NONLINEAR INTERACTIONS DURING EARLY STAGES OF BOUNDARY LAYER TRANSITION INDUCED BY FREE-STREAM TURBULENCE

Dmitry S. Sboev

Central Aerohydrodynamic Institute n.a. prof. N.E. Zhukovsky (TsAGI), Zhukovsky, Russian Federation

Abstract The experimental study of a disturbed flat plate boundary layer subjected to moderate free-stream turbulence (FST) is presented. All measurements were conducted in a flow region with zero intermittency. By means of bispectral analysis it was found that after initial linear growth of low-frequency streaks two distinct nonlinear processes arises in a boundary layer. The first one is represented by interactions between low frequencies in the upper third of a boundary layer and in immediate vicinity of it and the second one is an interaction of streaks with high-frequency disturbances across whole layer. In present experimental setup the region of nonlinear development had taken length about two-thirds of the measurements domain. Inside boundary layer the critical r.m.s.-amplitude of disturbances needed to initiate nonlinear development was found to be about 2 per cent of free-stream velocity.

BACKGROUND AND EXPERIMENTAL SETUP

It is known that in a boundary layer subjected to intense FST elongated streaks of streamwise velocity appear. Despite the success of transient growth theory in description of streaks formation mechanism, the considerable discrepancies between the linear receptivity theory (*e.g.* [1, 2]) and experiment still exist. It is suggested that the most probable reason for the discrepancies is the nonlinearity of disturbances development. The main goal of present experiment was to clarify these issues.

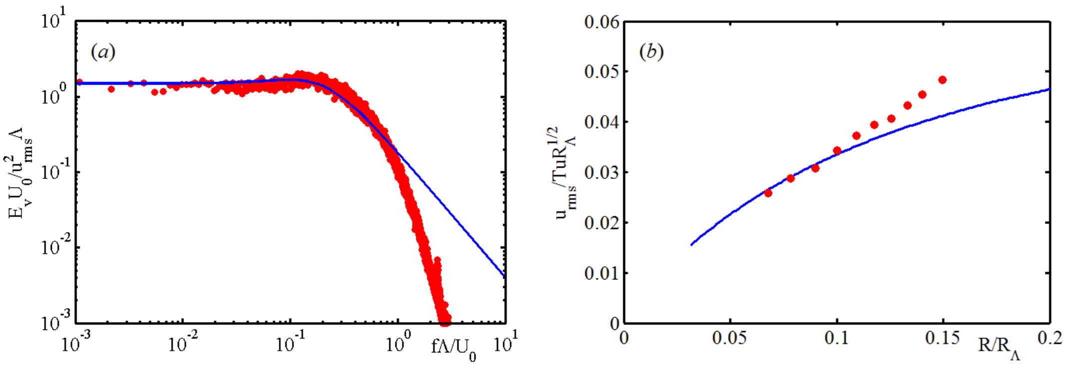

Figure 1. (*a*) The free-stream transverse fluctuations spectrum in comparison with the von Karman spectrum. (*b*) Downstream development of the wall-normal maximum of u_{rms} in comparison with the linear calculations by Ustinov [2], $R = Re_X^{1/2}$ and $R_\Lambda = U_0\Lambda/\nu$.

The measurements were performed in the low turbulence wind tunnel T-324 at the ITAM SB RAS, Novosibirsk, Russia. FST was generated by a grid, installed in the test section 1.02 m upstream of the leading edge of a flat plate. Chosen combination of the free-stream velocity ($U_0 = 7.4$ m/sec), the turbulence level ($Tu = 1.15\%$) and streamwise integral length scale ($\Lambda = 7$ mm) allowed to rather slow boundary layer disturbances development, so the intermittency was equal to zero in entire domain of the hot-wire measurements up to $Re_X = 3\cdot10^5$. The spectral density of the three components of fluctuations in the free stream was measured with an X-wire probe. These measurements had showed some degree of anisotropy of the FST ($v_{rms}/u_{rms} = 0.9$). The streamwise fluctuations spectra of FST were in good agreement with the one-dimensional Taylor spectrum, while the transverse fluctuations spectra well coincides with von Karman spectrum up to frequencies about 1100 Hz (Fig. 1*a*). The von Karman spectrum was used in the linear receptivity calculations [2]. As tool to detection of quadratic phase coupling (QPC) between frequencies f_1, f_2 and $f_1 + f_2$ the bispectral analysis was applied to the measured hot-wire signals. The bispectra were used in a form of bicoherence. Due to symmetry properties of bispectrum the bicoherence needed to be computed only in the triangle with vertices (0, 0), (0, $f_s/2$) and ($f_s/4$, $f_s/4$) on the bifrequency plane (f_1, f_2). For the boundary layer measurements the sampling frequency f_s was 1200 Hz. The very long hot-wire traces of 600 sec duration were measured in the boundary layer in order to obtain statistically significant and stable bispectral estimates. To distinguish between zero/nonzero values of bicoherence the significance level equal to 0.9999 was chosen.

