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VELOCITY WAVES IN THE BOUNDARY LAYER DISTURBED BY WAKES OF NEGATIVE AND POSITIVE JETS IN ACCELERATING FLOW

Experimental boundary layer investigation was performed for two values of velocity acceleration at the edge of layer. The flow was disturbed by oncoming wakes from a pendulating upstream rod yielding negative and positive jets in turn (negative jet if the rod goes upwards making suction in boundary layer on the upper surface of the flat plate, positive jet – the rod goes downward). Velocity traces and phase-averaged velocity traces were obtained using periodic phase mark. Mean velocity profiles and longitudinal distribution of mean or integral parameters stayed close to laminar pattern. The shape of wakes on velocity traces were these same regardless of jet direction. However, past negative jets velocity waves were observed on velocity traces. They were placed in the damped region of Tollmien-Schlichting waves. Past positive jets there was no evidence of velocity waves, which is main difference between influence of both kind of jets on boundary layer development.

Key words: *boundary layer, wake, wave, negative jet, positive jet, phase-averaged, velocity traces.*

Introduction

Unsteady boundary-layer flows over the blades of turbines and compressors contribute to the loss and heat transfer to the blades. Particularly it is responsible for earlier laminar-turbulent transition. In multistage turbomachinery upstream blades shed wakes on following ones. The process of wakes action that impinge on blade surfaces is periodic. The wake can be identified as velocity deficit in the stationary frame, whereas as a jet in the frame relative to the mean flow. The jet is consider as a positive or negative one depending on jet vector sign. Jet with vector pointing surface is called positive one. The negative jet is considered inversely.

Tollmien-Schlichting velocity waves in boundary layer flows are well known, however their presence in the flow disturbed by strong wakes a bit less. Generally influence of jet sign direction – negative or positive on boundary layer development is not clearly distinguish by many researchers. The first author who noticed this difference between negative jet which causes suction in boundary layer and a positive jet which makes enlarged pressure was Meyer [1], Fig. 1. Wakes of negative jets make earlier laminar transition which was probably for the first time reported by Wiercinski [2] and then confirmed in detail by Zabski [3] who observed diffusion of turbulence form negative jets. However some reports, for instance Jeon et al [4], also indicate a difference of wakes direction with respect jet orientation towards the surface, but it was no stated explicitly. Consideration of their experimental setup leads to conclusion that their counter-clockwise rotation of the squirrel cage gives negative jets in terminology of this paper. In the same manner their clockwise rotation should give positive jets. Of course not every flow disturbed by wakes is driven to full turbulence. There can exist calm region between them if the frequency of wakes generation is low. In some circumstances this region can originate waves as reported by Stieger [5] who identified them as TS waves. This paper describes appearance of small waves in accelerating (which is an enhancement of previous paper [6]) flow behind a wake of negative jet. It is significant feature as there is no clear evidence of waves past positive jets.

Measurements were carried out in a subsonic wind tunnel of low turbulence level that did not exceed Tu = 0.08% and the flow in free stream of front of test section was U= 15 m/s. Dimensions of the test section were 600×460×1500 mm (width, height, length) and the corners were chamfered. Scheme of the test chamber, a flat plate and a pendulum mechanism is shown in Fig. 2. The plate width, length and height are: 600×700×14 mm respectively. The leading edge was rounded with a radius 2 mm. The incidence angle was adjusted and for this measurement amounted α = -2.44o and -0.44o. That corresponds to flow acceleration over upper surface of the flat:

$$K = \frac{\nu}{U^2}\frac{dU}{dx} = 3.36 \cdot 10^{-7} \qquad (1)$$

and $K = 9.96 \cdot 10^{-8}$ respectively, where: $\frac{dU}{dx}$ – velocity gradient along the plate.

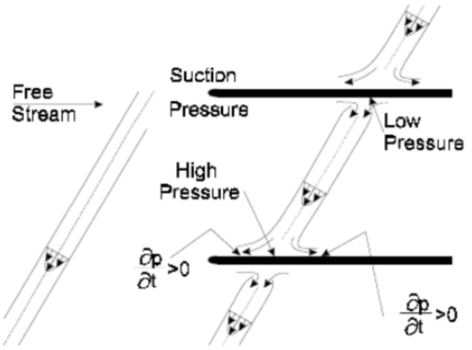

Fig. 1. Wake as a negative (Low Pressure) positive (High Pressure) jet in the boundary layer Exeprimental rig and instrumentation

That means that for smaller angle the flow was of nearly at constant velocity. Wakes were generated by means of a rod of 3 mm diameter which moved up and down by means of pendulum mechanism mounted in front of the plate. The rod movement frequency equaled to f = 4 Hz what gives a period of T = 0.25 s for one negative and one positive jet. The non-dimensional parameters of wake generation are Strouhal number and Φ coefficient:

$$Sr = \frac{fC}{U} = 0.19, \tag{2}$$

$$\Phi = \frac{U}{U_b} = 5.74, \tag{3}$$

where: C – plate length,

f – frequency of wakes generation,

U_b – rod maximal velocity when it is at the same height as leading edge of the plate.

