On developing methods for predicting the laminar–turbulent transition in aerodynamic applications

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Abstract. Actual fundamental and computational problems of laminar–turbulent transition prediction in aerodynamic flows are discussed. The author's approach based on the \( \exp(N) \)-method is briefly described. The results of experimental studies aimed at clarifying the calibration of the \( \exp(N) \)-method is highlighted. Particularly, one of the main problem is a limited experimental database for verification of different approaches for the transition prediction. To extend such a database, it is necessary to document in detail the flow parameters (velocity, free-stream turbulence level, etc.) and the model parameters (geometry, surface roughness, angle of attack, etc.) as well as to document in a statistically sound way the position of laminar-turbulent transition on the surface of experimental model. To this end we develop an experimental method of parametric measurements in different flow regimes of three-dimensional aerodynamic flows based on the thermal analysis of the surface.

1. Introduction
Interest in forecasting the position of laminar-turbulent transition on the surface of transport aircraft in cruise regime of flight is actual since the 50s of XX century. Over the past decade, the studies to improve the forecast accuracy has intensified significantly as the traditional means to reduce the drag aiming to reduce fuel consumption and/or increase the range of flight by profiling and eliminating the flow separation approach their limit [1]. Hence, laminarization of the flow at some elements of aircraft is considered as one of the promising ways to reduce the drag caused by turbulent boundary layer. To this end, engineers and designers need to have appropriate approaches to predict the position of laminar-turbulent transition in aerodynamic applications with a required accuracy.

Currently, engineering gas-dynamic packages as ANSYS Fluent are widely used to solve various problems of gas dynamics and heat transfer. These packages do not have built-in tools to analyze the position of laminar-turbulent transition based on the theory of hydrodynamic stability. However, the transition position mainly depends on the dominant types of the boundary-layer instability as Tollmien–Schlichting waves and cross-flow vortices. The development of the Tollmien–Schlichting waves is typical for the boundary layers occurring at the most elements of the aircraft as fuselage, wings, etc. The appearance of strong cross-flow on a swept wing can lead to the predominance of cross-flow vortices in the laminar-turbulent transition. The intense interest of engineers to the \( \exp(N) \)-method of laminar-turbulent
transition prediction in aerodynamic applications is stipulated by the physically sound linear theory of hydrodynamic stability, which is the foundation for the method to operate in two-dimensional and three-dimensional incompressible and compressible boundary layers, if the level of free-stream turbulence is low enough (low-noise and low-turbulence wind tunnels or cruise flight conditions) [2, 3].

2. Outline of the laminar-turbulent transition prediction package
The software bundle LOTRAN 3 is used to determine the position of the laminar-turbulent transition in three dimensional boundary layers using the \( \exp(N) \)-method with the laminar flow from an arbitrary RANS solver. The complete linearized heat and mass transfer equations for compressible flows, original matrix algorithms for the stability analysis of boundary layers, and original preprocessing of data on the flow under study are used [4]. Currently, different versions of this software bundle are used for fundamental scientific and engineering computations (see, e.g., [5–8]).

In developing LOTRAN 3 the following main objectives were considered:

- The operation should be fully automated, i.e. exclude virtually a manual fitting;
- The software must be modular to separate from each other the problems of computational 3D geometry, analysis and assimilation of the boundary layer, boundary-layer stability analysis and estimation of the transition position;
- In analyzing the hydrodynamic stability, the basic computations must be performed with standard, carefully tested matrix algorithms.
- The software must operate robustly with data on laminar flow obtained with an engineering precision.

They were completed by the original technology of forming and solving the hydrodynamic stability problems for three-dimensional boundary layers, the use of physically reasonable ranges of variation of local wave numbers and the use of filters to avoid spurious instability modes of different kinds.

3. Experimental results
One of the main objectives of experimental studies under consideration is an extended experimental database for verification of methods for the transition prediction. To create such a database, it is necessary to document in detail the flow parameters (velocity, free-stream turbulence level, etc.) and the model parameters (geometry, surface roughness, angle of attack, etc.) as well as to document in a statistically sound way the position of laminar-turbulent transition on the surface of experimental model. To this end we develop an experimental method of parametric measurements in different flow regimes of three-dimensional aerodynamic flows based on the thermal analysis of the surface.

