SMALL DISTURRBANCES WAVES IN BOUNDARY LAYER INDUCED BY ONCOMING WAKES

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Introduction

The flow in the fluid-flow machinery is inherently three-dimensional and unsteady mostly due to wakes from preceding balde rings. It makes ealier inception of the laminar-turbulent transition, what affects the friction on the surface of the blade and heat transfer between flow and blades.

The wake can be identified differently depending on the choice of co-ordinate system: as a velocity defect in the absolute system of co-ordinates or as a jet in the system of co-ordinates fixed with the mean velocity of flow. In the turbomachinery the blades cut the wake into segments. The boundary layer on the blade is affected by the positive jet when the speed of the jet is orientated towards the surface of the blade so the jet impinges the blade and affected by the negative jet if the velocity of the jet is directed from the blade towars the external flow. Meyer [2] using potential flow solution recognized nemerically the impinging and suction effect of the wake on the boundary layer. He also considered the motion of vorticiy of jets, Fig.1.

Wiercinski [3] for the first time reported the earlier incipient of laminar-turbulent transition

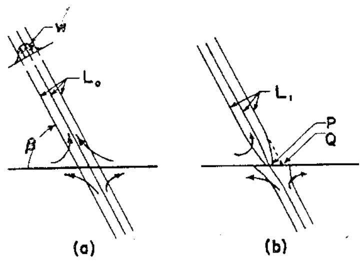

Figure 1: A flat plate and a wake, a) suction and pressure action, b) extra vorticity influence [2]

behind the negative jet than behind the positive one. Later on he [5] reported the differences in measured velocity fluctuations behind both kind of jets. Large and detailed enhancement of this investigation was given by Zabski [6]. It was shown that behind negative jets develop strong disturbances which gradualy cover the whole area between wakes. Thus the boundary layer changes its character from laminar one disturbed by oncoming wakes to fully turbulent one.

Though the boundary layer flow is cut by periodically approaching wakes laminar flow persists in between in some circumstances. This is possible for accelerating flow and for early stages of laminar-turbuelnt transition. It appears that for a flow with adverse pressure gradient some phenomena that are typical for natural transition take place. These are waves that take some features of Tollmien-Schlichting waves. The presence of oncoming wakes do not distrurb the rest of flow if only accelaration is large enough. The observed wave disturbances occurred in the mid-area behind the negative jet and before the positive one. There is nothing like that behind the postivie jet. In next paragraphs some charaterisrics of these waves will be dicussed and their siginicance for transition.

Experimental rig

Measurements were carried out in a subsonic wind tunnel. Turbulence level did not exceed Tu=0.08%, speed of flow in front of plate and wake generator amounted to $U = 15\ m/s$. Dimensions of the measurement chamber (width, height, length) were: $600 \times 460 \times 1500\ mm$ and the corners were chamfered. The boundary layer was studied on the upper surface of a flat

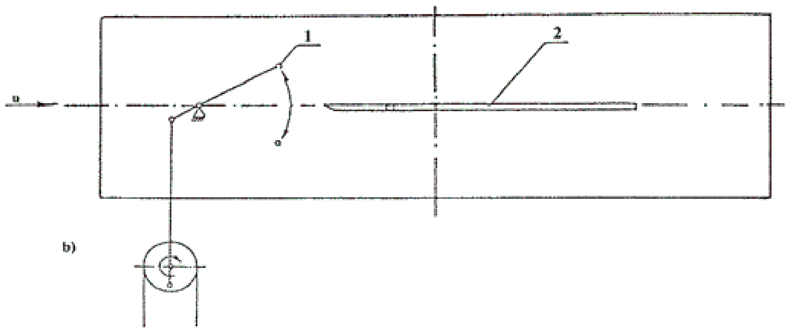

Figure 2: Working section of the wind tunnel: the flat plate and wake generator - a pendulating rod

