Experiments in bypass boundary layer transition under a stream with and without shear

G Balamurugan, Alakesh C Mandal
Department of Aerospace Engineering, Indian Institute of Technology, Kanpur, India
E-mail: alakeshm@iitk.ac.in

Abstract. Effect of mean flow shear on bypass boundary layer transition is investigated experimentally in a low-speed wind tunnel. To initiate bypass transition on a flat plate, the level of freestream turbulence is intentionally enhanced using a uniform parallel rod grid and a non-uniform parallel rod grid. The non-uniform grid produces a mean velocity profile with shear, and therefore, turbulence production due to this shear will be non-zero compared to a uniform grid which produces a mean velocity profile without shear. The growth rate of the disturbance energy for the non-uniform grid is found to be higher compared to the uniform grid. The intermittency values are also found to be higher for the non-uniform grid under same flow conditions. Particle Image Velocimetry (PIV) measurements in the spanwise plane reveal instability characteristics similar to the one reported in the literature.

1. Introduction
Boundary layer transition is influenced by several factors such as freestream turbulence (FST), pressure gradient, wall roughness, leading edge geometry, etc. Rapid boundary layer transition that occurs at an elevated level of turbulence is often called as bypass transition. Various studies [1, 2, 3, 4, e.g.] were carried out to understand bypass transition in a boundary layer. These studies clearly reveal that, at an elevated level of freestream turbulence, low- and high-velocity streaks appear in the flow. The experimental work of Matsubara and Alfredsson [1] shows that the growth of these streaks are algebraic, and these streaks eventually break down into a turbulent spot due to instability. The numerical simulation of Jacobs and Durbin [2] also shows that localized instability on a lifted low-speed streak can lead the flow to the turbulent state. The PIV measurements of Mandal et al. [4] also indicate breakdown due to similar instability mechanism.

Generally two types of secondary instabilities are reported in the literatures, i.e. sinuous and varicose instabilities. These instabilities are often held responsible for generation of incipient turbulent spots in the flow. Inviscid secondary instability studies on optimal streaks were performed by Andersson et al. [5]. They have reported that instability develops beyond a critical streak amplitude of 26%. Asai et al. [6] studied the breakdown characteristics of an artificially generated low speed streak and observed that sinuous modes are more unstable, if the streak width is comparable with the boundary layer thickness. In their numerical simulation, Brandt et al.[7] observed similarity between their spot precursors and the instabilities reported earlier in various controlled studies [5, 6, e.g.]. Dye flow visualizations of Mans et al. [8] in an actual bypass transition clearly show the presence of these sinuous and varicose instabilities. A
comprehensive and comparative study by Schlatter et al. [9] indicates that these instabilities are perhaps triggered by localized perturbations which are present in the freestream. To elucidate the role of these freestream perturbations, a comparative study has to be performed between two cases differing only in the amount of perturbation produced. In our present work, we attempt to investigate this aspect by using a uniform and a non-uniform turbulent generating grids in the freestream.

2. Experimental Setup
Experiments were performed in an open circuit wind tunnel available at the Department of Aerospace Engineering, Indian Institute of Technology, Kanpur, India. The tunnel has a 3000 mm long test section with a square cross section of 610 mm × 610 mm. The tunnel has a square three dimensional contraction section with 16:1 contraction ratio. Measurements were carried out on a flat plate placed horizontally in the mid-plane of the tunnel test section. The plate has an asymmetric modified super elliptical leading edge which was designed following the guideline of Hanson et al. [10]. This leading edge shape is chosen to reduce the receptivity of the boundary layer to external disturbances by eliminating the leading edge and flat plate juncture curvature discontinuity which can affect the stability properties of the flow [11]. The streamwise turbulent intensity of the tunnel was found to be 0.1% of the freestream velocity.

