Validation of a laminar-turbulent transition prediction technique for a swept-wing boundary-layer flow

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Abstract. The laminar-turbulent transition in the boundary layer of a 45° swept wing model installed at zero attack angle in the test section of a subsonic wind-tunnel was detected with the help of an infrared camera. The camera recorded sequences of frames, the evolution of the preheated model surface temperature acquired and used for differentiating between the laminar and turbulent regions. The transition onset was evaluated at both sides of the model. Corresponding main flow computations in the virtual wind tunnel test section were performed at the same flow conditions with ANSYS Fluent. The computed main-flow velocity profiles along inviscid streamlines were used for analysis of hydrodynamic stability of the boundary layer with respect to Tollmien-Schlichting waves and stationary cross-flow vortices to obtain N-factor distributions along the model chord. A comparison of the experimental and the computed transition onsets was performed.

1. Introduction
Modern computational technologies are becoming increasingly important in the design and optimization of modern aircraft and their individual elements. Hence, validations of engineering transition prediction techniques and corresponding software packages and modules are especially relevant.

The aim of this work is to compare the experimentally observed onset of three-dimensional laminar-turbulent transition with the predictions of an implementation of the eN-method in LOTRAN 3 software package. The results are presented for 45° swept-wing model installed at zero-angle of attack in the subsonic wind tunnel test section at different incident flow velocities. At the experimental conditions the boundary layer flow under the study is subjected to both Tollmien-Schlichting waves and cross-flow (CF) instabilities.

2. Experimental set-up
The experiments are performed in the low-turbulent subsonic wind tunnel T-324 of Khristianovich Institute of Theoretical and Applied Mechanics of SB RAS (Novosibirsk, Russia). The wind tunnel test section has dimensions 1×1×4 m and turbulence level of 0.02% (evaluated with high-pass filter of 1 Hz). Due to the low-turbulence level the wind tunnel is suitable for studying the laminar-turbulent transitions at the turbulence levels comparable with cruise flight turbulence conditions.

The model under study is 45° swept wing model SW45 installed in the test section at zero angle of attack. The wing model has modified laminarized profile NACA 67 1-215 with its chord length
SK45 model comprises a rigid frame formed by ribs and stringers and very smooth skins made of 3 mm thick acrylic sheets (with a roughness of order 0.1 micron) fixed to the frame. The nose part of the model (up to 10% of the chord length) is CNC-milled and has a painted surface with the roughness of the order 10 micron. The angle of attack of the model may be changed by rotating the model around a hard rod at the middle of the chord (0.5C). The transition positions measurements are performed at incident flow speeds \( Q \) from 10 to 50 m/c. When the SK45 model with correspondent equipment is installed in the test section the free-stream turbulence level increases to about 0.1% (slightly depending on the incident flow speed).

Figure 1. SK45 model installed in the test section of T-324 wind tunnel. View to the suction (‘upper’) side of the model. The wind tunnel flow direction is from right to left.

3. Application of infrared thermography for laminar-turbulent transition detection

Positions of laminar-turbulent transition were detected experimentally with the help of infrared (IR) thermography. A FLIR SC7300 infrared camera with 0.02K sensitivity and matrix size of 320×256 pixels was directed to the SK45 surface under study through a frontside or backside window of the test section (Fig. 1). The diameter of the window allowed observing a large part of the wing surface (about 0.7C in diameter) and, hence, a significant extent of the transition line along the wing span.

In order to “highlight” the difference in the heat exchange between the model surface and the boundary layer flow in laminar or turbulent state, the model was initially preheated with respect to an ambient air temperature by several degrees (4–6°K). The preheating did not notably influence the stability characteristic of the boundary layer, but it was significantly helpful to detect the laminar-turbulent transition. Every time the preheating was applied immediately before performing the wind-tunnel tests using a specially designed preheater, consisted of an array of 15 W halogen bulbs, spread uniformly over mirrored panels, that provided a more uniform preheating of SW45 compared with a single point light source. When the preheating was finished, the wind-tunnel was started and the acquisition of IR data began. Instead of single IR-frames, sequences of IR-frames were acquired at a rate 50 fps and for up to 70 s of full recording.