The measurements were made by means of StreamLine thermoanemometry system with the StreamWare 3.41.20 software and the probe 55P15 DANTEC. The data were recorded via 12 bit NI 6040E acquisition card. The sampling rate was 5 kHz. In order to synchronize hot-wire output with passing wakes for farther phase-averaging of velocity traces procedure (Dong and Cumpsty call it ensemble averaging [7], other authors call it phase-lock) a mark signal was recorded when the rod was going up and was in equal height with the leading edge of plate. Sample duration amounted to t = 10 s for each point of velocity profile. Time averaging was used to obtain mean values of velocity and fluctuations profiles as well as longitudinal parameters derived from them: skin friction coefficient, shape coefficient, boundary layer thickness and so on. Phase-averaging yielded velocity traces filtered from random disturbances. This was done by averaging phase matching points of real time velocity traces. The duration of each phase-averaged velocity trace was t = 0.25 s and that is one period of one negative and one positive jet passing. Farther non-dimensional period $\tau = 1$ is used for phase-averaged traces. Measurement traverses were located at distances from the leading edge: x= 165, 215, 255, 295, 335, 365, 560, 650 mm which corresponds to Re_x = 165677, 218600, 258355, 303167, 339593, 367920, 570338, 657117 ($K = 9.96 \cdot 10^{-8}$, α = -0.44o). For higher pressure gradient ($K = 3.36 \cdot 10^{-7}$): x = 295, 335, 365 mm, Re_x = 277718, 317720, 346604. Each traverse consisted of at least 100 points.

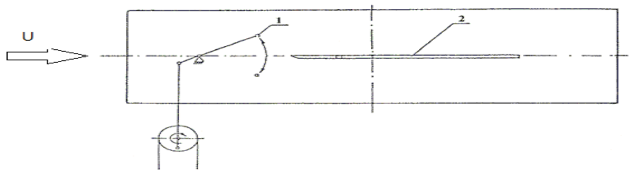

Fig. 2. The flat plate and wake generator
1 – a thin rod generating wakes, 2 – a flat plate

1. Results

Time averaged results were typical. Only skin friction coefficient distribution is shown in Fig. 3. Although flow was strongly disturbed by oncoming wakes mean-time parameters remain rather laminar, the same refers to mean velocity profiles, not shown in this paper. Only mean velocity fluctuation u'/U profiles reveal presence of wakes – a second a peak value in the outer zone of layer.

Fig. 4 and Fig. 5 show phase-averaged velocity traces versus non-dimensional period for the distance from attack edge x = 365 mm for two values of accelerating flow coefficient K. There were more charts for earlier mentioned travers locations, but they were similar to those from Fig. 4, and are not presented here.

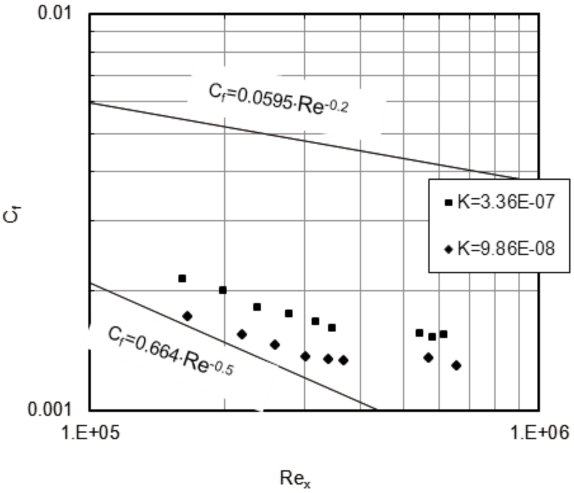

Fig. 3. Skin friction coefficient distribution

The upper traces are taken at the edge of layer, the lowest ones are in the close vicinity of wall – viscous sub-layer. First strong velocity defect is due to negative jet, second – positive one. Traces behind the positive jet are much smoother than traces following the negative jet. For the flow at K = 9.96·10-08 (α = -0.44o) there are velocity waves behind the negative jet. They occupy whole mid-jet area or only a part. In Fig. 4 they begin shortly after the negative jet and reach the centre of calm region between wakes. The waves in Fig. 5 (K = 3.36·10-07, α = -2.44o) seem to have bigger magnitude and they are concentrated in narrow belt around centre of calm region between wakes. In both cases the waves shown start at the vicinity of wall – traces of lowest velocity – and end up at about U = 12 m/s. Fig. 6 shows waves range in velocity profile. They end up in a trough between fluctuation peaks. That may indicate dumping effect of external turbulence, taking into account that second peak in velocity mean fluctuation profile is supposed to be evoked by wakes.