![Figure 1. Simple sketches for the uniform grid (a), the non-uniform grid (b) and the PIV setup for the spanwise plane measurements (c).](image)

However, the freestream turbulence level in the tunnel test section was intentionally enhanced using two types of passive grids, as shown schematically in figures 1(a) and (b). The grid with equal spacing of parallel rods is called as uniform grid (see figure 1(a)) and the grid with non-uniform spacing of the rods are called as non-uniform grid (see figure 1(b)). Both the uniform and non-uniform grids in figures 1 (a) and (b) are made of 10 mm diameter circular rods and the numbers of rods were kept same for both the grids. The non-uniform grid was fabricated by varying the spacing among the parallel rods linearly, whereas the uniform grid has a uniform spacing between two consecutive rods. These grids were designed such that the solidity ($\sigma$, defined as the ratio of the blockage area by the grid to the tunnel test section area), remains the same for both the grids. The solidity value was smaller than 0.45 as suggested by Kurian and Fransson [12] to avoid interaction of the jets that gets created between the rods. The distance between the grid and the leading edge was maintained more than 20 mesh widths to ensure the development of isotropic turbulence [3] for both the grids. For a same rotational rpm of the tunnel, the measured turbulent intensities for both the grids at the plate leading edge position are shown in table 1, along with the integral length scale and Taylor micro scale.

A hotwire anemometry system (procured from Dantec Dynamics) along with a National Instruments data acquisition card and Labview software was used for data acquisition. A single
Table 1. Free stream parameters at the leading edge.

| Grid                  | $u_{rms}/U_0$ (%) | $\Lambda$(mm) | $\lambda$(mm) |
|-----------------------|-------------------|----------------|---------------|
| Uniform grid          | 2.3               | 14.8           | 7.02          |
| Non-uniform grid      | 2.3               | 13.95          | 6.88          |

wire miniature hotwire probe with 5$\mu$m diameter tungsten wire as the sensing element was used to measure the instantaneous streamwise velocity, $U_I$, and the fluctuating streamwise velocity, $u$. The length to diameter ratio of the probe was 250. The probe was calibrated using a Pitot-static tube connected to a Furness FC012 digital manometer and King’s law fit.

We also utilize the particle image velocimetry (PIV) technique to measure the instantaneous velocity fields in the spanwise plane, i.e. in the $x-z$ plane, where $x$ and $z$ denote the streamwise and the spanwise distances. The wall normal distance in this work is denoted by $y$. The experimental setup for the PIV measurements is schematically shown in figure 1(c). A double pulsed Nd:YAG laser (Innolas Spotlight Compact 400 PIV, 180 mJ/pulse, 10 Hz) is used for illuminating the flow field. The flow is seeded with the help of a fog generator placed at the rear end of the tunnel entrance. The fog is distributed uniformly across the tunnel using a small fan in front of the fog generator. A CMOS camera (model Motion pro Y5, IDTpivot, USA) of 2336×1728 pixel resolution was used to capture the particle images. The laser and the camera were synchronized with the Motion pro timing unit (procured from IDTpivot, USA). The field of view of the PIV measurements in the $x-z$ plane was 100 mm× 70 mm. For the PIV measurements, the laser sheet was made parallel to the flat plate at $y = 2.5$ mm. We acquired 700 image pairs for both the grids and these images were analyzed using Provision-XS software developed by IDTpivot. The software utilizes a mesh free cross-correlation algorithm (see Lourenco and Krothapalli [13], for details). While processing these images, we used a 32 pixel×32 pixel correlation window, and the spatial resolution based on this correlation window is found to be 1.4 mm. Further details of image processing using this software is given in our previous work [4].

