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Disturbance Initiated by Convergent Riblet in Flat Plate Boundary Layer

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Abstract

The characteristics of the disturbance initiated by convergent riblet, in the form of streamwise counter-rotating vortices, is examined experimentally using hot-wire anemometry. The parameter considered is riblet height to Blasius boundary layer thickness of 0.5. The turbulent intensity contours and the frequency spectrum reveal that the streamwise counter-rotating vortices are already at the verge of breakdown. The possible path towards the breakdown of the structures has also been discussed.

Introduction

The inevitability of flow transition to turbulence to include the streamwise vortices, led to the transition studies involving different kind of surface roughness that can artificially induce streamwise vortices. Though the characteristics of the streamwise vortices is surface-roughness-dependent, the route to turbulence has to take place in any of those fashion recommended by Morkovin et al [5]. Naturally occurring transitional flow structures, on flat plate boundary layer [1], and that involving the flow over concave surfaces [4], are counter-rotating vortices with low momentum fluid lifting up away from the wall. Within the context of experiments, the transition is dependent on the spanwise wavelength of the disturbances (also depends on the type of surface roughness), the total disturbance initiated due to receptivity and the free stream turbulent intensity. Given the case dependent scenario, a surface roughness like convergent riblet that can initiate naturally occurring transition like structures [3,6,7], has been employed to bring out the dependence of the flow transition on the above mentioned parameters. The aim of this paper is to study the characteristics of the initial disturbance induced by the convergent riblet using hot-wire anemometry.

Experimental Set up

The experiment was conducted in a straight plexiglass test section connected to a low speed blow down wind tunnel with a maximum operating velocity of 20m/s as shown in figure 1. The test section was 60 inch long with rectangular cross sectional area of 0.15m x 0.60m. Two smooth plexiglass flat plates were mounted successively inside the test section through the slits provided on the side walls of the test section. The slits were fabricated at a distance of 0.05m from its bottom surface. Three supports of 0.01m thickness and 0.05m height were mounted with equal spacing on the bottom floor of the test section to support the flat plates. The flat plates were 3mm thick, 1000mm long and 600mm wide. The front plate, with the leading edge tapered at 15˚, is the test surface where the investigation has been carried out, while the other plate behind the test surface is to ensure that the constant free stream velocity is maintained till the end of the test section. Thus the investigation area is the one formed between the test surface and the top floor of the test section. The divided arrangement of flat plates would prevent the plates from sagging and bending, which would be not be the case otherwise as a single long plexiglass plate would deflect due its own weight. A convergent riblet, which was manufactured using rapid prototyping, with ceramic as the green material, as shown in the figure 2 was mounted at a distance of 320mm from the leading edge of the test surface. At this location, the ratio of riblet height (h) to Blasius boundary layer thickness (δ), at an operating velocity of 3m/s, is 0.5.

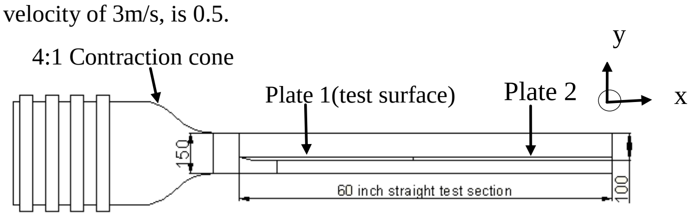


Figure 1. Sketch of Experimental Set-up

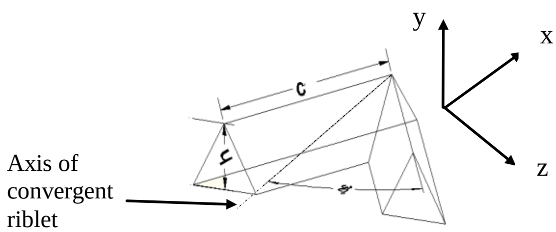


Figure 2. Convergent riblet

A specially designed single hot wire probe, Dantec 55P15, to measure boundary layer, operated in a Constant Temperature Anemometer mode, was used to traverse along a spanwise and wall normal distance of 15mm to obtain mean and fluctuating streamwise velocity component data. The CTA was operated at an over-heat ratio 1.8. The probe was coupled to an analog filter. The signal was low pass filtered at 3Khz and sampled at 6Khz for 21 seconds. An analog to digital converter card DT3016 installed in a personal computer was used to digitize the data, which was further analyzed using HPVEE software. The procedure is the same as carried out by [9].

A pitot-static tube connected to a pressure-transducer (Setra 239), calibrated against a standard micromanometer, in conjunction with a T-type thermocouple, was held in the free stream region to calibrate hot-wire and to measure the free stream velocity and its corresponding temperature as well. Periodic calibration checks were performed by placing the hot-wire probe at the free stream region. More than 2% drift of the free stream stream velocity measured by the sensor in comparison with the pitot-static tube and a temperature variation of ±0.5˚C led to data rejection and the data acquisition process to be repeated.

