Numerical simulation of the transition to turbulence in subsonic and transonic flows

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Abstract. The goal of the paper is to determine the position of the laminar-turbulent transition in subsonic and transonic two-dimensional boundary layers on an airfoil with the use of the a laminar-turbulent transition module based on the $e^N$-method and using the results of numerical simulations of the laminar flow around the model performed by the ANSYS Fluent software. The combined operation of the CFD software and the laminar-turbulent transition module is illustrated by an example of the air flow around the NASA-SR-0410 supercritical airfoil. It is demonstrated that the predicted and experimental data on the laminar-turbulent transition are in good agreement.

1. Introduction

It is necessary to determine the laminar-turbulent transition (LTT) in the boundary layer (BL) for solving the problem of laminarization of the flow around wings, engine nacelles, and other elements of flying vehicles, aimed at reducing their drag in the ranges of Mach numbers and angles of attack corresponding to the cruising flight of civil aircraft [1]. The description of the LTT process in flows with low free-stream turbulence is usually divided into three consecutive stages. The first stage, which occurs near the leading edge, is called receptivity. Receptivity describe the process where forced perturbations, such as free-stream noise, free-stream turbulence, vibrations, small roughness elements, etc., enter the laminar BL and excite its own modes. At the second stage, these modes acquire the shape of periodic waves. Some of them are amplified in the streamwise direction and initiate the LTT. In two-dimensional flows, linearly growing waves are called the Tollmien-Schlichting (TS) waves. The evolution of these waves is accurately described by the linear stability theory; therefore, the LTT position in the BL can be calculated by using criteria based on reaching certain threshold amplitude by perturbations ($e^N$-method). This method is fairly popular in aerodynamic applications because it is based on a physically grounded linear theory of hydrodynamic stability, which is valid for both two-dimensional and three-dimensional incompressible and compressible flows up to hypersonic velocities if the free-stream turbulence level is sufficiently low (flight conditions, quiet wind tunnels). At the moment, there are many specialized commercial CDF software systems; the most popular ones are the GTPT (Graphical Transition Prediction Toolkit) [2] and NOLOT (NOnLOcal Transition analysis) [3]. It should be noted that there are no other methods that can be applied in compressible and three-dimensional flows [4]. The empirical model for LTT prediction [5] (called Transition SST in the ANSYS Fluent software), which is popular in academic and industrial communities, was calibrated only for subsonic incompressible flows.
In 2013, the co-authors of the present paper developed and registered the LOTRANxx software package for calculating the LTT position in the boundary layer of a viscous incompressible fluid above small-curvature surfaces [6, 7]. After that, significant efforts were applied to develop this software package further for calculating the LTT position in a compressible BL [8], which resulted in a new software package called LOTRAN 2.0. LOTRAN 2.0 is an autonomous software package implemented in the MATLAB environment for the analysis of aerodynamic stability and LTT calculation in two-dimensional boundary layers on the basis of data on the laminar viscous compressible fluid flow computed by an arbitrary CFD code.

In the present work, the LOTRAN 2.0 autonomous software package is transformed to the LTT module integrated into the ANSYS Fluent system as an additional module calculating the LTT position (Fig. 1). The coordinates of the LTT beginning and end are calculated in several stages. At the first stage, the laminar flow around the model is computed by means of solving two-dimensional Navier-Stokes equations by the ANSYS Fluent CFD software. Then the normals to the model surface are constructed with the use of an export module specially developed for the ANSYS Fluent system, the data for the laminar flow along these normals are interpolated, and a data file to be transferred to the LTT module is generated (the file contains all data: computational grid, flow parameters along the normals to the model surface, boundary conditions, etc.). At the next stage, the LTT module ensures data assimilation with the use of a specially developed import module integrated into the LTT module, analyzes the temporal and spatial stability of the flow, and determines the LTT position by the $e^N$-method by means of analyzing the growth of low-amplitude perturbations in the streamwise direction.

Figure 1. Scheme of integration of the LTT module with the ANSYS Fluent software for two-dimensional flows.

Operation of the LTT module integrated into the CFD software is demonstrated by an example of the air flow around the NASA-SR-0410 airfoil at subsonic and transonic velocities. This airfoil was chosen because of availability of experimental data on the LTT position measured in a transonic wind tunnel at Mach numbers from 0.25 to 0.85 [9].

