Experiments on effective tripping device in a zero pressure gradient turbulent boundary layer

Rengasamy K, Alakesh Ch. Mandal
Department of Aerospace Engineering, Indian Institute of Technology Kanpur, Kanpur, Uttar Pradesh, India
E-mail: alakeshm@iitk.ac.in

Abstract. Laminar-turbulent transition for flow over a flat plate can artificially be excited by introducing a tripping device. This will promote early transition in the boundary layer; hence a turbulent boundary layer can be realized at low Reynolds number. In this work, we consider three different types of tripping device, i.e., a circular rod, a square rod and a zigzag trip. Height of these three trips has been maintained same, i.e. 2 mm. Hotwire measurements have been carried out at several streamwise locations behind these trips. Measured flow characteristics behind these tripping devices have been presented in terms of recently suggested diagnostic plots along with the streamwise normal stress scaled by inner variables, and an effort has been made to characterize the best tripping device.

1. Introduction
A laminar boundary layer over a flat plate is often tripped to promote early transition-to-turbulence in the boundary layer. This process of promoting early transition-to-turbulence by introducing a tripping device in the boundary layer is known as boundary layer tripping. It is also used to prevent flow separation and to reduce drag in bluff bodies. Boundary layer tripping can be done by various methods such as vibrating ribbons, blowing/suction through walls, passive roughness elements on the wall. Various tripping devices can be used to achieve fully turbulent flow. For example, Elsinga and Westerweel [1] have carried out measurements using zigzag trip. Height of the zigzag trip used was 1.6 mm, which corresponds to the critical Reynolds number of 200. They have chosen the spanwise wavelength for the zigzag trip to be 6 mm, as suggested by Andersson et al. [2]. They reported hairpin like structures due to spanwise vortices behind the trip, and streaks in the separated flow region due to waviness in the spanwise vortices. Undulating spanwise vortices from the shear layer separating from the trip were seen in their instantaneous flow measurements. They also reported that the spanwise vortices could be seen in cylindrical wire, as well, but at a higher Reynolds number than zigzag trip. Adrian et al. [3] studied hairpin vortices in the outer region of the turbulent boundary layer. In their experiments, they carried out measurements for three different Reynolds number for flow over a flat plate. They used a circular trip of diameter 4.7 mm in all three cases. For their measurements at $Re_\theta = 2370$ and 6845, they placed the trip at 110 mm from the leading edge. Based on their data for these two Reynolds numbers, the estimated boundary layer thicknesses ($\delta$) based on the Blasius boundary layer are found to be 3.4 mm and 2 mm at the trip location, respectively. For $Re_\theta = 930$, trip wire placed at 1520 mm from the leading edge which corresponds to $\delta = 19.4$
mm. This shows that the ratio $k/\delta$ (trip height/boundary layer thickness) is 1.4 and 2.35 for $Re_\theta = 2370$ and 6845 cases, respectively. Even though the trip height is higher than the boundary layer thickness, they mentioned that there is no discernible differences in the boundary layer structure from the PIV measurements that they carried out without the trip.

Comparing a wide range of low Reynolds number data from the literature along with their simulated data, Schlatter and Örlü [4] found considerable differences in the boundary layer parameters, such as skin-friction coefficient, shape factor and also in the mean and fluctuation profiles. However, they speculated that these differences might be from the simulation set up like inflow conditions, turbulence generation and boundary conditions. Schlatter and Örlü [5] spent an effort to explain the reason for differences in the boundary layer parameters given in Schlatter and Örlü [4]. They found that the upstream flow conditions and the tripping effects are main reasons for the differences in the boundary layer integral properties. They suggested that the upstream memory due to the presence of tripping device can be removed if the transition is initiated at the Reynolds number range of $Re_\theta < 300$, and no differences in the flow properties due to the tripping effects could be seen in the boundary layer for $Re_\theta > 2000$. Hutchins [6] recommended some caution remainder for using tripping devices in transition to turbulent boundary layer. He suggested that for flow to become fully turbulent, trip should be introduced inside the boundary layer. He also recommended that further work is needed for over-stimulating case where upstream velocity to the trip is increased.

In this work, three different tripping devices are used to excite early transition in the boundary layer, and the measured data behind these trips are utilized to find the effective tripping device for a turbulent boundary layer.

