Simulation of the transition to turbulence in the boundary layer on complex-shaped bodies at an angle of attack

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Abstract. The paper deals with the numerical simulation of the laminar-turbulent transition as the gas flow moves at a nacelle at transonic speeds. The laminar-turbulent transition position in the 3D boundary layer of the nacelle is found with the aid of the laminar-turbulent transition module based on the eN-method which involves the data of the numerical simulation of the laminar flow at the model with the gas-dynamic software package ANSYS Fluent. Performance of this module is demonstrated as the laminar-turbulent transition, caused by the Tollmien-Schlichting wave and crossflow instabilities, takes place. It is shown that the Tollmien-Schlichting wave instability is the dominating mechanism of the laminar-turbulent transition on the nacelle up to the angle of attack of 7°.

1. Introduction

It is known that the position of the laminar-turbulent transition (LTT) and its length dictate the economic efficiency of the aircraft. The concept of the natural flow laminarization (NLF or the Natural Laminar Flow) suggests that, to reduce the drag of various aircraft elements (wings, nacelles, etc.), it is necessary to design its shape in such a way to provide the maximally extended zone of the laminar flow within the Mach number and angle of attack range intrinsic for the cruising flight. This leads to the problem of simulation of the laminar-turbulent transition in the boundary layers of complex-shaped bodies.

Using of software packages which simulate the propagation of small amplitude disturbances in the boundary layer and calculate the LTT position by the criteria based on a certain threshold value of the amplitude (the N-factor method, or eN-method) is among up-to-date approaches for the transition simulation. This method applied to aerodynamic problems is widely used due to its foundation on the physically vindicated linear theory of hydrodynamic stability. The theory of hydrodynamic stability is valid both for 2D and 3D incompressible and compressible flows at quite a low degree of free stream turbulence (Tu < 1 – 2%). Today, the eN-method of LTT determination is not presented in the general-purpose gas-dynamic packages [1], but it can be implemented as an individually connected module – the LTT module.

In recent years, the co-authors of this work developed the LOTRAN 3.0 software package implemented in the MATLAB environment for analysis of stability and LTT in 3D boundary layers to
be used with independent data on the laminar viscous compressible flow computed at an aerodynamic body with a practically acceptable accuracy by any CFD code. In this work, LOTRAN 3.0 was transformed into a corresponding LTT module integrated into the gas-dynamic package ANSYS Fluent as a plug-in to be able to estimate the transition position in 3D boundary layers of the complex-shaped bodies.

The numerical solution of 3D problems is still quite a complicated challenge. Many factors should be taken into account when determining the LTT, such as the presence of pressure gradients in different directions, surface roughness, free stream turbulence, etc. The paper deals with the effect of such aspects as the crossflow caused by the spanwise pressure gradient, and possible flow separation in the presence of the streamwise pressure gradient occurring possibly at nacelles, bodies of revolution, swept wings, etc. The development of Tollmien-Schlichting waves and stationary cross flow vortices as primary instabilities was suggested as the main possible mechanisms of the transition to turbulence. It is based on the fact that one of these mechanisms is dominating in different flow areas at ellipsoids set at a given angle of attack [2, 3]. At the same time, their relative significance is still not completely understood for the nacelles.

The main purpose of this work is to make conclusions about the dominating mechanism of the LTT in the boundary layer of a transonic gas flow at a nacelle set at an angle of attack.

2. Transonic flow at the nacelle

To create the nacelle model (NM), the profile LNT76 was designed; it provides quite an extended section of the laminar and transition boundary layer. Preliminary computations were carried out for the flow around the LNT76 profile in the axisymmetric statement at the zero angle of attack; these computations were later used to construct the 3D computational domain and numerical grid on the NM. Note that validity of the predicted LTT position based on the LOTRAN 2.0 software package aimed for LTT analysis of 2D flows with the help of eN-method and integrated into ANSYS Fluent has been shown [4] by the good agreement of the results with experimental data [5] obtained in a transonic wind tunnel at the wing profile NASA-SR-0410 with the chord length 0.2 m.

