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The investigation of laminar-turbulent transition behind the localized roughness on the swept wing in the favorable pressure gradient region

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Abstract
The aim of this work to discover the physical mechanisms of laminar-turbulent transition behind the localized roughness element on the leading edge of the swept wing. The combination of hot-wire measurements and liquid crystal thermography the properties of 3-d boundary layer were researched. Localized roughness element excited a pair of counterrotating vortices, which destabilized the boundary layer to high-frequency disturbances. Technique of determination of position of maximal receptivity to the roughness elements based on liquid-crystal thermography was proposed. A sharp increase of phase velocity of secondary disturbances during the transition from linear to nonlinear regime was observed. The effect of excitation of additional longitudinal structures by high amplitude acoustics (80 dBA) through the mechanism of nonlinear secondary disturbances development was revealed.

Nomenclature

X	=	coordinate along the freestream;
Y	=	coordinate rests on the plane X-L and orthogonal to coordinate X;
Z	=	coordinate, orthogonal to X and Y;
Xw	=	coordinate, directed along the X with zero point on the axis of the cylindrical part of the wing model;
c_h	=	chord of the wing model;
χ	=	sweep angle of the wing model;
r	=	radius of cylinder part of wing model;
U_∞	=	freestream velocity;
U_0	=	mean velocity in the measurement point;
U_{dist}	=	stationary disturbance of velocity;
f	=	frequency of velocity pulsations;
$\tilde{U}(f)$	=	velocity Fourier transformation;
U	=	instantaneous velocity.

1. Introduction

Modern aircraft manufacturers are intensively developing a laminarized aircraft, which in the future can provide a 15% reduction in fuel consumption (see on Figure 1 potential areas for laminarization, highlighted by blue). However, in this way there are a lot of problems, since even micron-sized roughnesses can cause a localized area of laminar-turbulent transition in the transverse direction so the line of transition becomes a jagged.
Flights at transonic speeds require the use of swept wings on aircraft. However, this wing, in comparison with the straight one, has an additional instability mechanism due to the presence of a secondary flow, which leads to a laminar-turbulent transition in the region of a favorable pressure gradient. The majority of the modern aircrafts have swept airfoils. There are several linear instability mechanisms, which take place over a swept wing: Tollmien-Schlichting instability, Goertler instability [1], attachment line instability [2], [3], streamline curvature instability [4], cross-flow instability, and secondary instability of the longitudinal structures of boundary layer. There is a comprehension to design the airfoil to minimize first three of them. Experiments [4] shown that the cross flow instability mechanism is more intensive, than streamline curvature. Hence, at the negative pressure gradient region it plays principal role in the laminar-turbulent transition process. Bippes in [5] observed that at the high turbulence level (Tu > 0.2% of freestream velocity) the travelling waves were dominating. Interesting result was received in [6]:

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the receptivity of swept wing to the external turbulence lower than in the case of straight wing. This fact should be taken in account during the tests of laminarized wings in industrial wind tunnels. At lower turbulence levels stationary modes became dominant. This case is most valuable in respect to the flight conditions. Sufficiently detailed review of the problem of a laminar-turbulent transition on a swept wing is presented in [7].

Figure 1: The most urgent areas on the airplane surfaces (blue color) for the laminarization and air drag reduction tasks.

The wing design contains a lot of localized roughness elements due to the technological process. One of the brightest examples are rivets. But even in the case of smooth leading edge the problem of its contamination by insects and dust have place. There is a lack of information about the influence of single roughness element on the process of laminar-turbulent transition at the swept-wing leading edge.

2. Experimental setup and methodology

2.1. Measurement conditions

The experiment was carried out in the low turbulent wind tunnel T-324 of Institute of Theoretical and Applied Mechanics SB RAS (Figure 2). The dimensions (W×H) of wind tunnel test section are 1000×1000 mm^2 and 4000 mm of length. The level of turbulence did not exceed 0.03%. The freestream velocity during the experiment varied in the range U_∞ = 6.8 – 14.6 m/s and controlled by the Pitot tube, connected to the electronic micro manometer. The temperature of the air was in interval 290 – 293°K.
To provide good quality of visualization pattern the illumination of test section was improved with the help of two 100 Watt halogen lamps with reflector. The position and orientation of these lamps was chosen to avoid glares and to minimize their influence on the flow structure near the research area.

