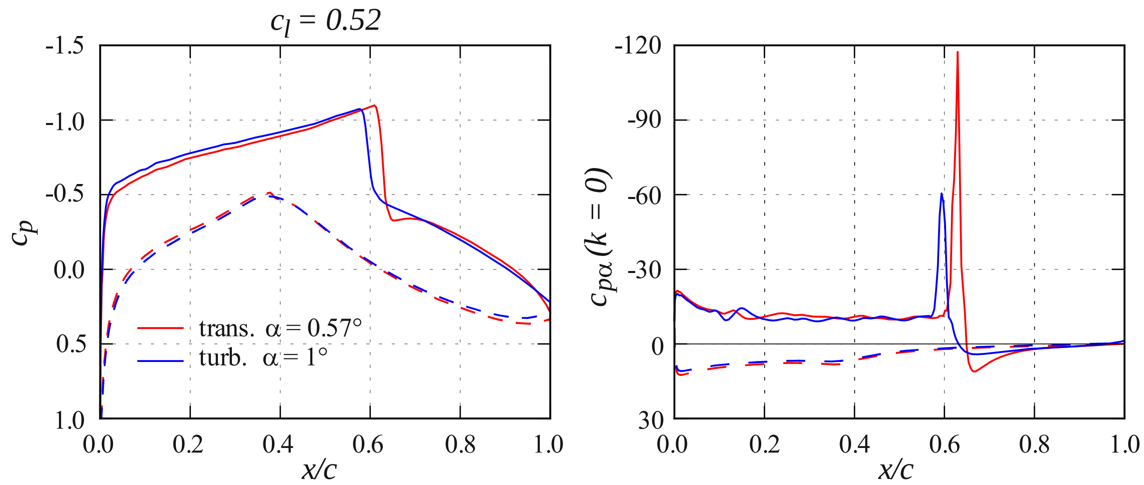

Figure 5: Influence of transition on a) shock position (steady pressure distribution, left), and b) shock motion (quasi-steady pressure distribution, right). RANS results for RAE 2822 at M=0.75, Re=20·10^6, c_l=0.52 for both fully-turbulent and free transition cases and fully attached flow.

In contrary to high flight Reynolds numbers, in a wind tunnel experiment at moderate Reynolds numbers a lambda shock configuration can occur, because the first, oblique shock causes a laminar separation bubble in front of the main shock. The resulting effect on the lift coefficient is shown in fig.6 (left) for M=0.75.

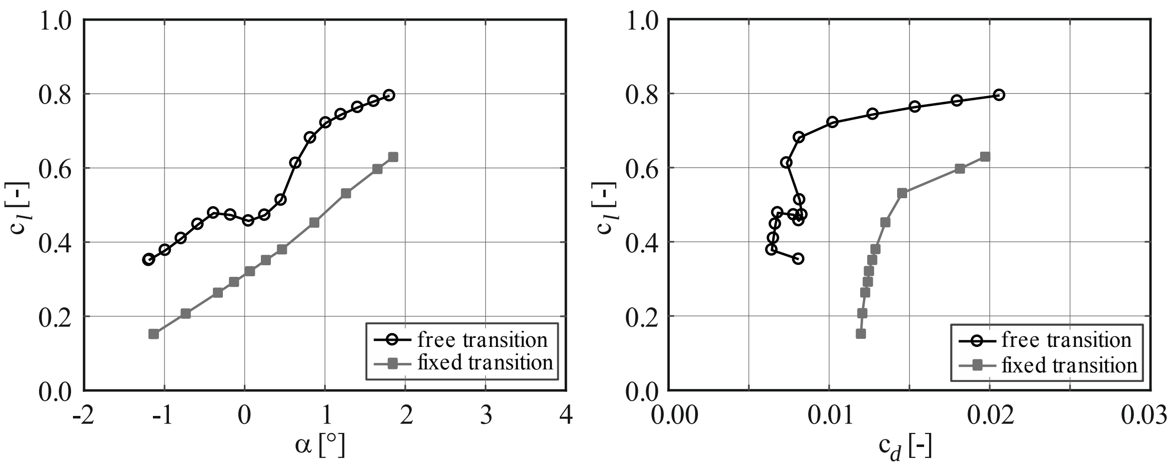

Figure 6: Lift curve (left) and drag polar (right) for M=0.750, experimental results from [9]

The difference between the lift curves of free and fixed transition is much larger than for the lower Mach numbers in fig. 3 and 4. Investigations of the state of the boundary layer showed, that for M=0.75 laminar separation bubbles occurred for α<-0.25 degree and α>0.50 degree, see fig. 7.

