11th World Congress on Computational Mechanics (WCCM XI)
5th European Conference on Computational Mechanics (ECCM V)
6th European Conference on Computational Fluid Dynamics (ECFD VI)
E. Oñate, J. Oliver and A. Huerta (Eds)

THE FREE-STREAM TURBULENCE EFFECT ON THE LAMINAR-TURBULENT TRANSITION IN THE SWEPT WING BOUNDARY LAYER

SERGEY L. CHERNYSHEV, ALEXANDER I. IVANOV, ANDREY PH. KISELEV, VLADIMIR A. KUZMINSKY AND DMITRY S. SBOEV

Central Aerohydrodynamic Institute n.a. prof. N.E. Zhukovsky,
140180, Zhukovsky Moscow reg., Russia
e-mail: a-ph-kiselev@ya.ru,www.tsagi.ru

Key Words: boundary layer, crossflow instability, transition, turbulence.

Summary. *The experimental investigation of laminar-turbulent transition caused by cross-flow instability in a boundary layer over swept wing was conducted. The influence of increasing of free-stream turbulence level on transition location was determined. The comparison is made of the results obtained with the boundary layer transition data for the straight wing with the same airfoil at similar external condition. It was shown that at high free-stream turbulence the "streaky structures" localized in space and time, which transforms into turbulent spots, are observed in the boundary layer of the swept wing. The transition location on the swept wing in this case shifts downstream compared with the straight wing tests. This fact contrasts sharply with the available data concerning the sweep angle influence on the transition location at the low-turbulence external flow. Application of the semi-empirical* e^N*-method and empirical criteria to transition prediction is discussed.*

1 INTRODUCTION

Problem of the laminar-turbulent transition prediction in the 3D boundary layer, such as the swept wing boundary layer, is of great applied importance. Tests of the advanced aircraft in the industrial wind tunnels (WT) are carried out, as a rule, at the high free-stream turbulence. In connection with this, the researchers should have in their possession methods, allowing to calculate with the enough precision the boundary layer stability characteristics and laminar-turbulent transition both in flight conditions and in different WT.

Boundary layer on the swept wing surface is subjected to many kinds of instabilities, the cross-flow instability representing the most interest for the researchers. This kind of instability reveals in the negative pressure gradient area near the wing leading edge as running and stationary disturbances (longitudinally-oriented vortexes). As it follows from the investigation of the turbulence effect on the laminar-turbulent transition [1, 2], at low turbulence level the stationary cross-flow disturbances dominate in the transition process, while the running disturbances begin to play the leading role with the turbulence level rise. Another transition mechanism was investigated in study [3], when under the influence of rather intensive external turbulence the low-frequency disturbances, stretched along the flow and localized in space and time are developed. These disturbances are called "streaky structures”. Laminar-turbulent transition in this case is realised through the appearence of turbulent spots as a result of the secondary instability of these structures.

The purpose of the experiments described in this report was further investigation of the free-stream turbulence effect on the laminar-turbulent transition parameters for the swept wing boundary layer. The proposed work continues the researches accomplished in TsAGI in the framework of the TELFONA Project (FP6), [4].

2 EXPERIMENTAL EQUIPMENT AND TESTING TECHNIQUE

The experiments were carried out in a low turbulent WT T-124 TsAGI [5] at $U_0 = 77.6$ m/s on the models with straight and swept wings. Both models had an identical chord $C = 1000$ mm and an identical LV6 laminar airfoil in the section along free stream direction, with the relative thickness of 11%. This airfoil was designed by DLR as part of the TELFONA Pathfinder Wing design activity. The swept wing model had the sweep angle $\chi = 35°$. The general view of swept wing model with 3D traverse gear in T-124 wind tunnel test section is presented in Figure 1.