plate (position 2 in Fig.2) which dimensions were: $600{\times}700{\times}14\ mm$ (width, length, thickness). The plate attack angle was equal to $\alpha = -2.44^o$ that made flow acceleration over upper surface characterized by coefficient $K = \nu/U^2 \cdot dU/dx = 3.36 \cdot 10^{-7}$. Measurements were made at several stations that traverse most of the plate length from $Re_x = 168843$ ($x = 165\ mm$) to $Re_x = 686918$ ($x = 650\ mm$). The round rod of $d = 3\ mm$ diameter and $l = 600\ mm$ length served as wakes generator (position 1 in Fig.2). It moved up and down and the magnitude of its motion amounted to $200\ mm$. The frequency of this pendulum device was $f = 4Hz$. When the rod is on equal height with the leading edge of the plate in horizontal position phase mark is recorded for further data processing. Velocity and its fluctuations were measured by means of DANTEC StreamLine 90N10 Frame with CTA Module 90C10 with SteamWare software. The probe was DANTEC 55P15 and the data was collected by National Instruments 6040E acquisition computer plug-in. Sampling frequency was $f = 5kHz$ and sample length $t = 10\ s$. The final distance of the last point in traverse was determined by means of so-called „hydraulic-zero method”. The same method yielded also the slope of velocity curve at the wall and hence friction velocity and drag coeffcient. The use of so-called phase-averaging procedure was the farther step of investigation. Single periods of velocity ensemble were put one on another and the averaging along matching points was performed. These result was a single period of velocity time-trace with suppressed random disorders. The time duration of the averaged period was equal to $t = 0.25\ s$. A screenshot of the procedure in MATLAB with illustrative lines is given in Fig.3. Taking into account ensemble duration, sampling frequency, frequency of rod movement the obtained period is a result of averaging 40 periods. More details was included by Zabski [6].

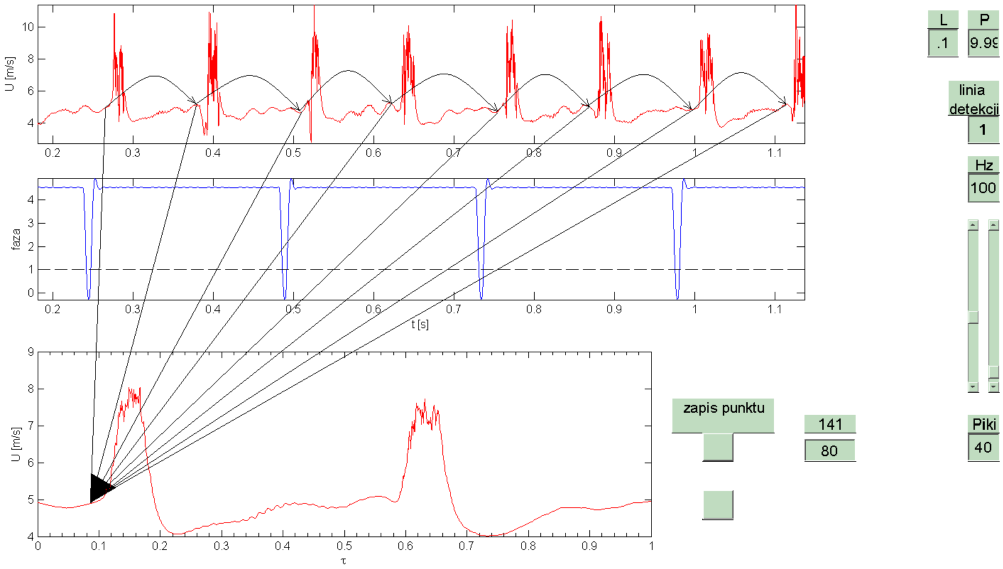

Figure 3: Phase-averaging process

α	K
0.29^o	$8.66 \cdot 10^{-8}$
1.05^o	$1.55 \cdot 10^{-7}$
2.44^o	$3.36 \cdot 10^{-7}$

Table 1: Mean values of acceleration coefficient K

Results

Measurements were carried out for three attack angles of the plate: the aforementioned $\alpha = 2.44^o$, $\alpha = 1.05^o$ and $\alpha = 0.29^o$. These angles refer to the acceleration coefficient values given in Tab.1. The most interesting results were obtained for $\alpha = 2.44^o$. Some time averaged results are shown in Fig.4 and Fig.5. The former produces mean drag coeffcient along the plate, the latter mean velocity profile at $x = 365\ mm$ ($Re_x = 346604$). The flow seems rather laminar with increased turbulence level. The evidence of that is drag coefficient distribution wchich is parallel to laminar curve in Fig.4 ($C_f = 0.664 \cdot Re^{-0.5}$) but above it. Last three points go slightly upwards that indicates an incipience of transitiotion to turbulence. The red marked point indicates positon of velocity profile produced in Fig.5. Mean velocity profile seems also laminar, however it is situated mostly above the Blasisus curve. There is an inflexion point in the profile.