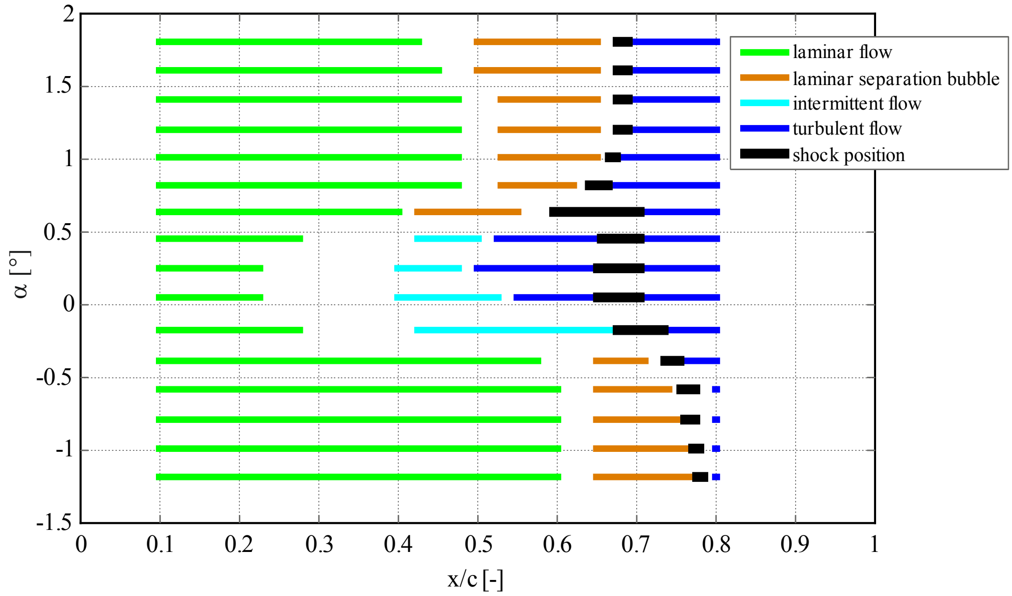

Figure 7: Flow conditions at M=0.75 dependent on incidence (taken from [9])

The cambering effects, which are caused by the separation bubbles, lead to a significant difference in the pressure distribution and result in an even higher difference in lift at high and low α than due to transition. When the transition took place further upstream and the compression shock encountered a turbulent boundary layer for -0.25°<α<0.50°, no separation bubble occurred. The difference in the lift coefficient between free and fixed transition is comparable to M=0.70 at these angles of attack (see fig.6). It has to be remarked, that the CAST10-2 airfoil shows at M=0.75 a double shock system in this α-range, which is very sensitive to changes of α, see fig. 8.

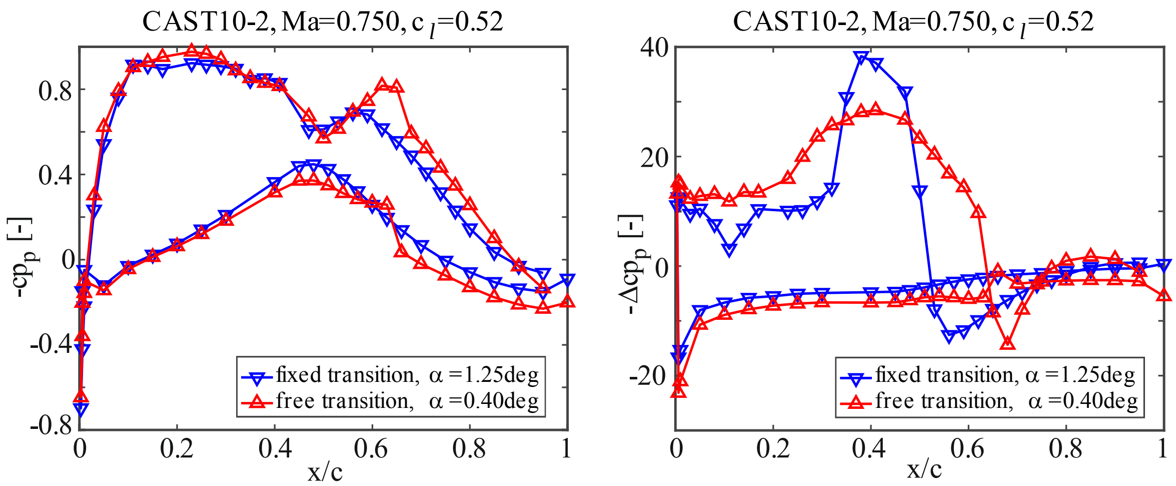

Figure 8: Influence of transition on shock position (left, steady pressure distribution) and shock motion (right, quasi-steady pressure distribution. Wind tunnel test results for CAST10-2 airfoil at M=0.75, Re=$2{\cdot}10^6$, c_l=0.52 for both fully-turbulent and free transition case

A schematic interpretation in fig. 9 shows the different principle effects of transition on the lift coefficient versus α, with or without separation bubbles.
With the objective of an applicability to transport aircraft at higher Reynolds numbers, at M=0.75 only the limited range -0.25°<α<0.50° from the wind tunnel test could be seen

therefore as representative for flight conditions and Hebler [11] performed the subsequent flutter tests mainly at these low α values.