2.2. The wing model

For the investigations a swept wing model made of organic glass (polymethylmethacrylate) was chosen with the chord c_h = 400 mm, sweep angle χ = 45° and adjustable angle of attack. To simplify the hot-wire measurements the simplest airfoil was chosen, which consists of cylinder with radius r = 40 mm and two convergent plates. Such configuration stimulates the formation of local separation near the junction of the cylindrical part of the airfoil and the flat part. To exclude influence of this phenomenon on the experimental results the angle of attack -12° was chosen. To suppress the separation on the bottom side of the wing a turbulator was used. The model was attached to the test section walls. The disturbances developed in the boundary layer of the test section walls were cut off by end plates, mounted on wing model.

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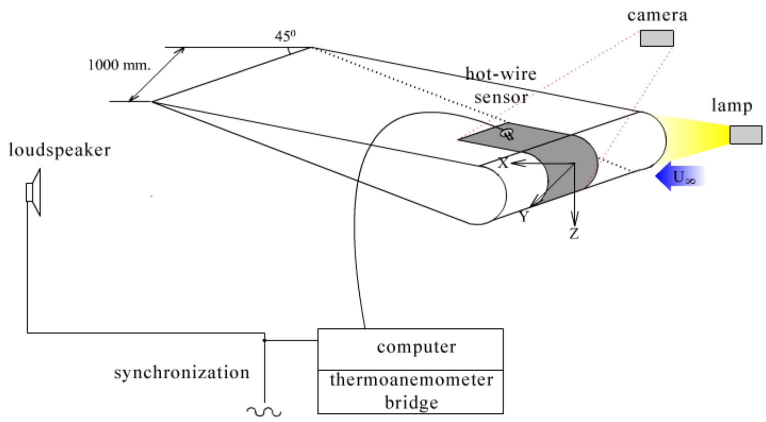

Figure 2: The scheme of experiment for the investigation of stationary mode of cross-flow instability and secondary disturbances.

2.3. Disturbance sources

Cylindrical roughness elements with diameter 1.6 mm and height 0.4 to 1 mm were used for the excitation of stationary disturbances. A sticky side of roughness element allowed to place it in any position on the model of the swept wing.
The secondary disturbances were excited by sound from a loudspeaker placed in the wind tunnel diffusor. The loudspeaker was feed by a signal generated by a sound generator synchronized with hot-wire data acquisition.

2.4. Experimental techniques

Constant temperature hot-wire measurements were carried out with the help of a single-wire sensor. The diameter of the wire was 6 microns, the length was about 1 mm. The sensor was calibrated in freestream near the Pitot tube in the velocity range 0 to 12 m/s. The velocity measurement error was estimated to be less than 2%. The acquired data has a form of oscillograms of velocity U(t) for different positions defined by the Cartesian coordinates *X-Y-Z*.
Hot-wire measurements were carried out over the flat part of the wing to reveal the process of secondary disturbances appearance and development. Over the cylindrical part only the boundary layer thickness was measured.
The liquid crystal thermography technique was used for the visualization of stationary structure of near wall flow. The basis of this technique is the thermosensitive film, the color of which depends on its temperature [8]. A heater with uniform distribution of power allows putting the temperature of the film in operating interval, so it is possible to find the locations, where the heat transfer differs from the mean value. In this visualization pattern the stationary vortices locations, position of laminar-turbulent transition, separation zones can be identified. The visualization picture was captured by digital camera connected to a computer. The position of digital camera was chosen to make its influence on the flow negligible.
The liquid crystal technique was advanced using a spatial transformation to obtain the image in the coordinates of the surface to exclude the influence of the relative position of the digital camera, the wing model and its curvature.

3. Experimental results

3.1. Conditions outside the boundary layer

Hot-wire measurements over the upper side of the wing surface outside the boundary layer (**Figure 3**) showed the presence of negative pressure gradient.

