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Experimental investigation of the vorticity amplification on a swept wing with a blunt leading edge

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Abstract

A high level of turbulence is generated in the region upstream of the leading edge of a wing. The phenomenon has been investigated on two-dimensional wings and the existence of coherent structures at the stagnation point has been observed. The present paper deals with the flow upstream of the leading edge of a *swept* wing.
A swept wing with a blunt leading edge has been used as a model in order to have a relatively thick boundary layer on the attachment line. The experiment has been carried out in a low turbulence wind tunnel and the freestream turbulence has been changed through a metallic string positioned ahead of the model. Two different configurations for the same string have been studied and compared to the clean case.

1. INTRODUCTION

The region upstream of the leading edge of an aerofoil is a centre of disturbances in which a high level of turbulence intensity is established. This observation, firstly studied by Piercy and Richardson in 1928 [9], led to the vorticity amplification theory developed by Sutera et al. in 1963 [15]. Superimposing a sinusoidal perturbation onto the incoming flow the theory analyses how the stretching and tilting of the vortex tubes generate a local increase of the turbulence. Furthermore, the theory demonstrates that the vorticity is amplified only if properly oriented and if the wavelength is greater than the natural wavelength λ_0, which depends on the geometry of the body and on the flow conditions.
A first experimental investigation was carried out by Sadeh et al. [12] on a normal flat plate. The mean and the fluctuating components of the velocity were measured using a hot-wire anemometer. In agreement with the theory, the experiment revealed an increment in the fluctuating component of the velocity at the edge of the boundary layer. Furthermore, the existence of coherent structures at the edge of the boundary layer were demonstrated by flow visualization using smoke. To study the influences of the oncoming freestream turbulence on those structures, Sadeh et al. extended the experiment by inserting different grids in the wind tunnel ahead of the model. The amplification was in some cases even higher than 100%. The same phenomenon on different bodies has been reported by several researchers. In particular, Sadeh et al.[11] found amplification up to 255% on a cylinder, Bearman studied a wing with a blunt leading edge [1], Sadeh and Sullivan observed the structures on a NACA65-010 aerofoil [13].
A comprehensive mathematical model of the same problem has been independently developed in 1994 by Kerr and Dold [6]. They found an exact solution to the Navier Stokes equation for the Hiemenz flow with a steady spanwise periodic perturbation superimposed. The solution shows an array of rotating-vortices at the edge of the stagnation boundary layer, figure 1.
The vorticity amplification has been widely studied on

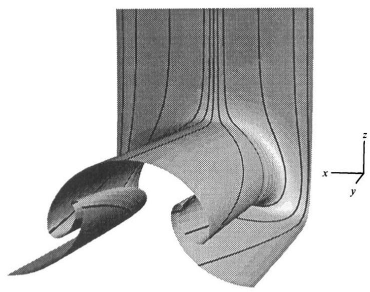


Figure 1: Coherent structures at the stagnation point of a Hiemenz flow [6].

two-dimensional flows, but not on swept wings.
In a previous work [5] the flow along the attachment line of a highly swept NACA0050 wing has been compared to the flow at the stagnation points of an unswept cylinder. The experiments have been carried out in a wind tunnel with a freestream turbulence of 1% using

a two-dimensional Laser Doppler Anemometers, which enabled to measure two velocity components at the same time. The comparison has shown a different behaviour for the two models. An amplification in the fluctuating component was observed on both models; but whilst the existence of the coherent structures along the axis of the cylinder was clearly discernible, the same cannot be said of the result on the swept wing.
It is known that the freestream turbulence influences transition from laminar to turbulent boundary layer [14], and in particular the cross-flow instability on swept wings [2], but the physical mechanism of interaction between freestream turbulence and boundary layer is not completely understood. The attachment line of a swept wing plays a crucial role in establishing the initial conditions for the downstream flow over an airfoil. The study of the interaction of freestream turbulence and boundary layer at leading edge may be of help in understanding this and other phenomena.
This paper describes a second experiment of the flow upstream of a swept wing with a blunt leading edge, similar to the one used by Bearman [1]. The model was tested in a low turbulence wind tunnel and the freestream turbulence is changed by placing a metallic string upstream of the wing. A similar technique has been previously used by Nagib et al. [7] on an unswept body. The string has been placed at two different locations in the wind tunnel and the two experiments are compared to the case without a string.

2. MODEL

The model has been designed to have a thick boundary layer on the attachment line, in fact on a vertical flat plate the boundary layer is $\sqrt{2}$ thicker with respect to an equivalent size swept cylinder. Furthermore, the surface does not present a curvature and this enables the hot-wire to be aligned easily to the wall and to reduce the uncertainty of the measurements.

Figure 2: Model: swept wing with blunt leading edge. Overview of the design.