More information carries phase-averaged chart, Fig.6. These are time traces of velocity in a station corresponding to $Re_x = 346604$. Time on the graph is made dimensionless t/T and T denotes the period equal to $T = 0.25\ s$ as earlier described. The upmost trace is located at the edge of boundary layer at $y/\delta = 1$, $y^+ = 82.97$. On the other hand the most lower put trace corresponds to $y/\delta = 0.03$, $y^+ = 2.80$. There is a gap in velocity traces at the middle of chart, between $U = 10\ m/s$ and $U = 8\ m/s$. The first trace of strongly concentrated traces refers to $U = 8.57\ m/s$, $y/\delta = 0.27$ and $y^+ = 22.24$. Two strong velocity defects considering from left to right are negative and positive jets respectively. However this is not the main objective of this

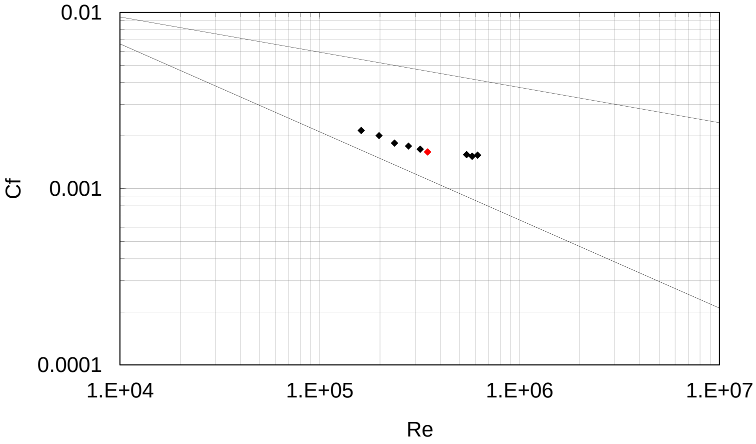

Figure 4: Drag coefficient C_f longitudinal distribution, red point - $Re_x = 346604$, $x = 365\,mm$

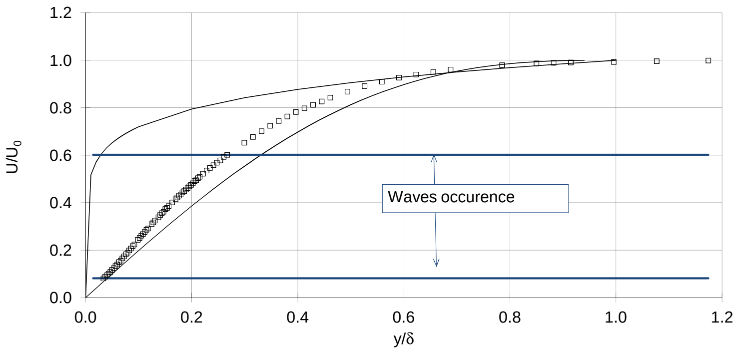

Figure 5: Mean velocity profile

paper.

A red rectangle marked wit section B-B encloses a zone in centre between the negative and positive jet with small, smooth disturbances. A thin chart on the right side produces them zoomed. These disturbances look like periodic waves and their duration amounts to about $t/T = 0.1$ of period, that is $t = 0.025\ s$. The flow around seems undisturbed and laminar up to jets. Above $y/\delta = 0.27$, $U = 8.57\ m/s$ waves vanish. To calculate frequency some of them surrounded with small rectangle were chosen. It is equal to $f = 337Hz$. This value is convergent to most amplified Tollmien-Schlichting waves according to Walker [4]

$$f = \frac{3.2U_0^2 Re_{\delta^*}^{-\frac{3}{2}}}{2\pi\nu} = 334Hz. \tag{1}$$

Furhter investigation reveals that the waves are put up in a region of amplified frequcencies of TS waves, Fig.7. Neutral curves were taken from Levecenko [1] for three acceleration coefficients Λ