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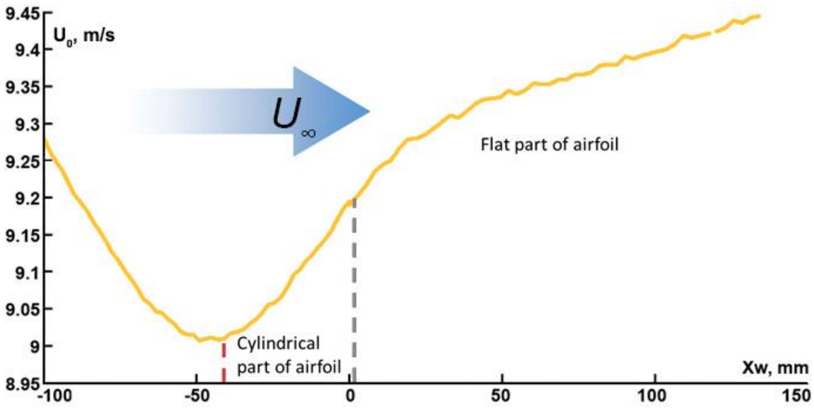

Figure 3: Velocity distribution over the swept wing model.

Hot-wire measurements inside a boundary layer showed an increase of displacement thickness along the flow (**Figure 4**) from 0.4 mm to 1 mm.. The Reynolds number, calculated using the displacement thickness, is in the range $\mathrm{Re}_{\delta^*} = 292 - 730$.

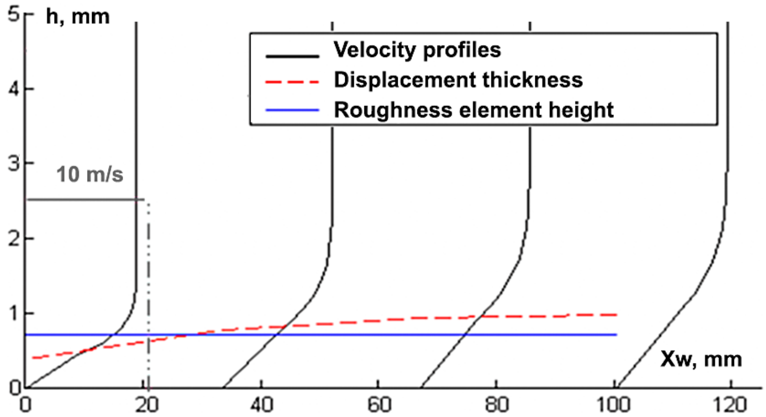

Figure 4: Velocity profiles and displacement thickness of the swept wing boundary layer.

3.2. Appearance of natural secondary disturbances

Cylindrical roughness elements were created with height 0.4 mm, 0.8 mm, 1 mm and placed at 53.8° to the line of airfoil symmetry. Using the liquid crystal thermography technique the investigations of influence of roughness element height on the stationary disturbances development were carried out. The results are present in Figure 5.
Longitudinal structures can be observed even behind of the roughness element with 0.4 mm height, their intensity being enough for the secondary disturbance appearance at high freestream velocity (14.6 m/s). On the other hand, the roughness element with 1 mm height generated very intensive longitudinal structures, on which strong nonlinear effects and turbulization can be observed. Finally, the roughness element with 0.8 mm height was chosen for the investigation of secondary disturbance appearance and development. The freestream velocity was chosen 10.4 m/s.

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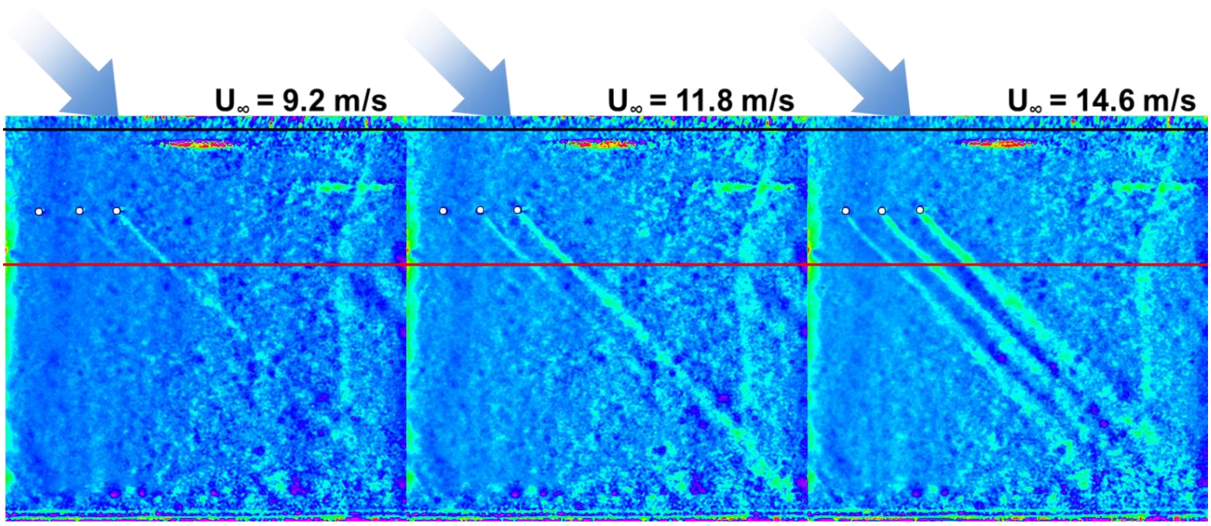

