Thermal imaging of laminar-turbulent transition on experimental model of swept wing. Creating database of experimental data

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Abstract. The paper is devoted to the problem of creation of experimental database obtained due to systematic extended series of experiments aimed at registering the laminar-turbulent transition in boundary layers on a swept wing model. The experiments were carried out in a low-turbulence wind tunnel in boundary layers developed on ‘suction’ and ‘pressure’ sides of experimental model of an airfoil in a broad range of problem parameters (angle of attack, freestream velocity, free-stream turbulence etc.). The main feature of performed experiments is using of a new panoramic experimental technique based on application of sensitive infrared camera. Digital postprocessing of obtained thermograms that gave a possibility to detect the position of transition occurred due to amplification of cross-flow instability modes, TS-waves or both of them. The article includes description of the approaches used and the first preliminary results.

1. Introduction
The problem of laminar-turbulent transition (LTT) in shear flows is one of the most important fundamental problems of fluid mechanics. The phenomenon of transition to turbulence is widespread in practice and is often implemented in the conditions of operation of a broad range of aerodynamic devices: aircraft wings, air intakes, nozzles, etc. Suppression or, visa versa, stimulating the LTT can significantly increase the efficiency of their operation, improve operational characteristics, and simultaneously enhance their reliability and durability as well. For example, it is well known that most of the drag losses of a modern aircraft are caused by friction forces occurred in the turbulent boundary layer on its aerodynamic surfaces. As a result, one of the key challenges in the modern aircraft design is the problem of laminarization of the flow on its aerodynamic elements and predicting the LTT-position in the corresponding boundary layers.

The overall goal of the work is to create database of reliable experimental data that will be suitable for verification of various modern software packages of predicting the LTT-position in boundary layers on swept wings occurred due to amplification of cross-flow (CF) and Tollmien-Schlichting (TS) instability modes [1, 2]. The database should contain comprehensive information about the conditions of performed experiments: the experimental model parameters (its geometry, the angle of attack to the oncoming flow, the roughness degree of the model surface, etc.); the freestream speed and the freestream turbulence level; the mean flow parameters in vicinity of the model (its three-dimensional structure, integral characteristics of the boundary layer, etc.); as well as the information about the LTT-positions in a broad range of problem parameters. The database should contain results of the new systematic experiments performed in winter campaign of 2019-2020 using the original thermal
imaging technique of registration of the LTT-position. Since the obtained extended experimental information is under intensive processing now, this paper presents the first preliminary results.

2. Experimental setup

The experiments were carried out in a low-turbulence wind tunnel T-324 ITAM SB RAS (Novosibirsk, Russia) using an experimental model of the swept wing “SW45” (having NACA 67 1-215 profile (modified), 700 mm chord, 45°sweep angle). The model (figure 1) is equipped with static pressure taps to measure the static pressure distributions on the ‘suction-‘ and the ‘pressure‘ sides of the wing (along its center line) in a broad range of the longitudinal chordwise coordinates. The main measurements of the LTT-position were made on both sides of the model for three angles of attack to the oncoming flow (α = −5, 0 and +3 degrees) in the range of freestream velocity Q from 15 to 50 m/s (measured at the inlet of the test section of T-324). Experiments were carried out at several turbulence levels of the flow ε (approximately in the range from 0.1 to 1% of Q), which were varied by using turbulizing grids.

![Figure 1. Photo of experimental model SW45 (made of transparent acryl) in test section of T-324 taken during preparation of the experiment. 1 – leading edge; 2 – tubes of the static pressure measurement system (during the main experiments they were fixed on the floor); 3 – turbulator (used to eliminate unsteady flow separation at the end of the model).](image-url)

The mean flow characteristics at both working surfaces of the model were carefully documented using static pressure taps and hot-wire measurements for each setting of the angle of attack. Hot-wire measurements included mainly (i) boundary layer wall-normal profiles of the mean flow velocity which were obtained in a broad range of chord positions and (ii) documentation of streamlines at the edge of the boundary layer. The streamlines were evaluated by original technique of tracking the weak wakes past thin wires mounted upstream the model.