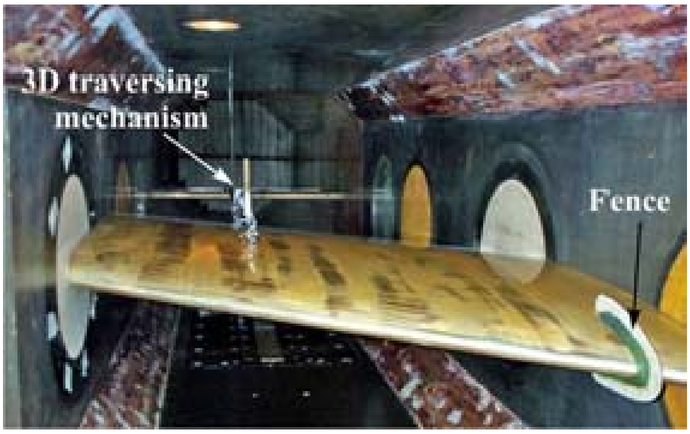

Figure 1: The general view of the swept wing model in T124 wind tunnel test section. 3D traverse gear and the fence are seen.

We used the system of coordinates with the longitudinal axis X directed perpendicularly to the leading edge of the wing, and the transversal axis Z directed along the leading edge. The origin of coordinates is located on the leading edge in the center of the wingspan of the models (Figure 2).

When carrying out the experiments, we fulfilled the pneumometric and thermoanemometric measurements and visualization by means of the liquid crystal (LC) termography method [6]. The equipment used and models are described in detail in [4, 7, 8].

The pressure distributions over the surface of wings had a portion of almost constant pressure at $0.2 < X/C < 0.5$, which was preceded by the acceleration portion in the leading edge region.

The degree of turbulence under the natural conditions of the WT test section amounted to 0.064%. For the turbulence generation with a higher intensity, we used two grids, which enabled us to obtain in the leading edge region of the models Tu = 0.61 and 0.91%, respectively. The turbulence generated by grids is described in more detail in [8]. In the results submitted below, all investigated flow regimes are characterized by the pair of parameters χ and *Tu*.

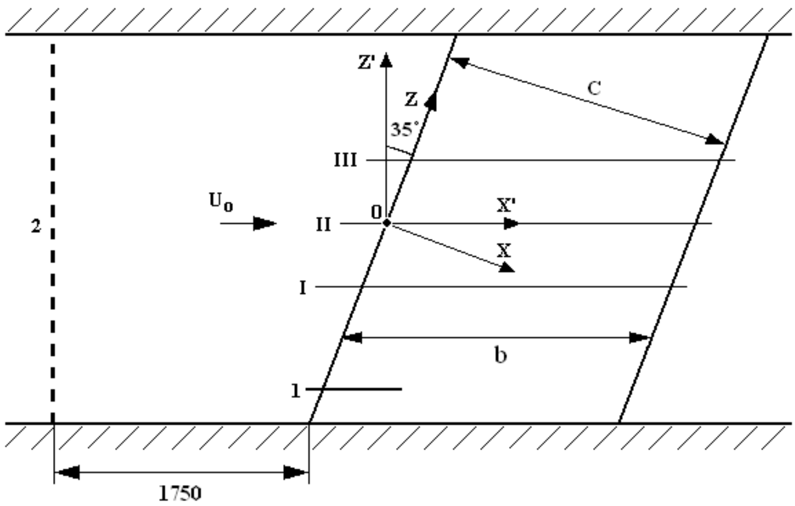

Figure 2: Scheme of the model and system of coordinates: the Roman figures designated rows of pressure taps of the model, 1 – the fence, 2 – turbulizing grid, distance in mm.

In this work, primary attention is given to investigation of the destruction zone in the laminar flow mode in the boundary layer. With this purpose, we studied the distributions of the intermittency in the thermoanemometer signal γ obtained at the height from the wall corresponding to the middle of the boundary layer.

The intermittency detector is described in [7, 8]. The dependence of γ on the longitudinal coordinate can be presented as

$$\gamma = 1 - \exp\left[-\frac{n\sigma}{U_0}\left(X - X_t\right)^2 \right],$$

where X_t – co-ordinate of the transition area beginning, n – generation rate of turbulent spots, σ – parameter depending on the angle and velocity of the turbulent spots propagation.