2. Numerical simulation of the laminar flow around the airfoil

The coordinates of the LTT beginning and end are determined in a procedure including several stages. At the first stage, the laminar flow around the NASA-SR-0410 airfoil with the chord length $c = 0.2$ m is calculated by solving two-dimensional Navier-Stokes equations by the ANSYS Fluent CFD software. Figure 2a shows the general view of the computational domain: the airfoil is located at the center, while the external boundary of the computational domain is shifted to a distance of more than ten chord lengths, i.e., $\geq 2$ m. To resolve the BL, a prismatic sublayer is formed on the body surface, whereas the remaining space of the computational domain is filled with triangles in an irregular manner (Fig. 2b). The height of the prismatic sublayer is chosen to be equal to the doubled maximum BL thickness whose parameters were determined in preliminary laminar computations.
Figure 2. General view of the computational domain (a) and fragment of the computational domain near the leading edge of the airfoil (b).

The two-dimensional Navier-Stokes equations are solved by a density-based solver with the use of an implicit scheme of the second order in space with the Roe-FDS method of splitting of convective fluxes. The outer boundary of the computational domain is subjected to the free-stream conditions: pressure $P_\infty$, Mach number $M_\infty$, temperature $T_\infty$, and angle of attack AoA. It should be noted that positive and negative AoA values in this work correspond to flow impinging from below and from above, respectively. The no-slip condition and constant temperature $T_w=300$ K are imposed on the model surface.

In modeling the laminar flow around the NASA airfoil, laminar separation arising closer to the trailing edge leads to significant unsteadiness of the flow. Figure 3a shows the shear stress distribution $w_{ss}$ over the model surface, which was obtained in computations of the laminar flow around the airfoil.

Figure 3. Shear stress distribution over the upper surface of the airfoil: 1 – laminar flow; 2 – flow with nonzero turbulent viscosity beginning from xturb_up=0.15 m and xturb_down=0.1 m (a) and flow field of the velocity derivative with respect to the streamwise coordinate (b); $Re_1 = 5\times10^6$ m$^{-1}$, AoA = 0, $M_\infty =0.25$, $T_\infty = 296$ K, and $T_w= 300$ K.

The values $w_{ss} = 0$ mark the laminar separation region. It is seen that the value of $w_{ss}$ on the upper surface of the model decreases to zero at $x = 0.15$ m. Figure 3b shows the field of the velocity derivative with respect to the streamwise coordinate, which shows that flow oscillations on the upper surface of the airfoil appear starting from $x = 0.15$ m. They are manifested as alternation of flow acceleration and deceleration regions. A similar behavior of the flow on the lower surface is observed from $x = 0.1$ m.

One of the methods for preventing unsteadiness in the laminar separation region is to perform a steady computation with the flow region divided into two subdomains: laminar subdomain (near the
leading edge), where the turbulent viscosity is equal to zero, and turbulent subdomain including the separation region, where the turbulent viscosity is not equal to zero. The points of this division (xturb_up and xturb_down) are determined in preliminary calculations of the laminar flow on the basis of the beginning of unsteadiness on each side of the airfoil and are then defined by a specially developed UDF module built into the package. The Spallart-Allmaras turbulence model is used for implementation of the method. The distribution of the shear stress over the model surface (velocity gradient along the normal) obtained in calculating the flow around the airfoil with nonzero turbulent viscosity is also shown in Fig. 3a. In solving the problem, the BL characteristics on the airfoil are obtained and transferred at the next stage to the LTT module.

3. Determination of the transition position with the use of the integrated LTT module
For determining the LTT transition in two-dimensional boundary layers, the LOTRAN 2.0 software package was transformed to the LTT module to be integrated into the ANSYS Fluent CFD software. For this purpose, the LTT module contains a special data import module, as well as multistage preliminary processing and analysis of BL characteristics for increasing the accuracy of subsequent computations of stability.

The module calculates the integral characteristics of the BL (displacement thickness and momentum thickness) for qualitative evaluation of the result of data assimilation from ANSYS Fluent, and data assimilation is performed, including replacement of data outside the BL by constants. The LTT position is determined by the eN-method on the basis of the analysis of streamwise growth of low-amplitude perturbations. Enhancement of perturbations is calculated by the equations of propagation of three-dimensional disturbances based on the full equations of heat and mass transfer for a viscous compressible medium, which are linearized with respect to the laminar flow under consideration. A detailed description of these equations and algorithms can be found in [8].

![Figure 4](image)

**Figure 4.** Curves of the N-factors, their envelope (red curve), threshold values of the N-factors, and LTT positions (straight lines) calculated in the course of LTT module operation:

(a) – M∞= 0.25, Re1=5×10⁶ 1/m, T∞=296 K, AoA=0, and Tu=0.33%;
(b) – M∞= 0.7, Re1=11.6×10⁶ 1/m, T∞=296 K, AoA=0, and Tu=0.5%.