During the main experiments, the process of LTT was recorded by using a high-sensitive thermal imaging camera FLIR SC7300. The surface of the model was preheated by about 6 °C relative to the ambient temperature. Preheating was carried out just prior to the wind-tunnel run using a special illuminator (a set of 32 halogen lamps mounted on a special frame) installed in the test section of T-
324 opposite to the wing side under test. When the temperature of the model reached the desired value, the lamp was removed from the test section and the wind-tunnel was launched simultaneously with the start of IR-camera recording. The IR-camera recorded the thermograms with a framerate of 50 Hz through a round window of the wind tunnel test section, which was closed by IR-transparent membrane. As a result, the obtained IR-movies included records of all stages of flow formation on the surface of the wing, including the moment of the wind tunnel start, flow acceleration and the setting of target flow velocity as well as formation of quasi-steady thermal image of the LTT both along the model chord and span for each of the studied regimes.

3. Demonstration of the results and outlook
This chapter shows some examples of the LTT-images obtained in different studied regimes. The imaging of LTT is done in accordance with previous methodological findings [3] by mapping temporal surface temperature change $\Delta T$, per chosen time interval (instead of surface temperature $T_s$ readings). As it was shown in [3] the monitoring of relative surface temperature changes provides much better resolution of LTT in the presence of thermal and structural non-uniformities of the model, especially in cases of enhanced turbulence level of the free-stream.

![Figure 2](image-url)

**Figure 2.** Temporal surface temperature change $\Delta T$, (per 2 sex) visualizing LTT on suction side of SW45 in cases when LTT caused by amplification of CF-instability modes.

$\alpha = -5^\circ$, $\varepsilon = 0.8\%$, $Q = 23$ m/s (a), $Q = 33$ m/s (b)

Figure 2 shows LTT on the suction side of the SW45 at $\alpha = -5^\circ$ at enhanced level of free-stream turbulence ($\varepsilon = 0.8\%$). Chordwise pressure distribution at this angle of attack is such that the TS-modes are stable and CF-instability fully dominates at transition process. Figure 2a corresponds to velocity case $Q = 23$ m/s. The flow above the main part of the model is laminar ($\Delta T_s$ is about $-0.05 \div -0.1 \, ^\circ C$) and transition starts at the end of the model only. At the flow velocity $Q = 33$ m/s (Figure 2b) the LTT starts about the chord position $C \approx 20 \div 23\%$ and it is finished in the area of the maximum cooling ($\Delta T_s$ is $-0.3 \div -0.35^\circ C$). Figure 3 shows transitions images taken for the same enhanced turbulence level, but at $\alpha = +3^\circ$, on the pressure side of the model. (Dark circular spots along the center line of the model are tracers of static pressure taps having another heat capacity) Chordwise pressure distribution in this case damps TS-modes only at the initial part of SW45, but TS-dominated transition may happen in the second half of the model (see 2D transition line at $C \approx 50\%$ at $Q = 15$ m/s). At higher flow velocity (Figure 3b, $Q = 33$ m/s) transition line moves upstream (the end of the LTT process and maximum surface cooling $\Delta T$, now at $C \approx 40\%$) changing 2D shape to “saw-tooth” shape due to significant presence of the three-dimensional cross-flow modes.

Thus, three main scenarios of LTT-transitions may be successfully identified due to post-processing of the present IR-experimental data (CF-modes dominated transition, TS-waves dominated
transition and transition in the presence of both boundary-layer instabilities) and then can be used for verification of various transition prediction codes. For automatic detection of LTT-position in numerous studied regimes an advanced computer code is being developed. This code will detect both LTT-position and its length with improved accuracy. These data will be included in the created database.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3.png}
\caption{Temporal surface temperature change $\Delta T_s$ (per 2 sec.) visualizing of LTT on pressure side of SW45 in cases when LTT is caused by amplification of: (a) TS-waves and (b) TS- and CF-instability modes simultaneously. $\alpha = +3^\circ$, $\varepsilon \approx 0.8\%$, $Q = 15$ m/s (a), $Q = 33$ m/s (b)}
\end{figure}

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**References**
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