$$\Lambda = \frac{\delta^2}{\nu} \cdot \frac{dU}{dx}. \tag{2}$$

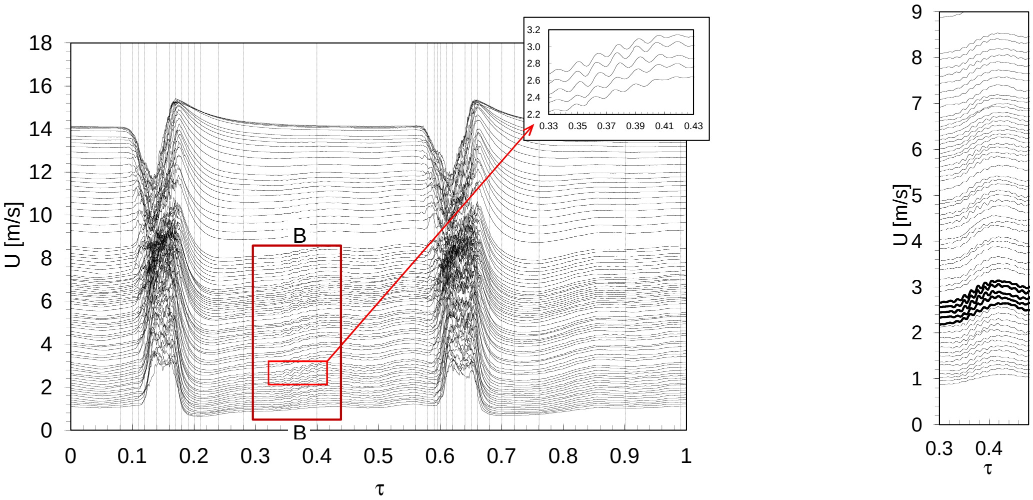

Figure 6: Pahse-averaged velocity traces at $Re_x = 346604$

The neutral curves used in Fig.7 seem rather rough. The investigated frequencies lie it the unstable region for $\Lambda = 0$ and on the Walker curve. However, they are not enclosed it the area of $\Lambda = 1$ and $\Lambda = 2$. It is worth reminding that mean external flow accelaration was equal to $K = 3.36 \cdot 10^{-7}$ and local accelaration coefficient Λ referring to boundary layer thickness δ at the investigated distance from the leading edge equaled to $\Lambda = 2.34$. More precise neutral curves would be an advantage. Though wave disurbances occured at the distance from the leading edge of $Re_x = 346604$, $x = 365\ mm$ there was no evidence of them in other sites. That refers also to two neigbouring stations $Re_x = 317720$, $(x = 335\ mm)$ and $Re_x = 542542$, $(x = 560\ mm)$, Fig.4. For nearly horizontally positioned plate $(\alpha = -0.29^o)$ there was no

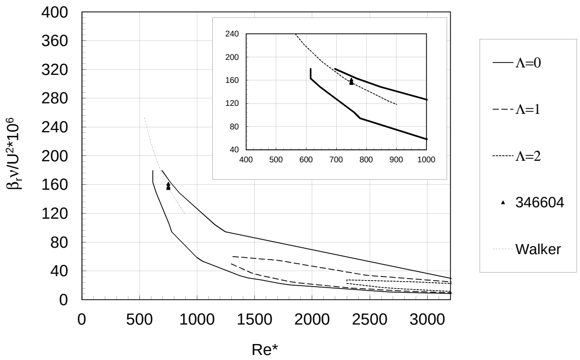

Figure 7: Curves of neutral stablility of TS waves

evidence of waves for all traverses investigated $(Re_x = 168843 \div 686918$, $x = 165 \div 650\ mm)$ in phase-averaged charts. It is intriguing, however, that in the middle of a region behind a negative jet and in front of positive one there are strong harsh disturbances, Fig.8, section B-B. Two subsequent measured traverses in Fig.8 reveal laminar-turbulent transition induced by widening sharp velocity distortion past negative jet, section A-A. The phenomenon of negative jet influence on turbulization was touched at the beginning of this paper. Hier one should notice the coincidence of TS-like waves in accelerated flow locus, Fig.6, and present disurbances locus, Fig.8. Taking into consideration both charts it seems that velocity distortions in section B-B are excited by disturbances sheding from the negative jet. However, the appearnace of the region between wakes suggests some instablility in B-B and its amplification by the negative jet. No evidence of distortions in section B-B was obsereved for the first station measured for this case ($\alpha = -0.29^o$, $Re_x = 168843$).