Figure 5: The visualization pattern of disturbances developing behind the cylindrical roughness elements with a height 0.4 mm, 0.8 mm and 1 mm (black line – line of symmetry of an airfoil; red line – line of junction between the cylindrical and flat part of the airfoil; white black contoured circles – locations of roughness elements).

Hot-wire measurements along the transversal direction (Figure 6) showed two areas of velocity defect and one area of velocity exceed. This configuration describes the presence of two closely spaced counter-rotating vortices. Using the Fourier analysis of velocity oscillograms a wavepacket of high-frequency disturbances was found close to the core of stationary vortex between the velocity exceed and defect. The overlap of the positions of stationary and high-frequency disturbances allowed us to categorize the latter as the secondary disturbances [9]

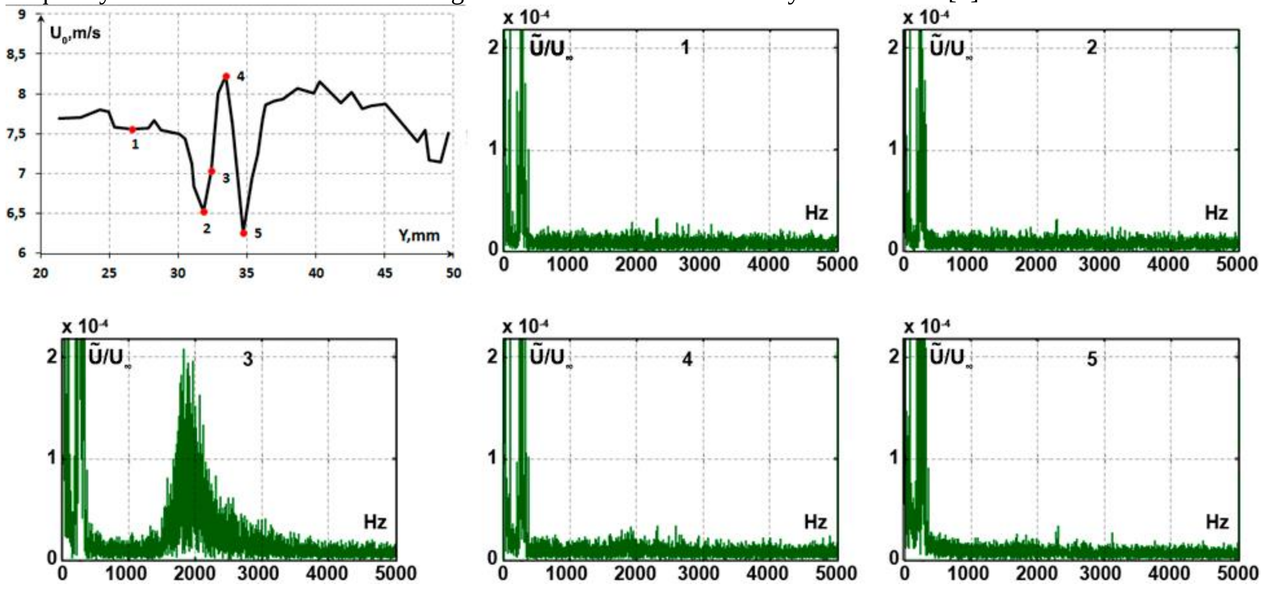

Figure 6: Velocity distribution along the transversal direction and spectra in representative points for Xw = 0 mm.

