Experimental study of localized disturbances at straight and swept wing boundary layer

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Abstract
Laminar-turbulent transition is one of the most studied aerodynamic phenomenon. In this respect, studying the role of localized boundary layer disturbances on this transition is important. Previous our researches on different kinds of models and flow conditions (such as flat plates, straight wings and swept wings, low and high free stream turbulence level) shown that local effect on the boundary layer can generate streaky structures in the boundary layer, preceded by wave packets ("forerunners") which are responsible of the transition. The current paper give short review of previous our investigations of forerunners together with new experiment on the influence of an artificial disturbance created outside a swept wing boundary layer, thanks to a blowing pipe in front of the leading edge. The characteristics and dynamics of longitudinal localized streaks and wave packets - forerunners have been studied experimentally under the low free stream turbulence level.

1. Introduction

In recent years, much attention has been given to the study of longitudinal localized disturbances, or structures, developing in boundary layer under the action of high or enhanced level of free-stream turbulence. Such structures create conditions for the development of high-frequency wave disturbances (secondary instability, forerunners) that can subsequently transform into turbulent spots; as a result, the boundary-layer flow changes its state from laminar to the turbulent. Experiments under natural conditions fail to give exhaustive answers to posed questions because the emergence of boundary-layer disturbances is a stochastic process, and in most cases it is almost impossible to trace the origin and subsequent evolution of a particular disturbance. For a detailed study, longitudinal structures, or localized disturbances, are to be artificially modeled in boundary layer. The experiments are shown that at the vicinity of the edges (leading and rear) of longitudinal structures the wave packets - forerunners can appear under the some conditions. Actually, the forerunner is excited by the impact of a rectangular pulse (time dependent blowing or suction) on the boundary layer. As a result of dispersion, the rectangular pulse front is spread into frequencies, of which the most unstable ones are enhanced by the boundary layer. At the experiment [1] the behaviors of the artificial streaky structures and the Tollmien–Shlichting (TS) wave packets in flat plate Blasius boundary layer were studied. The streaky structures were created by applying suction or blowing through a thin spanwise slot at the plate surface. It was found that the magnitude of $\partial u/\partial t$ in the streaky structures, which was varied, is a critical fact in determining whether high-frequency wave packets are generated in the leading and rear edges of the disturbances, figure 1. Damping the streamwise velocity gradient at the edges of the disturbances prevented the formation of high-frequency wave packets named us "forerunners" (see figure 1, b, d).

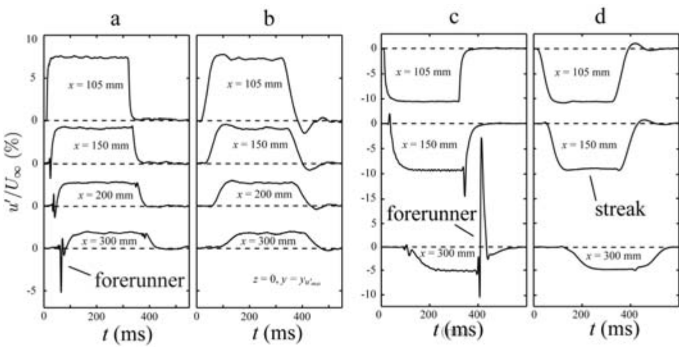

Figure 1: Time traces, suction (a, b) and blowing (c, d) case, leading and rear edges ($\partial u/\partial t$) of streak is damped (b, d)

1.1. Forerunners at the straight wing

Investigations [2] show the outbreak of the interaction between long artificial disturbances generated from a blowing or sucking slot into the straight wing profile and the boundary layer. It was found different results which defer depending on the leading or trailing edge of the disturbance. Anyway, in each case, was noticed the appearance of wave packets, also called precursors or forerunners, which features matched with characteristics of TS-waves. It has been shown that those forerunners, along with the instability of the longitudinal structures, are elements of the laminar-turbulent transition process. Indeed, the artificial disturbance created has a broad spectrum of frequencies which some of them can fall into the region of flow instability. As a result, wave packets are created and they can develop downstream to finally give rise to a turbulent spot and later, the transition. It was noticed later that those wave packets tend to be damped at the leading edge of the disturbance and to grow at the trailing edge in the case of blowing from a slot whereas in the case of suction or blowing from a pipe, the opposite phenomenon can be observed [3]. Moreover, it has to be shown too that forerunners are all damped if the experiment is led under a favorable pressure gradient whereas when the adverse pressure gradient increase, forerunners grow and the transition process arrives quickly.

1.2. Forerunners at the swept wing

The experiments [4] showed that, on straight wings, forerunners are TS-waves packets. Thanks to the same experimental set up (using a slot on the leading edge of the wing and parallel to it), it also showed the existence of similar forerunners with swept wings which can evolve in turbulent spots and then lead to the transition. However, due to the three-dimensional structure of a swept wing boundary layer induced by the asymmetric structure of the flow, these forerunners, as well as longitudinal structures, become asymmetric and acquire some vortical characteristics.

Researches [5] studied deeply the case of swept wings. First, longitudinal disturbances parallel to the leading edge appear, and then quasi-2D wave-packets arise. They grow and acquire a 3D structure, before evolving in Λ-structures in the case of injection. These Λ-structures seem not to exist in the case of suction. Nevertheless, when a frequency filter is applied to eliminate low frequencies due to longitudinal structures, Λ-structures appear.

1.3. Effect of enhanced and high free stream turbulence level on forerunners

From the experiments [6] it was observed that the wave packets-localized disturbance forerunners can exist and produce turbulence in gradient flow under an enhanced ($0.8\%U_\infty$) and high ($2.5\%U_\infty$) level of free stream turbulence. It was found that under the enhanced free stream turbulence level, the TS wave can be suppressed in the linear region of its growth; this finding complies with data gained in previous studies. It is obtained that for a straight wing, the forerunner amplitude under enhanced turbulence level starts growing earlier than under low level of free-stream turbulence. The greater is the initial amplitude of the forerunners, the earlier the laminar-turbulent transition due to the breaking of the forerunners occurs. Because of 3D flow pattern, the forerunners and longitudinal structures in the swept-wing boundary layer grow asymmetric; nonetheless, their downstream behavior is analogous to that in the straight-wing case.

2. Experimental setup

The current experiments were carried out at the Institute of Theoretical and Applied Mechanics, Siberian Branch of Russian Academy of Science (ITAM SB RAS). The MT-324 wind tunnel was used under a low free-stream turbulence level (Tu = 0.18%) in the empty test section. Test section was 800 mm long, with a square section of 200x200 mm². The free-stream velocity was U_∞= 6.8 m/s.