![Figure 1. Nacelle model with the numerical grid on the surface (each 4th cell).](image1)

![Figure 2. Velocity field in the NM plane of symmetry (the laminar mode): $M_\infty = 0.75, \alpha=7^\circ$.](image2)
block hexahedral computational grid fine toward the NM surface in both domains. The NM has the streamwise size 500 mm. Total amount of the numerical grid cells is 10.3 million.

Figure 2 shows that the free-stream Mach number $M_c = 0.75$ provides the flow at the NM with the extended supersonic section and closing shock wave typical for the transonic flow mode.

The flow at the NM is numerically simulated with the ANSYS Fluent 18.0 package with the following parameters: $P_\infty = 1$ atm, $T_\infty = 300$K, $M_\infty = 0.5$, $Re_l = 1.11 \times 10^7$ $1/m$, $\alpha = 0 \pm 7^\circ$ and $P_\infty = 2$ atm, $T_\infty = 300$K, $M_\infty = 0.75$, $Re_l = 3.32 \times 10^7$ $1/m$, $\alpha = 0 \pm 7^\circ$. The free-stream conditions assigned on the external boundary of the computational domain: pressure $P_\infty$, temperature $T_\infty$, Mach number $M_\infty$, and angle of attack $\alpha$, the non-slip and adiabatic wall conditionson the NM surface and the symmetry conditions in the plane of symmetry of the computational domain. In the numerical simulation, the stationary Navier-Stokes equations were solved with the aid of the solver based on density; the implicit scheme of the 2nd order of space accuracy with the Roe-FDS method of convective flow splitting was used. During the simulation of the completely laminar flow near the trailing edge of the NM, the laminar separation results in an essentially non-stationary flow. Thus, to improve the convergence and increase the computation quality, it is advisable to use the artificial turbulization deliberately downstream from the laminarized domain.

3. LTT computation module based on LOTRAN 3.0
The $e^\omega$-method is one of the most common engineering methods of LTT determination. Today, it is not presented in the general-purpose gas-dynamic packages, but it can be implemented as a plug-in for the LTT analysis. In 2013 the authors of this paper developed and registered the software package LOTRAN for the computation of the LTT position in the boundary layers of the viscous incompressible fluid flows above slightly curved surfaces [6, 7]. Then the significant work has been done to expand this software for the computation of the LTT position in compressible 2D and 3D boundary layers [8], which gave two new packages LOTRAN 2.0 and LOTRAN 3.0, respectively. They are purposed for fundamental scientific research of stability of 2D and 3D boundary layers of the viscous compressible fluid and determination of the LTT positions in them using the $e^\omega$-method. In this work, the LOTRAN 3.0 package was transformed into the LTT module for integration into the gas-dynamic package ANSYS Fluent.

The scheme of the integration of the 3D LTT module with the gas-dynamic package ANSYS Fluent [3] is the following. First, ANSYS Fluent is used to compute the laminar flow at a body with the 3D Navier-Stokes equations (see Sect. 2). Then, files with extension *.cas and *.dat are sent in the LTT module (case file contain the mesh, boundary and cell zone conditions, and solution parameters for a problem). A specially formed module of data import from ANSYS Fluent, the LTT module assimilates the obtained data and determines the boundary layer boundary. Then, the assigned number of streamlines are computed on the boundary layer boundary by the specially developed algorithm (figure 3 shows the computed streamlines on the NM). Each streamline is broken up to sections by the nods over its length; normal lines to the surface are built from these nods. Thus, the cross section forms along each computed streamlines (20 pcs).
streamline perpendicularly to the surface. Grids that are condensed near the surface are constructed on the normal lines, and the data on the main flow are interpolated into their points.

Then for each streamline the boundaries of instability regions of the most unstable disturbances and their time frequencies were computed by solving the local temporal stability problems for some given values of longitudinal wave number. The amplification factors (N-factors) of these disturbances in the instability regions were computed by solving the local spatial stability problems and then the envelope of the N-factors is computed. The \( \text{e}^N \) method suggests that the transition to the turbulence is observed when one of the N-factors rises up to the critical (threshold) value. The empirical formula \( N_c = -8.34 - 2.4 \ln(T_u) \) is used as the threshold value of the N-factors for the LTT start position at the moderate degrees of turbulence of the free stream.