The model has been manufactured in three parts: a wooden wing-shape body and two aluminium inserts to make up the leading edge. This structure provides a cleaned high quality surface on the leading edge in the area of interest.

The model has been mounted horizontally from one side of the wind tunnel to the other , so as to avoid any sagging on its own weight.
A swept-back wing was the only possible solution due to the location of the traverse system used to hold and move the hot-wire inside the wind tunnel. On a swept-back wing the disturbances from the tunnel wall might propagate along the attachment line resulting in a turbulent boundary layer. The experiment has been carried at 18 m/s, which corresponds to a Reynolds number at the attachment line of $\bar{Re} = 240$. Although this value is theoretically just below the limit to avoid attachment line contamination [8],[4],[10], the effects of the disturbances propagating from the wind tunnel wall were experimentally observed downstream along the attachment line. To avoid this phenomenon a device similar to Gaster bump [3] has been designed. It consists of an aluminium foil attached on the leading edge and held by a wooden structure at a convenient distance from the surface. In this way the turbulent boundary layer coming from the wall bleeds from the sides of the device and goes over the wing body, while on the device leading edge a new laminar boundary layer is established and can propagate downstream.
The flat leading edge is 200 mm wide and the sweep

Figure 3: Blunt leading-edge wing mounted in the wind tunnel

angle is 40° to maximise the cross-flow instability downstream on the leading edge.

3. EXPERIMENTS

The experiment has been carried out in the low velocity Gaster wind tunnel at City, University of London, with a test section of 0.91m x 0.91m x 3m, a contraction ratio of 6.75:1 and a turbulence intensity less than 0.01%.
A constant temperature anemometer (CTA) with single hot-wire boundary layer probe has been used for the measurements. The data have been acquired for 10s at a sample frequency of 20kHz. The signal has been band-pass filtered between 2Hz and 10kHz with a gain of 20dB ap-

plied. Temperature corrections have been carried out to the data. The mean velocity and and the ambient pressure have been also acquired for the whole duration of the experiment together with the wind tunnel temperature.
In the following discussion the coordinate system (x,y,z) will be referred as in figure 4: x perpendicular to the flat leading edge, y along the attachment-line and z the vertical axis parallel to the flat leading edge. The velocity components will be (u,v,w) respectively.
The hot-wire has been traversed along the attachment-line, parallel to the flat surface to measure the v-velocity component inside the boundary layer. The attachment-line location has been experimentally determined by looking for the minimum of the velocity along z-axis at different x positions. The location has also been checked looking at the zero-pressure on the pressure taps on the model.
The aim of the experiment was to investigate the flow impinging on the swept blunt leading edge changing the freestream turbulence level by placing a metallic string ahead of the model at two different locations of the string have been studied, figure 4.
In the following discussion three test cases are compared. The first one is the model without any variation from the turbulence already presents in the wind tunnel, the others involve a metallic string ahead of the model at two different locations, figure 4.
The string crosses the whole width of the wind tunnel

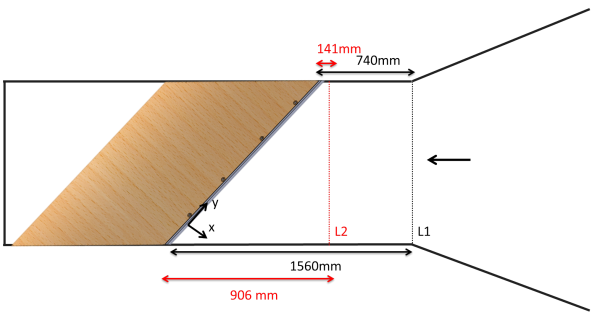


Figure 4: Top view of the model in the in tunnel. L1 and L2 are the two positions of the string. Flow from right to left.

and it is held by a wooden bracket. On the bracket a mechanism made from a guitar string tuning system ensures that the string is kept tight, figure 5.
Assuming the string to be a straight cylinder immersed in the flow, the wake vortices create a turbulent region that will interact with the boundary layer. The experiment has been carried out at a speed of 18m/s and the string had a diameter of 0.23mm corresponding to a Reynolds number of $Re_D = 238$ and a Strouhal number $Sr = 0.18$. The shedding frequency of the Von Karman vortices will then be $f_{sh} = 16347Hz$.

