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METHOD OF THE DESCRIPTION OF THE LAMINAR–TURBULENT TRANSITION POSITION ON A SWEPT WING IN THE FLOW WITH AN ENHANCED LEVEL OF FREE-STREAM TURBULENCE

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Abstract: A new experimental method for panoramic contactless determination of the laminar–turbulent transition position in a three-dimensional boundary layer is described. It is demonstrated that this method allows accurate determination of the transition region boundaries at both low and enhanced levels of free-stream turbulence.

Keywords: boundary layer, laminar–turbulent transition, panoramic methods of measurements, swept wing, crossflow vortices, hydrodynamic instability.

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INTRODUCTION

Experimental determination of the positions of the beginning and end (length) of the laminar–turbulent transition (LTT) region on various aerodynamic surfaces under different flow conditions is important for improvement of validation of semi-empirical and fully empirical LTT models [1]. If the LTT process is essentially three-dimensional, for example, as it often happens in the case of domination of stationary vortices (e.g., crossflow vortices) in the boundary layer, significant advantages in terms of time expenses of the experiment are provided by panoramic methods of LTT visualization.

There is a method of determining the LTT position on the basis of the difference in heat transfer in the laminar and turbulent regions of the boundary layer on the tested aerodynamic model. In this method, the heat transfer between the gas flow and the tested laboratory aerodynamic model is usually artificially intensified by means of model heating or cooling with respect to the ambient medium. If the model has a higher temperature and is cooled by a colder gas, intense heat transfer between the model and the turbulent flow leads to lower surface temperatures in turbulent regions than those in laminar regions. Thus, the model surface temperature is chosen as the governing parameter for determining the state of the boundary layer under study. In this case, the positions of laminar and turbulent regions can be visualized by using temperature-sensitive films or paints; another option is the use of infrared (IR) imaging.

However, detection of laminar and turbulent regions in the boundary layer on the basis of the model surface temperature can be rather difficult or even impossible if the laboratory model cannot be uniformly heated or is structurally inhomogeneous, e.g., includes regions with different values of the thermal conductivity and (or) heat capacity. In such cases, the temperature of the model surface in the case of steady-state heat transfer between the

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model and gas flow is determined to a large extent by the above-mentioned factors rather than by the heat transfer difference in the laminar and turbulent regions of the boundary layer.

These problems can be avoided by using the rate of changing of the model surface temperature as the governing parameter. For this purpose, instead of individual thermograms, it is necessary to record and analyze a sequence of infrared images, i.e., arrays of data on changes in the model surface temperature in time. Thus, in the experiments on LTT control on a swept wing [2, 3], it was found that determining the model cooling rate (i.e., the derivative of the model surface temperature T_s with respect to time t: dT_s/dt) allows one to prevent undesirable background inhomogeneities of heating and inhomogeneous thermophysical properties of the model under study and to successfully estimate the LTT position on a swept wing in the incoming flow with a low turbulence level (LTL). It should be noted that the dominating disturbances in the case of the LTT in the LTL flow are steady vortices induced by crossflow instability (generated by the leading edge roughness), whereas unsteady disturbances induced by free-stream turbulence produce a minor effect [4]. In this case, the transition line is significantly nonuniform over the swept wing span (has a typical saw-tooth shape); moreover, the transition from the laminar to turbulent state along individual vortices occurs almost instantaneously. As a result, the border between the laminar and turbulent regions is usually fairly contrasting. The method of determining the LTT position on a swept wing on the basis of the model cooling rate was applied in [3] to find the averaged LTT position in LTL regimes; computer algorithms were also successfully involved.

One of the factors significantly complicating determination of the LTT position on a swept wing with the use of IR imaging is the enhanced level of free-stream turbulence. Up to now, it was impossible to determine the beginning and end of the LTT on a swept wing at the enhanced turbulence level (ETL) with the use of IR imaging. The reason is a significant effect of unsteady disturbances of the boundary layer generated by free-stream turbulence; as a result, the clear steady border between the laminar and turbulent regions of the flow observed under the LTL conditions becomes smeared, and the temperature difference decreases. Therefore, the method developed in [3] and used for LTL regimes (Tu $\approx 0.09\%$) was found to be inapplicable for determining the LTT position on the swept wing model used in the study (SW-45) in regimes with the use of turbulizing grids, i.e., at Tu $> 0.5\%$.

