POSSIBILITY OF PASSIVE CONTROL OF A SWEPT FLAT PLATE BOUNDARY LAYER

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ABSTRACT

In order to control the crossflow dominated transition process, an experimental investigation in a 3D-boundary layer was conducted using a swept flat-plate model with a displacement body. A generation of a stationary vortex structure is done, placing micron sized roughness elements in span wise direction at x/c = 0.17, generating a fixed vortex streaks wavelength of λ = 12.5 mm, equal to the most amplified wavelength under natural condition.

Based on this, a second row of micron sized roughness elements was placed further downstream to reduce the secondary instability which is responsible for transition in highly distorted 3D-boundary layers. Hot wire measurements in the 3D-boundary layer at various chord wise position were conducted detecting the secondary instability locations. A localization of the ideal positioning of the second roughness elements was done by a variation of three different span wise positions. Maintaining the wavelength of λ = 12.5 mm, a transition delay for one of the test cases was obtained.

INTRODUCTION

The transition mechanism of a 3D-boundary layer has been investigated for a few decades. Especially in order to reduce the drag of a swept wing aircraft and thus its fuel consumption by enabling a fully laminar region over the wing where crossflow dominated transition is present, the control of stationary vortices has become a popular research topic.

In order to obtain first information about the process of cross-flow dominated transition, Kohama et al. (1991) investigated the dependence of stationary crossflow vortices which dominate the transition process, due to the evolution of high frequency secondary instability. Deyhle and Bippes (1996) discovered that surface roughness is responsible for the initiation of stationary crossflow. Thus placing surface roughness in the boundary-layer lead to an artificially stimulated instability. Surface roughness was also used by Saric et al (1999) and Radeztsky et al. (1993) in order to fix the primary mode and thus the vortex structure in the 3D boundary-layer. Subsequently a second row of micron sized surface roughness elements was applied as a passive transition control method. By placing the roughness row in span-wise direction, using different spacing between the elements, different cross flow wave length were generated. From this a transition delay was obtained by damping the most amplified wave length using a sub-critical linear forcing of λ_{2nd} / 8. A validation of the experiment was done by Janke et al. (1999) using the nonlinear PSE. Based on this experiment, Saric et al. (2000) presented a pressurized roughness actuator as an active method for transition control.

Another active method was presented by Abegg et al. (1999) using suction holes. From this an attenuation of the crossflow disturbance and thus a boundary layer stabilization was obtained. Likewise the experimental results were confirmed by a nonlinear PSE.

Kohama & Egami (1999) studied the effect of the selective suction in a 3D-boundary layer by changing the suction speed, -volume and -position. Using the suction in the high shear region close to the up wash of the cross flow vortex, a significant transition delay was achieved, due to the secondary mode being strongly influenced by the high shear region of the vortex (Kawakami et al., 1999). Using the selective suction leads to the same controlling effect as in case of a uniform suction but with a lower suction rate and thus less energy.

According to the investigations mentioned, the present work deals with transition delay by influencing the high shear region, using micron-sized roughness. The newly point of this experiment is the application of a second row of roughness elements placed at a specific location of the growing streak vortices. Streak vortices were originated using a first row of roughness inducing a uniform growth crossflow vortices. From this a more efficient and less energy consuming transition control is expected.

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EXPERIMENTAL SET-UP AND PROCEDURE

The experiments were carried out in the low turbulence wind tunnel at the Institute of Fluid Science, Tohoku University. In the open wind tunnel test case, the turbulence level is less than Tu = 0.05%. The experimental set-up is shown in Fig 1.

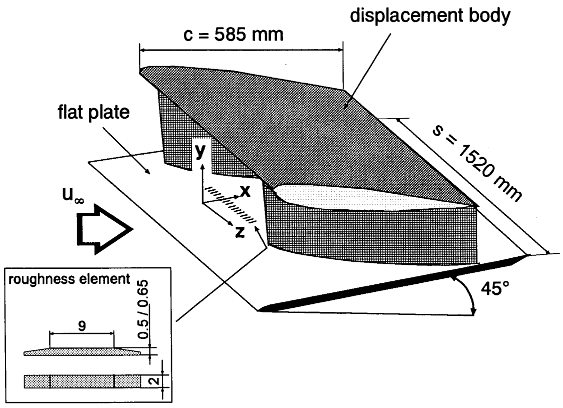

Figure 1 : Experimental set-up

In order to investigate the transition process on a flat plate, which is dominated by crossflow instabilities, a favorable pressure gradient is generated in stream wise direction. This gradient is imposed using a displacement body located above the flat plate, causing a linear favorable pressure gradient, Fig 2.