This dependence was proposed for two-dimensional flows; however, its use in three-dimensional flows is justified by the data of [9]. In the majority of flows, the intermittency function

$$F = \sqrt{-\ln(1-\gamma)}$$

in the zone of the laminar-turbulent transition can be approximated by a straight line. The straight-line slope is determined by the product $n\sigma$. For the starting point X_t of the transition zone, we accepted the intersection point between the straight line $F(X)$ and the axis X; for the final point X_T of the transition, accepted the point corresponding to $F = 2.14$ ($\gamma = 0.99$). The value $\Delta X = (X_T/C - X_t/C)$ gives the length of the transition zone. As one of parameters describing the transition position in this work, we accepted the value of $X_{0.5}$ corresponding to $\gamma = 0.5$ from [2].

3 RESULTS AND DISCUSSION

3.1 Experimental results

The measurements in the low-turbulent flow showed that the transition proceeded on the straight wing model in the zone of a separation bubble started at X/C = 0.59 [8]. At χ = 35° and Tu = 0.064%, the transition was caused by the development of cross-flow disturbances and their high frequency secondary instability; for this mode, X_t/C = 0.32. These results correspond to well-known data (see, for example, [10]) according to which high increments of the increase of the inviscid cross-flow instability lead to faster transition on the swept wing in comparison with the similar straight wing.

In Figure 3, we show the data obtained in experiments on the intermittency in various experimental conditions.

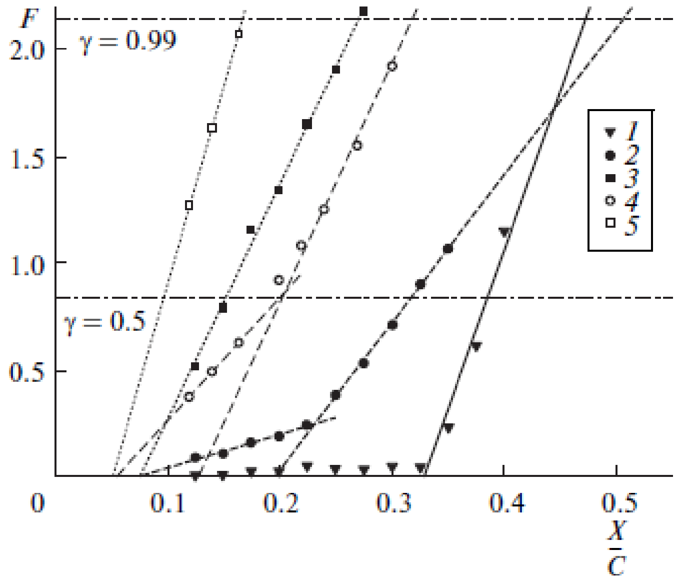

Figure 3: Distributions of the intermittency function F in the boundary layer: 1 – χ = 35°, Tu = 0.064%, 2 – χ = 35°, Tu = 0.61%, 3 – χ = 35°, Tu = 0.91%, 4 – χ = 0, Tu = 0.61%, 5 – χ = 0, Tu = 0.91%.

Also in Figure 3 the straight lines obtained by approximation of measured values of F by the least-squares method are shown. It can be seen that the experimental dependences are described very well by linear functions.

The typical oscillograms of the signal of thermoanemometer for X/C = 0.2 are shown in Figures 4; they demonstrate that the used detector of γ makes it possible to measure this value correctly.

The thermoanemometric data on the transition position were confirmed by means of LC-termography method of visualization, which demonstrated a sharp increase in the surface temperature caused by the laminar–turbulent transition corresponding to the position with $\gamma \approx 0.8$ (Figure 5) on the longitudinal coordinate.

In the case of Tu = 0.61%, the dog-leg of the dependences $F(X)$ in Figure 3 in the region of $X/C = 0.2$ is observed both at χ = 0 and at χ = 35°. It is the so called effect of "subtransition" [9] manifesting itself in the variation of the parameter σ for reasonably fast changes in the pressure distribution, which took place on both models.

From the data shown in Figure 3, it can be seen that the values of X_t and X_T are higher at the increased degree of external turbulence on the swept wing than on the straight wing. In addition, the slope of lines $F(X)$ on the swept wing is less than on the straight wing.