The goal of the present study was to develop experimental methods for detecting the LTT position on a swept wing in ETL regimes and to determine not only the averaged LTT position, but also the LTT length, i.e., the boundaries of the LTT beginning and end under these conditions.

1. EXPERIMENTAL SETUP AND SWEPT WING MODEL

The experiments were performed in the T-324 subsonic low-turbulence wind tunnel based at the Khristianovich Institute of Theoretical and Applied Mechanics of the Siberian Branch of the Russian Academy of Sciences (Novosibirsk). The test section size of this wind tunnel is $1 \times 1 \times 4$ m. The wind tunnel is characterized by a low level of turbulence comparable with the cruising flight conditions (Tu $= 0.02\%$ at frequencies above 1 Hz in an empty test section). For this reason, the wind tunnel can be used for studying LTT scenarios in aerodynamic applications. For LTT scenarios in ETL flows, it is necessary to use turbulizing grids.

The laboratory model of the SW-45 wing shown in Fig. 1 is based on the NACA 67 1–215 laminarized airfoil modified at the lower side; the sweep angle of the wing is 45°. The model consists of a rigid frame including acryl ribs and stringers. The wing model surface is formed by transparent acryl sheets 3 mm thick. The CNC-milled leading edge of the model (of length $0.1C$) is painted; the leading edge roughness has the root-mean-square amplitude of about 8.5 μm. The chord length C normal to the leading edge is 700 mm. The chordwise coordinate x is counted from the leading edge along the chord. The stainless steel rod mounted inside the frame at a distance $x = 0.5C$ serves as the axis of rotation for changing the angle of attack α of the wing model.

2. INFRARED IMAGING SYSTEM AND MEASUREMENT PROCEDURE

The panoramic diagnostics of the boundary layer on the swept wing model was performed by a highly sensitive FLIR SC7300 IR camera with a sensitivity of 0.02 K and a matrix size of 320×256 pixels. The camera allows high-speed recording of thermograms with a frequency up to 235 fps. The camera lens is directed onto the

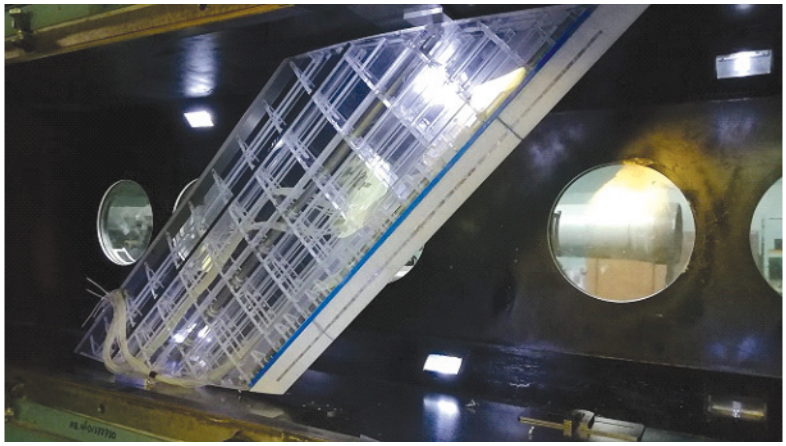

Fig. 1. Swept wing model SW45 in the test section of the T-324 low-turbulence wind tunnel.

surface of the examined model through a circular window of the test section. To prevent incidence of reflected IR beams onto the matrix, the camera was directed onto the wing model at a small angle (with small deviation from the normal); moreover, the camera was carefully covered by a closely woven black fabric curtain. Owing to these measures, the level of parasitic signals in the thermograms was significantly reduced. Additional measurements showed that the IR camera readings are close to the model surface temperature measured by other instruments. A window with the maximum possible diameter transparent for IR radiation was used in the experiments, which provided a domain of model surface visualization with a diameter of the order of 560 mm. Thus, a large part of the wing model span was captured by the camera, which allowed significant enhancement of statistical reliability of the LTT position estimate.