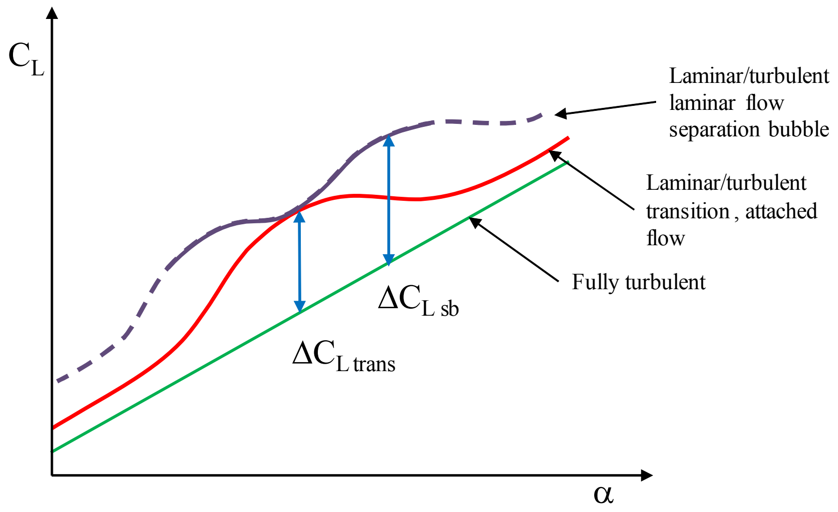

Figure 9: Schematic influence of transition and laminar separation bubble on lift coefficient.

2.3 Unsteady Transition Effects and Flutter Behavior

The quasi-steady model of Mabey [3] does not explain the excitation of pitch oscillations, which had been obtained in several cases with natural transition in contrary to fixed transition. The interpretation of the obtained oscillations with the experience from dynamic stall tests at extremely high amplitudes by Ericsson [5] could not be confirmed by the current tests and numerical results.

Hebler [10] measured directly the unsteady airloads for forced pitching motion and for natural and forced transition. Fig. 10 shows the complex lift coefficient dependent on reduced frequency and mean angle-of-attack at moderate pitch amplitude of 0.2 degree for M=0.70. It can be seen clearly that the free or fixed transition has a strong influence on the complex lift coefficient in magnitude as well as in phase.

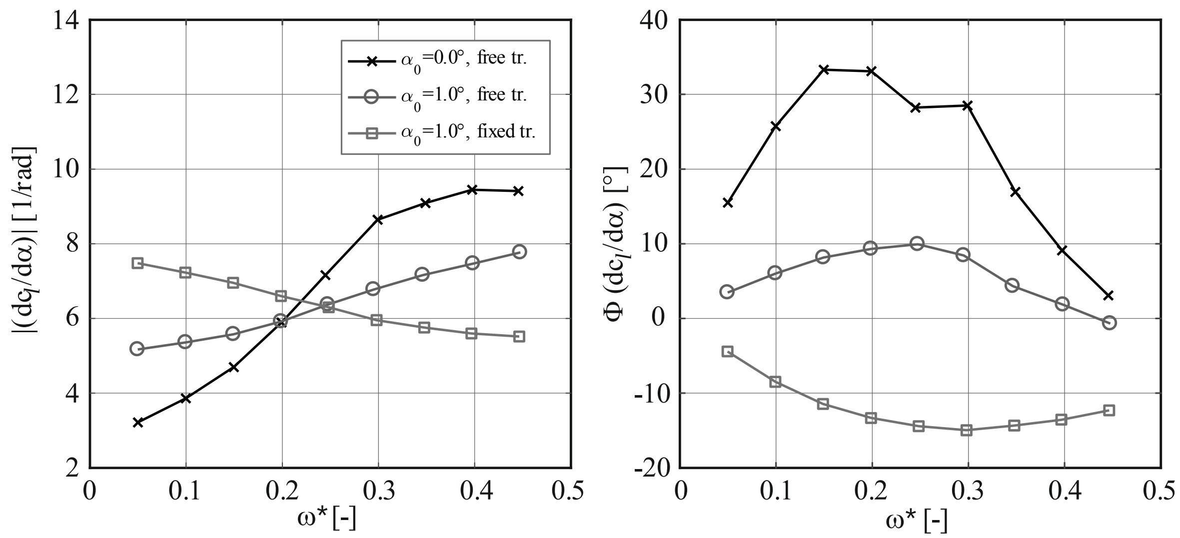

Figure 10: Influence of reduced frequency on amplitude and phase of lift coefficient for pitch oscillation for free and fixed transition in subsonic flow, M=0.70, pitch amplitude 0.2 degree.

The oscillations observed by Mabey [3] were of a limit cycle type. The aerodynamic excitation reduced the total damping to almost zero and resulted in very high oscillation amplitudes of the model. To investigate nonlinear effects, Hebler [10] varied the pitch amplitude of the CAST10-2 airfoil. One example at M=0.75 in fig. 11 for α=0.2 degree and without separation bubble (compare fig. 7) shows strong nonlinearities for the complex lift coefficient.