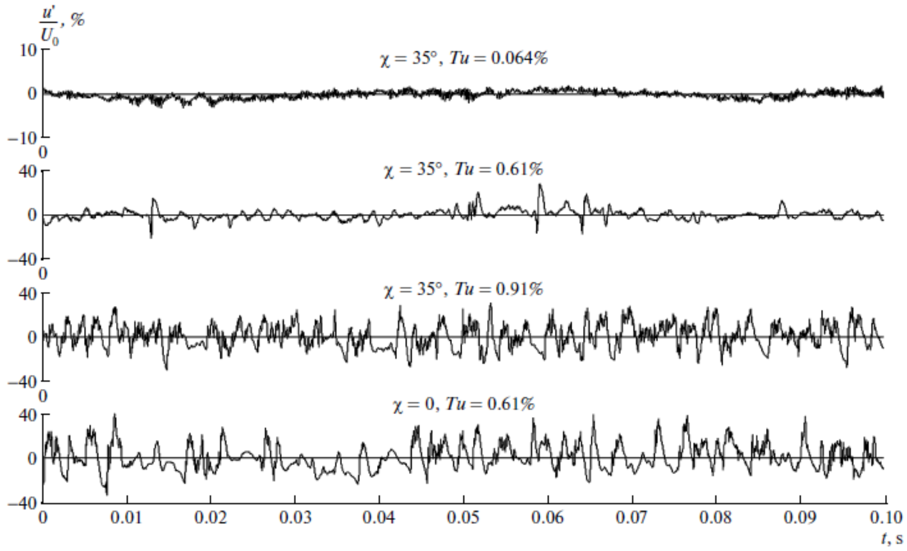

Figure 4: Typical oscillograms of thermoanemometer signal at $X/C = 0.2$. The oscillogram scale for $\chi = 35°$ and $Tu = 0.064\%$ is increased four times.