Representative examples of two unprocessed raw IR-images are shown in Fig. 2. They clearly visualize the surface temperature of the suction (‘upper’) side of SW45 exposed to the flow with the lowest and the highest examined speeds \( Q = 15 \) m/c and 50 m/s (Fig. 2 left and right, respectively). As the transition at zero angle attack is two-dimensional and sharp (short along the chord) over the surface under study and surface temperature differs in the laminar and turbulent regions significantly (about 2C) it is easy to evaluate the averaged laminar-turbulent transition position with a single IR-frame at about 0.82C and 0.79C for \( Q=15 \) m/c and 50 m/s, respectively.
Similar IR images acquired at the pressure ('lower') side of SK45 at the same flow velocities Q=15 m/c and 50 m/s are shown in Fig. 3. The detection of laminar-turbulent transition position is more difficult in the present case, as the wing skin at this side of SW45 has no uniform thickness along the chord (due to design restrictions) and, thus, the skin has no uniform thermal capacity. This leads to a faster cooling of the surface in the leading part of the model (blue/green colored cold areas at the left part of the images), but the middle part of the model remains hot (red colored). In accordance with [1, 2] the differentiation between laminar and turbulent regions may be simplified by analyzing the evolution of the model surface temperature in time. Figure 4 shows the corresponding changes of the model surface temperature per one second (i.e., the cooling rates). According to [2] the cooling rates have to be estimated in the specific narrow (about 2 second sonly) time interval taking place immediately after the wind tunnel flow settling. The evaluated cooling rates (Fig. 4) demonstrate pretty good uniformity through the whole laminar domain as well as a very pronounced difference between the laminar and turbulent regions. Thus, in the present case the cooling rates in the end of the transition region are about 4–5 times greater than those observed in the laminar region, so they allow reliably detecting the laminar-turbulent transition ending at 0.46C and 0.37C for Q=15 m/c and 50 m/s, respectively. The shape of transition region at Q=15m/s (Fig. 4 left) again appears to be quite straight that indicates the TS-dominated transition, while at Q=50 m/s (Fig. 4 right) it has a saw-tooth shape testifying a significant role of cross-flow vortices.

**Figure 2.** Raw FLIR SC7300 IR-images visualizing laminar-turbulent transition position at SW45 suction side: Q=15m/s (left); Q = 50m/s (right). The flow direction is from right to left.

**Figure 3.** Raw FLIR SC7300 IR-images visualizing laminar-turbulent transition position at SW45 pressure side: Q=15m/s (left); Q = 50m/s (right). The flow direction is from left to right.

4. Results and discussion
The three-dimensional Navier-Stokes equations were solved by a density-based solver, an implicit scheme of the second order in space with the Roe-FDS method of convective flux splitting. The computational domain was a parallelepiped with the sizes corresponding to T-324 test section. The domain was covered by a regular computational grid refined toward the wing surface and nose part. The grid was generated with the use of the C-grid type topology. When the angle of attack was changed, the entire block structure of the grid near the wing was turned. Thus, for all angles of attack, the computational grid was identical near the wing surface. The left (inlet) boundary of the computational domain was subjected to the free-stream conditions: pressure $P_\infty$, Mach number $M_\infty$, and temperature $T_\infty$. The no-slip condition and the adiabatic wall temperature were imposed on the model surface. The N-factors were determined by the LTT module developed by the authors on the basis of the LOTRAN 3.0 software package designed for basic research of stability of boundary layers of viscous compressible media and determination of the LTT position. For a more detailed description see [3].

![Figure 4. Calculated surface cooling rates dT/dt visualizing laminar-turbulent transition at SW45 pressure side: Q=15m/s (left); Q = 50m/s (right)](image)

The computed N-factor distributions at $Q = 15$ and $50$ m/s are shown in Figs. 5 and 6, respectively, together with the shape of NACA 67 1-215 airfoil and experimentally determined positions of transition onsets (found by a dipper processing of the surface cooling rates). As far as NACA 67 1-215 has laminarized shape at the upper (suction) side, the N-factors of Tollmien-Schlichting instability start to grow intensively only in the rear part of wing (starting from 0.6 of the chord length $C$). The cross-flow (CF) instability appears close to the leading-edge, but its N-factors remain low. Hence the transition at the upper (suction) side of SK45 is categorized as the TS-instability dominated one, that is also supported by two-dimensionality of experimentally found transition line (Fig. 2).

The behavior of calculated N-factors at the lower (pressure) side of the model is more involved. In particular, at $Q=15$ m/s, the N-factors of cross-flow instability experience a minor growth only in the leading part of the model, while TS-waves appear and heavily grow in the positive pressure gradient region (0.2 downstream of the chord length $C$). Thus, transition in this case is TS-dominated again. At $Q=50$ m/s, the N-factors of TS-instability again grow intensively, but now CF-modes also display significant values comparable with those obtained for TS-modes. A comparison of the threshold N-factors for TS-instability shows that in the first three cases they are very similar, being in the range from 8 to 12. So, an average value of about 10 could be assumed for engineering purposes. However, in the latter case (wing lower side at 50m/s) this behavior is violated. The three-dimensional shape of the transition area found in the experiment (Fig. 4 right) indicates that the transition there could be governed by a combination of both instabilities and needs an additional investigation.
Figure 5. N-factors for the TS-instability (brown) and CF-instability (blue) in the boundary layers of the pressure side (left) and suction side (right) of SW45 wing model at incident flow velocity \( Q = 15 \text{ m/s} \); transition onset (vertical dashed line); shape of the airfoil (black dashed line); \( x/C \) is the relative coordinate along the chord; \( y/C \) is the relative profile thickness.

Figure 6. N-factors for the TS-instability (brown) and CF-instability (blue) in the boundary layers of the upper (left) and lower (right) sides of SW45 wing model at incident flow velocity \( Q = 50 \text{ m/s} \); transition onset (vertical dashed line); shape of the airfoil (black dashed line); \( x/C \) is the relative coordinate along the chord; \( y/C \) is the relative profile thickness.

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