Figure 2. Transverse distribution of the normalized mean velocity (a) and rms velocity (b) along with the integral scale, $\Lambda$, (c) and Taylor micro scale, $\lambda$, (d), for the uniform grid (unfilled symbol) and the non-uniform grid (filled symbol) at the leading edge. The length scales are found by using the autocorrelation function, $R_{uu}$ and the local mean velocity, $U$. 
3. Results and Discussion
The freestream turbulence characteristics along the transverse direction (i.e. along $y$ direction) are shown in figure 2, for both the grids. These measurements are carried out at $x = 0$ in an empty test section; that is at the streamwise location where the plate leading edge starts if the plate is placed inside the tunnel. These measured quantities describe the conditions imposed by these grids on the developing boundary layer over the plate after its installment in the test section. The normalized mean velocity profile in figure 2(a) shows nearly uniform variation for the uniform grid, whereas the velocity profile for the non-uniform grid shows a increasing trend, although the difference is small after the plate leading edge. Here, the mean velocity, $U$, and the root-mean-squared velocity, $u_{rms}$, are normalized by the center-line velocity, $U_c$, measured at $y = 0$ location. The variation in the mean velocity for the non-uniform grid produces a mean shear in the freestream which in turn keep alive the turbulence production, and thereby the turbulence produced by the non-uniform grid is comparatively more active. The variation of $u_{rms}/U_c$, the integral length scale, $\Lambda$ and the Taylor micro scale, $\lambda$, is shown in figures 2(b), (c) and (d), respectively, for both the grids. One may notice that the values of these parameter in the working side of the plate are nearly of same magnitude.

Figure 3. Mean (a) and $u_{rms}$ (b) velocity profiles in the boundary layer, for the uniform grid at $x = 300, 400, 500, 600, 700$ mm. Mean (d) and $u_{rms}$ (e) velocity profiles, for the non-uniform grid at $x = 250, 300, ..., 1250$ mm. Comparison with the non-modal theory of Luchini [14], for uniform (c) and non-uniform (f) grids. Solid line in (a) & (d) corresponds to the Blasius profile.

The boundary layer flow, subjected to the above flow condition (figure 2), was measured on the flat plate after placing it at $y=0$ location in the tunnel. Figures 3(a) and (d) show the mean velocity profiles in the boundary layer measured at different $x$ locations, for the uniform and the non-uniform grids, respectively. The Blasius profile is also shown in these figures for comparison purpose. We may note that the mean and the $u_{rms}$ velocities in the boundary layer are normalized by the boundary layer edge velocity, $U_e$, and the displacement thickness, $\delta^*$, is estimated based on the edge velocity. The $u_{rms}$ velocity profiles normalized by $U_e$ and $u_{rms, max}$ are shown in figures 3(c-d) and (e-f), respectively, for the uniform and the non-uniform grids. Figures 3(c) and (f) show that the $u_{rms}$ distribution compares well with the optimal perturbation theory of Luchini [14].

The variation of $u_{rms, max}^2/U_e^2$ with the streamwise distance is shown in figure 4, for both the grids. A linear growth region can clearly be seen in this figure, for both the grids. This is similar to the measurements by Matsubara & Alfredsson [1]. However, we find that the growth rate is higher for the non-uniform grid compared to the uniform grid.

The boundary layer transition is often quantified by flow intermittency, which indicates the fraction of time a flow resides in turbulent state at a spatial location. Here, we use the 'Dual
Figure 4. Growth of disturbance energy inside the boundary layer. □, Uniform grid; ■, Non-uniform grid

Figure 5. Intermittency for uniform grid (unfilled symbol), and non-uniform grid (filled symbols). (a) At $x = 700$ mm for $U_e = 7$, 8, and 9 m/s. (b) At $x = 550$ mm (triangle), and $x = 700$ mm (left triangle) location, for $U_e = 7$ m/s.

Slope Method’ of Kuan and Wang [15] for estimating the flow intermittency. Briefly, a double derivative of the velocity signal is used as a criterion function. After estimating intermittency with various threshold value of the double derivative function, a plot of intermittency vs the double derivative is obtained, and the curve shows a sharp change in the slope when plotted in a semi-log graph. By fitting two straight lines for these two regions, an intersection point is found which corresponds to the actual estimated intermittency value. The intermittency plots at $x = 750$ mm for three velocities, i.e. 7, 8 and 9 m/s are compared for both the grids. It is clearly seen in figure 5(a) that the value of intermittency function for the non-uniform case is always greater than the uniform grid for a corresponding velocity. The intermittency comparison at same velocity but at different streamwise locations also shows that the flow intermittency is higher for the non-uniform grid, as may be seen in figure 5(b). This again confirms that the presence of shear increases the turbulent activity in the freestream.