The wing model used, which had a near-plane region of low curvature, had a sweep angle β = 45°. The profile had a chord C = 410 mm long and a 200 mm span length. The wing's angle of attack (AOA) was -1°. This angle was chosen empirically in order to get a good fit between the size of the whole development of the studied structures and the length of the chord. The coordinate system (0,X,Y,Z) and (O,X1,Y,Z1) were used as shown in the following scheme (see figure 2). Indeed, the origin of the axis was put on the leading edge of the wing in the middle of the test section width. The Z1 axis was chosen following the direction of the leading edge and the X1 axis, orthogonal with Z1, was used to describe the position of the spanwise cross-sections during measurements.

The blowing pipe represented in the previous scheme (see figure 3) was used to introduce artificial disturbances. The edge of pipe was positioned at X = -1 mm and Z1 = 5 mm. The Y- position of pipe was empirically chosen in order to allow the disturbance going on the extrados of the wing, and to make the noise created by the pipe going under the intrados. Moreover, putting the pipe further from the wing leading edge would have increased the number of random (unsincronized) velocity fluctuations which comes into the boundary layer from pipe. This pipe was feed by a 20 liters pressurized tank, and regulated by an electromagnetic valve and a damper volume of 35 mL to smooth the slope of the disturbance fronts. The electromagnetic valve produced 300 ms long pulses which were synchronized with the signal recording system. Mean and fluctuations of *u*-component of velocity was carried out thanks to a hot-wire technique. The single wire probe and the Constant Temperature Anemometer (CTA) AN-1003 were used. The probe was calibrated thanks to a Pitot tube. Collected datas were sent to a PC station by means of analog to digital converter L-card E14-440. The probe was manually moved in the X and Z1 directions, whereas an automatic traverse system was used for the Y one.

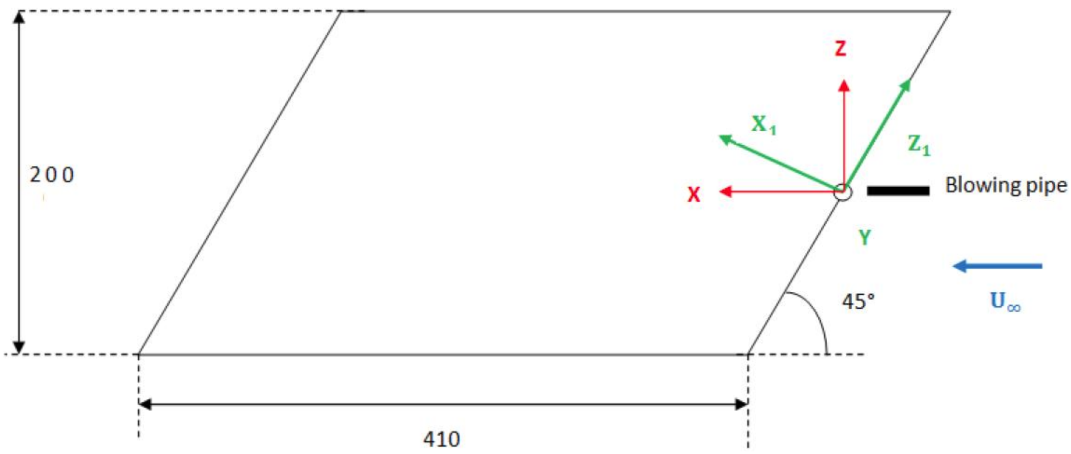

Figure 2: The wing model and the coordinate systems

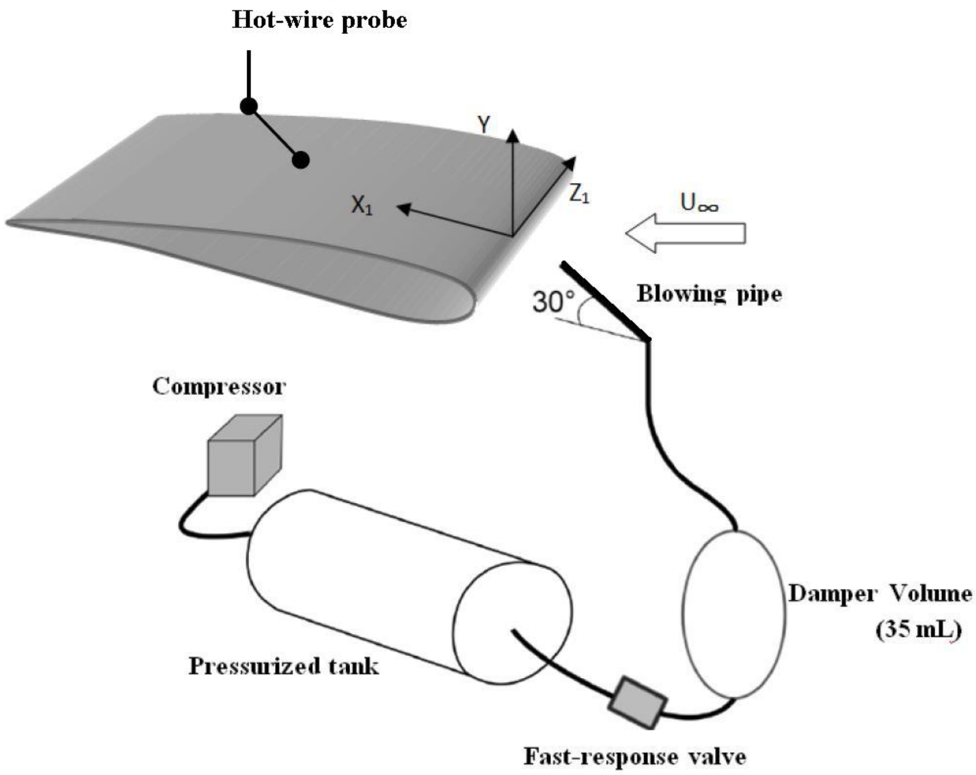

Figure 3: Experimental set-up

3. Results

The first step of the current study was to probe the speed distribution alongside the chord, on the extrados and outside of the boundary layer. This velocity will be called U_o. It has to be noticed too that this velocity profile was obtain over the middle of the wing (for Z1=0). The following curve (see figure 4) presents these results.