For the investigation of the dependence of development of secondary disturbances on the freestream velocity and the distance along the flow the hot-wire sensor was placed in the stationary vortex core. The results of the corresponding hot-wire measurements is presented in Figure 7.
Analysis of the obtained data showed that in our experimental configuration at flow velocity 7.7 m/s the high-frequency perturbations do not occur and the flow regime remains laminar. Increase of the velocity to 10.4 m/s leads to appearance of a wavepacket with selected frequency interval. The spatial evolution of the wavepacket occurred with the change of the shape of the spectrum through the filling the low frequency part. The amplitudes of low-frequency components grow and lead to the flow turbulization. Further increase of freestream velocity up to 13.2 m/s leads to the amplitude of the wave packet exceeding 0.01 U_∞, when multiple harmonics appeared in the spectrum. Thus, depending on the flow velocity different nonlinear mechanisms take place.

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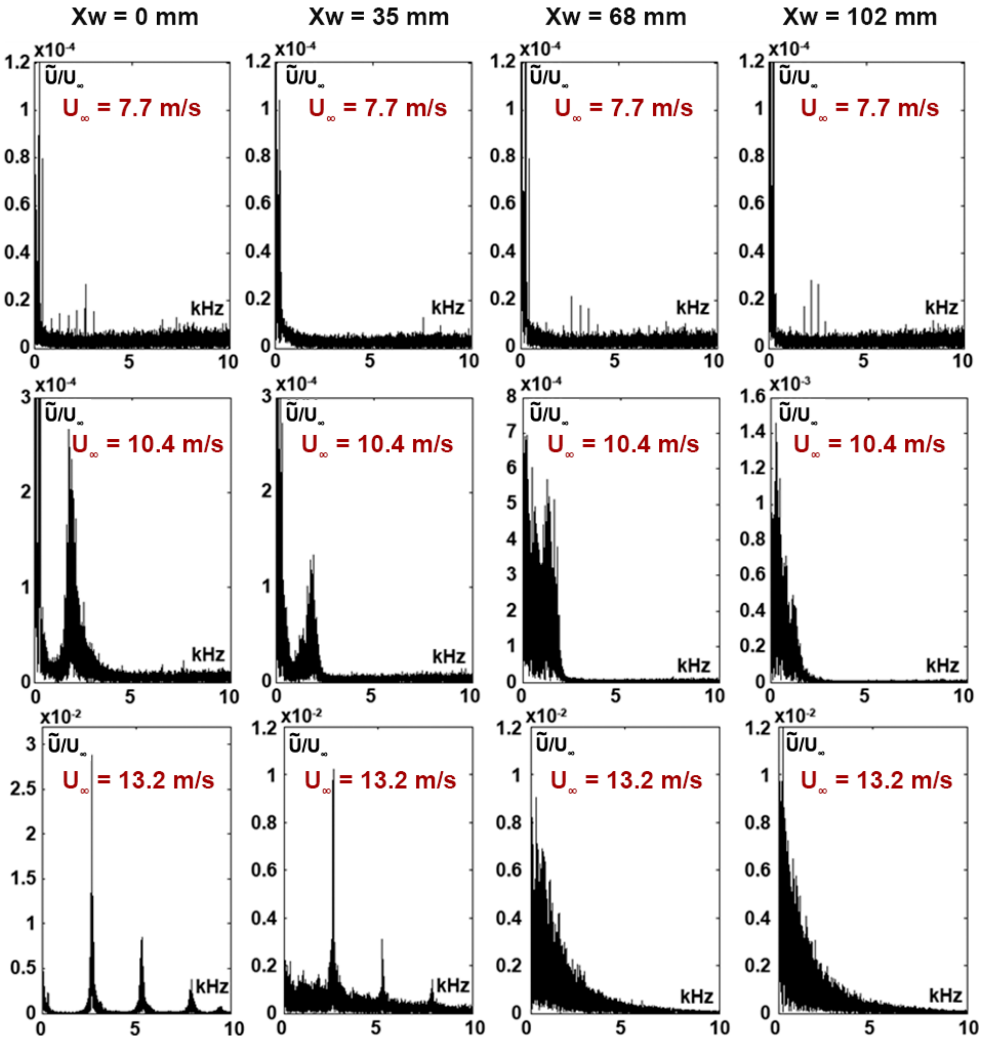

Figure 7: Disturbance spectra near the stationary vortex core at different freestream velocities at four points along the flow.

