Mitteilung

Fachgruppe: Turbulenz und Transition

Experimental Design for the Validation of Extended Hybrid Laminar Flow Control and Transition Prediction in Complex 3D Flows

Lajos Fohlmeister, Rolf Radespiel
Institute of Fluid Mechanics, TU Braunschweig, Germany, lajos.fohlmeister@tu-braunschweig.de
Sebastian Helm, Cornelia Grabe
Institute of Aerodynamics and Flow Technology, DLR Göttingen, Germany

The need for a Transition Experiment

Laminar Flow Control (LFC) and Hybrid Laminar Flow Control (HLFC) offer significant potential to reduce drag on aircraft, particularly by minimizing skin friction drag on lifting surfaces and fuselage [1]. This is critical for improving fuel efficiency and reducing emissions. However, successful implementation of LFC, especially HLFC, faces two primary challenges:

1. **Accurate Transition Prediction**: Predicting the transition from laminar to turbulent flow during the design process is essential but remains difficult for industrial applications [2]. This is especially true for complex three-dimensional flows involving Tollmien-Schlichting instabilities (TSI) and cross-flow instabilities (CFI), significant deviations from ideal pressure distributions as well as laminar flow control. Therefore, current models, often based on empirical data, require validation through experiments to test their capabilities and assumptions [2].
2. **Active Laminar Flow Control**: Laminar flow can be controlled through passive methods like optimizing airfoil geometry, active methods like suction (LFC), or hybrid approaches (HLFC) that combine both. Active methods typically involve trade-offs between system complexity and achievable laminar length [2]. The extended hybrid laminar flow control (xHLFC) concept proposed by Traub et al. [3] aims to extend laminar flow up to 80% of the chord length while reducing system complexity and improving off-design performance. Although the feasibility of this concept has been demonstrated on unswept wings at moderate Reynolds numbers [4], it has not yet been tested on a swept wing at higher Reynolds numbers.

To address these challenges, this paper presents an experimental setup that measures transition in three-dimensional flow scenarios and tests the xHLFC design on a single wing model.

Validation Experiment Design

The experiment involves a 2.25-meter span untapered wing model with an unswept root section and a 35-degree swept outer section, see Figure 1. The sections are connected by a progressively increasing sweep angle, approximating a circular segment. The model is designed to be tested in the DNW-NWB low-speed wind tunnel. To enable testing at high Reynolds numbers, the model's airfoils are designed to be almost symmetrical. Combined with the restriction to small angles of attack (AoA), this reduces the lift generated at high chord lengths and, consequently, minimizes the wind-tunnel's influence. As a result, Reynolds numbers between 4.5 and 5 million are achieved at design speeds.
The model is divided into two sections:

1. **xHLFC Concept validation**: The outer wing section, which includes a suction chamber, simulates the amplifications present in free-flight conditions of a reference airfoil in the wind tunnel. The planform is designed to create nearly parallel isobars in this regime. Due to the significantly lower Reynolds number in the wind tunnel experiment, the used airfoil requires modifications to achieve similar levels of instability amplification. This is achieved by increasing the airfoil thicknesses and reducing the chord position of the maximum thickness to start the adverse pressure gradient earlier to amplify the TSI.
   A fully integrated suction chamber design, as suggested by Traub, is to be tested. In this design, the perforated skin surface and the suction chamber substructure are printed as a single part [3].

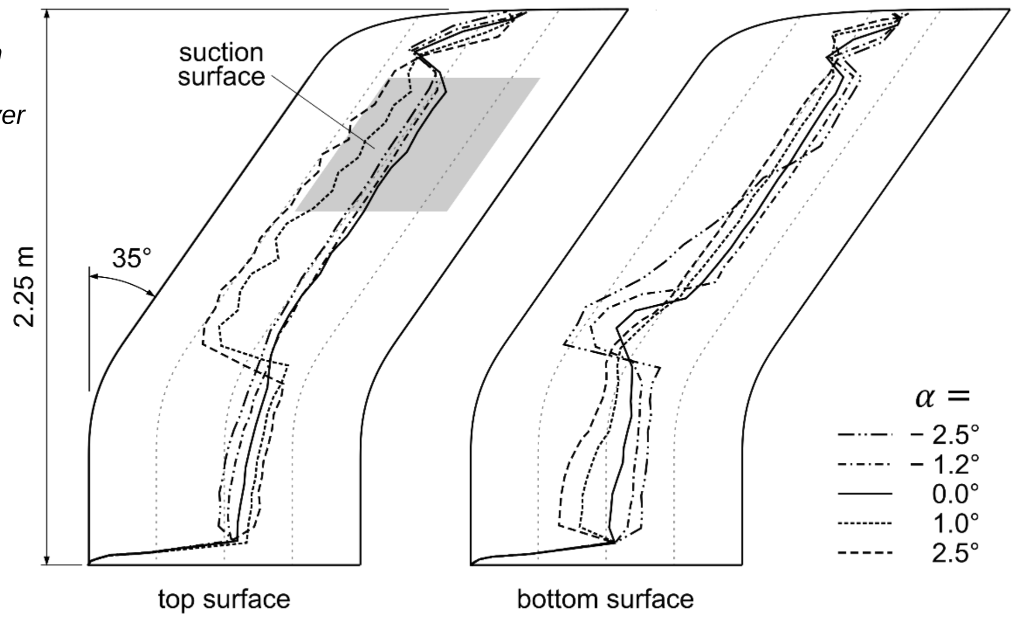

Figure 1 *Transition lines calculated with LILO based on the RANS boundary-layer data. Re = 4.45 Mio., Ma = 0.18*

2. **Three-Dimensional Transition Study**: The inner wing section, with a progressively increasing sweep, creates complex transition scenarios where TSI and CFI are both significant. Using the AoA it can be controlled, which instability is causing transition. The bottom side features different airfoil sections to create a spanwise pressure gradient, further varying the transition position.

First numerical Results

The model geometry was recalculated under wind tunnel conditions using the DLR-TAU code comparing different transition prediction methods. These calculations do not yet incorporate suction or wind tunnel effects. The resulting transition lines for a calculation employing the e^N method based on the LILO stability code and three-dimensional boundary layer data extracted from the RANS solution are shown in Figure 1. It can be seen that the 2.5d conditions for the xHLFC validation are satisfied as the transition line is almost constant in the outer wing section on the upper surface. The forward movement of the transition line between an AoA of 0° and an AoA of 1° is caused by a change in the transition mode from TSI to CFI. In this way, the suction chamber can be tested with both transition modes.

On the bottom surface, the sudden movement of the transition line is created by the gradually increasing sweep angle. A more subtle change in the transition line, further outboard, is caused by the spanwise variation of the airfoils. To validate the numerical results the transition line will be determined experimentally using infrared thermography.

Conclusion

A wind tunnel model with a spanwise-varying sweep angle was designed to serve two purposes: to test an extended hybrid laminar flow suction concept under conditions comparable to free flight and to create complex transition scenarios for numerical model validation. This model provides an opportunity to study the interaction between Tollmien-Schlichting and cross-flow instabilities in the presence of suction, advancing the understanding and application of laminar flow control in aviation.

References

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