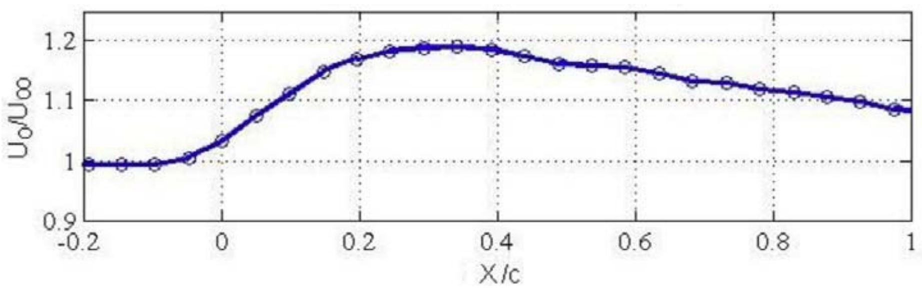

Figure 4: Mean velocity distribution alongside the chord outside the boundary layer

According to this curve, the shape and the feature of the wing profile induce a velocity deviation of the free stream which reach its maximum value at X/C = 0.34. It is possible to assume that between the leading edge and 34% of the chord, a favorable pressure gradient is created whereas an adverse one appears downstream. Moreover, according to previous results [3], it has been pointed out that forerunners should be damped in a favorable pressure gradient and grow in an adverse one. This characteristic was determinant for the good choose of the AOA. Indeed, because the purpose of this study was to monitor the appearance and the growth of forerunners before the transition occurs, we managed experimentally to find an AOA, and so a certain pressure gradient, which permitted a good fit between the size of the whole development of the studied structures and the length of the chord.
Next, the velocity profiles near the surface and alongside the chord have been plotted to study the behavior of the boundary layer (see figure 5).

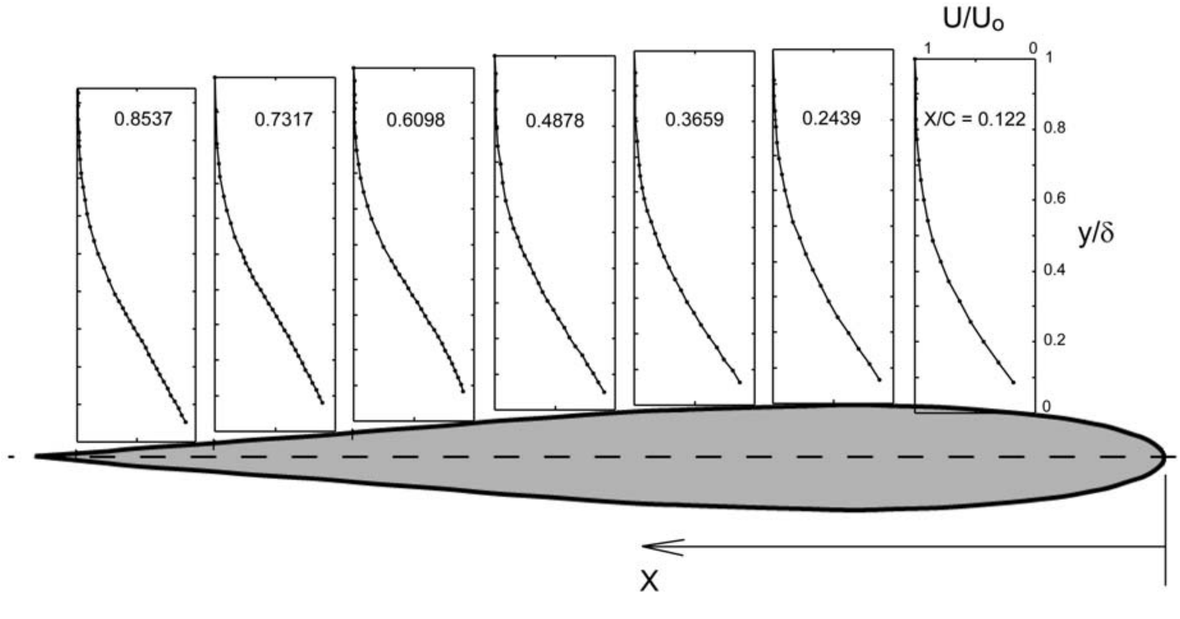

Figure 5: Velocity profiles inside the boundary layer alongside the chord at Z=0

We can notice that as close as the point of measure is from the trailing edge of the wing profile, as an inflexion point tends to appear in the velocity profile. It is to point out that due to the process of measurement with the hot wire probe, these velocity profiles are just describing the evolution of the streamwise (*u*) component of the velocity whereas previous results show that a transverse component also exists. However, even if we found an inflexion point for this velocity component, it does not mean that the laminar-turbulent transition is beginning contrary to the case of a straight wing. Indeed, because of the crossflow existing in the case of a swept wing, the interpretation is more complicated and the flow is different.

After the mean flow analysis, experiments were conducted to get, thanks to the hot-wire probe, an overview of the velocity fluctuations inside the boundary layer alongside Z1, at different positions (X/C = 0, 0.02, 0.12, 0.24, 0.37, 0.49, 0.61, 0.73 and 0.85), at the maximum velocity fluctuations in the Y direction. The areas of velocity defect and excess were plotted in the (Z1,t) plane, see figure 6.