3.3. Secondary disturbance excitation by sound

As the engines of aircraft produce acoustic noise, the knowledge of influence of acoustic field on the laminar-turbulent transition is important. The experiments showed that secondary disturbances were easily excited by the acoustic field. Acoustic level about 80 dBA in the frequency range corresponding to the natural secondary disturbances leads to a modification of the mean flow that is seen on the visualization patterns obtained with the method of liquid crystal thermography (Figure 8). Appearance of additional longitudinal structures could be the one of mechanisms of increase of transverse size of the region with turbulent flow regime.

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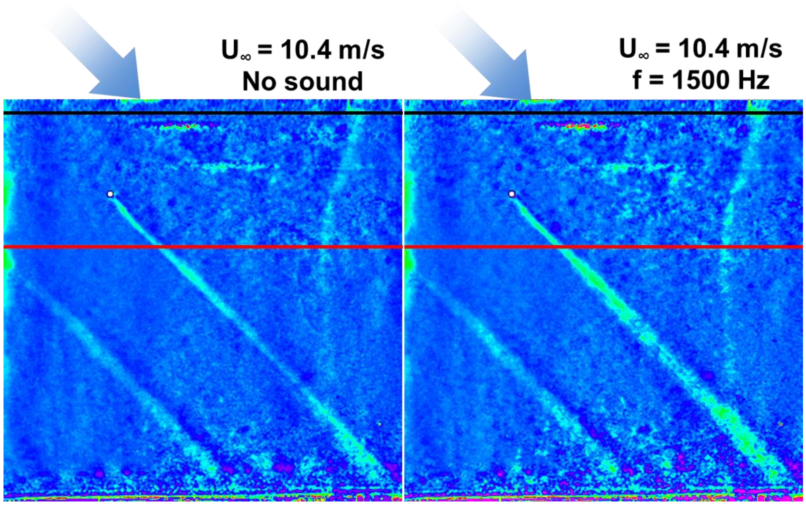
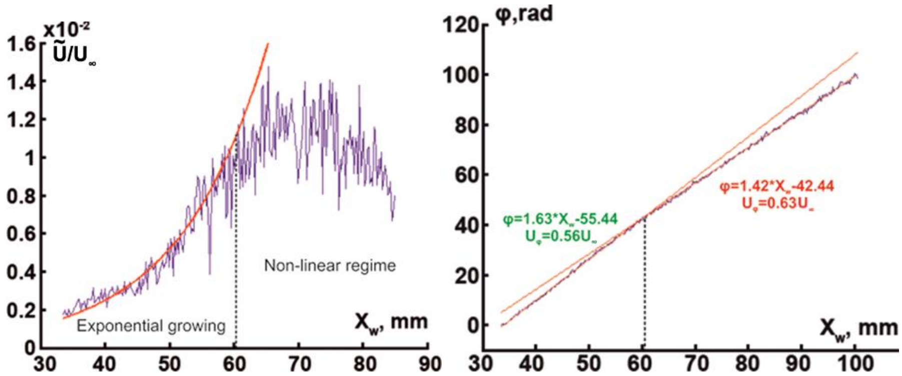


Figure 8: The influence of high-amplitude acoustics on the disturbances structure received by liquid crystal thermography visualization technique.

Usage of moderate acoustics (50.1 dB) allowed implementation of the linear stage of development of secondary disturbance mode. The technique of controlled perturbations permitted to track changing of the amplitude (Figure 9.a) and phase (Figure 9.b) of excited disturbance along the flow. A sharp change of the phase velocity from $0.56U_\infty$ to $0.63U_\infty$ at Xw = 61 mm, which agrees well with the position of distinction of the law of the excited disturbance amplitude growth from the exponential. This indicates the beginning of nonlinear stage of development of the secondary disturbance mode.



a) Distribution of amplitude **b) Distribution of phase**

Figure 9: Distribution of phase (a) and amplitude (b) of the secondary disturbances near the stationary vortex core.