Before each run of the wind tunnel, the SW-45 model was preheated by a special heater with 32 uniformly distributed halogen lamps [2]. The heater was mounted near the model and was withdrawn from the test section when a desired degree of overheat (about +6°C) was reached and the wind tunnel was actuated. Recording of the sequence of thermograms (i.e., IR movie) was started almost simultaneously with wind tunnel actuation; the time of IR movie recording was usually 40–70 s. For the velocity regimes considered in the study, this time was sufficient for reaching a required flow velocity, obtaining quasi-steady heat fluxes, and establishing the maximum contrast of the IR images. The coordinates of the wing model were related to the IR image pixels with the use of later frames of the IR movie taken when the wing model shell lost the major portion of the accumulated heat and the internal structural elements (ribs and stringers with known coordinates) became clearly visible owing to their higher heat capacity.

3. METHOD OF DETERMINING THE LTT POSITION

Figure 2 shows on of the most high-contrast IR image from the IR movie recorded at the free-stream velocity $Q = 30$ m/s at the low turbulence level Tu = 0.09%. The wing model is mounted at the angle of attack $\alpha = -5°$; for this reason, the flow on the upper part of the model is accelerated up to the chordwise coordinate $x = 0.7C$, the Tollmien–Schlichting instability is suppressed, and the transition is induced by instability of steady crossflow vortices. This IR image was taken at the 30th second of movie recording (approximately 20th second after reaching the operating velocity in the wind tunnel). As the process of flow turbulization along the steady vortices in the LTL regime occurs in an explosive manner and the temperature difference of the model surface in the laminar and turbulent regions is sufficiently large (more than 1.5°C), the characteristic sawtooth-shaped border between the laminar and turbulent regions is clearly expressed in the IR image in the interval of the coordinates $x = 0.35C$–$0.60C$. However, because of the inhomogeneity of model preheating and different heat capacities of the model elements, the LTT pattern is prone to “distortions,” which is evidenced, e.g., by the “cold” leading edge of the model (from 0 to $0.1C$) located in the laminar flow region (see Fig. 2a).