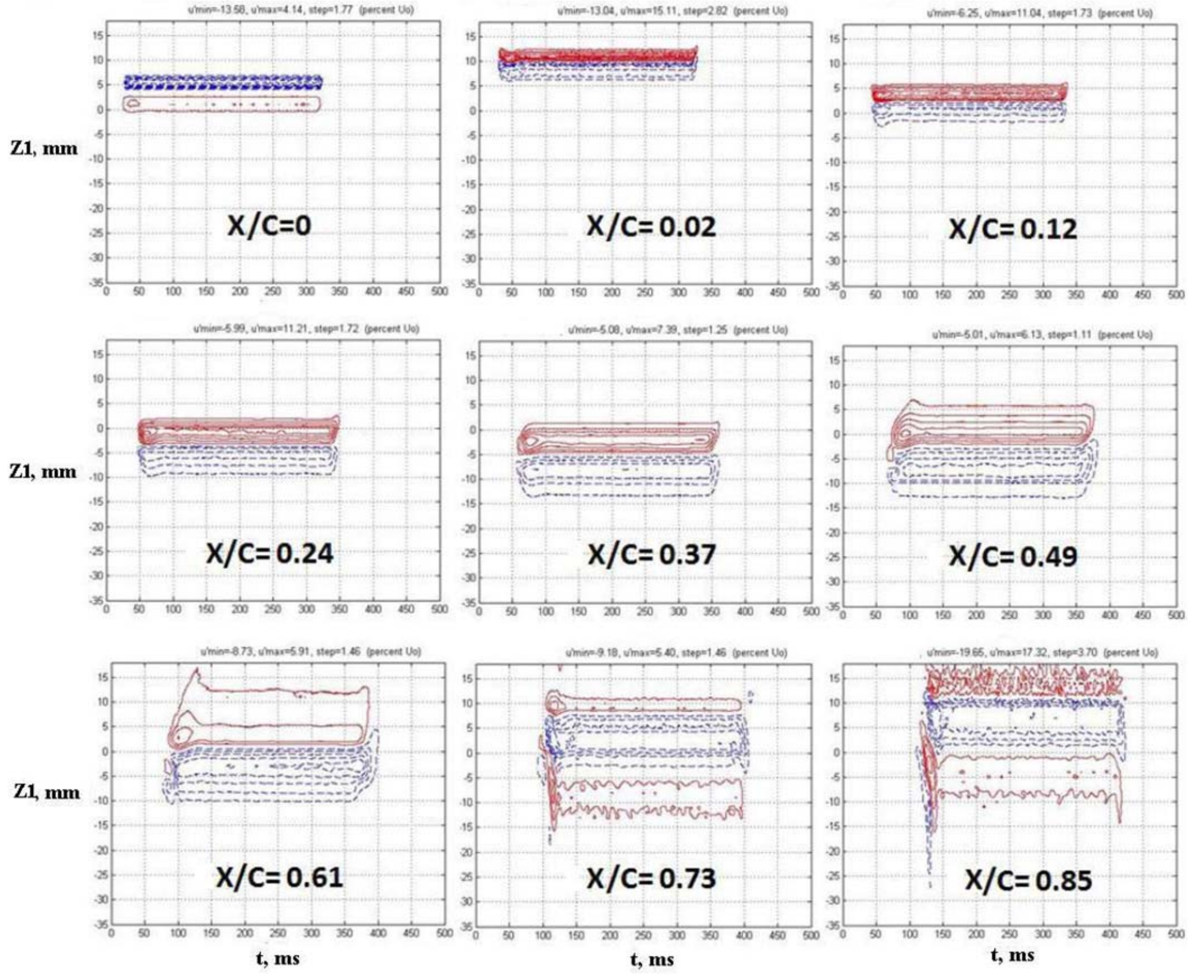

Figure 6: Downstream evolution of artificial disturbance; contour lines in (Z,t) plane of equal velocity fluctuations, red curves - velocity excess and blue ones velocity defect

These graphs point out several main features of the streaks development inside the boundary layer. First, it is to be noticed that because the blowing from the pipe last during 300ms (from 0ms to 300ms on the time scale), the disturbance has a leading and trailing front between which it seems to be stational. That is why this artificial disturbance can be characterized as quasi-stational. Moreover these results are in a good agreement with the experiment of [7] because they pointed out that the difference of velocity between the leading and trailing front of the disturbance induce a continuous elongation of the disturbance. Indeed, the figure 6 shows this difference of velocity and it can be pointed out that downstream (for X/C = 0.85), the disturbance last during approximately 20ms more than when it was generated. Nevertheless, these streaks do not only elongate in the X direction. These results show perfectly a significant spanwise spread when the flow goes downstream, especially in the area of adverse pressure gradient (after X/C = 0.34). The amplitude of velocity deviation tends also to decrease in the area of favorable pressure gradient whereas the phenomenon becomes opposite when the pressure gradient comes back to negative values. It is necessary to underline the huge increase of deviation amplitude between X/C=0.73 and 0.85. Nevertheless, according to previous results, the amplitude of streaks tends to stay approximately constant during the downstream development whereas the spanwise size increase with the growing thickness of the boundary layer. This comment shows that among these streaks, the amplitude of forerunners (at leading and trailing fronts of streak) seems to significantly grow. Indeed, the peak of amplitude for the last spanwise direction appears to be directly representative of the forerunner development.

As far as the feature of the streaks is concerned, it is obvious that they are composed, during the first steps of their development, with two main areas of respectively exceed and defeat velocity. As we saw, these areas tend to grow significantly after X/C= 0.37 and a particular feature appear and develop progressively at the leading front of the disturbance: it is a wave packet - forerunner. This wave packet seems to develop more easily in the defect velocity area because, as previous results showed, this area is more unstable than the exceed velocity one [1]. As a result of this phenomenon and of the growing size and instability of the streaks, another exceed velocity area appears below the defect one. This new area combined with the two former ones seems to be the result of a vortical structure of the streaks.

Otherwise, the figure 6 seems to point out another essential characteristic of the swept wing flow. It is well known, the swept wing contain crossflow, the streamlines in the boundary layer take an S-shaped form. Analyzing and collecting values from the previous measures which traduce the spanwise elongation of the two main velocity areas composing the streaks, the figure 7 and 8 have been plotted.

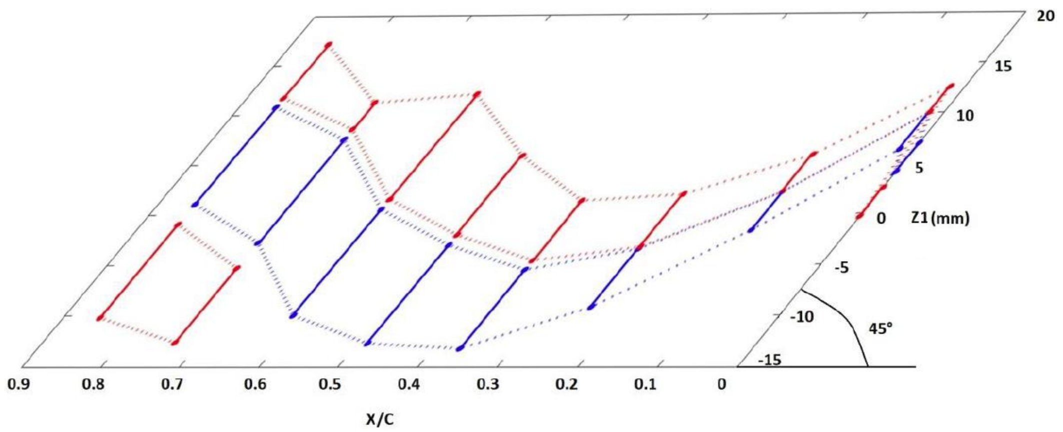

Figure 7: Evolution of the spanwise elongation and position of the velocity defect and exceed areas composing the streaks alongside the chord; red lines - velocity excess and blue ones velocity defect