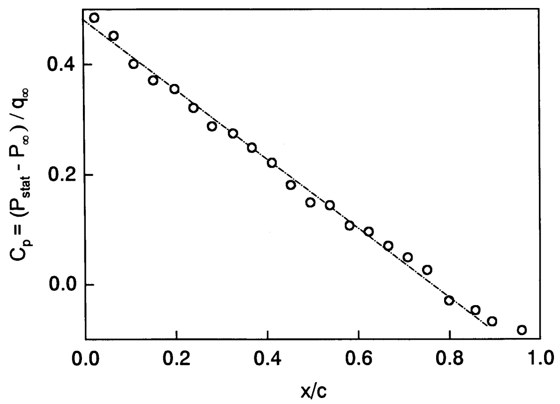

Figure 2 : Pressure distribution of the swept flat plate in chordwise direction

The sweep angle of the flat plate is set to 45° and in addition two end plates are mounted to the flat plate in order to simulate the infinite sweep condition.

Because of the favorable pressure gradient limiting the boundary layer growth, the flat plate is positioned 200 mm upstream of the leading edge of the displacement body. This is done in order to guarantee a boundary layer growth to some extent, before entering the favorable pressure gradient region and thus the measurement area.

The determination of the coordinate system was done as can be taken from Fig 1. The origin in x-direction of the coordinate system is located at the projection of the leading edge of the displacement body and in the middle of the two side plates in z-direction.

The streamwise velocity component u is measured by a single hot wire probe (CTA mode). The traversing of the probe is done using a step size in z-direction of 2 mm. During the experiment the free-stream velocity u_∞ is maintained at 12.5 m/s, resulting in a Reynolds number (based on the chord length of the displacement body) of $Re_c = 4.9*10^5$.

In order to get a uniform wave structure in span wise direction, micron sized roughness elements are mounted on the flat plate in span wise direction. The spacing between each element is set to λ = 12.5 mm, representing the most dominant wave length in the boundary layer under natural condition.

The first row of roughness elements is placed at x/c = 0.17, Fig.3, generating equal spaced cross flow vortices and thus inducing a uniform growth. A second row of roughness elements is placed outside the linear growth stage at x/c = 0.25. Three different z-locations maintaining a fixed spacing in between the elements are selected, being stated as can be seen from Figure 3.

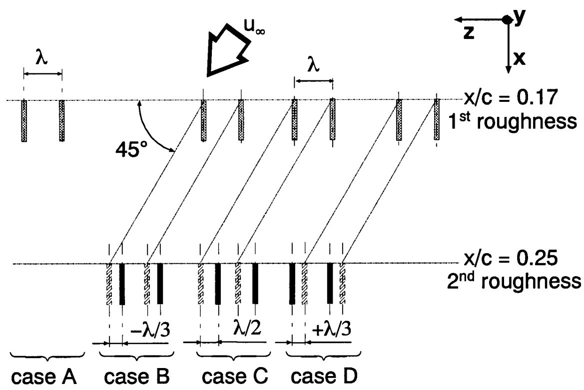

Figure 3 : 1st and 2nd roughness position on the flat plate for all cases investigated

The micron sized roughness elements are made out of a plastic rectangular plate, with a length l = 18 mm, a width of w = 2mm and a height of h = 0.5 mm for the first roughness (19% of the local boundary layer thickness at x/C =0.2) and h = 0.65 mm for the second roughness.

RESULTS AND DISCUSSION

Fig. 4 shows a velocity contour plot at the position of the second roughness row (x/c = 0.25) in addition the locations of the second roughness elements are identified. The roughness elements are placed at three different locations in the high shear region, which is responsible for development of the secondary instability.

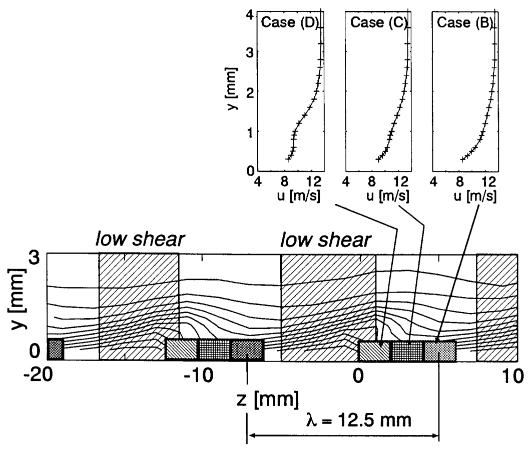

Figure 4 : Velocity contour at x/c = 0.25 including the roughness location of case (B), (C) and (D)

The velocity profiles which are present at the roughness position clearly show that the boundary layer profiles for case (D) and case (C) are still inflected while the profile at the position of case (B) remains a stable trend.