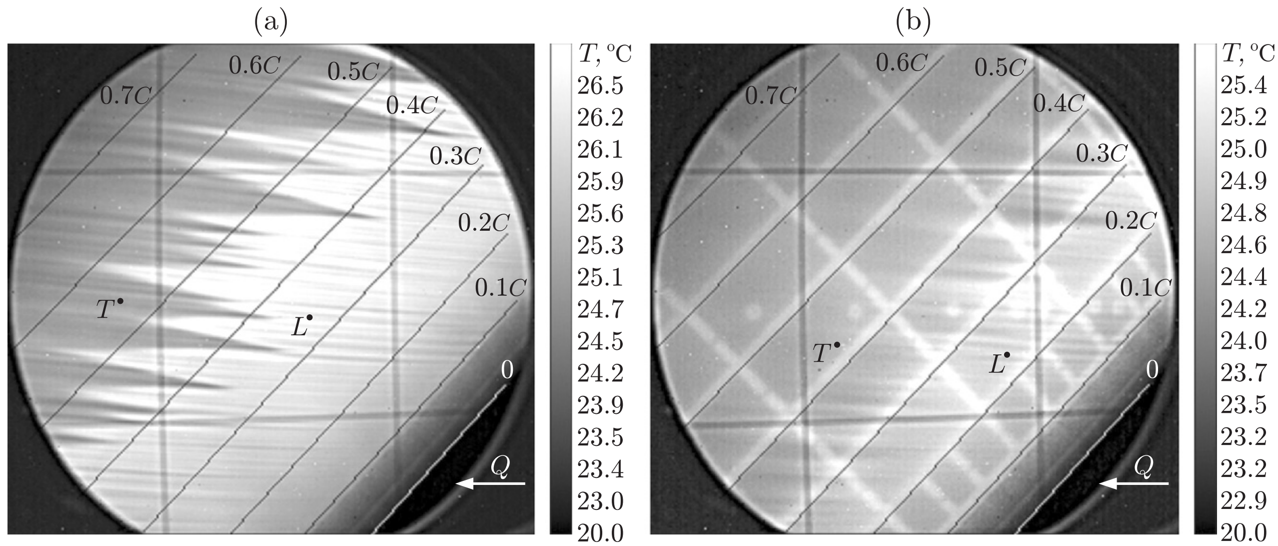

Fig. 2. Maps of the surface temperature T_s of the swept wing model at the angle of attack $\alpha = -5°$, $Q = 30$ m/s, and Tu $= 0.09\%$ (a) and 0.84% (b).

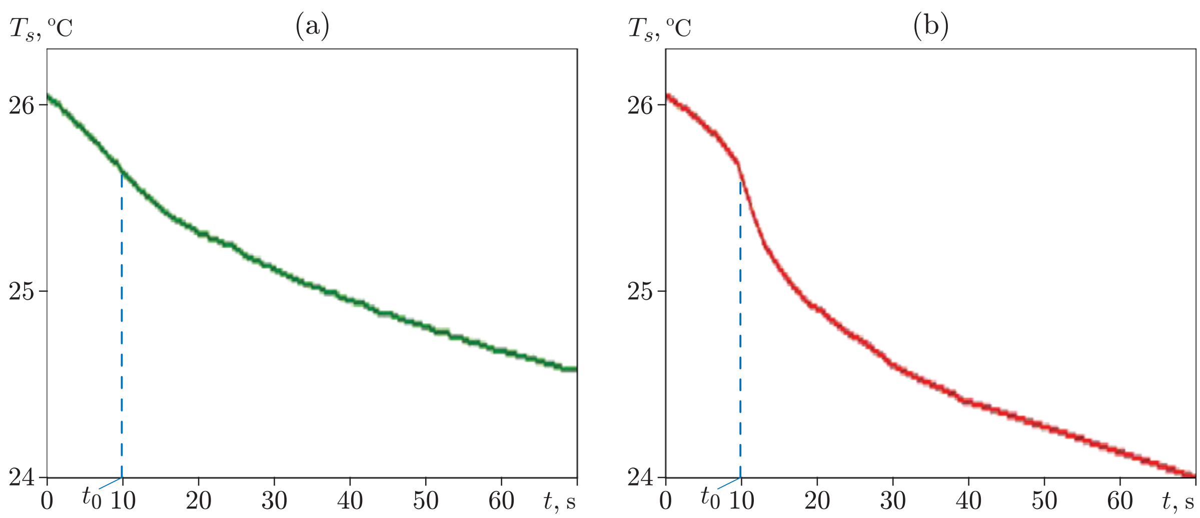

Fig. 3. Surface temperature versus time in the laminar region (a) and turbulent region (b) of the boundary layer.

Figure 2b shows a similar high-contrast frame recorded approximately in 20 s after reaching the operating velocity and illustrating the LTT at the same parameters, but in the ETL regime (Tu $= 0.84\%$). In this case, the readability of the IR image decreases so that it is even difficult to estimate the span-averaged LTT position. As was noted above, the pattern is complicated by the enhanced influence of unsteady disturbances on the process, resulting in essential unsteadiness and significant extension of the LTT region [4]. Another factor complicating the problem is the fact that the model shell is already cooled when a sufficient contrast of IR images is reached and the model frame with the elements having higher heat capacities becomes visible (see Fig. 2b).

