Experimental Study on the Wake Characteristics of Vane-Type Vortex Generators in a Flat Plate Turbulent Boundary Layer

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Abstract: - An experimental investigation was conducted to identify the wake characteristics downstream of various vane-type vortex generators using the stereoscopic particle image velocimetry over turbulent flat plate boundary layer. We considered three different planform shapes of vortex generator: triangular, trapezoidal, and rectangular shape. The height of the generator was chosen to be about the boundary layer thickness at the position of its installation. Two different lengths of the generator were chosen: two and five times the height. Wake measurements were carried out at three angles of attack for each configuration. Wake characteristics for each case such as overall vortical structure, vorticity distribution, and location of vortex center with downstream distance were obtained from the PIV data, and are compared one another. Wake characteristics, as expected, were found to vary strongly with the geometry and angle of attack so that no general tendency could be deduced.

Key-Words: - Vortex Generator, Wake Characteristics, Stereoscopic-PIV, Wind Tunnel, Vorticity

1 Introduction

Vortex generator, as is well known, is a typical passive flow control device and is used to delay flow separation in many engineering applications because of its geometrical simplicity and high performance as reviewed in Lin [1]. A study about vortex generator was first carried out by Taylor [2]. He applied the vane-type vortex generators having the height of the order of the boundary layer thickness and found the near-wall momentum increase through momentum transfer from outer flow to near wall region. Many experimental and computational studies with vortex generators were carried out since Taylor.

The height of the vortex generator is an important design parameter. The vortex generator whose height (h) is around boundary layer thickness is referred to as conventional vortex generator [1-4]. The vortex generator whose height (h) is shorter than local boundary layer thickness (\( \delta \)) is referred to as low-profile vortex generator or micro vortex generator [4-8]. It was shown that the low-profile vortex generator could also be effective in spite of its shorter height for flow control [1].

The shape of the vortex generator is obviously an important factor as well. There are various vortex generator shapes; triangular, trapezoidal, rectangular, wishbone and doublet, etc. Klausmeyer et al. studied the flow physics of trapezoid-wing type vortex generators on an airfoil and measured velocity field downstream of the vortex generators with laser doppler velocimetry [5]. Ashill et al. carried out experiments on wedge and triangular vane types of vortex generators of h/\( \delta \) = 0.3 on a bump [6]. Yao et al. measured flow field downstream of a single rectangular vortex generator using stereoscopic particle image velocimetry (Stereo-PIV herein after) [4]. Angele and Muhammad-Klingmann performed experiments over a separating boundary layer using rectangular vortex generator with three different heights and streamwise positions [9]. Lin et al. conducted experimental study to evaluate boundary layer separation control using triangular and trapezoidal shapes of small surface-mounted vortex generators on a high lift airfoil with a leading edge slat and a flap [10]. Studies on wishbone and doublet vortex generator were also conducted [11]. Godard and Stanislas carried out parametric study (angle of attack, length, transverse distance, etc.) of vortex generators and tested both co-rotating and counter-rotating configurations [12]. They found that triangular vortex generators produced a significant drag improvement compared to rectangular vortex generators. Velte et al. measured a flow field downstream of a row of triangular vortex generators mounted on a bump [13]. Significant reduction of reversed flow in separated region of the bump was observed when counter-rotating vortices were generated. Stillfried et al. carried out computations of
flow on a bump with various rectangular vortex generator arrays in adverse pressure gradient boundary layer flow [14]. They found that vortex generators should be placed some distance upstream of the separation bubble location.

As mentioned above, previous studies were performed for the various shapes of the vortex generator. The representative shapes of the vane-type vortex generator were triangular, trapezoidal, and rectangular. Previous studies mainly focused on aerodynamic control efficiency such as drag reduction, separation delay etc. Studies on the wake characteristics are somewhat rare.

To examine the effect of various vane-type vortex generators over a flat plate turbulent boundary layer, the present study was carried out. Stereo-PIV measurements in cross flow planes downstream of various vane-type vortex generators were conducted to investigate the wake characteristics.

2 Experimental Setup

2.1 Test facility and test conditions

Experiments were performed in the subsonic wind tunnel of the Korea Aerospace Research Institute (KARI). The wind tunnel has a test section of 1.0 m width, 0.75 m height and 2.0 m length. The streamwise turbulence intensity of the KARI wind tunnel was 0.06 %. Experiments were conducted at the freestream velocity of 10 m/s.

The flat plate on which vane-type vortex generator was installed was made of aluminum and was 990 mm wide, 1866 mm long, and 12 mm thick as sketched in Fig. 1 where the coordinate system adopted in this study is also shown. The flat plate was mounted at the center line of the wind tunnel test section. The leading edge of the flat plate was of a super-ellipse shape to prevent the leading edge separation [15].