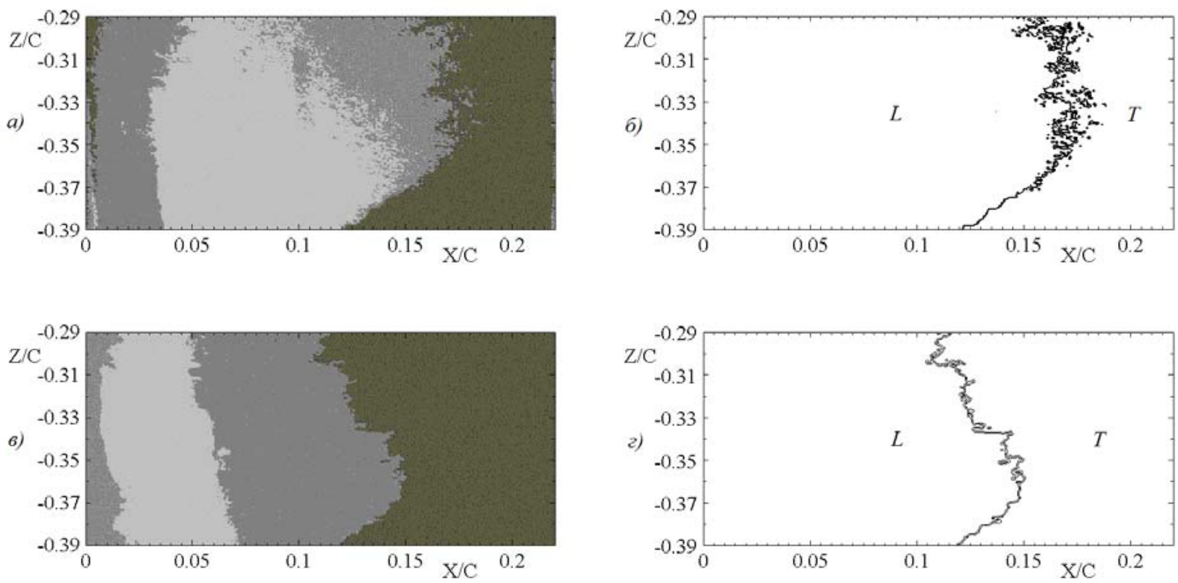

Figure 5: Laminar–turbulent transition line at $\chi = 35°$ according to the LC- termography method of visualization. (*а*, *в*) – fields of surface temperature; (*б*, *г*) – the lines of maximum temperature gradients. а), б) –$Tu = 0.61\%$, в), г) –$Tu = 0.91\%$. More dark shades of the gray correspond to higher temperature. "L" denotes the region of the laminar boundary layer, while "T" denotes the turbulent one.

Taking into account that there is no gradient of pressure at $X/C > 0.2$ on both models, it is possible to conclude that the generation rate of turbulent spots on the swept wing is lower than on the straight wing at an identical degree of turbulence. For Tu = 0.61%, the characteristic values of $\Delta X/C = 0.43$ and $X_{0.5}/C = 0.32$ are obtained on the swept wing, while they are 0.26 and 0.2, respectively, on the straight wing. As can be seen from Figure 3, the same effect also takes place at Tu = 0.91%.

The observed features of the laminar–turbulent transition under conditions of the increased degree of external turbulence on a swept wing are also explained by the presence of disturbances of different types at the boundary layer in addition to the unstable cross-flow disturbances. These are the so called “streaky structures” excited by the localized vortex disturbances of the external flow in both the two-dimensional and three-dimensional boundary layers [3]. Developed in the boundary layer, the “streaky structures”, localized in space and time, result in the occurrence of turbulent spots also localized in space and time.

The disturbances of the type of the “streaky structures” and the arising turbulent spots at different stages of development are seen clearly on the oscillogram for $\chi = 35°$ and Tu = 0.61% ($\gamma = 0.04$) in Figure 4 at t = 0.013, 0.05, 0.06, and 0.088 s. Therefore, under the conditions of this experiment at the increased external turbulence, the dynamics of destruction zone of the laminar flow in the boundary layer was determined on both the straight wing and the swept wing by the arising and the subsequent merging of turbulent spots excited by the external turbulence instead by the development of instability of the average velocity profiles in boundary layer.

Observed in the presence of intense external turbulence on the swept wing, the downstream displacement of the laminar–turbulent transition sharply contrasts with the known data for low-turbulent external flow in comparison with that on the straight wing [10]. However, this conclusion confirms the results of theoretical investigation [11] in which it is shown that the presence of the cross-flow in the boundary layer on the swept wing considerably decreases its receptivity to the external turbulence in comparison with the two dimensional boundary layer. Thus, the initial amplitude of disturbances generated by the external turbulence in the boundary layer on the swept wing is lower than that on the straight wing, which leads to a delay in the development of the laminar–turbulent transition. This fact should be taken into account by preparation and carrying out of the investigations of configurations with swept wings in the industrial WTs having a reasonably high degree of turbulence of the incoming flow.

3.2 Analysis of the empirical and semiempirical transition prediction methods

Prediction of the laminar-turbulent transition location on the swept wings is a very complex problem for the CFD nowadays. The results obtained in this work may be used for verification of empirical and semi-empirical transition criteria used in the engineering practice. As it was shown above, the laminar flow destruction zone has finite length. That is the reason why it is convenient to choose a certain character point inside the laminar flow destruction region as a specific transition point for comparison with the calculation methods. For this purpose in paper [2] it was proposed to use the point corresponding to $\gamma = 0.5$. This value is accepted also in the present work. Because in the 3D boundary layer the external turbulence influence can’t be reliably taken into account now using the e^N-method, for comparison the experimental data should be used which were obtained at the low-turbulence external flow. In these conditions the transition line on the swept wings has the serrated form, with critical *N*-factor values for another values of *Z*' co-ordinate possibly being slightly different from the obtained ones. However, the dimension of turbulent wedges in the longitudinal direction usually do not exceed 10% of the chord, giving rise to the error in definition of the critical N-factor values no more than ±1.