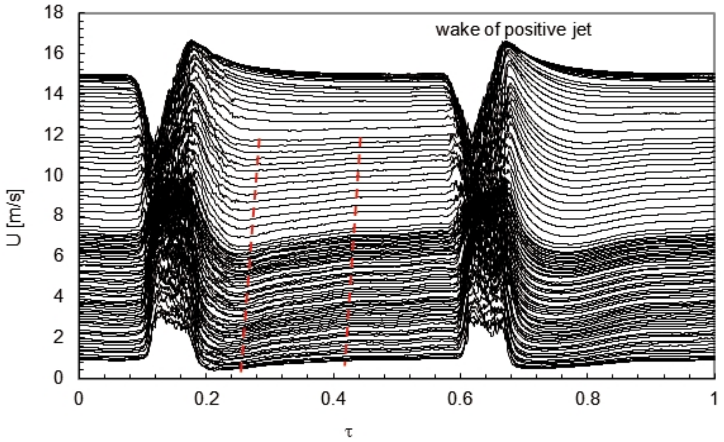

Fig. 4. Phase-averaged velocity traces for slightly accelerating flow K=9.96E-08, Re$_x$=367920

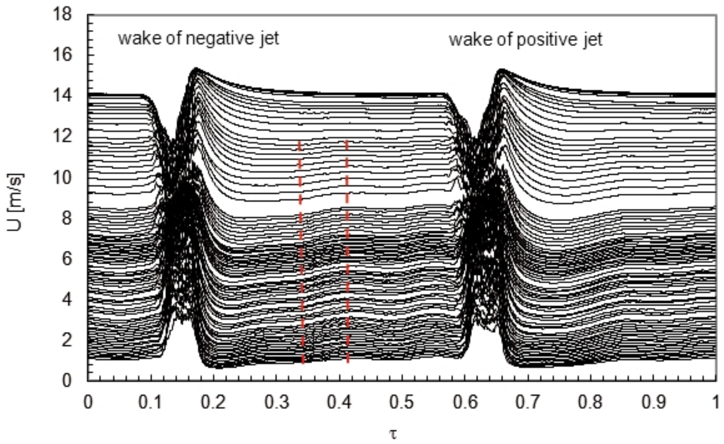

Fig. 5. Phase-averaged velocity traces for accelerating flow K=3.36E-07, Re$_x$= 346604

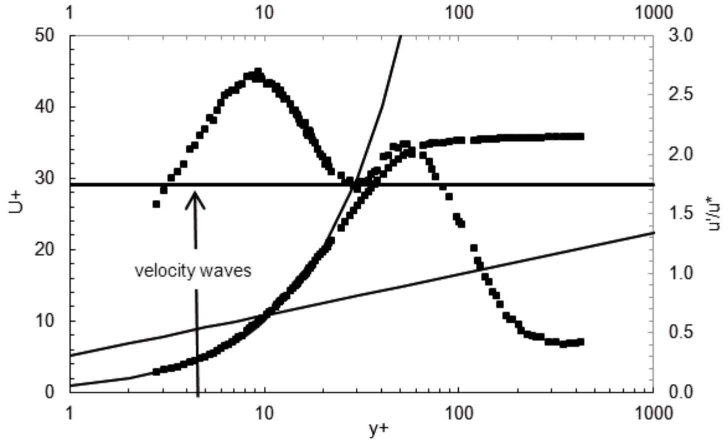

Fig. 6. Mean velocity and fluctuation profiles, K=3.36E-07, Re_x=346604

Some measured frequencies are marked with their Λ values to better locate them against neutral curves. Taking this into account all frequencies lie in the region of damp frequencies. If fact there was no laminar-turbulent transition for described flows. The data in Fig. 7 reveals some scatter that depended on which trace was chosen for frequency counting. It seems the real range is wider and spectral analysis is indispensable. Also magnitudes should be investigated.