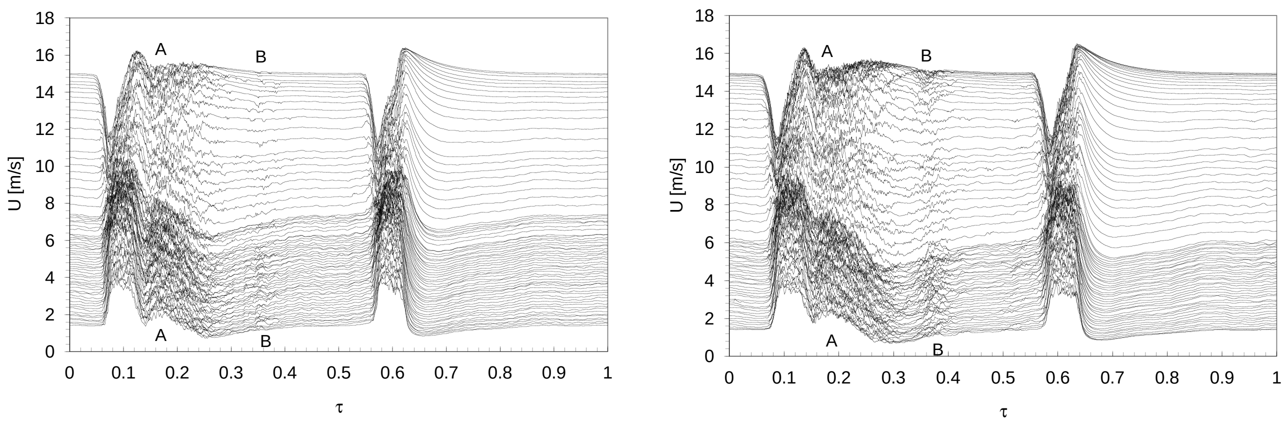

Figure 8: Phase-averaged velocity traces for constant velocity at $Re_x = 216979$ and $Re_x = 257412$

Conclusions

Unexpected disturbances that take some features of TS waves were observed in the boundary layer strongly disturbed by oncomig wakes. The flow was accelerating and the wave locus was at the centre of the laminar area behind a negative jet and in front of positive one. On the other hand there was no such evidence past a positive jet and behind a negative one. For a constant velocity flow there were observed sharp velocity distortions at the same site as TS waves for accelerating case. They had the same appearance as disturbances shedding from the negative jet which drove to turbulent flow. Further investigation seems necessary to get to know the phenomena which take place behind negative jets which is supposed to be a source of disturbances.

References

[1] V. Levecenko, A. Volodin, S. Gaponov, „Charakteristiki ustojcivosti pogranicnych sloev", Izdatelstvo „Nauka" (1975) Sibirskoe Otdelenie, Novosibirsk

[2] R. Meyer, „The effect of wakes on the transient pressure and velocity distributions in turbomachines", Transactions of ASME 80 (1958) 1544-1552

[3] Z. Wiercinski, „The influence of the Periodic Wake behind a Cylinder Pendulating in the Cross-Stream Direction on the Laminar-Turbulent Transition in the Boundary Layer of a

Flat Plate”, Proc. Conf. Unsteady Aerodynamics and Aeroelasticity of Turbomachines, Ed. Y. Tamida and M. Namba, Elsevier Science B.V. (1995) pp.461-479

[4] G. Walker, J. Gostelow „The effect of adverse pressure gradients on the nature and length of boundary layer transition”, ASME (1989) 89-GT-274

[5] Z. Wiercinski, „Przejscie laminarno-turbulentne w warstwie przysciennej indukowane sladami splywowymi, Zeszyty Naukowe IMP PAN (1999) 499/1450/99”

[6] J. Zabski ”Wplyw gradientu cisnienia na przejscie laminarno-turbulentne w aerotermicznej indukowanej warstwie przysciennej” (2009) IMP PAN Gdansk (dissertation)