Let us consider two arbitrary points on the wing model surface; these points are located in the laminar and turbulent regions of the flow (points L and T in Fig. 2b, respectively). Figure 3a shows the time evolution of the model surface temperature at the point L. At this point, the model surface is cooled by the laminar flow fairly monotonically during the entire period of recording of IR images (70 s); the surface temperature decreases in accordance with a close-to-exponential law. At the point T, which is located in the turbulent region after reaching

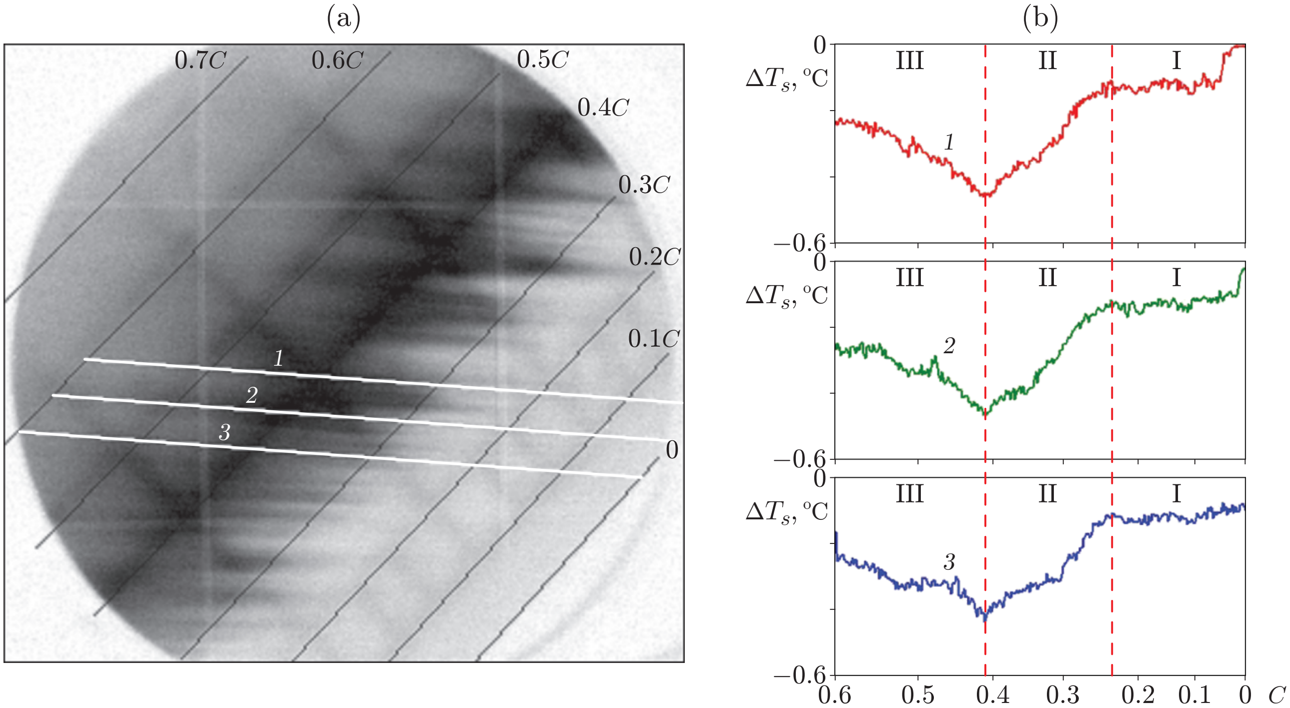

Fig. 4. Distributions of the temperature difference ΔT_s over the model surface (flow direction from left to right) (a) and along curves *1*, *2*, and *3* (b) for Tu = 0.84%, $\alpha = -5°$, and $Q = 30$ m/s: laminar flow region (I), LTT region (II), and turbulent flow region (III).

the operating velocity, the temperature behavior has a specific kink observed for several seconds after the time t_0, namely, a drastic decrease in the model surface temperature (Fig. 3b). This is caused by the following factor. As the flow in the wind tunnel is accelerated and the transitional Reynolds number is reached, a turbulent zone is formed in the rear part of the model; this zone moves upstream with a further increase in the flow velocity until the operating velocity is reached in the wind tunnel and the LTT position ceases to move. The characteristic time t_0 corresponds to the time of arrival of the turbulent zone at the observation point, followed by a transient thermodynamic process typical for the turbulent flow. It is seen in Fig. 3b that the major temperature difference between the laminar and turbulent regions is formed in a small time interval when the most intense cooling of the model by the turbulent flow takes place. Thus, for estimating the LTT position on the basis of the surface temperature, it is preferable to use IR images with the maximum possible contrast taken in 10–20 s after the instant t_0 of reaching the operating velocity, whereas the maximum difference in the model cooling rates dT_s/dt is observed immediately after setting the wind tunnel velocity regime (see Fig. 3b).

