Simulation of a laminar-turbulent flow in three-dimensional aerodynamic configurations

T V Poplavskaya, A V Boiko, K V Demyanko, S V Kirilovskiy and Y M Nechepurenko

1 Khristianovich Institute of Theoretical and Applied Mechanics, Novosibirsk, 630090 Russia
2 Marchuk Institute of Numerical Mathematics of RAS, Moscow, 119333 Russia

E-mail: popla@itam.nsc.ru; boiko@itam.nsc.ru; kirill.demyanko@yandex.ru; kirilov@itam.nsc.ru; yumnech@yandex.ru

Abstract. The goal of the paper is to determine the position of the laminar-turbulent transition in the boundary layer of a prolate spheroid using the e\textsuperscript{N}-method with the calibration of threshold N-factors. It is demonstrated that the predicted and experimental data on the laminar-turbulent transition are in good agreement.

1. Introduction

To accurately compute heat transfer, friction drag, and thermal protection of aircraft objects, in many situations it is necessary to take into account the presence of laminar, transitional and turbulent regions in the boundary layers. Hence, modeling of laminar-turbulent near-wall flows is an important scientific and practical problem.

The purpose of this study is to compute the laminar-turbulent flow at a prolate spheroid using the computational technology proposed by the authors [1], which includes an integration of the ANSYS Fluent gas-dynamic package with a laminar-turbulent transition module developed on the basis of the LOTRAN 3 software package [1, 2]. The result of this software package is the distribution of N-factors for small-amplitude disturbances propagating along selected inviscid streamlines. According to the e\textsuperscript{N}-method, the position of laminar-turbulent transition is to be found from the distribution using threshold N-factor values. In order to obtain the values, the authors use a calibration technique which requires reference experimental data.

In the present case the technique is outlined by comparing the computed data of the transition onset with the experimental data obtained for the subsonic boundary layer at the prolate spheroid.

2. Numerical simulation of the laminar-turbulent flow around 3D bodies

Numerical simulation of the laminar-turbulent flow in the boundary layer of prolate spheroid was performed using the computational technology proposed by the authors [1]. It includes an integration of the ANSYS Fluent gas-dynamic package with a laminar-turbulent transition module developed on the basis of the LOTRAN 3 software package [1, 2] and implemented in MATLAB environment to perform hydrodynamic stability analysis and predict the onset of transition in three-dimensional boundary layers using the e\textsuperscript{N}-method.
The algorithm to simulate the laminar-turbulent flow and determine the transition onset in the boundary layer of the prolate spheroid is as follows. At the first stage, a computational domain and a block hexagonal computational grid for the model in free flow are constructed. A rather thick near-wall zone (five boundary-layer thickness or more) is selected, and a regular computational grid is built. In the next step, the basic flow is computed with an acceptable accuracy using the k-ω SST turbulence model with values of the intermittency function provided by an ANSYS Fluent user-defined function. The results of the basic flow computation from the near-wall zone are transferred to the laminar-turbulent transition module (LOTRAN 3). In the module, the data are converted into an internal representation using a special assimilation procedure. Computation of the transition onsets in three-dimensional boundary layer is reduced to computing transition positions in two-dimensional sections along inviscid streamlines selected by the module. For each section, the complete linear-stability equations in local formulation taking into account the viscous flow compressibility are considered. The main result of the module are the envelopes of the N-factors along the streamlines in the case of Tollmien-Schlichting waves (TS), and crossflow vortices (CF).

Next, the calibration by finding separate N-factors is performed, which includes the steps outlined below:

1. The computation of the N-factor distributions along a set of inviscid streamlines along the azimuth are carried out.
2. The computed distributions are transferred to the calibration module, in which the available experimental data are superimposed on the computed N-factors and the threshold N-factors of transition onset for each streamline are determined.
3. Then, the threshold N-factors are averaged that provides the final individual threshold values NTS and NCF for the Tollmien-Schlichting and crossflow instabilities, respectively.
4. A validating computation is carried out in the standard mode of operation of the transition module using the threshold N-factors. The obtained data on the transition onset are compared with the experimental data.