The hot-wire probe, the pitot-tube and the thermocouple were mounted on a two-axis traversing mechanism. The traverse was performed by two stepper motors along the normal(y) and spanwise(z) directions with an accuracy of ±0.1mm. In the present experiment the probe was moved in steps of 0.5mm along the spanwise direction and in steps of 0.2mm (near wall region) to 1mm (near the boundary layer edge) along the normal direction. The measured data has been plotted using commercially available software called TECPLOT. The finer isolines compared to measurements are the interpolated values of the software.

Results and Discussion

The unavoidable situation, as to where the location of initial disturbance originates, is attributed to the separation of the flow behind the riblet. As the prediction of flow reversal is not feasible using hot wire technique, a distance of 10mm from the trailing edge of the riblet is considered to be the location of initial disturbance. It is to be noted that the laboratory co-ordinates has its origin at the trailing end of the convergent riblet. Any measurement station mentioned is with respect to the laboratory co-ordinates.

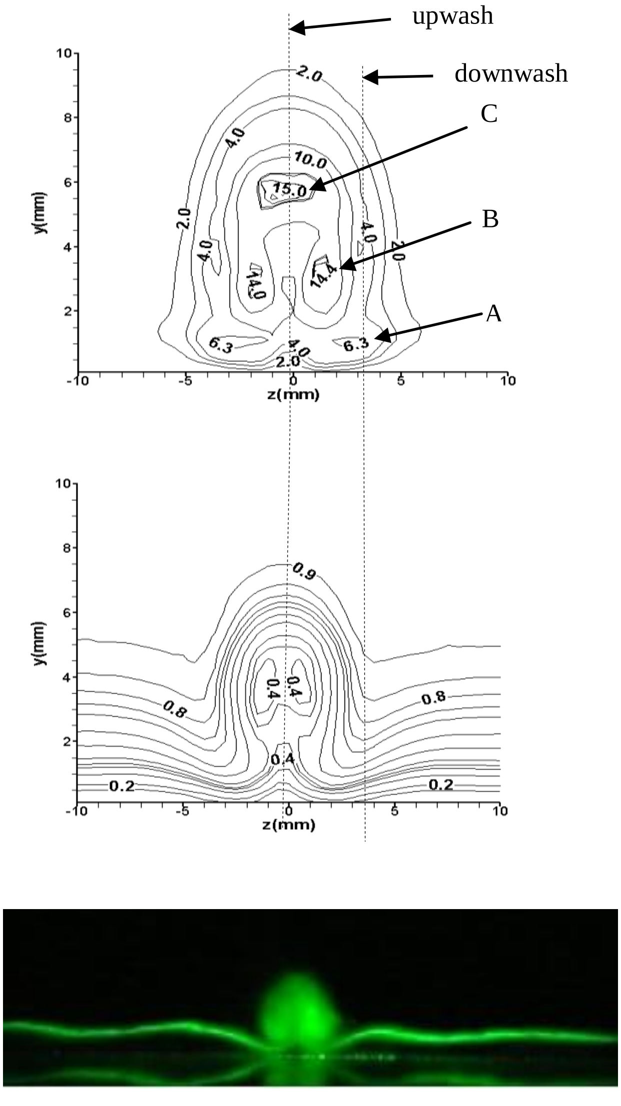
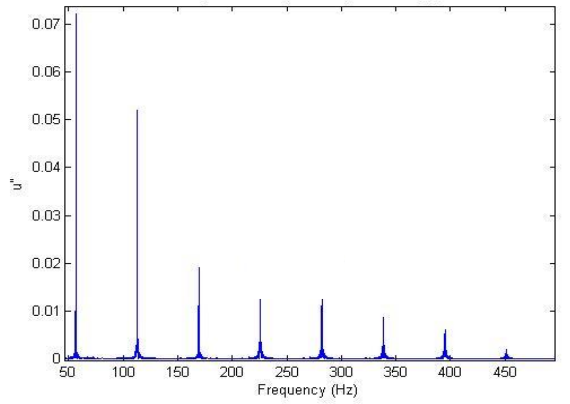
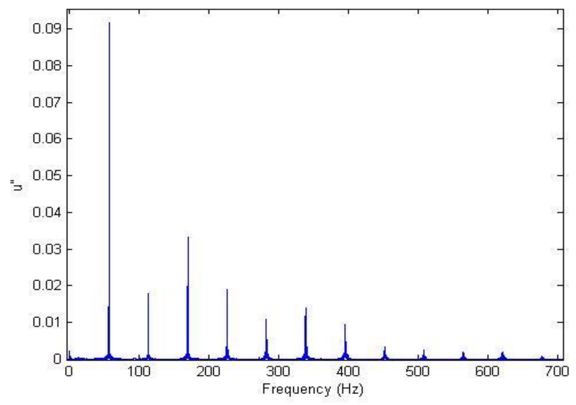


Figure 3. From top to bottom: Isolines of Turbulent intensity (Tu%) at x=10mm; Isolines of streamwise component of velocity normalized by free stream velocity at x=10mm; Streamwise counter-rotating vortices observed by smoke flow visualization technique.