The experiments were performed in subsonic laminar wind tunnel T–324 of Khristianovich Institute of Theoretical and Applied Mechanics SB RAS. The model of 45° swept wing (SW45) installed in the tunnel test section is shown in figure. 1. The model has a comprehensive structure including a rigid frame (comprising ribs and stringers), a skin made of transparent acrylic sheets (attached to the frame) and an attachable CNC milled leading edge. The model has profile NACA 67 1-215 modified on the pressure side (the same as in the studies [9, 10]) and the chord length \( C = 0.8 \) m in the direction normal to the leading edge. Pressure distributions at the model were measured with help of 34 static pressure taps available on its surface. The integral boundary-layer characteristics, potential flow streamlines, stream-wise distributions of velocity over the model and free-stream turbulence levels were documented with help of hot-wire technique for different angles of attack studied. The model surface roughness was documented.
Figure 1. Swept-wing model SW45 installed in the test section of T-324 low-turbulent wind tunnel.

with help of scanning laser displacement sensor optoNCDT 1700 (Micro-Epsilon Messtechnik). The free-stream turbulence levels were varied from a low level (\(Tu = 0.09\%\) without turbulent grids) up to enhanced levels (\(Tu = 0.8\%\) with turbulent grids application). The incident flow velocity \(Q_\infty\) was varied in the range from 10 to 50 m/s in order to follow the transition position shift due to the Reynolds number variation.

To increase the thermal contrast between the laminar and turbulent flow regions the swept-wing model was externally preheated before each wind tunnel run with the help of array of halogen lamps up to \(+6^\circ C\) above ambient air temperature. Then the wind-tunnel starts together with the start of model surface temperature records performed by IR-camera FLIR SC 7300 (with the frame rate about 100 fps). A processing of the recorded IR-movies have shown that in the case of low free stream turbulence level, when the transition is caused by the amplification of stationary cross-flow vortices only, the IR-images (movie frames) have their maximum temperature contrast in 10 to 20 s after the wind tunnel reach desired flow velocity \(Q_\infty\). In this case the averaged transition position may be detected from a single IR-frame, even if the frame is somehow spoiled by different artifacts caused by initial non-uniformity of the model preheating and significant non-uniformity of the model parts thermal capacity. It was demonstrated (see also[9]) that the use of time derivative of surface temperature \(dT_s/dt\) instead of surface temperature \(T_s\) provides significant improvement of the transition imaging and helps to get rid of the mentioned artifacts.

It is found that when the IR-frames reach their maximum contrast (10 to 20 s after the wind tunnel speed settling) the values of \(dT_s/dt\) usually differ in laminar and turbulent regions only moderately.

Much more involved cases for the transition detection by IR-technique are found in the studied regimes with cross-flow dominated transition at the enhanced levels of free stream turbulence. In these cases, the transition process becomes unsteady due to significant presence of traveling cross-flow modes excited due to the flow receptivity to the free-stream turbulence. Temperature contrast of the IR-frames in laminar and turbulent areas become much less pronounced than in the case of low free stream turbulence, the number and value of different artifacts growing significantly. The calculation of time derivative \(dT_s/dt\) from the recorded IR-movies helps to improve the transition imaging, however the signal to noise ration still remains low and insufficient for successful detection of the transition.

The solution of the problem was found due to detailed analysis of the recorded time sequences of surface temperature. It was found that just after the wind tunnel speed setting, there is a very short time (1 to 4 s only) when the surface in turbulent areas cools significantly faster than
in laminar ones. In fact, during this short time interval the main surface temperature difference between areas with laminar and turbulent flows is set. The derivatives $dT_s/dt$ calculated in this specified time interval differ in laminar and turbulent areas with the factor of 4 that allows detection not only an averaged transition position, but also a clear detection of the beginning and the end of laminar–turbulent transition.

![Figure 2. Results of the analysis of the thermal images of the swept-wing surface at the ambient flow velocity $Q_\infty = 30$ m/s (the flow is from right to left): single image (left); a sequence of images (right).](image)

Comparison of the results of the analysis of a single image and a sequence of thermograms in order to identify the position of the laminar–turbulent transition is shown in figure 2, the color encoding the temperature of the surface. The line with the large ‘teeth’ in the left top part (figure 2, left) is the line of laminar–turbulent transition, and the line lying below and to the right is an artifact that is associated with the imperfection of preheating of the wing. It is seen that the analysis of the sequence of thermograms (figure 2, right) leads to a significant reduction of the number of artifacts, so that the position of the transition is successfully detected in the entire visible region. In this case the transition line is detected in the wingspan range of about 500 mm, which makes the experimental evaluation of laminar-turbulent transition statistically more accurate and reliable.

The present experimental study resulted in development of highly resolving technique for detection of laminar-turbulent transition stages with help of IR-thermography. Application of the technique allowed evaluation of the laminar-turbulent transition position in numerous regimes with different model attack angles and flow speeds including cases of the transition dominated by Tollmien–Schlichting waves or cross-flow vortices (or a combination of both), as well at the low and enhanced free-stream turbulence levels.

4. Conclusions
Thus, the algorithm for determining the transition lines based on the analysis of the cooling rates of the aerodynamic surface under study, a key element of which is the use of a sequence of thermograms in contrast to the traditional analysis of single frames, was developed. The experimental technique for large-scale parametric measurements in different three-dimensional aerodynamic flows with dominance of either the cross-flow instability vortices or the Tollmien–Schlichting instability waves with the aim of statistically sound documentation of the position of the laminar-turbulent transition was tested.
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