Numerical simulation of the laminar-turbulent transition on a swept wing in a subsonic flow

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Abstract. A subsonic (U∞=30 m/s) flow around a swept wing with a sweep angle of 45° and a chord of 700 mm aligned at an angle of attack in the test section of the T-324 wind tunnel based at the Khristianovich Institute of Theoretical and Applied Mechanics of the Siberian Branch of the Russian Academy of Sciences is considered. The experiments include measuring the static pressure on the model surface and thermal imaging of the laminar-turbulent transition (LTT). The numerical simulations of the laminar flow are performed by means of solving three-dimensional Navier-Stokes equations with the use of the ANSYS Fluent CFD software. The LTT position is determined by an LTT module developed by the authors on the basis of a LOTRAN 3.0 software package. The predicted results agree well with the experimental data and confirm that the favorable pressure gradient in the flow around the wing aligned at an angle of attack of −5° prevents the growth of the Tollmien-Schlichting waves and the LTT on the major part of the upper surface of the wing due to instability of crossflow vortices.

1. Introduction

The design of various flying vehicles should include the position and length of the laminar-turbulent transition (LTT) region because the flow character affects the vehicle drag. In the turbulent flow, the drag is greater than that in the laminar flow, resulting in large fuel expenses.

The present paper describes the LTT computations by the ANSYS Fluent CFD software [1] combined with the LTT module developed by the authors. The LTT module for determining the beginning and end of the transition on the surface was based on the LOTRAN 3.0 software package, which was previously developed at the Khristianovich Institute of Theoretical and Applied Mechanics of the Siberian Branch of the Russian Academy of Sciences and the Marchuk Institute of Numerical Mathematics of the Russian Academy of Sciences [2]. The LOTRAN 3.0 software package is based on a physically grounded method of the N-factor (eN-method) implemented for LTT predictions in viscous compressible three-dimensional flows with the use of original specialized matrix algorithms for LTT predictions in viscous compressible three-dimensional flows. The LTT module developed on the basis of LOTRAN 3.0 is incorporated into the ANSYS Fluent as an individual module (Fig. 1). The coordinates of the LTT beginning and end are determined along the streamlines at several stages. At the first stage, the main (laminar) flow is modeled by solving the Reynolds-averaged Navier-Stokes equations within the framework of the ANSYS Fluent software. At the next stage, the data on the laminar flow around the model are transferred to the LTT module by means of reading ‘cas’ and ‘dat’ files and are converted to the internal presentation of the LTT module by a data import module (marked by the
gray color in Fig. 1) specially developed for working with the ANSYS Fluent. Then the LTT module constructs the streamlines in the boundary layer. The normals to the model surface are constructed along the streamlines. All necessary data (pressure, temperature, velocity components, etc.) are interpolated onto a grid chosen on these normal. The integral characteristics of the boundary layer (displacement thickness and momentum thickness) are calculated. Data assimilation is performed, including replacement of data outside the boundary layer edge by constants. For each streamline, the local time stability is analyzed, and the corresponding neutral stability curves are calculated, which allow one to determine the beginning of spatial instability intervals and the corresponding time frequencies and wave numbers. Then the problems of spatial stability are solved on each streamline considered, and the $N$-factors and their envelope are determined. As a result, the LTT position can be found on the basis of prescribed threshold values of the $N$-factors.

Figure 1. Diagram of computation of the LTT position for three-dimensional flows with the use of the LTT module integrated in the ANSYS Fluent software.

The goal of the present work was to determine the LTT position in a three-dimensional boundary layer on a swept wing model with a sweep angle of $45^\circ$ and a chord $C = 700$ mm aligned at an angle of attack in a subsonic air flow. Various mechanisms of instability may occur on such a three-dimensional model of a swept wing with a streamwise pressure gradient and crossflow curvature at different angles of attack: both the Tollmien-Schlichting (TS) instability waves and crossflow instability owing to flow turning along the wing chord.