2. Experimental setup

![Figure 1. A simple sketch of the low turbulence and low-speed wind tunnel.](image)

The experiments reported in this work were carried out in the low turbulence wind tunnel available at the low speed aerodynamics laboratory, Indian Institute of Technology, Kanpur, India. A simple sketch of this tunnel is shown in figure 1. It is an open suction type tunnel with a test section of length 3000 mm and 610 mm $\times$ 610 mm square cross section. The freestream turbulence level in the test section estimated based on the streamwise fluctuating velocity is about 0.1 % in the bandwidth of 2 Hz to 3 kHz. The contraction ratio of the tunnel is 16:1. The flat plate used for the measurements is 12 mm thick, 610 mm in width and 2000 mm in length. The leading edge of the plate is an asymmetrical modified super elliptic leading edge, which was designed following the work of Hanson et al. [7]. This leading edge is chosen because it reduces the receptivity of the boundary layer to disturbance by eliminating the leading edge and flat plate juncture curvature discontinuity and also maintains a larger region of zero pressure gradient over the working section of the plate. The flat plate is mounted horizontally at the mid-plane of the tunnel test section. The distance from the starting of the test section to the leading edge of the flat plate is 1250 mm. Tripping devices have been attached over the upper side of the plate at a distance of 150 mm from the leading edge.
Three different trips which are used in the present experimental work are circular, square and zigzag trip. A schematic of the three different trips, i.e. circular, square and zigzag trip, are shown in figure 2. All these trips are made of brass material. Spanwise wavelength of the zigzag trip is 7.5 mm. This has been chosen based on the suggestion of Andersson et al. [2]. Circular and square trip of 2 mm diameter and thickness, respectively, have been used directly for the measurements. The zigzag trip has been made from a rectangular plate of 2 mm thickness. Height of these trips has been chosen such that the Reynolds number based on the trip should be greater than the minimum critical Reynolds number, $Re_c$. This has been done to make sure that the flow becomes turbulent in the nearest downstream location behind the trip. Different critical Reynolds number values are suggested in the literature. For example, Gibbings [8] suggested that the critical Reynolds number based on the trip height and the freestream velocity should be more than 826, i.e. $\frac{U_\infty k}{\nu} \geq 826$, whereas Braslow and Knox [9] suggested that the critical Reynolds number based on the trip height and the local velocity at the height of the trip has to be more than 600, i.e. $\frac{U_k k}{\nu} \geq 600$; here $U_\infty$ and $U_k$ denote the freestream velocity and the velocity at the height of the trip location in the undisturbed laminar boundary layer, respectively, whereas the wire diameter/thickness and the kinematic viscosity are denoted by $k$ and $\nu$, respectively. For our all three trips, the value of the first critical Reynolds number, $\frac{U_\infty k}{\nu}$, is found to be 1032, and the second critical Reynolds number, $\frac{U_k k}{\nu}$, is found to be 973; here $U_\infty$ is same for all three trips. However, both $Re_c$ values are above the critical values suggested by these authors. Moreover, we find that the Reynolds number based on the momentum thickness and the freestream velocity velocity, $Re_\theta$, is 175 at the trip location. This value is less than 300, which is suggested by Schlatter and Örlü [5].

Measurements in the boundary layer have been carried out using a hotwire anemometry system procured from the Dantec Dynamics. Data acquisition have been carried out using the Dantec multichannel CTA system along with a 16 bit NI-6034E data acquisition card and the Labview software. The maximum frequency response attainable with the system is 10 kHz. The sensor is made of 5 $\mu$m diameter tungsten wire soldered between the two prongs. The hotwire is calibrated with the aid of a Pitot-static probe connected to a digital manometer and using the King’s law fit. Hotwire measurements were carried at a sampling rate of 6 kHz with a low pass filter of 3 kHz and without any gain.

3. Results and Discussions
Placing the tripping devices at $x = 150$ mm from the leading edge of the flat plate, boundary layer measurements have been carried out at eight different streamwise locations behind the
Table 1. Details of boundary layer parameters measured at a fixed $U_\infty$ for all three trips; ‘cir’, ‘sqr’ and ‘zz’ refer to the circular, square and zigzag trip, respectively.

| Trip | $x_1$(mm) | $Re_\theta$ | $\delta$(mm) | $\delta^*$$(mm)$ | $\theta$(mm) | $H$ | $C_f \times 10^5$ | $u_\tau$(ms$^{-1}$) |
|------|----------|------------|-------------|----------------|-------------|-----|----------------|------------------|
| cir  | 250      | 716        | 12.97       | 2              | 1.37        | 1.46| 508            | 0.408            |
| sqr  | 250      | 639        | 13.26       | 1.8            | 1.22        | 1.48| 530            | 0.419            |
| zz   | 250      | 803        | 13.49       | 2.3            | 1.55        | 1.47| 468            | 0.388            |
| cir  | 400      | 793        | 14.97       | 2.31           | 1.56        | 1.48| 483            | 0.387            |
| sqr  | 400      | 742        | 13.16       | 2.18           | 1.47        | 1.48| 486            | 0.386            |
| zz   | 400      | 937        | 16.09       | 2.68           | 1.83        | 1.47| 467            | 0.384            |
| cir  | 600      | 1030       | 19.42       | 2.97           | 2.02        | 1.47| 437            | 0.369            |
| sqr  | 600      | 993        | 17.07       | 2.85           | 1.95        | 1.46| 444            | 0.372            |
| zz   | 600      | 1102       | 18.73       | 3.12           | 2.15        | 1.45| 426            | 0.367            |
| cir  | 1000     | 1364       | 22.57       | 3.81           | 2.67        | 1.43| 407            | 0.357            |
| sqr  | 1000     | 1344       | 23.33       | 3.85           | 2.67        | 1.44| 404            | 0.35             |
| zz   | 1000     | 1398       | 23.11       | 3.96           | 2.76        | 1.44| 402            | 0.352            |