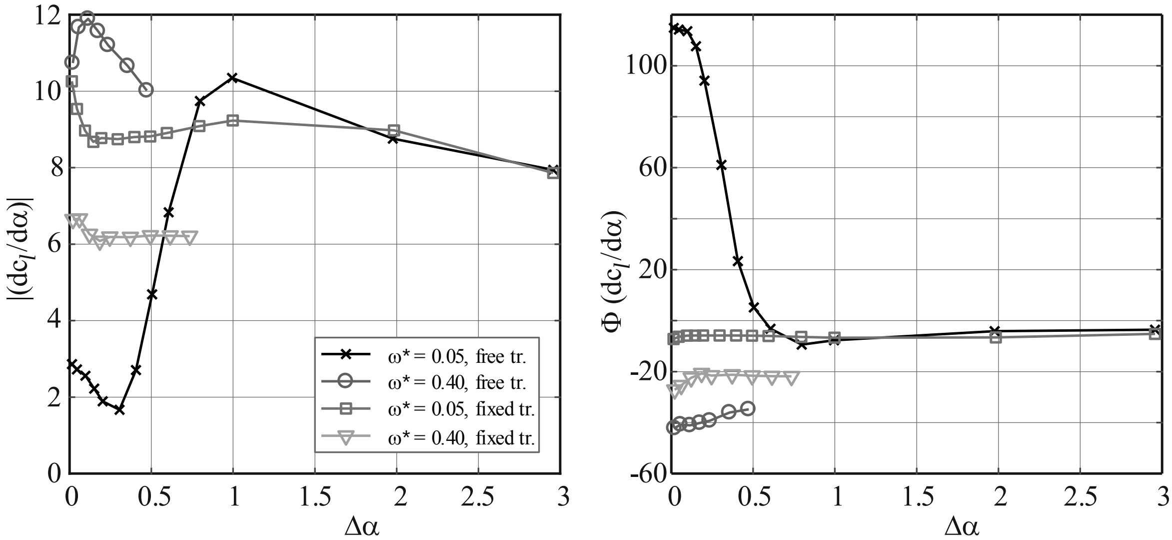

Figure 11: Nonlinear dependency of lift coefficient on pitch amplitude. M=0.75, α= 0.2 degree.

Later, Hebler investigated [11] the elastically suspended model with the classical plunge and pitch degrees of freedom. The mean angle-of-attack was kept constant at 0.0 degree. To investigate aeroelastic systems of different stability levels, the center of gravity and therefore the static moment x_α was kept variable. As expected from the previous forced motion results, limit cycle oscillations occurred for free transition in comparison to dynamically stable conditions for turbulent flow and $x_\alpha = 0$, see fig. 12.

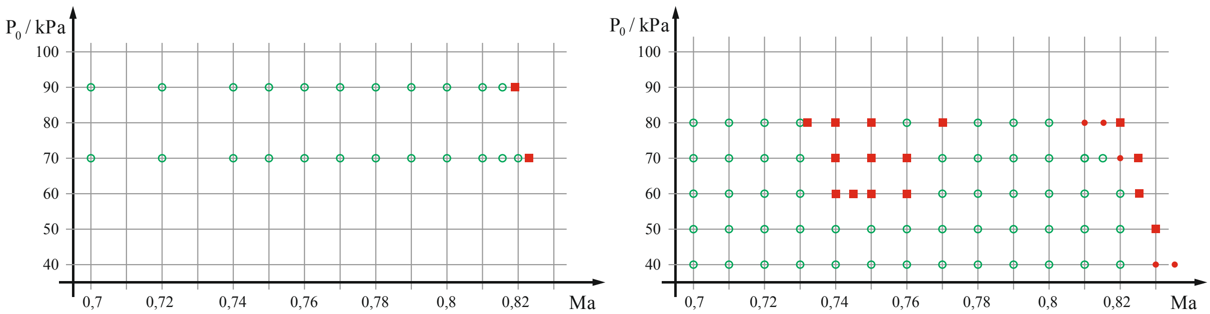

Figure 12: Limit cycle oscillations due to transitional flow (right) in comparison to turbulent flow (left), α= 0.0 degree. After Hebler [11].

For a less stable system with $x_\alpha > 0$ flutter can occur in the pressure range of the wind tunnel, see fig. 13. Comparable to fig. 12 also a destabilizing influence of transition on aeroelastic stability can be seen. For this case of constant angle of attack and therefore different steady lift, the transitional effects shift the flutter boundary considerably to lower Mach numbers and to lower static pressures.

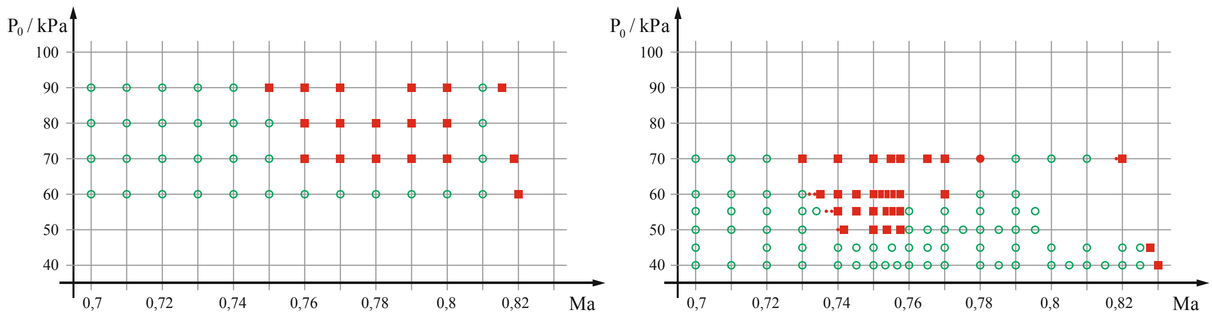

Figure 13: Effect of transitional flow (right) in comparison to turbulent flow (left) on flutter stability, α=0.0 degree. Experimental result of Hebler [11].