The flat plate surface was covered with the black thin film to reflect the laser in one direction but not to allow the reflected laser into the camera [16]. Average surface roughness of the flat plate was below 0.05 μm. Prior to the flow field measurement downstream of the vane-type vortex generator, the velocity profile on the flat plate was first measured by using 2-dimensional particle image velocimetry (2D-PIV).

The velocity profile at 750 mm from the leading edge was measured. The velocity profile without the trip strip was found to be that of the Blasius profile. The flat plate boundary layer was tripped to generate the turbulent boundary layer. The details of boundary layer characteristics at the generator fixing point are summarized in Table 1.

Table 1 Boundary layer properties at the fixing point

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Turbulent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boundary layer thickness</td>
<td>15 mm</td>
</tr>
<tr>
<td>Displacement thickness</td>
<td>2.54 mm</td>
</tr>
<tr>
<td>Momentum thickness</td>
<td>1.87 mm</td>
</tr>
<tr>
<td>Shape factor</td>
<td>1.36</td>
</tr>
<tr>
<td>Reθ</td>
<td>1310</td>
</tr>
</tbody>
</table>

2.2 Vortex generator configurations

In this study, we considered three different planform shapes of vortex generator: triangular, trapezoidal, and rectangular shape as shown in Fig. 2 where test conditions are given. The height of the vortex generator was set to be the same as the boundary layer thickness at the installation location of 750 mm (see Fig. 1). The turbulent boundary layer thickness, δ, at the fixing point position were approximately 15 mm. Godard and Stanislas recommended that a minimum value of the generator length was two times the height [12]. Thus, we selected one length to be the two times the height. To look into the effect of length, we also chose a much longer length of five times the height.

![Flow Direction](image)

Fig. 1 Schematic of geometry and coordinate system of flat plate with super ellipse leading edge

![Vortex Generator](image)

Fig. 2 Geometries of vortex generators and test conditions
To investigate the influence of the angle of attack, three angles of attack (10°, 15°, and 20° angle of attack) were selected. To generate angle of attack, the vortex generator is rotated about the fixing point which is positioned at 2.5 mm ahead of the trailing edge.

2.3 Stereo-PIV measurement
Stereo-PIV was used for the wake measurements. Fig. 3 is a schematic of the experimental setup. As briefly illustrated in Fig. 3, two high resolution CCD cameras whose angle with respect to the laser light sheet was 45 degrees were placed at both sides of the test section at the same distance from the laser light sheet. A 200mJ dual-head Nd:YAG laser of the QUANTEL Company was used. This provided the laser of 532nm wavelength. The laser was illuminated vertically in the x-y plane. As mentioned already, the surface of the flat plate was covered with black thin film not to allow the reflected laser into the CCD cameras.

PIV images were acquired using two high resolution (2048 x 2048 resolutions) cameras. As shown in Fig. 3 (b), two CCD cameras were installed such that each could be moved freely for necessary alignment. Geared head of the Manfrotto Company was used for horizontality adjustment of the camera and lens. The camera tilt angle was adjusted by the scheimpflug [17]. To supply the tracer particles, Laskin nozzle using DEHS-oil was installed at the test section breather, far downstream of the vortex generator.

The average diameter of the particles was about 1μm. The pulse generator of the BNC-555 model was used for synchronization between the laser and CCD cameras. Stereo-PIV time delay of 10μs between two images was decided by considering both the free stream velocity and the field of view. By employing a system of mirrors, convex lens and cylindrical lens, the laser light sheet was generated over the flat plate. PIVview 3C program was used for image processing which was developed by PIVTEC GmbH and the German Aerospace Center’s (DLR) PIV group [18].

Stereo-PIV measurements were performed at 7 downstream stations whose positions are listed in Table 2. In Table 2, Δz is the distance of the measurement station from the trailing edge of the vortex generator. Yao et al. showed that the vorticity contours exhibited a fairly concentrated vortex structure within Δz/h ≤ 20 [4]. We thus selected these 7 stations within Δz/h < 20.

<table>
<thead>
<tr>
<th>Station</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Δz/h</td>
<td>1.8</td>
<td>3.2</td>
<td>4.5</td>
<td>7.2</td>
<td>11.2</td>
<td>15.2</td>
<td>19.8</td>
</tr>
</tbody>
</table>

Prior to the wake measurement, calibration was performed at each measuring station. In this study, the magnification factor for the measuring area was 24 pixels/mm at each measuring station and the measuring area was approximately 65 mm wide and 55 mm high. After calibration, one hundred image pairs were acquired at each measuring station and averaged for mean values.