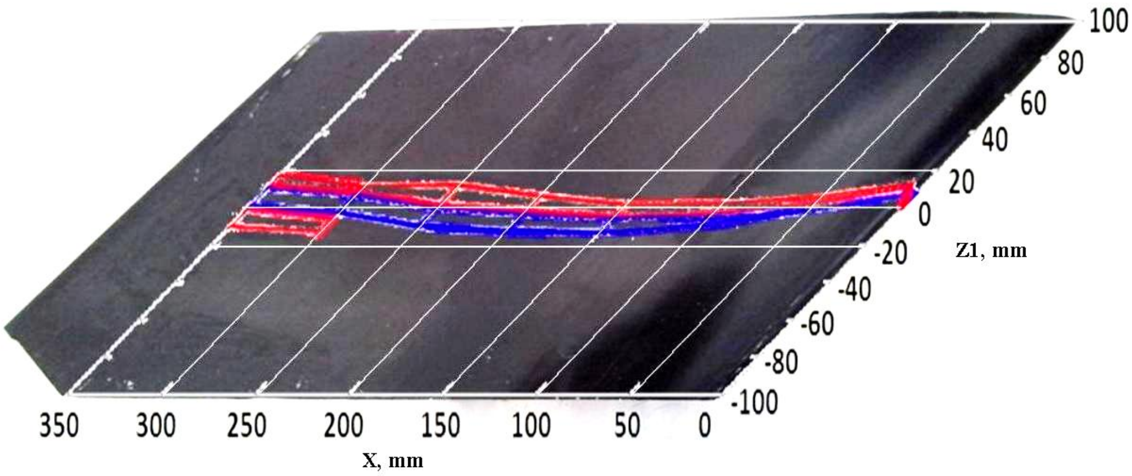

Figure 8: Evolution of the spanwise elongation and position of the velocity defect and exceed areas composing the streaks alongside the chord with a scale fitting of the swept wing model; red lines - velocity excess and blue ones velocity defect

On these two figures, the S-shaped form of the disturbance is clearly enhanced. It is to be noticed that an interisting phenomenon occurred at the leading edge of the wing profile. Indeed, on the one hand, the disturbance seems to go upper instead of following the sweep direction of the profile and on the other hand, an inversion of the velocity deviation areas occurred there. This phenomenon seems to be linked with strong influence of flow, which parallel to leading edge near the stagnation point of wing profile.

Other series of measurements were carried out in the Y direction to explore the three-dimensional feature of the streaks and the growth of waves packets. Regarding to the results obtained in the (Z1,t) plan, several (X,Z1) positions on the profile were chosen to proceed to some measures in the Y direction and to study one more time the velocity deviation in this area. The selected points of measure correspond, according to the (Z1,t) graphs, to the extremum in velocity defect and exceed areas and to the position between these two or three areas, see figure 9. These experiments were also a way to confirm that the maximum of velocity deviation in the Y direction was around the middle of the thickness of the boundary layer. These pictures show characteristic feature of the streaks with presence of crossflow. Indeed, in the (Y,t) plan, it is visible that between the two main opposite velocity deviation observed in the (Z1,t) plan, the same kind of area appear too with a velocity defect near the surface and a velocity exceed upper. It is necessary to point out that these areas did not exist for lower values of and that they disappear for higher values. It shows that the streaks created in this experiment tend to have some vortical characteristics. This idea seems to be confirmed thanks to the appearance on the third area, the velocity exceed one, which can be seen on the figure 7 for X/C = 0.73 and 0.85. This can be linked with the rotation induced by the vortical feature leading the first velocity exceed area going upper the defect one, turning around it and then going back down. This feature is just an interpretation of some measures collected during this experiment but for more precision, one should proceed to much more measures to be able to plot a three-dimensional visualization confirming this interpretation.