3 APPROPRIATENESS OF STATE-OF-THE-ART METHODS

3.1 Transferability of Subscale Tests to Aircraft Conditions

For subsonic flow, it can expected for larger Reynolds numbers, that the unsteady transition effects might be less severe than obtained by Hebler [10], because of the thinner boundary layers. In transonic flow, results from subscale tests are not transferable to the real aircraft, because of the inevitable occurrence of laminar separation bubbles at typical Reynolds numbers in conventional wind tunnels, which are provoked by compression shock waves. The remaining capability to assess the flutter risk of the laminar wing besides flight test is therefore a combination of test and simulation. Forced motion tests in cryogenic/pressurized wind tunnels like ETW or NTF are performed to measure the unsteady aerodynamics. The resulting data are used for validation or calibration of numerical models and then these numerical models can be applied for aeroelastic analysis.
Without a detailed design task, no general tendency can be given for the aeroelastic stability of a laminar wing in comparison to a turbulent wing in a serious way, because of the various and very complex influences of the design parameters. A laminar wing will have completely different airfoils, a reduced sweep angle, different shock configurations and dynamic behavior, different structural properties, and so on. The design risk can be reduced to the uncertainty and nonlinearity of the unsteady airloads at high Mach and high Reynolds numbers.

3.2 Validity of Numerical Models

Nowadays, CFD methods have reached a level of maturity and robustness that in the design and development phases of an aircraft it will be sought to apply these methods for any risk assessment of new technologies concerning flutter. Looking on the specifically relevant physical effects described above, the validity of the CFD methods for unsteady, transonic, transitional flows has to be checked very accurately. If we limit the investigation on *Reynolds averaged Navier-Stokes* (RANS) solvers, the analysis can be focused first on the inevitable models for turbulence and transition and their validity for the aspired Reynolds number range. Second, in the solver it has to be ensured that the transition is allowed to move on the oscillating wing surface and the relevant effects on the unsteady airloads are considered at all.
This subscale validation task with respect to aircraft flutter analysis can be seen as sufficient, if a) the transition and turbulence models are valid at both Reynolds numbers for the model in wind tunnel and the aircraft in flight, and b) the CFD-code including these models is validated for typical (low) frequency range of flutter, which is well below the frequencies of *Tollmien-Schlichting waves*.

Fehrs [12-14] used first the existing γ-Re_θ transition model of Menter [15] in combination with the SST k-ω turbulence model to demonstrate for a wind tunnel Reynolds number of Re = $2\cdot10^6$ the capabilities to capture the nonlinear lift curve in transonic flow (Fig. 14) and to make a qualitative comparison for the flutter behavior of the CAST10-2 (Fig. 15).

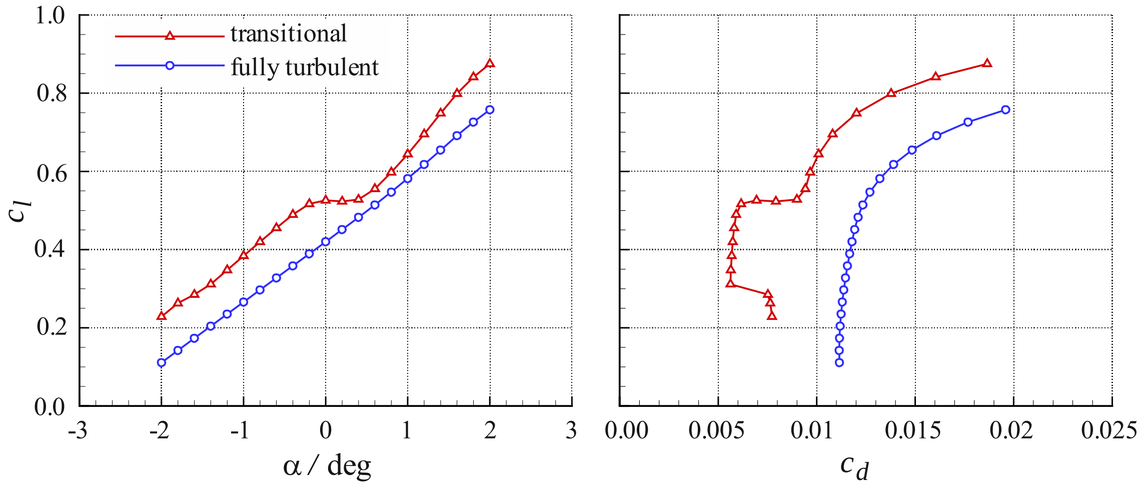

Figure 14: Lift and drag curve for the CAST10-2 airfoil for Re = $2\cdot10^6$ at Ma = 0.72 [14].