The spatial resolution which affects the measurement result is defined by the interrogation window and overlap size. To estimate the effect of the spatial resolution, the image calculation was performed with respect to the various interrogation window and overlap size. First, the interrogation window size of 48 × 48 pixels was chosen through 2D displacement histogram analysis. Secondly, the overlap size was varied from 0% to 91%, and 75% overlap size was selected. Therefore, the 48 × 48 pixels and 75% overlap size implies that we have one vector for the area of 0.50 mm × 0.50 mm.

3 Experimental Results

3.1 Mean streamwise flow
Fig. 4 shows mean streamwise velocity contours at three downstream stations of the three vortex generators at 10° angle of attack. The velocity contours are those viewed toward the upstream direction (see Figs. 1 and 2). The vortex generator...
projected onto each measurement station is also shown for convenience. We comment here that the height of the vortex generator was 15 mm. The formation of the streamwise vortex is clearly seen in Fig. 4. The pressure side of the vortex generator corresponds to the positive coordinate side of Fig. 4. Thus, the rotational direction of the streamwise vortex is counterclockwise as easily expected in these figures. Due to this vortex, the flow is swept upward in the pressure side region and downward in the suction side region resulting in greater streamwise mean velocity in the suction side.

3.2 Streamwise vortex structure identification

Vortical structure, as is well known, is not easy to identify clearly. There are several methods to identify the vortex from the flow field data as reviewed in Jiang et al. [19]. In the present study, we adopted the $\lambda_2$ method suggested by Jeong and Hussain [20]. The $\lambda_2$ denotes the eigenvalues of the velocity gradient tensor. The value of the $\lambda_2$ is negative within the vortex core [20]. The center of the vortex was located by using the maximum vorticity method [4, 19, and 21]. The streamwise vorticity and $\lambda_2$ operator were obtained by using PIVview 3C.

The streamwise vorticity in the present study (see Fig. 1) is given by. Fig. 5 illustrates vortical structures of the present work identified through the $\lambda_2$ method at a specific case.

Fig. 4 Mean streamwise velocity contours (h/δ = 1.0, l/h = 5, and α = 10 deg.)

Fig. 5 Streamwise vortex shape by using $\lambda_2$ contour plot (h/δ = 1.0, l/h = 5, α = 10 deg., and Δz/h = 1.8)

Line: $\lambda_2$ = 0, Point: vortex center
3.3 Vorticity distribution

Fig. 6 shows the streamwise vorticity distributions of three vortex generator at a downstream station ($\Delta z/h = 1.8$). Vorticity strength variations along the lateral and normal lines passing through the vortex center are illustrated. Fig. 6 demonstrates clearly the effects of the generator shape at this angle of attack. The vortical structure of the rectangular generator is most strongly generated, followed by the trapezoidal generator and the triangular generator.

Fig. 6 also shows that the differences of the vortex center location of the three vortex generators. We see that the lateral position of the streamwise vortex at $\Delta z/h = 1.8$ is in the left side of the vortex generator from Fig. 6 (a). From Fig. 6 (b), we confirm that the vertical positions of the vortex centers are all below the tip of the generators. We also see that the vertical position of the vortex center of the trapezoidal generator is almost equal to the case of the rectangular generator and that of the triangular generator is much lower than these two cases. We will discuss later how these positions vary with downstream stations.

![Streamwise vorticity distributions](image)

**Fig. 6** Streamwise vorticity distributions along the lateral and vertical lines ($h/\delta = 1.0$, $l/h = 5$, $\alpha = 10$ deg., and $\Delta z/h = 1.8$)

Table 3 lists the streamwise peak vorticities of the three shapes of vortex generator at $\Delta z/h = 1.8$. When $l/h = 2$, we see that the rectangular generator at all angles of attack produces the largest peak vorticity. However, when $l/h = 5$, we see that this is not the case. At $\alpha = 10^\circ$, the rectangular generator produces largest peak vorticity. At $\alpha = 15^\circ$, the trapezoidal generator produces the largest peak whereas the triangular generator does at $\alpha = 20^\circ$. For the rectangular and the trapezoidal generator cases, we also see that the peak vorticity at $\alpha = 15^\circ$ is greater than that at $\alpha = 20^\circ$. We conjecture that these are related to complicated separated flow structures around the vortex generators as commented in Yao et al. [4].

