Wave forerunners of localized structures on straight and swept wings at a high free stream turbulence level

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Main building
Low-turbulence wind tunnel T-324

At this paper an wave packets were detected at the leading and trailing front of the localized disturbance, which is generated at the boundary layer by membrane. At further experiments those wave packets were named as “Forerunners”.

Wave packets

Localised disturbances generated by membrane vibration on a straight wing: an overview of experimental set-ups: the structure of localised disturbances at a favorable pressure gradient (velocity, mass and deflection, for 1.6% and 0.17 of U∞, respectively), the structure of localised disturbances at an unfavorable pressure gradient (velocity, mass, and deflection, 2.2% and 0.43 of U∞, respectively). Solid lines, velocity; dashed lines, velocity; deflection; U∞ = 40 m/s, a = 0.17U∞ (Spriralov and Chertanov 2009).
Time traces of a 3-D vibrator generating simultaneously two types of perturbations in the boundary layer: quasi-steady streamwise structures of the “puff” type and wave packets accompanying the streamwise structures.

The streamwise structures induce unstable flow regions at their fore and back fronts. At those regions an intense growth of wave packets occurs in the case of an adverse pressure gradient.
LAMINAR-TURBULENT TRANSITION CONTROL AT HIGH LEVEL OF TURBULENCE OF EXTERNAL FLOW USING LOCALIZED INJECTION-SUCTION METHOD

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Experimental scheme

Turbulent spot (without control)
+Injection
Incipient spot
+Injection

Contours of velocity fluctuations $u'$ in the $z-t$ plane at $y = y_{\text{max}}, U = 0.5U_0$.

a - incipient spot, b - disturbance generated by 30 ms suction through a slot at $z = 0$, mean velocity profile of the undisturbed flow,

c - superposition of the incipient spot and localized suction.

d - interaction between the injection region and the incipient spot, $x = 195$ mm, $g, h$ are the results of interaction, $x = 700$ mm.
The experiments showed a possibility of real-time control of the growth of longitudinal structures (incipient spots) by affecting to them by localized injection/suction. Optimum position and duration of injection/suction were found for more effective application. The injection/suction should be applied before the front of longitudinal structure.

The localized suction can decrease the growth of the secondary, high-frequency oscillations on the streaks.

1. It was shown that the "passive" disturbances can exist in the boundary layer in a wide range of their amplitudes.
2. It was revealed a principal role of the velocity gradient \( \frac{du}{dx} \) in the regions of the leading and back fronts of the disturbances for excitation of the different flow structures in the boundary layer.
Time traces illustrating the influence of $du/dx$ ($du/dt$) gradient on the origination of forerunners. Suction.

Forerunner

Localised disturbance

High gradient $du/dt$

Low gradient $du/dt$

Detailed investigations of the wave forerunners on the straight wing

Experiment setup

Range of measurements at $y = u'_{\text{max}}$
Hot-wire anemometry visualization of the localized structure and the wave forerunner near the leading front of the streak. The localized structure was generated by suction through the spanwise slot.

Contour plots of velocity fluctuations $u'$ and mean velocity $U_{mean}$ for different positions.
Streamwise variations of the external flow velocity at two different angles of attack of the wing profile.

Influence of the streamwise pressure gradient on the development of wave forerunners.

Streamwise variations of the wave forerunners amplitude $u_{\text{rms}}$.

Localized structure generated by injection.

Localized structure generated by suction.

The late-stage spatial development of the wave forerunners (injection).

Contours of the high-frequency components of velocity fluctuations.

The trailing edge of the localized structure.

Yellow - high speed area ($u' = +2.5 \% U_\infty$),

blue - low speed area ($u' = -2.5 \% U_\infty$).

Wave forerunner is located at $140 \text{ mm} < X < 230 \text{ mm}$.
Note about the forerunner development

Development of the wave packet near the leading front of the localized disturbance. Flat plate boundary layer, suction technique.

The upper part of the localized disturbance interact with wave packet.


Experiment 2006, flat plate, T-324

High free stream turbulence level

Examples of grids

(Tu=0.79%U∞)

(Tu=0.27%U∞)
Wave forerunners on the straight wing

Development of the disturbances inside the boundary layer. Localized disturbance generate the large magnitude forerunner at the leading front.

Low free stream turbulence level $\frac{\Delta}{U_\infty}$=0.189%

High free stream turbulence level $\frac{\Delta}{U_\infty}$=0.79% $U_\infty$

(a) mean velocity $U$ distribution outside the boundary layer; (b,c,d)-distribution of the velocity fluctuations ($u_{y,\text{max}}$) at the maximum level of fluctuations in $Y$ direction along the wing chord.

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Detailed investigations of the wave forerunners on the swept wing

Experiment setup

y-x range of measurements (z = 0 mm)

Range of measurements at y = u'_{max}

Wave forerunners on the swept wing

Hot-wire anemometry visualization of the localized disturbance and the wave forerunner at the leading edge. The localized disturbance generated by suction through the spanwise slot.
The late-stage spatial development of the wave forerunners (injection)

Origination of the Λ–structure from the wave forerunner at the leading edge of the localized disturbance.

Leading edge
- t = 85 ms
- t = 244 ms
- t = 269 ms
- t = 293 ms

Trailing edge
- t = 244 ms
- t = 269 ms
- t = 293 ms

Origination of the turbulent spot from the wave forerunner at the trailing edge of the localized disturbance.

High free stream turbulence level \( Tu=2.31\%U_∞ \)

Downstream behavior of the boundary layer disturbances amplitude at the low and high free stream turbulence level

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In the present experiments the high-frequency perturbations, i.e. wave forerunners, at the leading and back fronts of the localized structures evolving in the laminar boundary layer have been found.

It was observed that the forerunners are strongly amplified in the adverse pressure gradient flow being much influenced by local velocity gradients.

The results of the study make reason to consider the forerunners as wave packets of 3D instability waves.

It was found that at downstream development of the forerunners they transform into the Λ-structures.

It is shown, that at high free stream turbulence conditions the T-S wave packet and low-amplitude forerunners are damped at the linear stage of development. That is in accordance with results of the previous researches.

It is revealed, in a gradient flow with high free stream turbulence level, with the increasing of the initial amplitude of a forerunner the laminar-turbulent transition shifted upstream.

It is found, that with increase in a level of free stream turbulence at the gradient flow, the forerunners transforms in to the turbulent spot faster.

Swept wing. Localized disturbance with forerunners at the leading and trailing fronts

Blue color – low velocity fluctuation region
Yellow color – high velocity fluctuation region
Swept wing.
Localized disturbance without forerunners

Blue color – low velocity fluctuation region
Yellow color – high velocity fluctuation region