2. Experimental model and equipment

This work was initiated by experimental investigations of crossflow instability and TS waves in a separated or reattached boundary layer on an SK-45 swept wing model with a sweep angle of $45^\circ$ (Fig. 2) performed in the T-324 wind tunnel based at ITAM SB RAS. The T-324 wind tunnel is a subsonic low-turbulence closed-type wind tunnel with the test section size of $1 \times 1 \times 4$ m and turbulence level of 0.02% (measured in the frequency range above 1 Hz). When the model was installed, the free-stream turbulence level increased approximately to 0.09%. The SK-45 test model is a laminarized NACA 67-1-215 airfoil modified at the lower side. The model structure consists of a rigid casing (including ribs and stringers) covered by a shell made of transparent acrylic sheets with a thickness of 3 mm. The chord length $C$ in the direction normal to the leading edge is 700 mm. A stainless steel rod at the chord position $0.5C$ serves as an axis of model rotation for changing the angle of attack. The leading edge of the wing (with a length of 10% of the chord) is painted and has a roughness level with the root-mean-square amplitude of about 8.5 microns. The model is equipped with 27 static pressure taps on the model surface aligned into one row at $z = 0$ (along the wing model centerline) and two shorter rows at $z \approx \pm 100$ mm.
Figure 2. Swept wing model in the test section of the T-324 wind tunnel based at ITAM SB RAS (flow direction from right to left).

The laminar and turbulent regions of the flow were determined by a FLIR SC7300 infrared camera with a sensitivity level of 0.02°C, matrix size of 320 × 256, and recording speed of up to 140 frames per second. The camera lens was directed to the model surface through a circular window of the wind tunnel test section. Before each wind tunnel run, the SK_45 model surface was preliminary heated from outside approximately to +6°C by a set of distributed halogen lamps. A typical time of IR movie recording after wind tunnel actuation was 40–70 s. This time was usually sufficient for the wind tunnel flow to reach a required velocity, for the “transitional pattern” to be stabilized, and for the LTT line to become visible in the thermograms owing to the difference in wing surface cooling in the laminar and turbulent regions.

3. Numerical simulations

In the numerical simulations, the computational domain was a parallelepiped with the sizes corresponding to the T-324 test section. The computational domain height and width along the z axis were 1 m, and the length along the x axis was 4 m. The swept wing model with the NACA 67 1-215 airfoil was located at a distance of 1.245 m from the computational domain inlet. The computational 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 (Fig. 3a). 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 model rotation axis used to set the angle of attack of the wing passes through the airfoil center at 0.5C and is shown by the dashed line in Fig. 3b.

Figure 3. Fragment of the computational grid in the central plane of the computational domain (a) and on the upper surface of the wing with the rotation axis denoted by the dashed line (b): the angle of attack is AoA= −5° (each 16th cell).

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 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 LTT position was determined by the above-described 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.

4. Results

Figure shows the streamlines at a distance of one half of the boundary layer thickness from the upper surface of the wing aligned at an angle of attack $\text{AoA} = -5^\circ$. Figure 4b shows the distributions of the streamwise and transverse velocity components in the central cross section at $x=0.5/C$ (the cross section is denoted by the white plus sign in Fig. 4a). It is seen that the streamlines have S-shaped profiles typical for the swept wing; the profile of the transverse velocity component has a peak inside the boundary layer and an inflection point at a height of 0.48 of the boundary layer thickness, which ensures crossflow instability. The relations of the velocity components (Fig. 4b) show that the flow at the boundary layer edge turns by four degrees, whereas the angle of flow turning inside the boundary layer is greater, and the velocity vector turns approximately by 13.5 degrees near the wall.

![Figure 4](image-url)

**Figure 4.** Streamlines above the upper surface (suction side) of the wing at a height of one side of the boundary layer thickness (a) and streamwise ($U_x$) and transverse ($U_z$) velocity components in the cross section $x=0.5C$, in the central plane (b): $U_\infty=30$ m/s, $\text{AoA} = -5^\circ$.