Figure 4a shows the change in the wing model surface temperature $\Delta T_s = T_s(t_0) - T_s(t_1) \approx (t_1 - t_0)(dT_s/dt)$ obtained by means of pixel-by-pixel subtraction of the IR image taken at the time t_0 from the IR image recorded in 2 s after t_0 ($t_1 = t_0 + 2$ s). It is seen that the temperature change ΔT_s directly proportional to the surface cooling rate dT_s/dt allows more precise separation of the laminar and turbulent regions than the surface temperature T_s itself (see Fig. 2b). This is caused by the fact that subtraction of the chosen IR images allows one to avoid parasitic and background signals to a large extent and ensures a good signal-to-noise ratio and, as a consequence, more precise determination of the LTT position, which is clearly distinguished in Fig. 4a in the vicinity of the chordwise coordinate $x = 0.3C$.

Let us consider the change in the surface temperature ΔT_s along arbitrary curves *1*–*3* (see Fig. 4a) aligned approximately along steady crossflow vortices, i.e., along the curves of disturbance growth. The distributions of the changes in the temperature ΔT_s along these curves testify that the surface temperature of the entire initial part of the wing model decreases approximately by 0.1°C during 2 s after the characteristic time instant t_0. The plateau observed at $\Delta T_s \sim 0.1$°C extends downstream up to the coordinate $0.23C$–$0.25C$ and corresponds to the laminar state of the boundary layer. Further downstream, the surface cooling rate increases owing to the LTT beginning. The LTT process is finalized at a distance from the leading edge approximately equal to $x = 0.41C$, where the maximum surface cooling is observed (approximately by 0.4°C). Thus, the mean length of the LTT region can be quantified: in this regime of measurements, its value is approximately $0.16C$–$0.18C$ [note that an acceptable error for the purposes of engineering modeling of LTT is usually assumed to be 5–10% of the model length (see, e.g., [1])]. Thus, the proposed algorithm of processing of IR imaging data offers a possibility of accurate quantification both of the LTT position and LTT length on a swept wing, including flow regimes with an enhanced level of free-stream turbulence.

The changes in the temperature $\Delta T_s = 0.1$°C in the laminar region and $\Delta T_s = 0.4$°C in the turbulent region are directly proportional to the surface cooling rates dT_s/dt in these regions. Thus, in the chosen two-second interval of observation, the averaged rates of model cooling in the laminar and turbulent regions differ by a factor of 4 (approximately 0.05 and 0.20°C/s, respectively) and can be chosen as the governing parameter for distinguishing these regions. It can be noted again that the model cooling rates in the laminar and turbulent regions become closer to each other at later times corresponding to almost steady heat fluxes, and it is difficult to distinguish them at the end of IR movie recording (see Fig. 3).

CONCLUSIONS

A new experimental technique of quantification of the LTT position on a swept wing is proposed. The technique is based on processing of time-dependent IR data. The main element of the processing algorithm is pixel-by-pixel subtraction (differentiation) of consecutively recorded IR images; as a result, the rate of changing of the model surface temperature can be estimated. For the laboratory swept wing model with a complicated and thermodynamically inhomogeneous structure, this approach allows elimination of the influence of significant inhomogeneities of model preheating and of different heat capacities of the structural elements of the model and, thus, a significant increase in the amount of information retrieved from the IR records.

The novelty of the method of determining the LTT position is the use of IR images recorded within several first seconds after reaching the operating velocity in the wind tunnel. In this small time interval, the model cooling rates in the laminar and turbulent regions are found to differ by several hundred percent. Thus, based on the proposed method, it is possible to determine the borders of the laminar and turbulent regions of the boundary layer on a swept wing in the flow with an enhanced level of free-stream turbulence with sufficient accuracy for engineering modeling of the LTT process with the use of the IR imaging system.

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