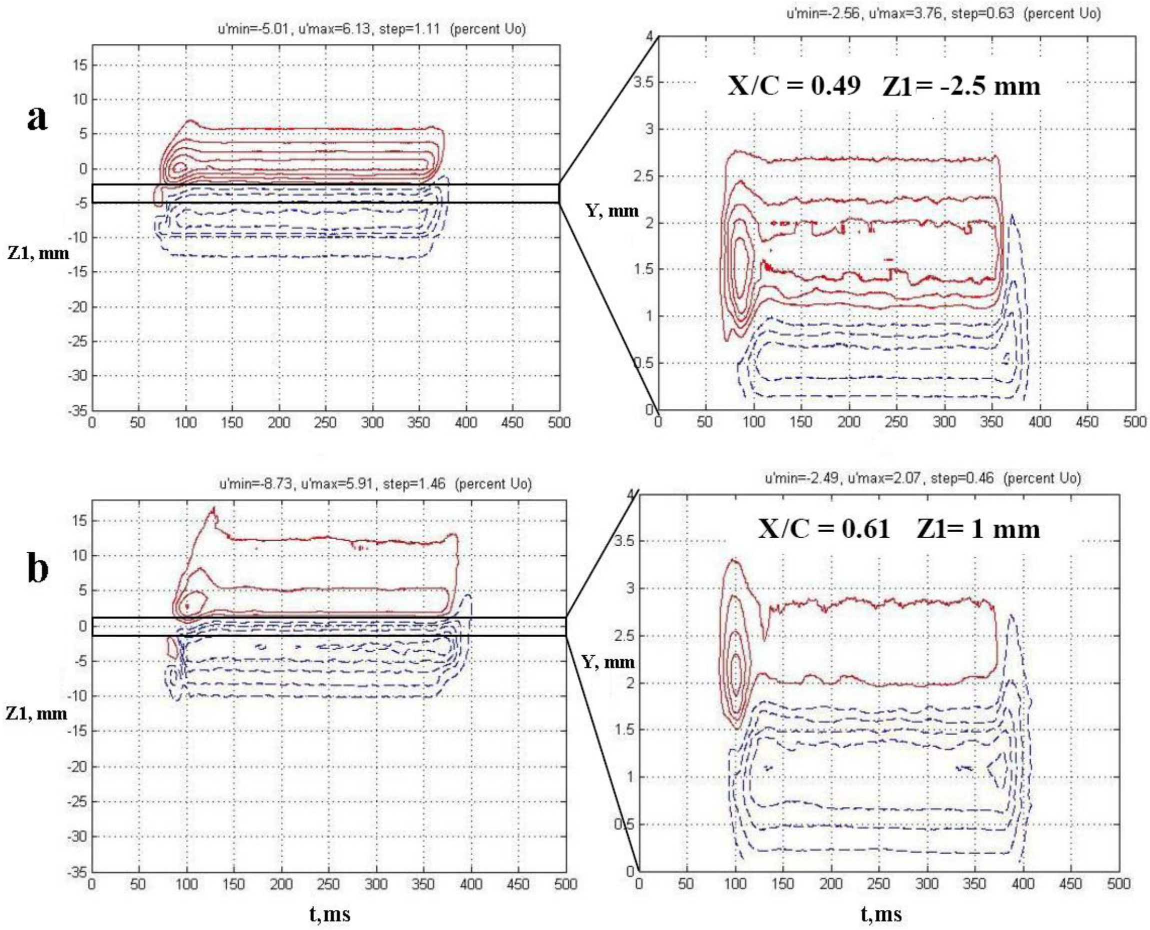

Figure 9: Contour lines of equal velocity fluctuations in the (Y,t) plane (right column) for X/C = 0.49 (a) and X/C = 0.61 (b) between the two main velocity deviation area of the (Z1,t) visualization (left column)

Measures in the Y direction give some more information about the distribution of velocity fluctuation in the boundary layer. Thanks to these data, and measurements in (Z1,t) plane, the maximum velocity deviation (u_{rms}) at the leading and trailing front of the disturbance was investigated alongside the chord. The results of this analysis are shown on figure 10.

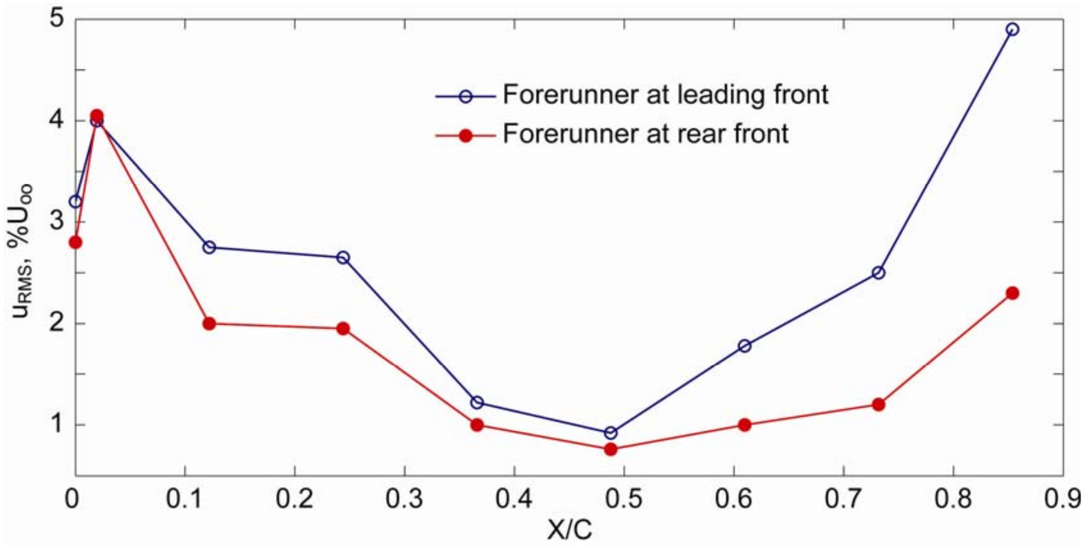

Figure 10: Velocity fluctuation near the leading and trailing front of the streak

According to previous results, forerunners appear and develop at the leading and trailing edge of artificial disturbance - streak. It has been noticed that, depending on the way the artificial disturbance is introduced, these forerunners grow differently between the leading and trailing edge and can even in some cases be damped. In this case, we have to point out two opposite tendencies in the evolution of forerunners. First, from X/C= 0.02 to X/C= 0.5, it is clear that the amplitude of velocity deviation at the two fronts of the disturbance decrease significantly to reach a minimum not far behind the point of inversion of the pressure gradient. Then, the amplitude of the two forerunners clearly increases downstream. The noticeable growth between the two first points can be easily explained due to the impact of the disturbance with the boundary layer and its receptivity. It has also to be pointed out that this graph shows a precise difference of growth after X/C= 0.5 between the forerunner at the leading edge and the one at the trailing edge which grow slower than the first one. The grow wave packet amplitude linked with the pressure gradient which evolves alongside the chord.

For best visualization of the growth and the feature of the forerunners of the leading and trailing front, a low frequency filter has been applied to illuminate only the frequencies corresponding to this wave packet - forerunner and to cut off the quasi-stational streak. Regarding to the frequency spectrum of the typical hot-wire signal (see figure 11), the frequency borders of the filter were chosen to be 10Hz and 140Hz to keep the 75Hz frequency (correspond to the wave packet - forerunner) and some harmonics.