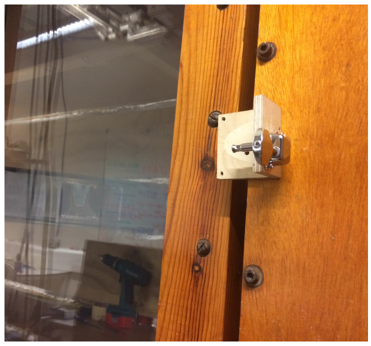
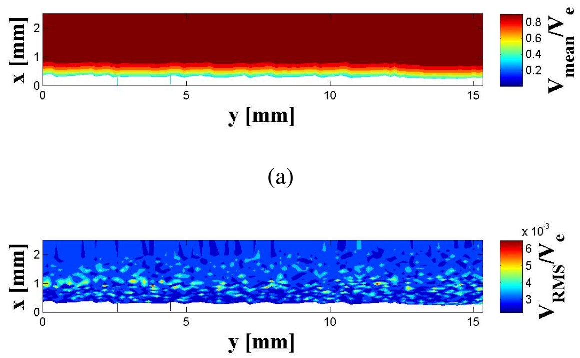


Figure 5: Mechanism to tighten the string upstream of the model

4. Results

4.1 No string

The hot-wire has been traversed from a distance greater than 1000mm (x=0mm) from wind tunnel wall 15mm downstream along the attachment line with a resolution of 0.15mm.
At the speed of 18m/s the boundary layer thickness at the attachment line is 1mm. The hot-wire is located as close as possible to the flat surface. A common technique for Blasius boundary layer, that can be applied also to the Hiemenz flow, is to interpolate the data points close to the wall with a straight line assuming that the first part of the boundary layer is linear. In the experiment only a few data points were available in the linear region of the boundary layer since it is not possible to measure closer than 0.2mm because of the hot-wire starts thermal effects. Unfortunately, this creates an artificial slightly wavy shape in the mean velocity along the attachment line.
In figure 6 the contour plot of mean and the Root Mean Square (RMS) of the velocity along y are shown. The



(a)

(b)

Figure 6: Natural case- a)Velocity along the attachment line. b)Root Mean Square (RMS) of the velocity along the attachment line.

flow field is constant everywhere along the attachment line, as shown by the mean velocity. The RMS shows an increment at the edge of the boundary layer with alternative regions of higher and lower intensity. After having divided the signal in blocks the data were Fourier transformed in the frequency domain. An example of the normalised power spectra density inside the boundary layer is reported in figure 7. The analysis in the frequency domain does not show a dominant frequency in the flow and most of the energy is in the low frequency region, but not a clear coherent structure is present in this area.

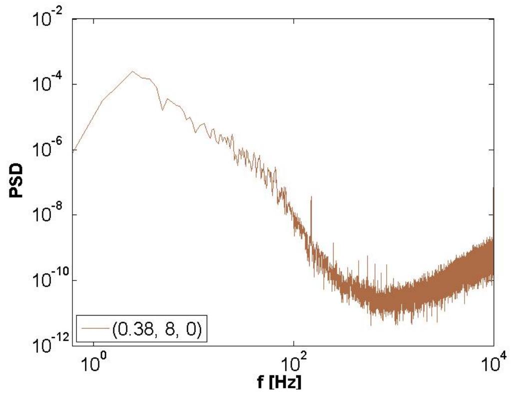
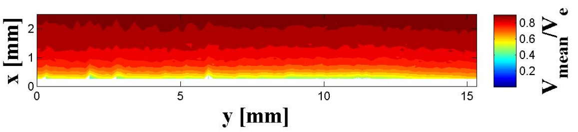


Figure 7

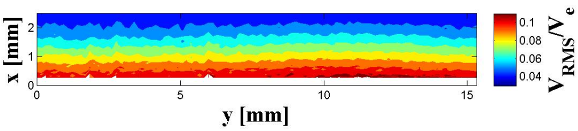
Figure 8: Normalised PSD inside the boundary layer at position of coordinates (0.38,8,0).

4.2 String at L1

In the first experiment the string has been placed straight after the contraction at a distance of 740mm from the closest edge of the leading edge and 1560mm from the farther edge. For this case the mean and RMS velocity



(a)



(b)

Figure 9: Horizonal string D=0.23mm L2- a)Velocity along the attachment line. b)Root Mean Square (RMS) of the velocity along the attachment line.

inside the boundary layer are shown in figure 9.
The boundary layer is already turbulent at the attachment-line and the level of RMS is much higher than the previous case.

Although the Reynolds number of the string is below the critical Reynolds number, the distance between the string and the flat leading edge is such that the wake has already broken down into smaller scale high turbulence structures and those are able to interact with the boundary layer and make it turbulent.