MAIN RESULTS

It was found that the low-frequency streaks were developing in the boundary layer with the wall-normal profiles in close agreement with the previous investigations. Growth of r.m.s.-fluctuations was proportional to $Re_X^{1/2}$ (Fig. 1*b*). The good agreement between the linear calculations [2] and measured growth up to $R/R_\Lambda = 0.1$, also agreement between the measured free-stream fluctuations spectra and those used in the calculations, allows to conclude that the initial growth of boundary layer disturbances was linear. As it seen from the Fig. 1*b*, the perturbations inside the boundary layer for $R/R_\Lambda > 0.1$ are growing faster in comparison with the calculations. The data of bispectral analysis shows that upstream of $R/R_\Lambda = 0.1$ there is no any sign of QPC inside the boundary layer and in the free stream. On contrary, downstream from this position the nonzero bicoherence values were found. The typical plots of bicoherence are shown in Fig. 2. Depending on wall-normal position, two distinct forms of QPC were observed, denoted as I and II in Figs. 2 and 3. In the upper part of the boundary layer ($Y/\delta^* > 2$) the interactions between relatively low frequencies ($F < 200\cdot10^{-6}$) leads to growth of disturbances in the $F = 0 \div 20\cdot10^{-6}$ band. This phenomenon is clearly seen from the Fig. 3 at $R/R_\Lambda = 0.15$ as amplification of the energy of harmonics with $F \leq 20\cdot10^{-6}$ at $Y/\delta^* > 3$ (*i.e.* in the free stream). Similar nonlinear effects were previously observed in DNS [3, 4]. In turn, this amplification of the low frequency perturbations results in a faster growth of the boundary layer disturbances in comparison with the linear theory. The second observed type of QPC was the interactions between low and high frequencies ($F_1 < 30\cdot10^{-6}$, F_2 up to 10^{-3}) across the whole layer. It leads to appearance of wave packets that rides on low frequency disturbances in the hot-wire traces. As the hot-wire moves to the wall, the frequency range of these interactions narrows and shifts to the low frequencies in manner similar to damping of FST-induced high-frequency perturbations inside the boundary layer (Fig. 3). Spectral analysis showed that the disturbances with $F > 200\cdot10^{-6}$ were growing near the wall despite the absence of any turbulent spots.

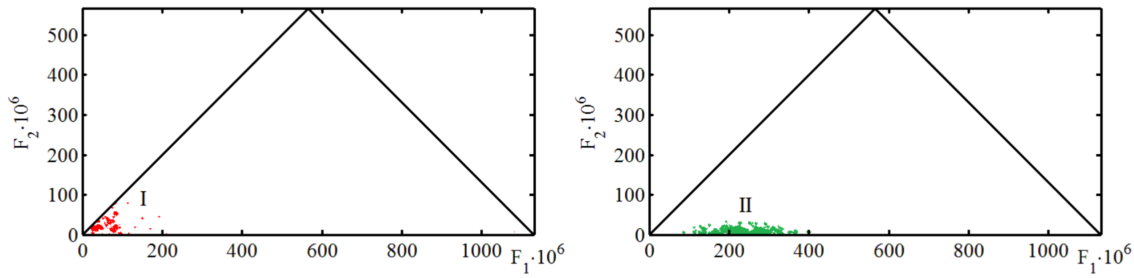

Figure 2. Contours of the statistically significant bicoherence at $R/R_\Lambda = 0.15$, $Y/\delta^* = 3.02$ (left) and 1.36 (right), $F = 2\pi f\nu/U_0^2$. Two types of nonlinear interactions are denoted as I and II.

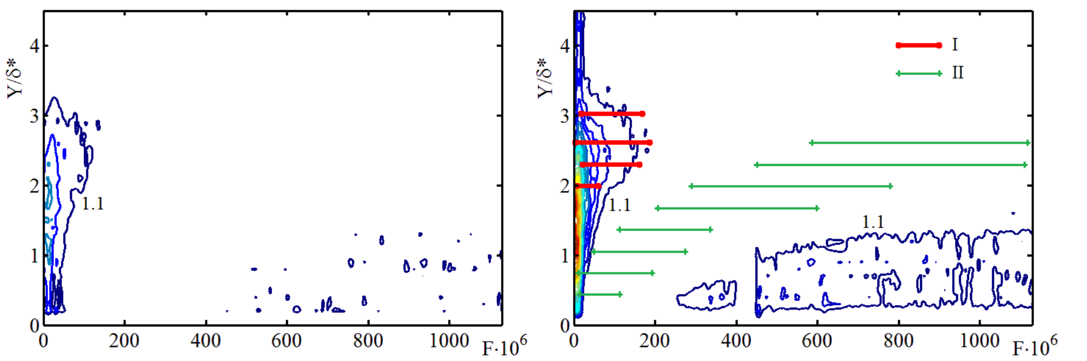

Figure 3. Contours of the disturbances energy amplification $E(R, Y/\delta^*, F)/E(R_0, Y/\delta^*, F)$ at $R/R_\Lambda = 0.09$ (left) and 0.15 (right), $R_0/R_\Lambda = 0.067$. Contour spacing is 0.5 starting with 1.1. The wall-normal positions and frequency range for the nonlinear interactions of two types are shown by the bars.

References

[1] S. J. Leib, D. W. Wundrow and M. E. Goldstein. Effect of free-stream turbulence and other vortical disturbances on a laminar boundary layer. *Journal of Fluid Mechanics* **380**: 169–203, 1999.

[2] S. V. Zhigulev, A. A. Uspenskii, M. V. Ustinov. Effect of the freestream turbulence scale and the leading edge shape on boundary layer laminar-turbulent transition. *Fluid Dynamics* **44**: 31–44, 2009.

[3] R. G. Jacobs, P. A. Durbin. Simulations of bypass transition. *Journal of Fluid Mechanics* **428**: 185–212, 2001.

[4] L. Brandt, Ph. Schlatter and D. S. Henningson. Transition in boundary layers subject to free-stream turbulence. *Journal of Fluid Mechanics* **517**: 167–198, 2004.