three trips, i.e. at $x_1 = 40$ mm, 100 mm, 170 mm, 250 mm, 400 mm, 600 mm, 800 mm and 1000 mm, where $x$ and $x_1$ are the streamwise distances from the leading edge of the plate and from the location of the trip, respectively. However, measured data at $x_1 = 250$ mm, 400 mm, 600 mm and 1000 mm are only presented in this paper, for brevity. Boundary layer parameters at those locations are summarized in table 1. Here, the Reynolds numbers are based on the momentum thickness, $\theta$; boundary layer and displacement thicknesses are denoted by $\delta$ and $\delta^*$, respectively; shape factor, skin-friction and the friction velocity are denoted by $H$, $C_f$ and $u_\tau$, respectively. We may note that the skin-friction, $C_f$, has been estimated using the Clauser chart method [10]. Accurate wall identification has been done using the local peak probability distribution function method proposed by Orlu et al. [11]. For the present data, this method is also discussed in details in [12]. In the following, we also compare our data with the available direct numerical simulation (DNS) data of Schlatter and Örlü [4].

Our measured data are presented in the form of a diagnostic plot proposed by Alfredsson et al. [14] in figure 3, for all the three tripping devices. Here, we plot $u_{rms}/U_\infty$ against the normalized local mean velocity $U/U_\infty$. Figures 3 (a), (b), (c) and (d) show the comparison of our experimental data at $x_1 = 250$ mm, 400 mm, 600 mm and 1000 mm, respectively, with the DNS data from Schlatter and Örlü [4] corresponding to $Re_\theta = 1000$ and 1410. At $x_1 = 250$ mm, data for the zigzag trip compare well with the DNS data compared to the data of other trips. As we go downstream, our measured data closely compare with the DNS data, for all the three trips. This indicates that early turbulence can perhaps be achieved using a zigzag trip. We may mention that diagnostic plot has also been used for checking the quality of our measured data in the near wall locations, as suggested by Orlu et al. [11].

Based on the diagnostic plot, Alfredsson et al. [14] suggest another plot where $u_{rms}/U_\infty$ is normalized by the local mean velocity $U$ and plotted against $U/U_\infty$. The parameter $u_{rms}/U_\infty$ is called as the local $TI$ which is found to increase with decreasing value of $U/U_\infty$. Local $TI$ is shown in the figure 4. Similar to the figure 3, zigzag trip data collapsed with the reference data for $x_1 = 250$ mm downstream location. Our measured data for all three trips correspond to the reference data well, as we go downstream location.

The wall-normal distribution of the streamwise component of the normal Reynolds stresses is shown in figure 5, for all the three trips; here the normal stress is normalized by the friction velocity, $u_\tau$. De Graaff and Eaton [15] suggested that the peak Reynolds stress in inner coordinates occurs at $y^+ = 14$, as is also seen in our present data. Although, figures 3 and 4 show
that our measured data collapse with the reference data from $x_1 = 400$ mm, the normal stress in inner coordinates, as shown in figure 5, indicates that the flow is yet to be fully turbulent even at $x_1 = 1000$ mm.
Figure 5. Streamwise component of the normal Reynolds stresses in inner coordinates. (a) $x_1 = 250$ mm. (b) $x_1 = 400$ mm. (c) $x_1 = 600$ mm. (d) $x_1 = 1000$ mm

4. Conclusion

To achieve turbulent boundary layer over a flat plate at a low Reynolds number, various tripping devices have been used. Measured data are presented at various downstream locations, i.e. from $x_1 = 40$ mm to 1000 mm behind a particular trip. While comparing the measured data with the available data in the literature, the present diagnostic and local TI plots (see figures 3 and 4) show that the flow may be considered to be fully turbulent at $x_1 = 1000$ mm. On the other hand, the wall-normal distribution of the streamwise component of the normal Reynolds stresses (figure 5) shows that the flow is yet to be fully turbulent, as compared to the reference data. This may be due to the memory effect of the tripping devices, as the Reynolds numbers, $Re_\theta$, in the present measurements are less than the value of 2000. Because, in their DNS simulation, Schlatter and Örlü [5] found that the upstream memory effect due to a tripping device may not be there if the Reynolds number, $Re_\theta$, is more than 2000. Although, closer to the trip location, comparatively better turbulence could be achieved using the zigzag trip with respect to the other trips, there may not be any significant effect of different trips if someone measures turbulent quantities far downstream, i.e. more than 1000 mm downstream from the trip location for the present freestream velocity.

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