![Figure 4. Schematic of the normal lines construction along each streamline followed with the interpolation of the main flow data in them.](image)

When determining the LTT, solving 3D problems, one should take into account many factors of the flow. In this work, the NM simulation involves such aspects as the cross flow with the pressure gradient and potential separation. The 3D LTT module based on the LOTRAN 3.0 complex, has its peculiarities. First, as was said above, it is the necessity to construct 3D streamlines on the boundary layer boundary and analysis of the temporal and spatial stability along each streamline. The second feature is the presence of two types of instability: the Tollmien-Schlichting waves and cross section vortices. In [3] it was demonstrated that during the flow around the elongated ellipsoid of rotation at the angle of attack, the instability of cross flow vortices imposes the dominating effect on the LTT process. The NM also presents the model of the rotation body with the strong cross overlow. The LTT module permits investigating both types of the flow instability and find the dominating LTT mechanism.

4. Numerical results
Figures 5a, b shows the streamlines colored by the N-factors obtained with the aid of the LTT module for the case of the flow around the NM at the angle of attack \( \alpha = 7^\circ \) at \( M_\infty = 0.5 \) and \( T_u = 0.2\% \). The data were acquired for the LTT position (the black line) for two types of instability: the Tollmien-Schlichting wave instability and cross flow vortices instability. Figure 5c demonstrates the LT transition zones plotted with due regard to both types of instability: the laminar (blue), transition (green) and turbulent (red) flow areas. It is evident that the Tollmien-Schlichting wave instability (TS) imposes the dominating effect on the LTT process on the NM with the cross flow at \( \alpha = 7^\circ \) and \( M_\infty = 0.5 \).

Figure 6 presents the same LTT characteristics but for the case of NM flow around at \( M_\infty = 0.75 \), \( \text{Re}_1 = 33.2 \times 10^6 \text{ m}^{-1} \), \( \alpha = 7^\circ \), \( T_u = 0.2\% \). It is evident that, similarly for \( M_\infty = 0.5 \), at \( M_\infty = 0.75 \) the LTT occurs earlier on the NM leeward than on the windward. It is also seen that at \( M_\infty = 0.75 \), the LTT comes later than at \( M_\infty = 0.5 \), in spite of the essential Reynolds number overrun. It means that, as the Mach number rises, the position of the transition start moves downstream on the NM. This very dependence was observed on the 2D bodies (the plate), too [10].
Figure 5. Streamlines colored by the $N$-factors: Tollmien-Schlichting wave instability (a); instability of cross flow vortices (b) and LT transition zone for both types of instability (c): laminar (blue), transition (green) and turbulent (red) flow areas. $M_\infty = 0.5$, $Re_l = 11.1 \times 10^6$ m$^{-1}$, $\alpha = 7^\circ$, $Tu = 0.2\%$.

Figure 6. Streamlines colored by the $N$-factors: Tollmien-Schlichting wave instability (a); instability of cross flow vortices (b) and LT transition zone for both types of instability (c): laminar (blue), transition (green) and turbulent (red) flow areas. $M_\infty = 0.75$, $Re_l = 33.2 \times 10^6$ m$^{-1}$, $\alpha = 7^\circ$, $Tu = 0.2\%$. 
5. Conclusion
The laminar-turbulent flow at the nacelle is numerically simulated at the transonic velocities and low degree of turbulence of the external flow by the package ANSYS Fluent with the LTT module based of the original software package LOTRAN 3.0.

The performance of the LTT module is demonstrated during the natural LTT caused by the amplification of the Tollmien-Schlichting wave amplitudes and instability vortices of the cross flow.

It is shown that, in spite of the strong crossflow, the Tollmien-Schlichting wave instability is the dominating mechanism of the LTT up to the angle of attack of 7° on the NM at $M_\infty = 0.5$.

The data obtained on the LTT position and dominating mechanisms in the boundary layer of the nacelle flown by the transonic gas flow at the low degree of turbulence are necessary for the creation of the laminarized NM in order to reduce the drag friction on its external surface.

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