The longitudinal distributions of the *N*-factor for the cases of angles of attack of $\alpha' = 0$ and -2° calculated using the linear theory are shown in Figure 6. The calculation was performed on the basis of the numerical matrix method of the hydrodynamic stability theory of three-dimensional boundary layer [12].

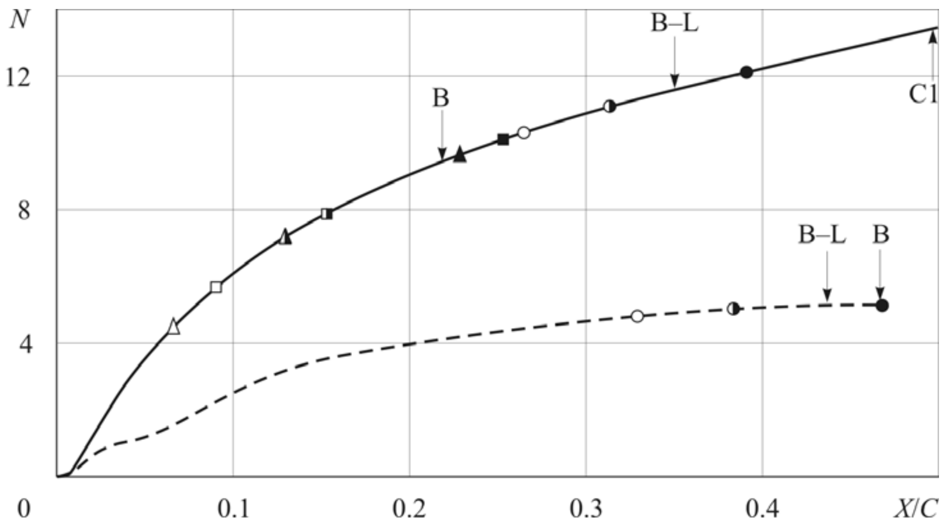

Figure 6: N-factor dependence from the longitudinal co-ordinate: – $\alpha' = -2°$, – $\alpha' = 0$, ○ – natural condition, *Tu* = 0.064%, □ –*Tu* = 0.61%, △ –*Tu* = 0.91%. Open symbols show the transition onset, filled symbols – points, where $\gamma = 0.99$, semi-filled – position $\gamma = 0.5$. Shooters showed the transition location defined by means of criteria C1, Brown (B) and Barinov-Lutovinov (B-L).

The specific points obtained at different experimental conditions are also marked on these curves. Figure 6 demonstrates that at zero angle of attack the calculated *N*-factor values are substantially lower than at $\alpha' = -2°$. It is explained by the fact that according to calculations the cross-flow intensity at $\alpha' = 0$ is approximately two times lower than at $\alpha' = -2°$. At $X/C = 0.2$ typical values of the maximum cross-flow velocity in the co-ordinate system associated with the inviscid flow streamline are equal to $0.023U_0$ and $0.042U_0$ respectively for these two cases. *N*-factor value corresponding to $\gamma = 0.5$ for low-turbulence external flow in the case of $\alpha' = -2°$ was 11.1. This value practically coincides with the well-known data [13, 14] for the tests in the low-turbulence wind tunnels in the presence of cross-flow instability. However, for the same external conditions at $\alpha' = 0$ the *N*-factor value corresponding to $\gamma = 0.5$ appeared to be only 5. This value is substantially lower than *N*-factors, obtained in the condition of the increased turbulence at $\alpha' = -2°$, where they were 7.9 for *Tu* = 0.61% and 7.1 for *Tu* = 0.91% (see Figure 6). It should be noted especially that in all calculation cases the cross-flow instability waves has become the most quickly rising ones. In both the experiment and calculations the evidence of the longitudinal instability (like the

Tollmien-Schlichting waves) was absent. So, it may be concluded that contrary to the 2D flows, for the swept wing boundary layer the semi-empirical e^N-method (in the variant of the envelope method) gives substantial scatter of the critical N-factor values and does not permit to correlate reliably the transition data. In the papers [1, 13, 14] similar conclusions were drown also for other variants of e^N-method. The reason of this phenomenon is dominating of the non-linear effects in the transition processes in the 3D boundary layer even at low level of the external turbulence.