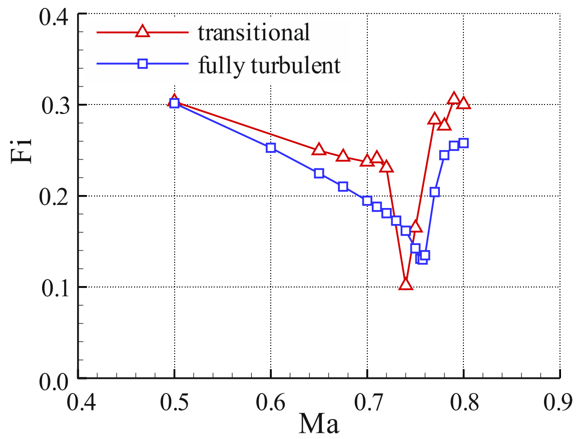

Figure 15: Effect of transitional flow on flutter stability. Numerical result of Fehrs [12].

However, a satisfactory quantitative agreement with the experimental data of Hebler was not reached by use of the γ-Re_θ transition model. Concerning state of the art numerical methods it has to be stated furthermore, that no transition model is known to be valid and robust enough for the assessment of laminar wing design for $10^6 < Re < 10^7$.

Flutter analyses for a laminar wing, which are based on CFD methods with state-of-art transition models, might be therefore as non-conservative as analyses for fully turbulent flow. As a consequence, a flutter case, which depends on transition effects, can today not be correctly predicted or not identified at all by numerical aeroelastic simulation.

4 RISK DEFINITION AND ASSESSMENT

4.1 Risk Definition

In the following, some risks for the aeroelastic behavior of a transport aircraft with a laminar wing are defined, which are later assessed in some detail.

Risk 1: Non-conservative Flutter Predictions. During the development or certification test of an aircraft, flutter occurs at lower Mach numbers or at lower dynamic pressures as predicted at least at one critical off-design point in the flight/operational envelope with the consequence of a delay of the entry into service.

Risk 2: Vibrations in Off-design. Limit cycle oscillations occur due to local aerodynamic excitations, which are reduced to moving transition areas at higher or lower local angles of attack (upper and lower limit of drag bucket).

Risk 3: Uncertainties due to *Boundary Layer Receptivity*. Loss of laminarity caused by surface contamination, surface waviness, or bypass transition [16] in a high disturbance environment reduces flutter stability and increases dynamics response amplitudes.

Risk 4: Non-conservative Gust Load Predictions. Gust of large amplitude causes unpredicted increase of loads due to non-conservative numerical methods comparable with risk 1.

4.2 Risk Assessment

Risk 1: Non-conservative Flutter Predictions. In the case of flutter prediction by numerical analysis, possible reasons are that the boundary layer is assumed to be fully turbulent or that the transition is not taken into account correctly in the calculation of the unsteady airloads for a wing oscillating in its elastic vibration modes. In the case of flutter predictions purely based on wind tunnel tests, reasons are that either the Reynolds similarity (with dynamically scaled models) or the Cauchy similarity (e.g. in cryogenic, pressurized tunnels) could not be fulfilled.
The quasi-steady transition effect as described for subsonic flow by Mabey [3] and confirmed by Hebler [10] for $Re=2\cdot10^6$, is related to the boundary layer displacement thickness. On the CAST10-2 airfoil, the transition location moves quite widely with changing angle of attack and also in the unsteady case for an oscillating wing. This transition movement increases the displacement thickness variation and therefore the effect on the unsteady airloads due to the different chord-wise boundary layer thickness developments in laminar and in turbulent flow. At flight Reynolds numbers with thinner boundary layers the transition motion effect will be therefore generally lower than in the wind tunnel tests. The difference of the test results for the unsteady airloads measured for free and fixed transition is nevertheless so large, that a remaining and remarkable effect for flight conditions can be assumed. For flutter analyses it has to be taken into account, that the reliability of CFD methods will be lower for laminar wings in comparison to turbulent wings due to the gaps in transition modelling, with the consequence of higher uncertainties in the motion induced unsteady airloads.
Due to limited available material and missing reliable numerical methods, a first risk analysis for a 3D wing might be done very roughly by use of the classical strip-wise approach. We assume that 3D effects on TS transition can be neglected. In this simple model, the discussed transition effects in a given section will depend therefore on local angle of attack, which is inside or outside the local laminar bucket or maybe just in the region with a nonlinear lift curve slope. Looking now on the several sections across the wing span, it is the question, if the described destabilizing effect occurs only in a very limited span-wise section or if it occurs across more or less the complete wing at a critical angle of attack of the aircraft. For simplicity we assume that the same airfoil is used across the wing span. The wing might be optimized for the design condition in such a way, that the local drag values are minimal for all the sections. In this case, the friction drag will be minimal in a maximum α-range. For a

critical higher angle of attack at the limit of the laminar buckets, the transition moves forward in all the sections together. Such a design of a laminar wing would be therefore the most risky case for flutter, because all the local transition effects would integrate up to a global effect on the complete wing.

Risk 2: Aircraft vibrations in off-design. Nonlinear effects due to transition occur additionally to or in interaction with nonlinear shock effects and cause limit cycle oscillations. In transonic flow, even local nonlinear effects can be sufficient to excite low damped modes (risk 1) to limit cycle oscillations.