Referring to the idea of using the second row of roughness elements in the high shear region, similar to boundary layer suction used by Kohama & Egami (1999), a weakening of the primary mode in the low shear region is expected.

Fig. 5 presents the u'_{RMS}-profiles of test case (A) in comparison with case (B), (C) and (D) taken from the low shear region of the streak vortex. Beginning with test case (B) a significant reduction of the turbulence intensity and thus of the disturbance can be seen.

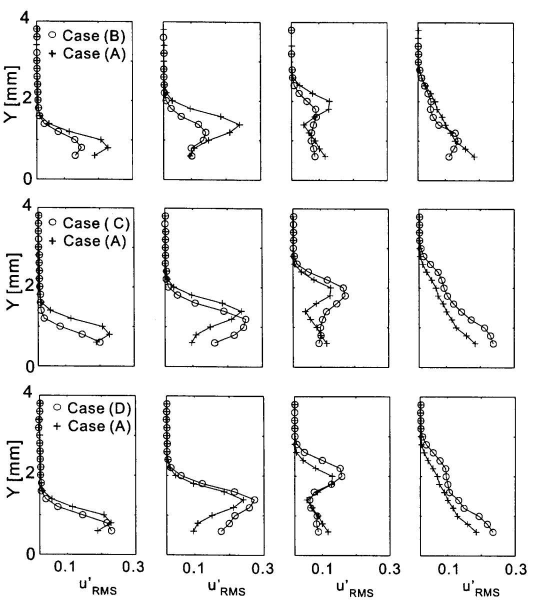

Figure 5 : Comparison of u'_{RMS}-profiles in the low shear vortex region at x/c = 0.3 for all test cases investigated

In test case (C) placing the 2[nd] roughness partly in the low shear region seems to increase the maximum turbulence intensity. Similar to case (C) an increase of u'_{RMSmax} is visible for case (D), which indicates a possible earlier stage of secondary mode.

A comparison of the turbulence intensity (u'_{RMS}/u_∞) distribution over the flat plate at a fixed distance from the wall of y = 1mm is shown Fig. 6. The location of laminar-turbulent transition without passive control (case (A)) can be expected for x/c > 0.6. Laminar-turbulent transition occurs at an earlier stage for case (C) and (D), while for case (B) laminar-turbulent transition is delayed. Latter was already assumed due to the decrease of the turbulence intensity and thus the weakening of the primary mode.

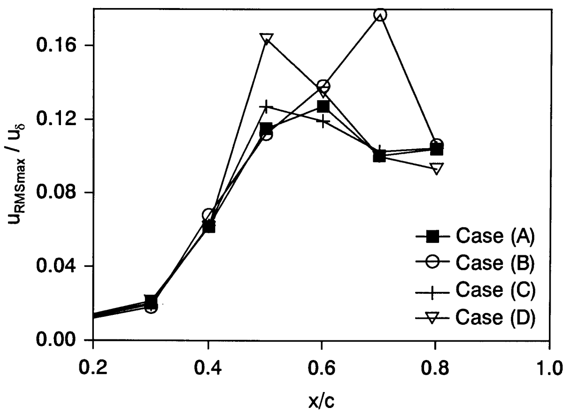

Figure 6 : Turbulence intensity distribution on the flat plate in chordwise direction

In order to get a more detailed information about the region close to transition where primary and secondary instability appear, an overlay of the velocity and the turbulence intensity contour is selected for x/c = 0.5 (Fig.7) and x/c=0.6 (Fig.8).

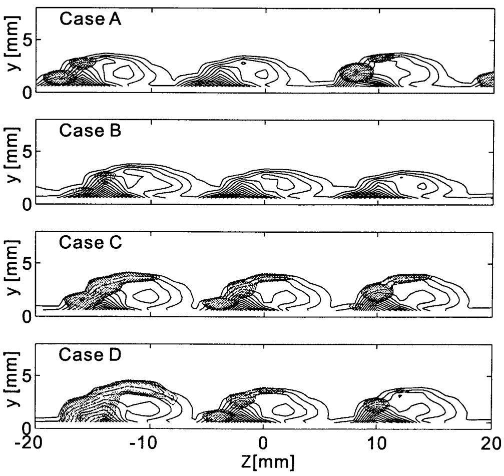

Figure 7 : Mean velocity and turbulence intensity contours at x/c = 0.5 for all test cases investigated (band pass filter f_b = 1.47 – 1.54 kHz)