Figure 3 clearly depicts that the disturbance initiated by the convergent riblet manifests itself as streamwise counter-rotating vortices. The spanwise modulation of the streamwise component of velocity occurs in such a fashion that the low momentum fluid upliftment coincides with the axis of the convergent riblet. The time-averaged isolines of turbulent intensity depict that the disturbance is symmetric of the upwash region. Three different regions of concentrations can be observed. A corresponds to the near wall streamwise vortices that lifts the low momentum fluid away from the wall. B corresponds to the lobes of the mushroom like structures formed due to turn over of the uplifted low momentum fluid and C corresponds to the shear layer formed by the interaction of the uplifted low momentum fluid with the free stream fluid. This structure is very similar to those that occur in the final stages of the non-linear development of the disturbances in a flat plate boundary layer [1] and Gortler instability problem [4]. The spanwise and wall-normally modulated velocity profile might imply the occurrence of the sinuous and varicose modes respectively [4,9]. However the transition of the flow to turbulence by any of those modes depends upon the wavelength of the vortex pair [2]. This is subjective of the initial conditions which is h/δ in the present case. However, the concentrations of turbulent intensity within the structure denote that the structure has attained its maximum amplification and is at the verge of breakdown [4], and is incident with the observation from smoke visualization. Hence any question of the possibility of the growth and breakdown of the structures due to the sinuous or varicose modes could be ruled out, only pertained to this assumed location of initial disturbance.





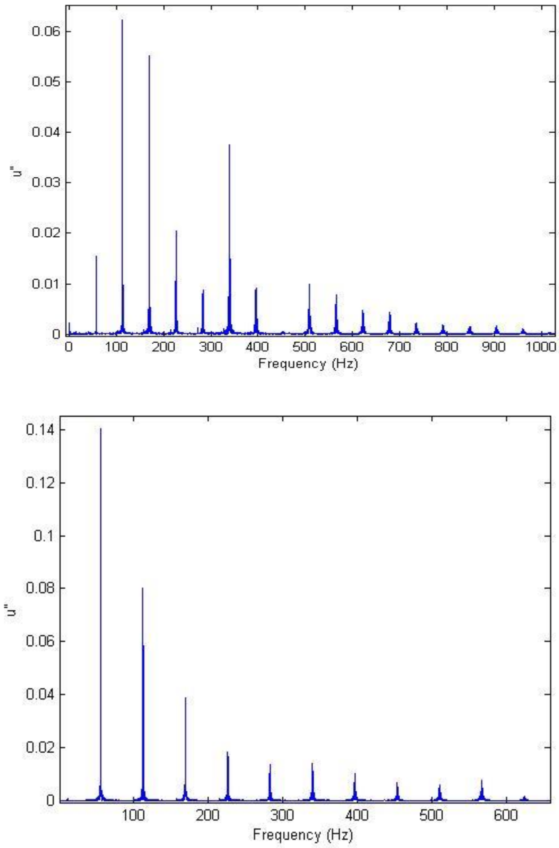


Figure 4. Frequency spectrum of the streamwise fluctuation (u”) at the upwash region; from top to bottom: At y/δ_L=0.25; At y/δ_L=0.5; At y/δ_L=0.75; d. at y/δ_L=1; where δ_L is the local Blasius Boundary layer thickness.

Figure 4 shows the frequency spectrum of the initial disturbance obtained by applying fast fourier transform to the streamwise fluctuating velocity waveform. The fundamental frequency 56.4 Hz, along with its harmonics supplements the idea that the vortices are already in the verge of the breakdown. A discrepancy of the most dominant frequency corresponding to the maximum amplitude at y/δ_L=0.5 corresponds to the turn over region of the low momentum fluid. It can be seen that, at this location the most dominant frequency is the second harmonic.

Conclusions and recommendations

The disturbance initiated by convergent riblet, whose height to local Blasius boundary layer thickness is 0.5, resembles the naturally occurring transition structures. The characteristics of the structure, though resemble the manifestation of the sinuous and varicose modes of instability, the frequency spectrum encompassing the fundamental and the harmonics suggest that the structures are already in the verge of breakdown.

The study could be carried out with different height to Blasius boundary layer thickness and the propagation of the disturbance with respect to its corresponding initial disturbance could be focused, thus accounting the case dependent transition scenario of the convergent riblet.

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