Validation of the method for laminar-turbulent transition prediction is a necessary and important stage in engineering applications. In the present work, the validation studies were performed for a fully three-dimensional flow at a prolate spheroid with the 6:1 aspect ratio [3] at different angles of attack (α=0-10°). In the boundary layer of the spheroid at large angles of attack a strong transverse flow occurs, in which case the transition may be caused by either TS instability, CF instability, or separated-flow instability. Figure 1 compares the computed data with the experiments [3]. It shows laminar, transitional and turbulent flow regions on the spheroid surface for the angles of attack of 0 and 10°. Computations of the transition onset are performed in this case using equal threshold values for both N-factors, calculated with Mack’s formula [4]

$$N_c = -8.34 - 2.4 \cdot \ln (Tu)$$

At the free-stream turbulence level Tu =0.1-0.2%, as indicated in [3], the transition onset is obtained if both transition mechanisms are taking into account.

Figure 1. The regions of laminar-turbulent flow for Re=3×10^6 1/m, Ma=0.13: α=0, Tu=0.1% (a, b) and α=10°, Tu=0.2% (c, d): laminar (white), transition (points), turbulent (black) and separated (dashed) flow regions, (a, c) - experiment [3], (b, d) – computed data of this work.
The peculiarity of the transition process in the presence of strong transverse flow under consideration is an interaction of Tollmien-Schlichting waves and crossflow vortices. This, however, is not an obstacle to the application of the $c^{N}$-method, when a flow stability diagram that relates corresponding threshold $N$-factors to each other is known. In particular, such stability diagram was presented in [5] for the DFVLR 3 m low-speed wind tunnel in Gottingen that works in a wide range of different angles of attack and Reynolds numbers. However, such an approach is not universal and, hence, in this paper, we determine the threshold $N$-factors separately for both instabilities from the available experimental data.

First, after computing the basic flow using ANSYS Fluent, the distributions of $N$-factors along the selected inviscid streamlines are found, and the $N$-factor distributions are drawn separately for the TS and CF instabilities (Fig. 2).

**Figure 2.** Distributions of $N$-factors along the inviscid streamlines projected to the surface of prolate spheroid for $Re=3\times10^6 \ 1/m, M\infty=0.13; \ \alpha=10^\circ$: TS (a), CF (b).

**Figure 3.** Projections of the streamlines along the surface of the prolate spheroid (blue) with the positions of the transition onset to $X,Y$-plane: experimental data (blue crosses), threshold $N$-factors for TS waves (black curve) and CF vortices (green curve), dashed curves show 10% deviations. $Re=3\times10^6 \ 1/m, M\infty=0.13, \alpha=10^\circ$. 
Then, the experimental data are superimposed on the $N$-factor distributions, and the threshold $N$-factors of the transition onset for both instabilities are determined using the above-described technique (Fig. 3). To validate the results, the computation in the standard mode of operation of the transition module using the obtained values of the threshold $N$-factors is performed and the obtained transition onset is compared with the experimental data. The advantage of this technique is the possibility to indicate the mechanism that initiated the transition on the plot (black and green curves in Fig. 3 correspond to the TS and CF instabilities, respectively).

A comparison of the computed transition onset with the experiments and other computations is shown in Fig. 5 for $Re_t=3\times10^6$ 1/m, $M_s=0.13$, $\alpha=10^\circ$. In particular, the experimental data, obtained in the DFVLR 3-m low-speed wind tunnel in Gottingen [3,6] and computations of Stock et al. [5] and Krimmelbein et al. [7] using the e$^\alpha$-method in combination with the stability diagrams, are taken. The results obtained using the proposed calibration technique with the separate threshold $N$-factors are presented. The difference between the computed and experimental data does not exceed 10% of the length of the model. It may be interesting to check whether the same calibration is valid at other flow conditions measured in the experiments. This work is now under way.

![Figure 4](image_url)

**Figure 4.** Positions of the transition onset as a function of the azimuthal angle $\theta$ in the boundary layer of the prolate spheroid for $Re_t=3\times10^6$ 1/m, $M_s=0.13$, $\alpha=10^\circ$.

**Conclusions**

Numerical simulation of three-dimensional laminar-turbulent flow in the boundary layer of a prolate spheroid at subsonic external velocity has been performed using the integration of the ANSYS Fluent gas dynamic package with the transition prediction module, developed on the basis of the LOTRAN 3 software package. A technique for calibrating the transition prediction module by finding separate threshold $N$-factors for different transition mechanisms using the available experimental data was used.

It is shown that such calibration provides accuracy of the transition onset at the angle of attack of $10^\circ$ comparable to other computations, using the diagram of the dependence of threshold $N$-factors on each other.

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