Passive Skin Friction Control Near Turbulent Separation – Preliminary Results

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Abstract. The paper deals with experimental analysis of passive skin friction control method applied for a high Reynolds number turbulent boundary layer close to separation. A proposed new method is based on the mechanism of scale interaction observed in the wall bounded flows known as amplitude modulation of small scales by large-scale motion. The applied control technique introduces artificially amplification of the modulation mechanism using a corrugated surface in the direction of flow at specific ratio of surface waving parameters. Preliminary results show that the method can be use in an efficient way to postpone the turbulent boundary layer separation for high Reynolds number, where methods based on classical turbulizers fail. This method introduces reorganization of turbulence production, which introduces asymmetry between sweep and ejection events. This results in positive skewness of streamwise fluctuations and additionally increases the momentum near the wall. The momentum is increased only in the inner part of boundary layer. The persistent of the developed flow control method is permanent farther downstream the corrugated wall.

1. Introduction

A broad variety of control methods aiming at the reduction of the global drag has been investigated in the past. Most of them do not offer real opportunities for practical implementation or are not efficient enough, what applies, in particular, to active control methods [1][2]. From practical point of view more valuable are passive control methods because of zero energy expenditure in comparison with energy consuming active methods.

The selection of appropriate methods for flow control concerns in particular high Reynolds number turbulent boundary layers (TBLs) that are under the influence of adverse pressure gradient conditions leading to separation. The majority of flow control studies concerning skin-friction drag reduction have attempted to manipulate structures within the near-wall region [2]. In case of turbulent separation it should be emphasized that, unlike the methods aimed at skin friction drag reduction, the method that increases skin friction should be used. This may be achieved by some form of roughness as it is well established that vortex generation caused e.g. by surface roughness can by-pass laminar-turbulent transition and delay flow separation. However, for high Reynolds numbers (i.e. above chord Reynolds number, $Re_c = 10^5$) using any kind of turbulizers are ineffective [1]. That is why there is a need to search for new methods. It is well known that turbulent coherent structures play a crucial role in the momentum transport of wall-bounded turbulent flow and generation of skin-friction drag. So, the alternative method can be based on the newly discovered phenomenon of amplitude modulation imposed by large-scale structures. The detailed description of this phenomenon has been presented in the paper
of Mathis et al. 2009 [3]. The large-scale motions are most energetic in the outer region of a high-Reynolds-number or of an APG TBLs, but they also have an influence in the inner-region. For relatively high Reynolds number TBL, the large-scale motion causes the sequential increase and decrease of flow velocity near the wall and in areas of high-speed fluid (increase of mean shear) the higher small scales amplitude and the higher convection velocity are observed [4][5].

Studies presented in the paper concern a new passive method of controlling TBL with detachment being the result of strong adverse pressure gradient (APG). The motivation of the study originates from the work of Dróždz and Elsner 2017 [4], who observed the increase of convection velocity of small scale structures being the effect of amplitude modulation phenomenon. The physical mechanism standing behind the rise of total convection velocity is the specific forcing of the near-wall small-scale turbulence by large scales in the regions of locally elevated velocity. This specific forcing enhances not only the energy but also convection velocity[4], which induces increase in momentum near the wall. This phenomenon is amplified as a function of the Reynolds number which to some degree was confirmed in Ref. [6].

The idea of the proposed concept is to artificial stimulate turbulent structures near the wall by appropriately designed wall topology e.g. stationary wavy surface (corrugated wall), aimed at enhancement the amplitude modulation mechanism. The suitable corrugated surface can affect the small-scales in the same manner as the large-scale structures i.e. increasing their activity in high speed zones (crests) forcing increased convection and thus increasing the wall-shear stresses. The random in nature turbulence production will be in this way ordered resulting in the assumed increase of wall-shear stresses. Effect of wavy wall on turbulent flow was already studied experimentally among the other by Segunda et al. [7], where the impact of wavy wall periods number on the recirculation zone in consecutive periods were experimentally analysed and turbulence modelling were evaluated. Recent papers by Hamed et al. [8][9] shows the influence of ratio of amplitude of waviness to incoming boundary layer thickness for the 2D and 3D wavy wall and conclude that there is lower modulation of boundary layer parameters for 3D wavy wall. However, there is no systematic optimisation analysis of this problem in the literature, in particular no attempt to assess the ratio of amplitude to period for high Reynolds number flow. The more so, there is also no data available on the analysis of the effectiveness of surface modification for a strong pressure gradient flows and close to separation.