Risk 3: Uncertainties of Flutter behavior due to boundary layer receptivity. Transition at arbitrary span-wise positions occur unexpectedly much more upstream than predicted due to external disturbances. The laminar region is hereby reduced and also the local lift. The necessary aircraft trim would cause additional changes of the aerodynamics on the complete wing with effect on flutter stability.

Risk 4: Non-conservative gust load predictions. The risk for gust load predictions due uncertainties of numerical methods and the boundary layer states can be generally transferred from the previous paragraphs for flutter. But it has to be evaluated specifically, what happens, if an aircraft with a laminar wing enters a gust field. The load increase due to a gust angle might be primarily even reduced, if transition from laminar to turbulent flow is shifted upstream. The dynamic behavior has to be investigated in more detail. Cases in the flight envelope might exist, where the boundary layer is changed by the gust from a turbulent to a laminar state with the effect of load increases.

5 RISK MANAGEMENT

Objective of all risk reduction actions is to mitigate the development risks of an aircraft with a laminar wing long before the flight test phase. Possible means are therefore improved numerical capabilities using validated models, adequate validation data from wind tunnel or flight tests. For a specific design of an aircraft, the risk can be quantified by uncertainty analyses and covered by the typical provisions for structural changes or compensation masses. Additionally the aerodynamic wing design can be optimized with the objective to reduce the risks.

5.1 Wing Design

With state-of-the-art numerical methods and wind tunnel tests with fixed models to measure performance and loads data, the risk management will rely on quasi-steady observations together with typical engineering assumptions and parameter variations.
Nonlinearities in the lift curve slope are always good indicators concerning uncertainties of the unsteady airloads and the LCO risks. It should be avoided, that the strong motion of transition takes place at the same angle of attack across a larger span-wise section, cf section 4.2, third paragraph. An obvious counteraction is therefore to ensure that the transition shifts smoothly along wing span. Special attention should be given to the transition behavior at the wing tip due to the large influence on generalized unsteady airloads for elastic modes.
Nevertheless, such a procedure might reduce but cannot cover the risks due to unsteady effects.

5.2 Improved numerical prediction methods - γ -Transition Model

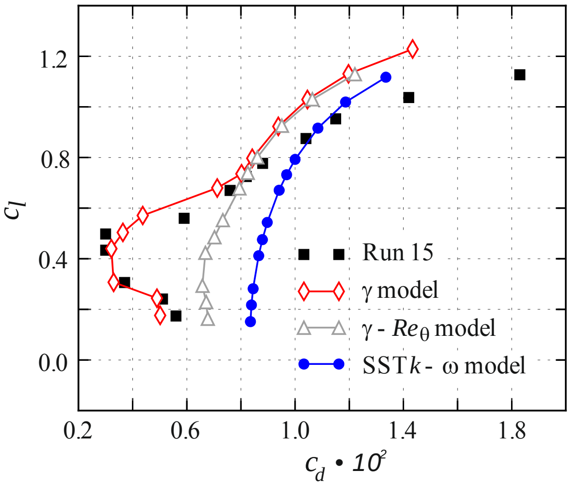

Figure 16: Drag polar for NLF1-0414F airfoil for Re = $9.5 \cdot 10^6$ at Ma = 0.4. Experimental Run 15 from [18].

Fehrs proposed recently [17] a one-equation transition model based on the γ-Re_θ transition model of Menter [15], which keeps the transport equation for the intermittency variable γ. The γ transition model is built to predict Tollmien-Schlichting transition in external aerodynamic flows in a low disturbance environment found in free flight. The revised transition onset correlation is validated for chord Reynolds number up to Re = $50 \cdot 10^6$ and for 2D and 3D flows. An example of the γ transition model prediction capabilities is depicted in Fig. 16 for a laminar airfoil.
Figures 17 and 18 depict computational results for the ALF 3 test data [10] for Ma = 0.7 and 0.75. Especially Ma = 0.75 is a challenging test case as the transition behavior is influenced by the separation behavior in combination with shocks as the angle of attack increases. The drag bucket limit is met reasonably well by the γ transition model.