The pressure fields near the wing surface (Fig. 5a) and the distributions of the pressure coefficients over the wing surface (Fig. 5b) as functions of $x$ (along the centerline of the computational domain) obtained in numerical simulations (curves) and in wind tunnel experiments (symbols) show that a favorable pressure gradient is formed on the major part of the upper surface of the wing. The existence of the favorable pressure gradient and inflections of the transverse velocity component ensure the prevalence of the crossflow instability over the instability due to TS waves. Figure 4b illustrates the good agreement of the computed and experimental pressure coefficients in the central plane of the wing.

The data on the laminar flow were transferred to the LTT module, followed by data assimilation, and then the space and time stability along each streamline was analyzed. Figure 6 shows the results of the analysis of the time stability of crossflow vortices (a) and the corresponding curves of the $N$-factors and their envelope (b) along the central streamline, which were computed by the LTT module. According to the $e^N$-method, the beginning and end of the LTT region are located in those places where the envelope of the $N$-factors reaches the corresponding threshold values. In the present study, the threshold values of the $N$-factors corresponding to the beginning and end of the LTT region were calculated by the formula derived in [3]; they were equal to 6.50 and 9.30, respectively [3].
Figure 5. Pressure field in the central plane near the wing (a) and distribution of the pressure coefficient $c_p$ along the streamwise coordinate in the central plane for the windward and leeward side of the wing obtained in numerical simulations and wind tunnel experiments (b): $U_\infty=30$ m/s, $Re_1=1.91\times10^6$ 1/m, $AoA = -5^\circ$.

Figure 6. Beginning (red points) and end (blue points) of the intervals of temporal crossflow instability (a), corresponding curves of the $N$-factors, and their envelope (b) calculated by the LTT module along the central streamline: $U_\infty=30$ m/s, $Re_1= 1.91\times10^6$ 1/m, and $AoA = -5^\circ$.

Figure 7 shows the laminar, transitional, and turbulent regions of the flow on the upper surface of the wing, which were computed by the LTT module for different types of instability. Since a turbulent boundary layer was developed on the side walls of the wind tunnel, streamlines necessary for calculating the flow stability were not constructed in flow regions near these walls (marked by the gray color). As was described above, the favorable pressure gradient prevents the growth of the TS waves (Fig. 7a); for this reason, the LTT occurs only at the end of the wing. However, the LTT induced by crossflow instability is observed on the major part of the wing surface (Fig. 7b). Figure 7c presents the flow pattern obtained with allowance for both instability types and the curves that show the distance from the leading edge of the wing normalized to the chord length (in percent).

Figure 7c shows that the numerical simulation predicts the LTT beginning at a distance of 0.4$C$ (40%) of the wing chord, and the LTT end at a distance of 0.7$C$ (70%). In the experiments, we measured the field of instantaneous temperature of the model surface by a thermal imager (Fig. 8a), and the LTT position was determined by considering the model cooling process (Fig. 8b). In Fig. 8b, the regions of slow cooling of the model (red color) correspond to the laminar state of the boundary layer, and the regions of faster cooling of the model (blue and green) correspond to the turbulent flow regions. The LTT beginning is assumed to be the averaged value of the coordinates of the beginning of the turbulent wedges, equal to 38% of the wing chord, which agrees with the numerical simulation results.
Figure 7. Flow regions (the laminar, transitional, and turbulent flow regions are marked by blue, green, and red colors, respectively) calculated by the LTT module (a-c) for the TS instability (a), crossflow instability (b), and both types of instability (c): $U_\infty=30$ m/s, $Re_1=1.91 \times 10^6$ m$^{-1}$, $AoA=-5^\circ$.

Figure 8. Field of instantaneous temperatures at the time $t_0$ (a) and field of variation of the model surface temperature ($\Delta T$) for 2 s near the time $t_0$ (b) obtained experimentally: $U_\infty=30$ m/s, $Re_1=1.91 \times 10^6$ 1/m, and $AoA=-5^\circ$.

Based on the results obtained, we can conclude that the LTT module developed on the basis of the LOTRAN 3.0 in-house software package integrated into the ANSYS Fluent software provides an adequate prediction of the LTT position in a subsonic flow around a swept wing aligned at an angle of attack with the instability mechanisms of the TS waves and crossflow vortices.

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