PIV measurements have been carried out mainly to identify the spanwise flow structures in the boundary layer. The secondary instabilities, as mentioned in the introduction, can clearly be seen in figure 6. These are distinguished as sinuous and varicose modes depending on the nature of streak oscillation. This confirms that the nature of transition is the same for both the grids, while the non-uniform grid only accelerates the transition process.

4. Summary and concluding remark
Bypass transition scenario under a stream with and without shear in the incoming flow is experimentally investigated using two parallel rod grids. For both the cases, measurements are carried out at the same rotational speed of the tunnel motor. Transverse distribution of the streamwise mean velocity at $x = 0$, without the flat plate inside the tunnel, reveals a moderate shear profile for the non-uniform grid and a nearly uniform velocity profile for the uniform grid. The $u_{rms}$ values and the length scales in the test section are also found to be nearly equal for
Figure 6. Sinuous (a) and varicose (b) instabilities, for the uniform grid. Sinuous (c) and varicose (c) instabilities, for the non-uniform grid. Origin is at (x, y, z)=(700 mm, 2.5 mm, 0 mm).

both grids in the working side of the flat plate. Boundary layer measurements over the flat plate revealed similar flow characteristics reported in the literature \[1\]. The wall normal distribution of the normalized $u_{rms}$ profile follows the non-modal theory of Luchini \[14\], for both the cases. The linear growth rate of the disturbance energy and the flow intermittency levels are found to be higher, for the non-uniform grid case (see figure 5), although similar secondary instability features are seen in the spanwise PIV realizations for both the grids (see figure 6). This is perhaps because of the fact that shear in the freestream contributes to turbulence production, however small it may be, and enhances the turbulent activity in the freestream. This enhanced turbulent activity in turn increases the generation of instability wave packets in the boundary layer, which enhance the energy growth rate and the flow intermittency.

References

[1] Matsubara M and Alfredsson P H 2001 J. Fluid Mech. 430 149–169
[2] Jacobs R G and Durbin P A 2001 J. Fluid Mech. 428 185–212
[3] Fransson J H M, Matsubara M and Alfredsson P H 2005 J. Fluid Mech. 527 1–25
[4] Mandal A C, Venkatakrishnan L and Dey J 2010 J. Fluid Mech. 660 114–146
[5] Andersson P, Brandt L, Bottaro A and Henningson D 2001 J. Fluid Mech. 428 29–60
[6] Asai M, Minagawa M and Nishio M 2002 J. Fluid Mech. 455 289–314
[7] Brandt L, Schlatter P and Henningson D S 2004 J. Fluid Mech. 517 167–198
[8] Mans J, Kadijk E C, de Lange H C and van Steenhoven A A 2005 Exp. Fluids 39 1071–1083
[9] Schlatter P, Brandt L, de Lange H C and Henningson D S 2008 Phys. Fluids 20 101505–1–101505–15
[10] Hanson R E, Buckley H P and Lavoie P 2012 Experiments in fluids 53 863–871
[11] Saric W S, Reed H L and Kerschen E J 2002 Annual review of fluid mechanics 34 291–319
[12] Kurian T and Fransson J H M 2009 Fluid dynamics research 41 021403
[13] Lourenco L M and Krothapalli A 2000 TRUE resolution PIV: a mesh-free second order accurate algorithm 
Proceedings of the International Conference in applications of lasers to fluid mechanics, Lisbon, Portugal
[14] Luchini P 2000 J. Fluid Mech. 404 289–309
[15] Kuan C L and Wang T 1990 Experimental Thermal and Fluid Science 3 157–173