3.4. Influence of surface roughness position on of the stationary disturbance and on the development of secondary disturbances

From a practical point of view it is important to find the area of maximum flow receptivity to the roughness. This knowledge can help to design a wing, which provide an extended laminar flow regime. This area should have maximal smoothness and should be cleaned.

In our experiment we used five cylindrical roughness elements located at different angles to the attachment line so that the disturbance from each of them had no effect on the other (Figure 10).

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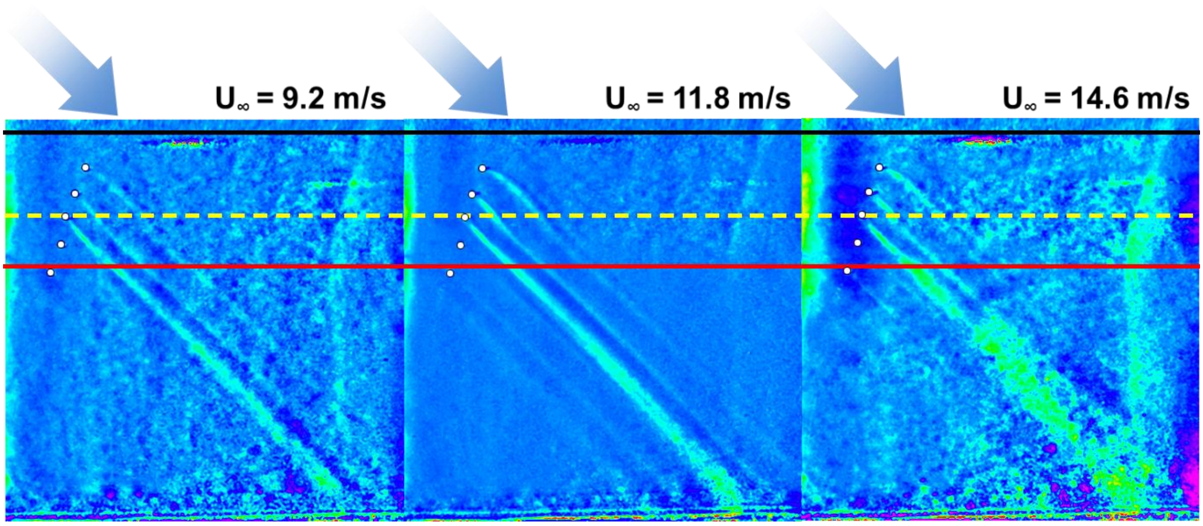

Figure 10: Visualization patterns obtained by liquid-crystal thermography for various positions of the roughness elements on the leading edge of a swept wing at different flow (black line – line of symmetry of an airfoil; red line – line of junction between the cylindrical and flat part of the airfoil; white black contoured circles – locations of roughness elements; yellow dashed line - the area of maximum receptivity).

As seen, the most intensive longitudinal structure excites by the roughness element placed at the 55.1° to the airfoil line of symmetry at a given experimental configuration, regardless of the freestream velocity. The set of roughness elements located closer to the attachment line, where the boundary layer thickness is smaller, leeds to less intensive longitudinal disturbances.

4. Conclusions

This paper demonstrates a synergetic effect of using the hot-wire measurements simultaneously with the liquid crystal thermography technique. The visualization of heat-transfer from the heated wall allowed us to quickly estimate the structure of boundary layer. During the research work a technique of detection the position of maximum flow receptivity to the roughness was developed. It has an outlook for the engineering and designing the aircraft with technologies of air drag reduction through the laminarization of boundary layers over the wings and nacelles.
On the swept wing such peculiarities of the laminar-turbulent transition were highlighted as the instability of the boundary layer to surface roughness, which lead to the appearance of a set of stationary disturbances. In the case of single roughness element a pair of closely spaced counter-rotating vortices appear. This process produces longitudinal structures, which are localized in transversal direction. In the experiment near the stationary vortex core a wave-packet of high-frequency disturbances was observed. They were easily excited by the acoustics of the frequency range corresponded to frequency range of the wave-packet. The high-amplitude sound produced an additional longitudinal structures and increased the transversal size of area with disturbed flow. So this process can put a limitation on the acceptable frequency range for the noise sources of airplane to maintain the maximal area of laminar flow regime.

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