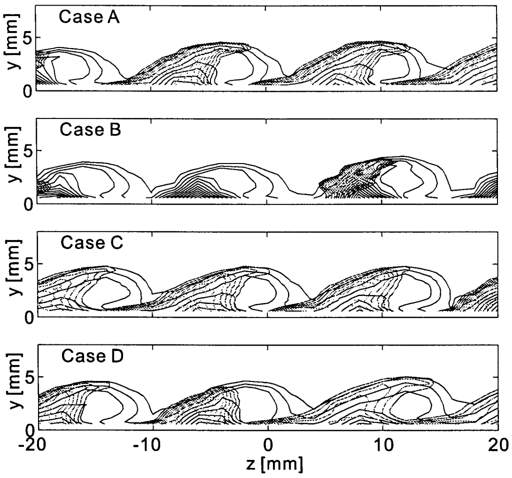

Figure 8 : Mean velocity and turbulence intensity contours at x/c = 0.6 for all test cases investigated (band pass filter f_b = 1.47 – 1.54 kHz)

According to a broad band peak in the power spectrum, a band pass filter of f_b =1.47 – 1.54 kHz was chosen for the presentation of the turbulence intensities to expose the region were second instability occurs.

For x/C = 0.5, respectively two peaks of high turbulence intensity in the low shear region of the streak vortices are present for case (A), (C) and (D), indicating the appearance of secondary instability. Slightly weaker disturbances can be found for case (B). At x/C=0.6, the location of the disturbance for case (A), (C) and (D) is widening, covering the low and partly the high shear region of the vortex. Due to the expected delay of the development of the primary and the secondary mode in case (B) the secondary mode still remains in the low shear region.

In order to get a more detailed view of the growth of the secondary instability for test case (A) and case (B), the power spectrum of u' (related to the $u_{RMS, max}$) for both cases are plotted in Fig.9 and Fig.10.

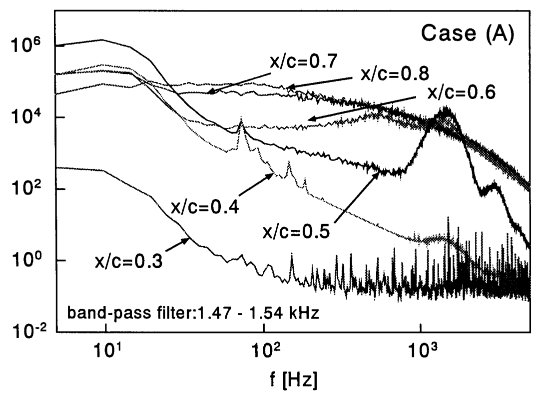

Figure 9 : Power spectrum for case (A) at 0.3 ≤ x/c ≥ 0.8 (band pass filter f_b = 1.47 – 1.54 kHz)

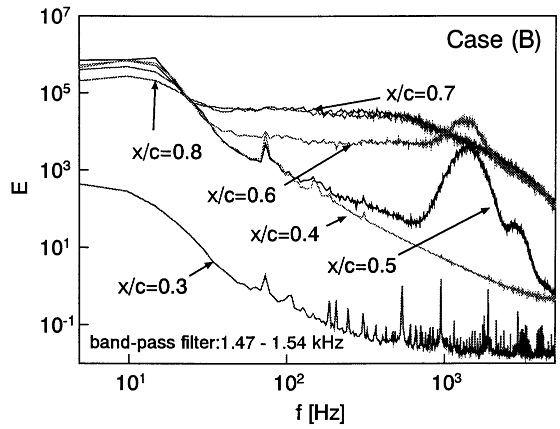

Figure 10 : Power spectrum for case (B) at 0.3 ≤ x/c ≥ 0.8 (band pass filter f_b = 1.47 – 1.54 kHz)

Additionally a band-pass filter was used to expose secondary instability. However, a broad band rise of the fluctuation signal in the laminar-turbulent transition region is visible at higher frequencies (f ≈ 1.4 kHz), indicating the secondary instability mode. This is found for both cases, starting from x/c = 0.4 for case (A) and x/c = 0.5 for case (B). At x/c ≥ 0.7 in both cases turbulent flow is indicated by the flat turbulence spectra.

CONCLUSION

In this paper the control of turbulent laminar-turbulent transition in a the crossflow-dominated flow over a plat plate is obtained, using micron sized surface roughness. By using a variation of span wise roughness settings, a strong dependence of the roughness location in the high shear region and the laminar-turbulent transition delay was found. Placing the roughness elements in the high shear region where the velocity profiles are less inflected leads to a significant delay in the growth of the secondary mode and thus to the location of laminar-turbulent transition. A second effect is emerged due to slightly changes of the roughness geometry, showing a strong sensibility in case of the stability growth.

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