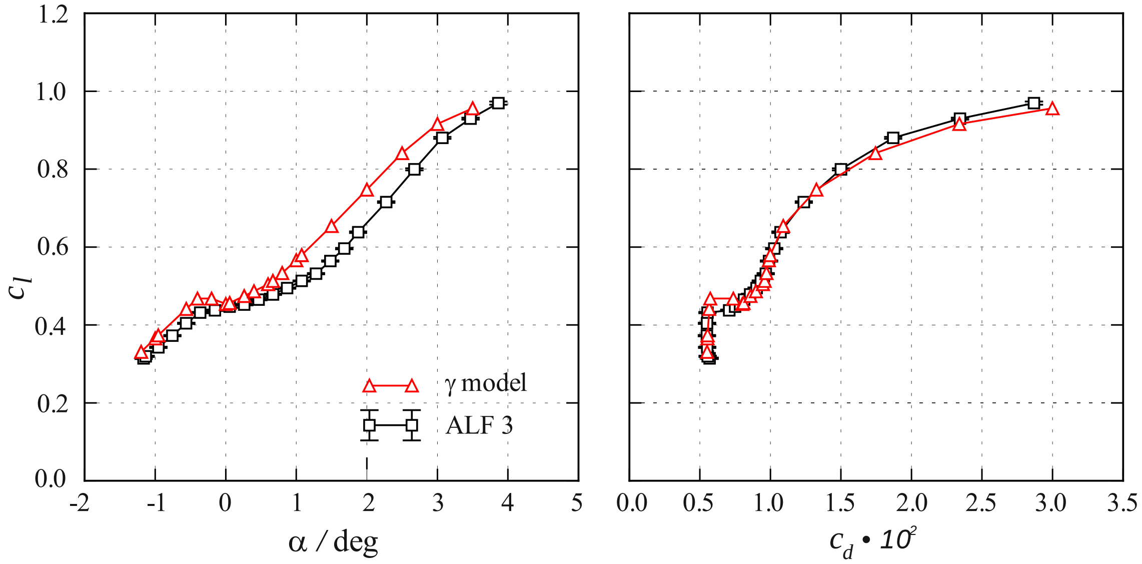

Figure 17: Lift and drag curve for the CAST10-2 for Re = $2 \cdot 10^6$ at Ma = 0.7.

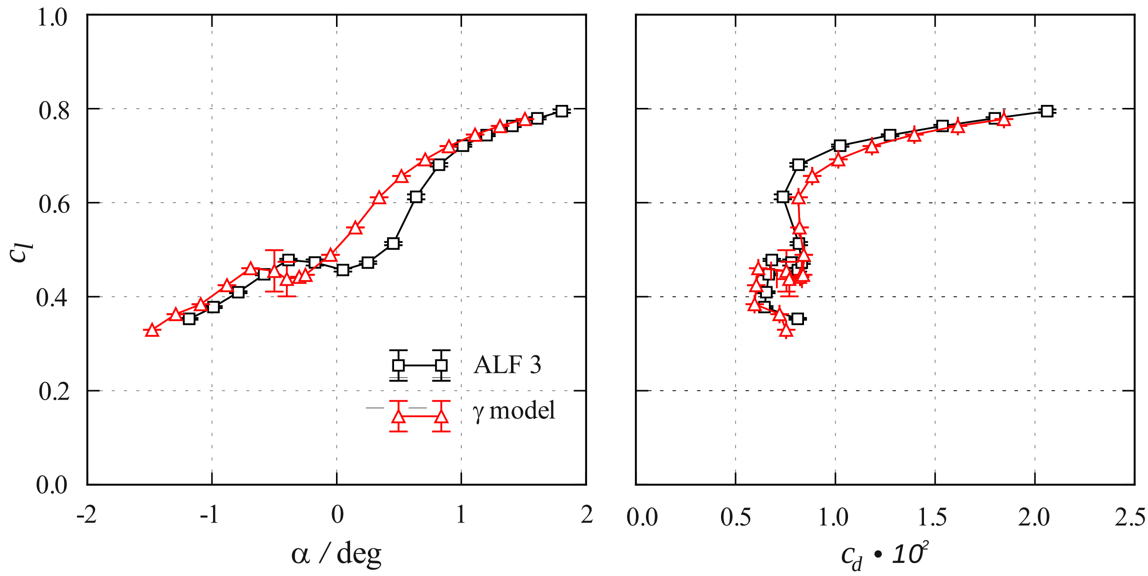

Figure 18: Lift and drag curve for the CAST10-2 for Re = $2{\cdot}10^6$ at Ma = 0.75 (same Mach number correction as in [10]).

Therefore, the γ transition model is currently seen as a very promising enhancement of the DLR-TAU code in order to make more reliable flutter predictions for laminar wings.

5.3 Experimental Validation at High Reynolds and Mach Numbers

Concerning motion induced unsteady aerodynamics and flutter of laminar wings, there is a lack of validation data in the Reynolds number range of $5{\cdot}10^6$ to $1{\cdot}10^8$ for 2D and 3D subsonic as well as for transonic flow. The reasons for this situation are manifold, technically and economically.

Such tests are very challenging, appropriate excitation capabilities would have to be developed for the large cryogenic wind tunnels like the ETW in Cologne and/or the NTF in Hampton, installed and tested. Furthermore, tests in such tunnels are extremely expensive. The feasibility of forced excitation under cryogenic conditions was already demonstrated by DLR in the DNW-KKK low speed wind tunnel in Cologne.

6 SUMMARY AND CONCLUSION

Laminar flow on transport aircraft wings is seen as a remaining risk for the aeroelastic behavior in comparison to a conventional wing with fully turbulent flow. The effects are expected to be lower than in existing tests results in conventional wind-tunnels, but are seen as non-negligible especially in off-design conditions.

For the practical realization of laminar wings on large transport aircraft it has be ensured that the reliability of flutter predictions are as robust as today for conventional wings. Much more emphasis should be given therefore to the research of the unsteady aerodynamic effects of a laminar wing at high Reynolds numbers, to adequate transition models and validation data in order to improve the technical basis of the risk analyses concerning flutter and gust loads.

The γ-transition model seems to be a suitable solution to improve current RANS solvers. It can be applied in numerical aeroelastic simulations already, but it must be validated properly in a dedicated wind-tunnel test with a laminar wing model at typical flight Mach and Reynolds numbers.

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