The problems of stability are considered in a local formulation. First, the problems of temporal stability for various streamwise and transverse wave numbers are solved, which ensures initial approximations for the problems of spatial stability (neutral stability positions, corresponding temporal frequencies and wave numbers). After that, the N-factors and their envelope are calculated for a series of unsteady perturbations. The eN-method implies that the LTT is observed when the envelope of the N-factors reaches a critical (threshold) value of the N-factor.
Mack [10] derived a formula relating the threshold value of the $N$-factor of the LTT beginning to the free-stream turbulence level $T_u = \left( \sqrt{\left( \frac{u'^2 + v'^2}{2} \right)} / U_{\infty} \right)$ (ratio of the root-mean-square amplitude of the perturbation velocities to the free-stream velocity) as

$$N_{c, \text{Mack}} = -8.34 - 2.4 \ln(T_u).$$

(1)

Hein [3] demonstrated that Eq. (1) can be surely applied for $10^{-3} < T_u < 10^{-2}$, though it is often used for moderate and high values of $T_u$.

Figure 4 shows the curves of the $N$-factors, their envelope, threshold values of the $N$-factors predicted by Eq. (1), and corresponding positions of the LTT beginning calculated by the LTT module for two regimes of the flow around the airfoil.

4. Results

Menter et al. [9] provided experimental results for the LTT in the BL on the NASA-SR-0410 supercritical airfoil for Mach numbers ranging from 0.25 to 0.85 and unit Reynolds numbers of 5×11.6 million per meter. The experiments were performed in a transonic wind tunnel with the use of film sensors, constant-temperature hot-wire anemometers, and pressure sensors. For determining the LTT position, Menter et al. [9] used two approaches, which were based on the distribution of the root-mean-square (RMS) value of the measured variable fluctuations and on the skewness distribution.

4.1. Experimental Data

Figure 5 shows the shear stress distributions over the upper surface of the airfoil versus the streamwise coordinate: (a) $M_e = 0.25$, $Re_1 = 5 \times 10^6$ m$^{-1}$, $AoA = 0$, and $T_u = 0.33\%$; (b) $M_e = 0.7$, $Re_1 = 11.6 \times 10^6$ m$^{-1}$, $AoA = 0$, and $T_u = 0.5\%$; 1 – results of computations with nonzero turbulent viscosity; 2 – data computed by the Transition SST model; 3 – experimental data on the LTT beginning [9]; 4 – data on the LTT beginning predicted by the LTT module (present study).

Figure 5 shows the shear stress distributions along the airfoil surface calculated for the laminar flow and with the use of the Transition SST model. Figure 5 also shows the LTT data obtained in the experiments [9] and with the use of the LTT module on the basis of the $e^N$-method. It is seen that the LTT beginning predicted by the LTT module agrees well with the experimental data: the difference in the streamwise coordinate is within 8\%, which is a good result for modern models of the transition to turbulence. The calculations by the Transition SST model of the ANSYS Fluent software predict that the LTT begins much further downstream than in the experiments and in the computation performed with the use of the LTT module. There are two possible reasons for that: first, the Transition SST model developed for LTT computations in flows with high-level turbulence of the external flow (in particular, flows around turbine blades) does not ensure adequate operation in flows with low turbulence; second,
the Transition SST included into the ANSYS Fluent software fails to properly take into account the flow compressibility typical for transonic flow regimes.

**Conclusions**

A two-dimensional laminar-turbulent flow around an airfoil at subsonic and transonic velocities of the external flow is numerically simulated with the use of an original software package LOTRAN 2.0 based on the eN-method. The computations are performed for the Mach numbers of 0.25 and 0.7. New data on the LTT position for the flow around the airfoil for the low level of the free-stream turbulence (Tu<0.5%) are obtained.

It is demonstrated that the LTT module based on the eN-method predicts the LTT beginning positions in two-dimensional subsonic and transonic compressible flows around the airfoil with an error smaller than 8% in terms of the streamwise coordinate.

It is shown that the LTT data predicted by the Transition SST model built into ANSYS Fluent differ significantly from the experimental results and the data calculated by the LTT module on the basis of the LOTRAN 2.0 package, i.e., the Transition SST model has to be improved to ensure an adequate prediction of the LTT in compressible flows with low degrees of free-stream turbulence.

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