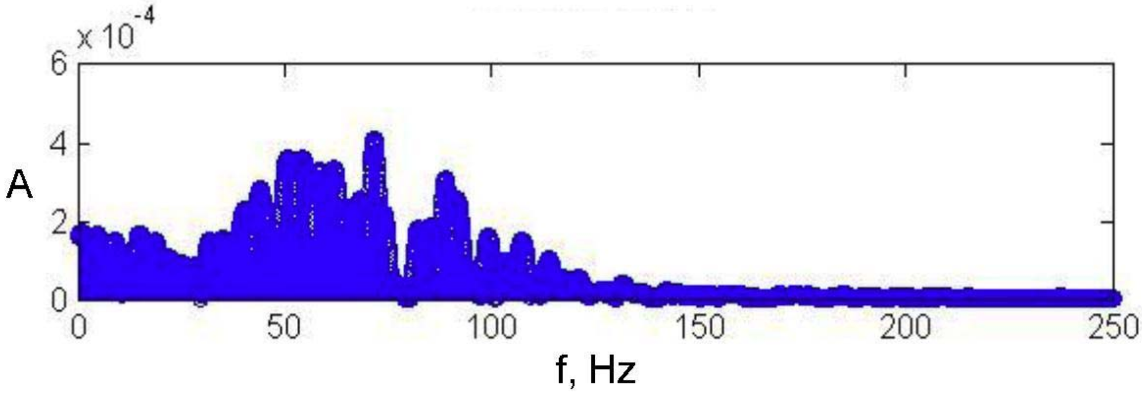

Figure 11: Typical power spectrum of the hot-wire signal obtained for X/C=0.85

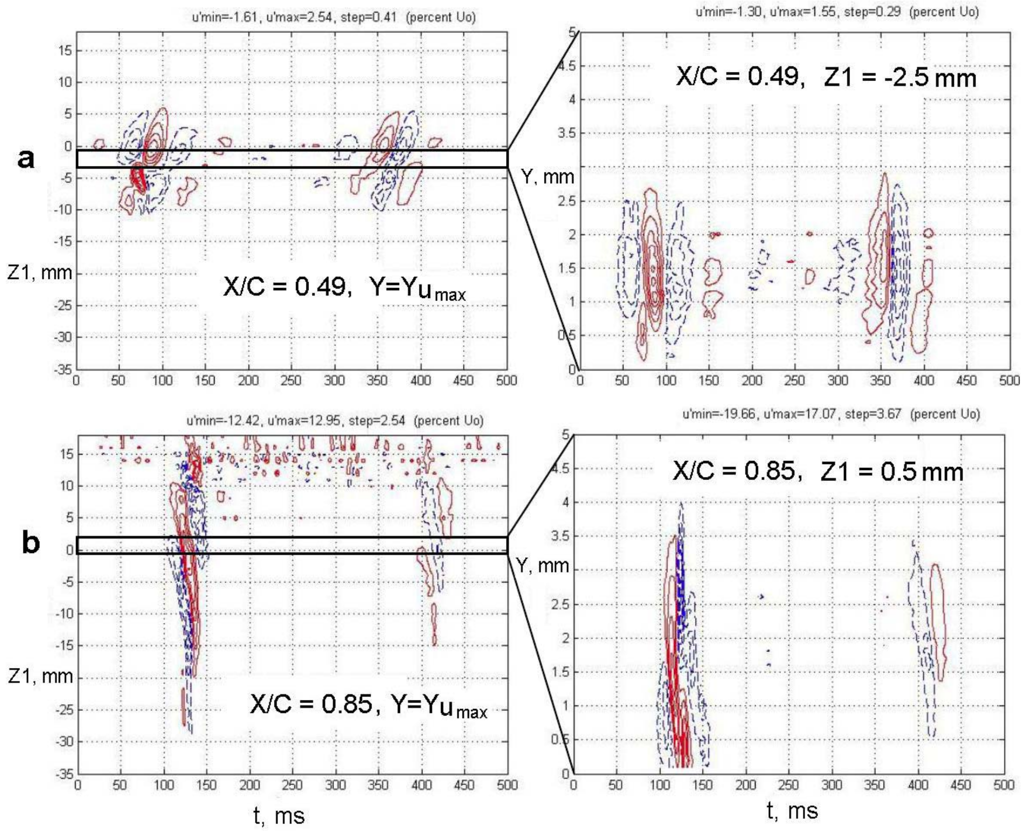

Figure 12: Contour lines of equal velocity fluctuations of the filtered hot-wire signal in the (Y,t) plan (right column) for two representative positions of the (Z1,t) (left column) at X/C= 0.49 (a) and X/C= 0.85 (b)

Contour lines of equal velocity fluctuations of the filtered hot-wire signal in (Y,t) and (Z1,t) plane is presented on figure 12. It is possible to confirm from figure 12, the growth either in the spanwise direction, in the Y direction but also in amplitude. Indeed, in the Y direction, the velocity deviation *u* reaches nearly 20% of U_∞ for X/C= 0.85 whereas for X/C = 0.49, this deviation is only between -1.3 - 1.6% of U_∞. Obviously, the same kind of assessment can be made alongside the spanwise direction.
Otherwise, this kind of visualization, successfully underlines the difference of growth between the forerunner of the leading and trailing front of the disturbance. While they had nearly the same amplitude at the beginning of their growth at X/C = 0.49, the difference of amplitude becomes huge for the X/C = 0.85 position. Indeed, the velocity deviation *u* is only around -7.3 - 3.7 % of U_∞ for the wave packets at the trailing front whereas it reaches -19.6 - 17.1 % of U_∞ at the leading front.

4. Discussion

The main purpose of this research was to study the effects of an external artificial disturbance (introduced by blowing pipe) on the swept wing boundary layer stability. Noteworthy results appear to be the shape of the flow, the effects of the pressure gradient on the forerunners behaviour, as well as the evolution of theses forerunners.
The first result was the demonstration of the S-shape nature of the streamlines of a swept wing boundary layer. This phenomenon was highlighted by the tracking of the disturbances evolutions thanks to velocity measurements (see figure 7 and 8). This effect can be explained by the three-dimensional structure of the swept wing boundary layer, which can be correlated with the existence of a spanwise pressure gradient on the swept wing extrados due to the sweep angle. Some notices about noteworthy phenomenon of the inversion of deviation velocity areas at = 0.02 (see figure 7). According to previous results, it is to point out that, on the leading edge of the swept wing, the *w* velocity component is very strong near the wall, about same order as the rest of the extrados. This component provokes a strong crossflow in the lower part of the boundary layer which create a rotation of the main flow between X/C= 0 and X/C = 0.02 and deflect sharply the disturbance toward positive values of Z1. Therefore, it is a phenomenon linked especially with the sweep angle and not with the existence or not of disturbances.