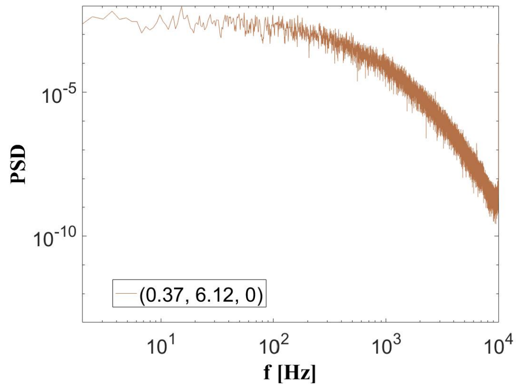
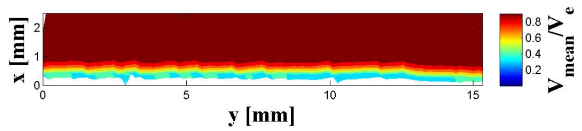


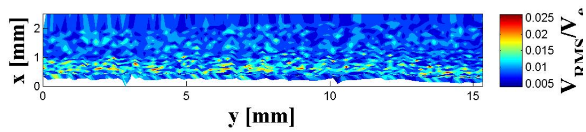
Figure 10: Normalised PSD inside the boundary layer at position of coordinates (0.37,6.12,0)

4.3 String at L2

In the second test the string has been moved downstream closer to the leading edge (L2 in figure 4). In this position the streamlines are curving approaching the leading edge and the velocity is decreasing, therefore the Reynolds number of the string is reduced. The distance that the wake has to travel before impinging on the plate is reduced as well. The mean and RMS for the string at L2 are shown in figure 11.
As in the case without the string the velocity profile are



(a)



(b)

Figure 11: Horizonal string D=0.23 L1- a)Velocity along the attachment line. b)Root Mean Square (RMS) of the velocity along the attachment line.

laminar and constant along the y-axis. The RMS shows an area of increased intensity approaching the model with a distribution in patches of higher turbulence. No distinguishably structures have been observed.

The flow along the attachment-line shows a different

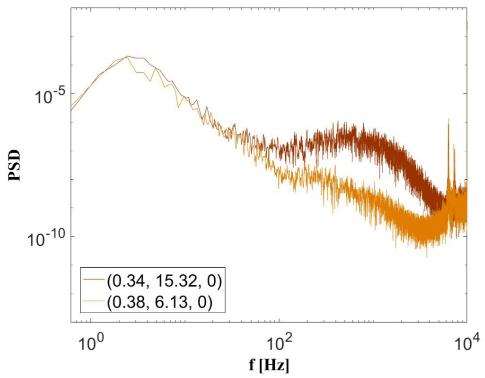


Figure 12: Normalised PSD inside the boundary layer at position of coordinates (0.34,15.32,0) and (0.38,6.13,0)

behaviour in the frequency domain. The figure 12 shows the power spectra density recorded on two different position along the attachment line at the same height inside the boundary layer. The energy in the high frequency region of the downstream point is greater than the one of the upstream location, while the energy in the low frequency domain remains similar. This difference in the flow is related to the different distance of the string from the leading edge at each attachment-line position. This distance is the spaces that the wake vortices propagating from the string have to travel. The energy content at high frequency is higher when the distance is higher.
In figure 13, the mean of the RMS distribution inside the boundary layer along the attachment line is shown normalized with respect to the RMS value at the edge of the boundary layer for the two laminar cases. The case without the string has a maximum at the boundary layer edge, while the maximum amplification of the case with the string is inside the boundary layer.

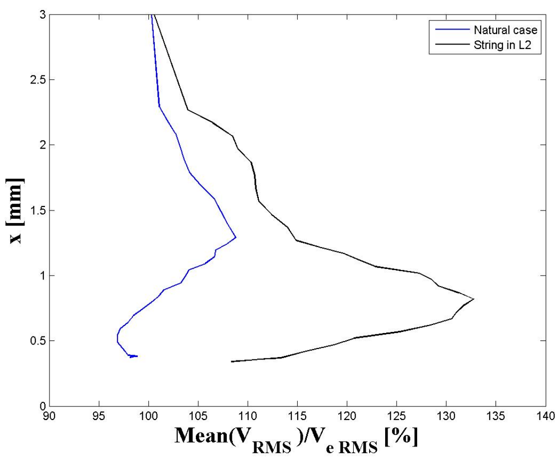


Figure 13: Comparison of the increases of fluctuations inside the boundary layer with and without the string.

5. CONCLUSION

An experimental investigation on the flow upstream of the swept wing with the blunt leading edge has been presented. The flat leading edge enables to measure the flow in a region where the boundary layer has not grown yet.
An increase in the velocity fluctuations closer to the leading edge has been found. The pattern of these fluctuations do not appear to be organized.
With the string far from the leading edge, the wake of the string has time to break down into small high turbulence structures before impinging on the leading edge. It results in a fully turbulent boundary layer at the attachment line. Whilst, with the string placed closer to the model the boundary layer remains laminar with fluctuations of a pattern similar to the case without string, but the maximum is inside the boundary layer.
The experiments just discussed are the preliminary investigation of the interaction between freestream turbulence and attachment-line boundary layer. In particular, the effect of the string positioned parallel to the leading edge, horizontally and vertically, will be studied.
This is expected to help understand the interaction of freestream turbulence and boundary layer on swept wings.

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