2. Experimental setup and apparatus
The experiment was performed in an open-circuit wind tunnel, where the TBL was developed along the flat plate, which was 5035 mm long, what allows to reach boundary layer thickness, \( \delta \approx 80 \text{mm} \) at the inlet to the test section. The inlet rectangular channel has two pairs of suction gaps aimed, at maintaining overpressure, to control the two-dimensionality of the flow by minimizing the boundary layers on the side walls. Triangular corner inserts were used in the whole inlet channel to reduce the effect of secondary vortices developing along rectangular channel. A slight inclination of the upper wall helped maintain zero pressure gradient (\( \frac{dP_{\infty}}{dx} = 0 \), where \( P_{\infty} \) is external static pressure and \( x \) is the streamwise direction) conditions at the inlet. The wavy wall was introduced on the distance 650 mm just before the inlet plane. The specially design diffuser shape test section with a length of 1.835 m (see Figure 1) equipped with a perforated movable upper wall allows to generate on the bottom wall the turbulent boundary layer, which is at the verge of separation. Wall perforation of 10.1% was adopted, characterized by 0.5mm circular holes. Modification of the shape and position of the upper wall and the suction flux allows for generation of a wide range of pressure gradient conditions, while the zero pressure gradient conditions were maintained at the inlet channel. With specific pressure conditions, it is possible to generate, on the bottom wall, a turbulent boundary layer which is at the verge of separation. Full separation on the lower flat plate does not occur even for the suction case. After that point, due to the cessation of suction, the flow returns to the attached state.

The velocity measurements were performed with hot-wire anemometry Dantec Dynamics Streamline Pro. A single hot-wire probe of a diameter \( d = 3 \, \mu \text{m} \) and length \( l = 0.4 \, \text{mm} \) was used. The hot-wire bridge was connected to a 16 bit A/D converter. Acquisition was maintained at the frequency of 25 kHz, with minimum 50 s sampling records. The ambient conditions were carefully controlled during the
measurements. To have the verified reference friction velocity \( u_\tau \) along the flow the fringe skin friction (FSF) technique was applied introduced by Tanner and Blows in 1976 [10], who related the evolution of oil droplet thickness to skin friction \( \tau_w \). For the purpose of skin friction measurement, the optical equipment was installed in the wind tunnel under the glass plate (see Figure 1a). It consisted of remotely controlled commercial camera equipped with Macro lens and SOX Whitecroft Lighting sodium lamp, emitting the monochromatic light of the wavelength \( \lambda = 0.5893 \) \( \mu \)m used to illuminate the oil droplet. For the current measurements the OM50 silicone oil with the viscosity of about 0.048 Pas was used. The accuracy of wall shear data was in the range of 1%. In the course of a single profile measurement the scatter of ambient temperature at the end of the test section did not exceed \( \pm 0.2^\circ \) and the temperature difference between the flowing air and the wall was also below 0.1\(^\circ\)C. Further details of the methodology and post processing was presented in Ref. [11]. The level of uncertainty was equal 1% of the initial value 0.2 Pa. High accuracy was obtained using at least 40 pictures taken each time of the measurement and at least 30 of them were processed. In order to obtain maximum of skin friction downstream the corrugation the measurement of skin friction using OFI method was performed in location 800 mm (150 mm downstream the corrugation) by changing sing wave amplitude.

![Figure 1: Test section and oil film experimental setup a); shape factor H distribution b).](image)

Basic inflow parameters have been summarized in Table 1, where \( Tu \) is turbulence intensity, \( U_{in} \) mean velocity outside of TBL, \( u_\tau \) friction velocity \( \left( u_\tau = \sqrt{\frac{\tau_w}{\rho}} \right) \), \( \theta \) momentum loss thickness and \( Re_\theta = \frac{U_{in} \theta}{\nu} \) is Reynolds number, where \( \nu \) is the kinematic viscosity. The pressure distribution imposed by the upper wall and the active suction is presented in figure 1b. Further details of the experiment can be found in Ref. [6].
As the corrugation, the sine wave was used. The corrugation was introduced at the beginning of adverse pressure gradient on the distance 650 mm (see Figure 1a). The 100 mm wide 2D wavy wall was introduced in the center of 250 mm flat plate then the side edges of the flat plate and wavy surface were rounded by the elastic tape. To characterize the local flow conditions, the shape factor $H = \delta^*/\theta$, where $\delta^*$ is displacement thickness as a function of the streamwise position for the reference case (flat wall) is shown in Fig. 2b. The parameter has a constant value slightly above 1.4 up to $x = 500$ mm, when it starts to increase its value. However, a sharp almost linear increase of $H$ can be observed from $x \approx 800$ mm, indicating the strong process of the flow destabilization. For streamwise distance of 1100 mm, the so called intermittent transitory detachment (ITD) is reached.

3. Results

The measurements were performed for the inlet Reynolds number $Re_\theta = 10150$ which is equivalent to Reynolds number based on friction velocity equal 3300. Four different wavy surfaces was used during step by step optimisation characterised by different $A/\lambda$ ratio, where $A$ is the amplitude and $\lambda$ is the wave period, in the following order of $A/\lambda = 0.05$ then 0.08, 0.16, and the last was 0.12. On each step the skin friction was estimated using oil-film interferometry technique and the velocity profile using hot wire was measured. The results presented in the Figure 2 show the wall shear stress distribution as a function of $A/\lambda$ measured 150 mm downstream the corrugated surface. The initial increase of wall shear stress with the increase of $A/\lambda$ ratio is observed (Figure 2). A significant rise, by 42.5%, of the wall shear stress occurs in the range up to $A/\lambda$ equal to 0.135. It is clearly visible that this effect disappears for higher values of the reduced amplitude. It should be noted that the wall stress zero point at $A/\lambda = 0.24$ has been entered into the graph to ensure approximation of the distribution using 3rd order polynomial. The above results show that the applied method, by appropriate selection of the geometrical parameter, allows to obtain a significant increase of wall shear stresses and thus affect the delay of turbulent detachment.