Thanks to our results, another feature of the disturbance in a swept wing boundary layer has been shown. Indeed, from X/C = 0 to X/C = 0.61, only two opposite velocity areas are visible in our case (see Figure 6), contrary to three in the case of a straight wing. Nevertheless, from X/C = 0.73, a third area of velocity deviation appears. This phenomenon can be explained thanks to the existence of a secondary flow into swept wing boundary layer which gives some vortical characteristics to the streamlines.
Another noteworthy fact is the influence of pressure gradient alongside the chord. In this respect, linking the figure 4 with the 10 one is interesting. Indeed, according to previous results, a positive pressure gradient (from X/C = 0 to 0.34) can be correlated with the decrease of disturbances amplitude. However, according to the figure 10, forerunners start to grow only from X/C = 0.5. It is the one of the main difference between straight wing and swept wing. Indeed, in the case of straight wing, there is a strict correlation between an adverse pressure gradient and the apparition and growth of forerunners. In the case of swept wing, there is a delay, which can be explicated by the existence of a secondary flow which changes the behaviour of the boundary layer. Moreover, we can wonder why the amplitude of velocity deviation is so high for the first values of while, according to previous results, it seems clear that there are no forerunners at this stage of the streaks development. The features observed in the figure 12 (filtered graphs) are just artifacts due to the dispersion of the initial disturbance leading front. Indeed, this high value is easily explainable thanks to the idea of the increasing instability of the disturbance after its impact with the boundary layer of the wing profile. But that feature does not affect the results of the experiments because thanks to the favorable pressure gradient in this area, this instability tends to be damped to give place downstream to the forerunners.
An adverse pressure gradient catalyzes the growth of forerunners. The common influence of the three-dimensional structure of the swept wing boundary layer and the adverse pressure gradient leads to the appearance of forerunners, between X/C = 0.48 and X/C = 0.61, which are revealed thanks to the filtered signal.
Observing the behaviour of leading and trailing front of the disturbance is interesting. Indeed, the figure 10 shows that forerunners grow more intensively at the leading front than at the trailing front. In the previous experiments, this behaviour was typical in the case of suction by a slot. It seems logical to have, in our case of blowing from the outside, the same kind of result. Indeed, suction from a slot induces the higher and so faster velocity part of the boundary layer going down while blowing from a pipe just increase the whole boundary layer velocity. The final effect which is the global increase of velocity inside the boundary layer is so reached in the two cases. Otherwise, according to previous results and to the nature of the current experiments, it is highly probable that the observed forerunners were TS-waves packets. Finally, it can also be shown that, for the two last positions, the forerunner tends to expand from the red area to the blue one, toward negative values of Z. This phenomenon can be explained by former results which underline the higher instability of negative velocity deviation areas compared to positive ones. This characteristic seems to allow a better growth of the forerunner in this area.
According to theoretical and experimental works, TS-waves packets (forerunners, in our case) lead to the creation of Λ-structures in the boundary layer. However, in spite of the frequencies analysis, Λ-structures, which are the consequence of the forerunners growth, cannot be detected here with Λ - shape. This fact is due to the sweep angle. Indeed, in the case of a non-swept wing, these Λ-structures are very clear and symmetric whereas for swept wings with a low value of β, these Λ-structures become asymmetric and less visible. Moreover, it appears that it exists a critical value of β (lower than 45°) for which Λ-structures are just blown by the secondary flow induced by the three-dimensional structure of the boundary layer. This “blowing” seems to transform normal Λ-structures into “one-leg-Λ-structures” in our case. The huge spanwise structure seen in the figure 12 for X/C = 0.85 between 100 and 150 ms is probably an example of this "one-leg-Λ-structure". Otherwise, it would be interesting to try different values of β to describe more precisely this phenomenon and find the critical value of sweep angle.

5. Conclusion

The goal of the current experiment was to study the effect of an external artificial disturbance on the stability of a swept wing boundary layer. Indeed, contrary to previous study, where the disturbance was directly injected inside the boundary layer through a slot in the extrados, it was there created thanks to a blowing pipe placed in front of the leading edge of the wing. Two major conclusions can be drawn.
1. It was shown that artificial disturbances can be successfully injected from the outside of the boundary layer and generate downstream wave packets - forerunners, which are probably TS-waves packets. Moreover, experimental piece of evidence was made that an artificial disturbance introduced thanks to a blowing pipe has similar effects on the boundary layer as in the case of suction from a slot on the surface of the extrados. It was also shown that the created TS-waves packets grow thanks to the adverse pressure gradient on the extrados. During all the experiments, conditions were chosen to keep a laminar flow; conversely, this TS-waves packets growth would have led to the transition. Moreover, the existence of a secondary flow has a stabilization effect on the swept wing boundary layer and delays the transition. The last interesting result about these TS-waves packets is their three-dimensional nature, due to the crossflow in the swept wing boundary layer, which do not exist in the case of the straight wing.

2. The trajectory of the artificial localized disturbance introduced from the outside was experimentally obtained. Thus, the S-shape feature of the streamlines of the swept wing boundary layer was observed thanks to velocity measurements realized with the hot-wire probe. The most interesting fact was the inversion of velocity deviation areas close to the leading edge, due to the large crossflow near the surface in this area. Moreover, another noteworthy fact was the apparition of a new area of velocity exceed near the trailing edge of the wing, due to a vortical phenomenon explained by the secondary flow induced by the swept character of the wing.
Theses results permit to increase the global knowledge about aerodynamic phenomenon on swept wing profiles. For the moment, it remains only a fundamental research, nevertheless, it can call for future technical development because the idea of a better control of the boundary layer aerophysical phenomenon is a permanent priority for the aeronautic industry.

Acknowledgements

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References

[1] Katasonov, M.M., Park, S.-H., Sung, H.J., Kozlov, V.V. 2005. Instability of streaky structures in a Blasius boundary layer. *Experiments in Fluids*. Vol.38. N°3:363–371.
[2] Gorev, V.N., Katasonov, M.M. Origination and development of precursors on the fronts of streaky structures in the boundary layer on nonswept wing. 2004. *Thermophysics And Aeromechanics*. Vol.11. N°3:391–403
[3] Gorev, V.N., Katasonov, M.M., Kozlov, V.V. Specific features of unsteady processes in the front regions of streaky structures in the boundary layer on a nonswept wing. 2008. *Thermophysics And Aeromechanics*. Vol.15. N°3:415–425.
[4] Gorev, V.N., Katasonov, M.M., Kozlov, V.V. 2006. Wave precursors on longitudinal structures on nonswept and swept wings. *Doklady Physics*. Vol.51. N°9:513–516
[5] Gorev, V.N., Katasonov, M.M., Kozlov, V.V. 2007. Wave Forerunners of streamwises structures in a swept wing boundary layer. *Fluid Dynamics*. Vol.42. N°5:732–739.
[6] V.V.Kozlov, M.M.Katasonov, D.S.Sboev. 2011.Experimental study of localized boundary layer disturbances at high free stream turbulence level (review). In: *The 11th Asian Symp. on Visualization. Niigata. Japan. Abstracts*. 167.
[7] Westin, K.J.A., Bakchinov, A.A., Kozlov, V.V. And Alfredsson, P.H. 1998. Experiments on localized disturbances in a flat plate boundary layer. Part 1: The receptivity and evolution of a localized free stream disturbance. *European J. Mech. B Fluids*. 17(6):823–846.