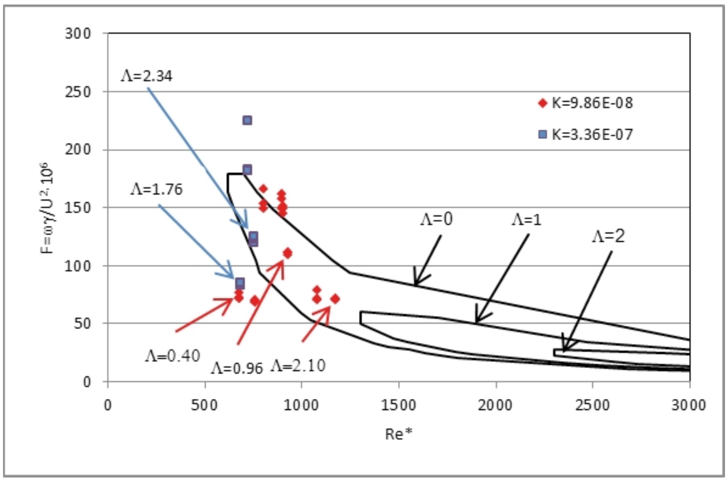

Fig. 7. Frequency of velocity waves on diagram of TS neutral curves

2. Conclusions

Wake-induced transition in boundary layer flow along a flat plate was experimentally investigated. The wakes were generated by pendulating cylinder yielding negative and positive jets by turns on investigated surface of the plate. Two incidence angle of plate were used yielding one slower and one faster accelerating flow given by K coefficient.

Mean-time velocity profiles and longitudinal parameters (Cf, δ, H) distribution remained close to laminar ones. Only mean-time fluctuation velocity profiles differed from laminar pattern. Second peak in outer zone of boundary layer is an evidence of wakes influence of boundary layer.

Phase-averaged profiles are smooth except regions of wakes. There is no merging of wakes observed and their width grows slowly. The mid-wake region remained laminar and no turbulence diffusion form wakes was noticed.

Behind wakes of negative jets little magnitude waves developed till next wake – wake of positive jet. The waves occupied the whole mid-wakes area or only part. Careful track of velocity traces shows waves origin close to the wall and final damping at a height where a depression between peaks on mean fluctuation is located. When a wake of positive jets passes no clear evidence of waves is observed.

Farther study with application of Fourier analysis is desirable. Another important issue is explanation of waves presence only past negative jets.

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Жабски Яцек. Волны скорости в пограничном слое, возмущенном спутными следами положительных и отрицательных струй в ускоряющемся потоке

Рассматривается экспериментальное исследование пограничного слоя для двух значений ускорения потока на его границе. Течение возмущено проходящими следами от колеблющегося выше по потоку стержня, создающего положительные и отрицательные струи поочередно (отрицательная струя – если стержень движется вверх, создавая разрежение в пограничном слое на верхней поверхности пластины, положительная – если стержень движется вниз). Траектории и осредненные по фазе траектории получены с помощью периодических фазовых меток. Профили средней скорости и продольные распределения средних или интегральных параметров оставались близкими к ламинарному виду. Форма следов на траекториях скорости была такой же, независимо от направления струи. Однако, в траекториях скорости наблюдались волны, вызванные прохождением отрицательной струи. Они размещались в затухающем диапазоне волн Толмина-Шлихтинга. После положительных струй волны скорости не наблюдались, в чем и проявляется основное различие влияния обоих видов струй на развитие пограничного слоя.

Ключевые слова: *пограничный слой, след, волна, отрицательная струя, положительная струя, фазовое осреднение, траектории скорости.*

Жабски Яцек. Хвилі швидкості в пограничному шарі, збуреному супутними слідами позитивних і негативних струменів у потоці, що прискорюється

Розглядається експериментальне дослідження примежового шару для двох значень прискорення потоку на його границі. Течія обурена прохідними слідами від стержня який коливається вище за потоком, що створює позитивні і негативні струмені по черзі (негативна струмінь - якщо стержень рухається вгору, створюючи розрідження в примежовому шарі на верхній поверхні пластини, позитивна - якщо стержень рухається вниз). Траєкторії і осереднені за фазою траєкторії отримані за допомогою періодичних фазових міток. Профілі середній швидкості і поздовжні розподілення середніх або інтегральних параметрів залишалися близькими до ламінарного вигляду. Форма слідів на траєкторіях швидкості була такою ж, незалежно від напрямку струменя. Однак, в траєкторіях швидкості спостерігалися хвилі, викликані проходженням негативного струменя. Вони розміщувалися в згасаючому діапазоні хвиль Толміна-Шліхтінга. Після позитивних струменів хвилі швидкості не спостерігалися, в чому і проявляється основна відмінність впливу обох видів струменів на розвиток примежового шару.

Ключові слова: *примежовий шар, слід, хвиля, негативний струмінь, позитивний струмінь, фазове осереднення, траєкторії швидкості.*