The empirical criteria, allowing to estimate the transition location on the swept wings basing only on the averaged flow characteristics, are widely used in the engineering practice. Application of these criteria doesn't demand of high expenses of time. This class of criteria includes the C1 criterion [15], connecting the transition Reynolds number based on the cross-flow momentum thickness with the boundary layer form-parameter H, and also criteria of Brown [16] and Barinov and Lutovinov [17], approximating the Orr-Sommerfeld equations solutions for different classes of the averaged velocity profiles. Basing on the criteria [16, 17] it is possible to define the Reynolds number of the cross-flow instability Re^*_{cf}. Local Reynolds number $\mathrm{Re}_{0.1}$ is calculated using the maximum value of the cross-flow $W_{\max}$ in the co-ordinate system associated with the streamline of the external flow, and the distance from the surface $Y_{0.1}$, where cross flow reduces to the value of $0.1W_{\max}$. It is considered that transition takes place when the ratio $\mathrm{Re}_{0.1}/\mathrm{Re}^*_{cf}$ exceeds certain value K_{cf}. According to the results of [18] the value K_{cf} was taken to be equal to 3.

The results of implementation of the criteria [15 - 17] for definition of the transition location in the conditions of the described experiments are also shown in Figure 6. It is shown, that C1 criterion at $\alpha' = -2°$ gives shifted downstream transition location, and at $\alpha' = 0$ this criterion predicts absence of transition up to the separation line in the adverse pressure gradient zone. Brown criterion [16] has scatter of about 10% of the chord length relative to $\gamma = 0.5$ point in both positive and negative. The best results was demonstrated by the criterion of Barinov and Lutovinov [17], which in both cases predicts the transition location shifted downstream from the point $\gamma = 0.5$ by approximately 5% of the chord, i.e. corresponding to $\gamma \approx 0.8$.

The results obtained confirm the conclusions [18, 19] that simple empirical criteria may be successfully applied for laminar-turbulent transition prediction on the swept wings.

4 CONCLUSIONS

- The laminar-turbulent transition caused by the cross-flow instability on the swept wing boundary layer was experimentally investigated.
- The comparison is made of the results obtained with the boundary layer transition data for the straight wing with the same airfoil at similar external condition. The transition location on the swept wing at high free-stream turbulence shifts downstream compared with the straight wing tests. This fact contrasts sharply with the available data concerning the sweep angle influence on the transition location at the low-turbulence external flow, but it confirms one of the theoretical mechanisms of the 3D boundary layer receptivity to the intensive external turbulence.
- The results of the semi-empirical e^N-method implementation to the transition location prediction are analyzed. It may be concluded that contrary to the 2D flows, for the

swept wing boundary layer the semi-empirical e^N -method gives substantial scatter of the critical *N*-factor values and does not permit to correlate reliably the transition data. The reason of this phenomenon is dominating of the non-linear effects in the transition processes in the 3D boundary layer even at low level of the external turbulence.

- The empirical criteria, allowing to estimate the transition location on the swept wings basing only on the averaged flow characteristics may be with a certain success applied for laminar-turbulent transition prediction on the swept wings.

REFERENCES

[1] Bippes, H. Basic experiments on transition in three-dimensional boundary layers dominated by crossflow instability. *Prog. Aerospace Sci*. (1999) **35**, No. 4: 363-412.

[2] Deyhle, H., Bippes, H. Disturbance growth in an unstable three-dimensional boundary layer and its dependence on environmental conditions. *J. Fluid Mech.* (1996) **316**: 73-113.

[3] Grek., G.R., Katasonov, M.M., Kozlov, V.V. Modelling of streaky structures and turbulent-spot generation process in wing boundary layer at high free-stream turbulence *Thermophysics and Aeromechanics* (2008). **15**, No. 4: 549-561.