In order to assess how the corrugated wall affect the boundary layer, it was decided to analyse the mean and fluctuation velocity profiles as well as skewness factor at a few distances downstream the modification of the plate surface for the parameter $A/\lambda = 0.12$, for which the response of the boundary layer was the strongest. Figure 3 presents the comparison of mean velocity profiles measured 800, 900, 1000 and 1100 mm from the inlet in each case compared with the reference data taken on flat plate (Fig. 3). In the figure, for both cases, the wall distance was scaled by $\delta$, although for corrugated wall the boundary thickness difference is up to 10% than for the flat plate. The mean profiles where reduced by $U_w$, which is the mean velocity outside the boundary layer thickness and it is the same for both cases.

For the first travers (Figure 3a), the significant increase of velocity is observed in the inner region of boundary layer ($<0.3\delta$), which coincides well with the area of the boundary layer where the effect of amplitude modulation is usually observed. This suggests that the amplification of this mechanism for the specific parameters of corrugated wall has been achieved. The analysis of downstream development of boundary layer reveals that this impact is permanent, because the effect of the increase in velocity
due to wavy wall is present at each consecutive traverse (Figure 3b). The more so, the area of flow modification increasing also in the direction normal to the wall, what indicate an enhancement of the momentum transport to the wall by strengthening of small scale sweep events.

![Figure 3. Assessment of the persistence of a disturbance: mean flow velocity downstream corrugation.](image)

In order to confirm this statement, the following figures show the streamwise Reynolds stress scaled on \(U_o = 2(U_\infty - U_{0.5})\) and the skewness factor for two chosen location i.e. 800 and 1100 mm from the inlet (Figure 4). As above, the new data were compared with those obtained for a flat plate. The outer scaling by \(U_o\) is the best for comparison between flat and wavy wall as it is based on the outer part of mean velocity profile, which is unaffected by the wavy wall (see Fig. 3). When analysing the distributions of Reynolds stress \(u'u'\) (Fig. 4a) it can be noticed that the outer part of the curve is modified in terms of location of the outer maximum, as for wavy wall (dark profiles) it is located slightly farther from the wall. This is very likely to be the result of the impact of the crest of the wavy surface. However, already above 0.5\(\delta\) all the profiles perfectly collapse using \(U_o\). It means that the most affected area is the near-wall region, where the increase of \(u'u'\) occurs due to increased strain rate. Downstream the flow the shift of streamwise Reynolds stress maximum towards the centre of the boundary layer is observed. For corrugated wall the increased \(u'u'\) stress value is observed below the outer maximum of \(u'u'\). The skewness factor analysis (Figure 4b) shows that for location 800 mm the changes are not so substantial as for two lower order moments, however further downstream (\(x = 1100\) mm) the skewness factor is again significantly affected in virtually the entire boundary layer thickness. It means that the proposed method provides long lasting effect on the near wall flow. The confirmation of the impact to be induced is the strong drop of the skewness value, which lead to the detachment delays. The turbulent structures, generated by the increased strain rate in modified momentum zone at location just after corrugation, induces the lower sweep event (in comparison to those for the flat-plate), which is manifested by the lower skewness.

The results of this experiment supports the findings of Segunda et al. [7] in channel turbulent flow, where the recirculation zone in the wavy wall valleys decreases in increasing the number of wave periods. However, the difference between experiments in the literature is that that the observed reduction of recirculation zone is assign to the increased of turbulent kinetic energy in the preceding recirculation zone, where the separation bubble occurs. For the optimum \(A/\lambda\) ratio (which is also function of Reynolds number) the flow is maintained at the edge of occurring of recirculation zone. The effect of increased momentum could be assign either to modulation of convection velocity or/and to production of TKE in preceding recirculation zone.
4. Conclusions

It was demonstrated that for the specific amplitude and the period of wavy wall the maximum of the skin friction value can be achieved when dealing with high Reynolds number turbulent boundary layer in adverse pressure gradient leading to separation. Preliminary results shows that the method can be use in an efficient way to postpone the turbulent boundary layer separation, where classical methods based on turbulizers fail. The optimized wavy wall shape substantially increases the momentum near the wall for high Reynolds number turbulent boundary layer and acts in similar way as the amplitude modulation mechanism leading to increase in convection velocity of turbulence. The significant increase of velocity is observed in the inner region of boundary layer (<0.3δ), which coincides well with the area of the boundary layer where the effect of amplitude modulation is usually observed. Such reorganization of turbulence production introduces dominance of the sweep over the ejection, which is manifested in positive skewness of streamwise fluctuations. Increased sweep enhanced momentum transfer to the wall and cause the higher turbulence production downstream the flow. The proposed method provides long lasting effect on the near wall flow.

5. References

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