[4] Chernyshev, S.L., Ivanov, A.I., Kiselev, A.Ph., Kuzminsky, V.A., Sboev,D.S., Zhigulev, S.V. Experimental and numerical investigation of the laminar-turbulent transition mechanisms in the boundary layer on 2D and 2.5D models in the low-turbulence wind tunnel. *Proceedings of 5-th European Conference on Computational Fluid Dynamics (ECCOMAS CFD 2010).* Ed. by Pereira J.C.F., Sequeira A., Pereira J.M.C. Lisbon, Portugal, June 14–17, 2010, paper No. 1786.

[5] Filippov, V.M. Characteristics of fluctuations in flow through low-turdulence arerodynamic wind tunnel T-124 designed for small speeds. *Uchenye Zapiski TsAGI.* (2008) **39**, No.1-2: 68-80 (*in Russian*).

[6] Zharkova, G.M., Kovrizhina, V.N., Khachaturyan, V. M. Experimental investigation of subsonic flow by liquid crystal termography method. *Prikl. Mekh. Tekh. Fiz.* (2002) **43.** No. 2: 122-128 (*in Russian*).

[7] Vlasov, V.A., Zhigulev, S.V., Ivanov, A.I., Kiselev, A.Ph., Kuzminsky, V.A., Sboev, D.S., Chernyshev, S.L. Laminar-turbulent transition on the LV6 laminarized airfoil: natural transition. *TsAGI Science Journal* (2011) 42, No.5: 565-591.

[8] Vlasov, V.A., Zhigulev, S.V., Ivanov, A.I., Kiselev, A.Ph., Kuzminsky, V.A., Sboev, D.S., Chernyshev, S.L. Laminar-turbulent transition on the LV6 laminarized airfoil. Part II: effect of free stream disturbances. *TsAGI Science Journal* (2011) 42, No. 6: 729-756.

[9] Narasimha, R. Subtransitions in the transition zone. *Laminar-Turbulent Transition*. Ed. by V.V. Kozlov. Berlin: Springer-Verlag, (1985). P. 141-151.

[10] Boltz, F. W., Kenyon, G.C., Allen, C.Q. NASA Techn. note TN D-338 (1960).

[11] Ustinov, M.V. Receptivity of the swept wing boundary layer to a steady flow inhomogeneity. *Fluid Dynamics* (2001) **36**. No. 3: 437-447.

[12] Kuzminsky, V.A. Matrix numerical method of stability calculation of three-dimensional boundary layers. *Uchenye Zapiski TsAGI*. (2007) **38**, No. 3-4:44-56 (*in Russian*).
[13] Arnal, D. Boundary layer transition: predictions based on linear theory. *Special course on progress in transition modelling*. AGARD Rep. 793, (1994). P. 2-1 - 2-63.
[14] Arnal, D., Casalis, G., Houdeville, R. Practical transition prediction methods: subsonic and transonic flows. *Advances in laminar-turbulent transition modelling*. AGARD RTO-EN-AVT-151, (2009). 34 p. [CD-ROM, ISBN 978-92-837-0090-6].
[15] Arnal, D., Habiballah, M., Coustols, C. Laminar instability theory and transition criteria in two- and three-dimensional flows. *La Rech. Aérosp*. (1984) No. 2: 125-143.
[16] Brown, W.B. A stability criterion for three-dimensional laminar boundary layers. *Boundary layer and flow control*. **2**. Ed. By G.V. Lachman. London: Pergamon Press, (1961). P. 913-923.
[17] Barinov, V.A, Lutovinov, V.M. On the parameters of approximate relationship of critical Reynolds number in the three-dimensional boundary layer. *Uchenye Zapiski TsAGI* (1973) **4**. No. 4:27–32 (*in Russian*).
[18] Kiselev, A.Ph., Bokser, V.D. Investigation of flow laminarization of swept wings. *TsAGI—principal stages of scientific activities 1993—2003*. Moscow: Nauka-Fizmatlit; (2003). P. 33-38 (*in Russian*).
[19] Chernyshev, S.L., Kiselev, A.Ph., Kuryachii, A.P. Laminar flow control research at TsAGI: Past and present. *Prog. Aerospace Sci*. (2011) **47**. No 3:169-185.