To examine the development properties of the streamwise vortex with downstream distance, variations of the peak and the average (avg.) vorticity with $\Delta z/h$ are depicted in Figs. 7 and 8. We recall here that $\Delta z$ is the distance between the measuring station and the trailing edge of the vortex generator. The avg. vorticity indicates the area averaged value of the streamwise vorticity in the negative $\lambda_2$ region. The streamwise peak vorticities downstream of the generator were divided by the peak vorticity at $\Delta z/h = 1.8$. Thus, at $\Delta z/h = 1.8$, $\omega/\omega_{max} = 1.0$. Figs. 7 and 8 demonstrate evidently the effects of generator length and angle of attack. We can hardly deduce any general tendency. We note from Figs. 7 and 8 that vortex decay characteristics depends strongly on the length and shape of the generator. Figs. 7 (a), 7 (b) and 8 (a), 8 (b) illustrate that the vortex of the rectangular generator decays much faster in these cases, and Figs. 7 (e), 7 (f) and 8 (e), 8 (f) show that the vortex of the triangular generator decays much faster in the near wake region. From Fig. 8 (f), we see that even though the largest vorticity was generated

<table>
<thead>
<tr>
<th>Shape</th>
<th>$\alpha$ (deg.)</th>
<th>2h</th>
<th>5h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Triangular</td>
<td>10°</td>
<td>2044.9</td>
<td>2831.2</td>
</tr>
<tr>
<td></td>
<td>15°</td>
<td>2739.9</td>
<td>4711.5</td>
</tr>
<tr>
<td></td>
<td>20°</td>
<td>2740.7</td>
<td>7125.8</td>
</tr>
<tr>
<td>Trapezoidal</td>
<td>10°</td>
<td>1929.4</td>
<td>3330.1</td>
</tr>
<tr>
<td></td>
<td>15°</td>
<td>2496.3</td>
<td>6195.5</td>
</tr>
<tr>
<td></td>
<td>20°</td>
<td>2356.0</td>
<td>5754.1</td>
</tr>
<tr>
<td>Rectangular</td>
<td>10°</td>
<td>5062.7</td>
<td>4451.0</td>
</tr>
<tr>
<td></td>
<td>15°</td>
<td>5455.3</td>
<td>5821.4</td>
</tr>
<tr>
<td></td>
<td>20°</td>
<td>2903.2</td>
<td>5705.7</td>
</tr>
</tbody>
</table>
by the triangular generator (see also Fig. 7 (f) and Table 3), the vorticity corresponding to the rectangular generator is much longer at further downstream stations ($\Delta z/h > 5$).

At $10^\circ$ and $15^\circ$ angles of attack, we notice that the vorticity strengths for two different lengths at $\Delta z/h = 1.8$ of the rectangular generator remain around the same compared to the other two cases of Table 3 and Fig. 8. However, at further downstream stations, we find that the vorticity strengths are much greater for the cases of the longer generator ($l/h = 5$) of the three generator shapes signifying that the vorticity decay characteristics are strongly affected by the generator length.

Fig. 7 Peak vorticity decay rate of three shapes of vortex generator ($\square$ : rectangular, $\Diamond$ : trapezoidal, and $\Delta$ : triangular generator)
3.4 Vortex path

Fig. 9 shows the lateral and the vertical path of the vortex center for various cases. The lateral position is referenced to the trailing edge location. Positive $\Delta x$ in the figure denotes the distance in the pressure side direction.

The vertical position of the streamwise vortex center is observed to be located in the region between 0.8h and 1.1h at all downstream stations for the cases of the rectangular and the trapezoidal vortex generators and between 0.6h and 0.9h for the triangular case. We see that the vortex of the triangular generator is generated at a considerably lower position than those...
of the other two cases. Compared with the lateral path variation, we see that the vertical paths do not vary much with downstream distance. In all the cases shown, the lateral positions of the vortex center in the near wake region (Δz/h = 1.8) are seen to be located in the suction side. We clearly see that the vortex center moves away from the trailing edge position in the direction of pressure side (Δx direction) with downstream distance as expected in Fig. 9. This reflects a simple fact that the mean flow in the wake is deflected to the right. Obviously, the lateral variation of the vortex center increases with angle of attack as seen in Fig. 9.

In the region very near the wake, we see that the vortex centers in all the cases are located to the left side of the trailing edge (that is, in the suction side of the vortex generator). From the figure, we find that the distance between the centerline and the lateral position is largest in the case of rectangular generator, and shortest in the triangular case. We also see that the vortex center position differences among the three generator shapes for the case of l/h = 5 are greater than those for the case of l/h = 2.

**Fig. 9** The lateral and the vertical path of the vortex center (Δ : triangular, ◇ : trapezoidal, and □ : rectangular vortex generator)
4 Conclusions

Experimental study using stereoscopic-PIV on the wake characteristics of vortex generators over a flat plate turbulent boundary layer was carried out. The triangular, trapezoidal, and rectangular generators of two different lengths at three angles of attack were tested. The tendency of peak vorticity generation in the near wake region for each generator configuration was very sensitive to angle of attack and length of the generator. When $l/h = 5$, the peak vorticity in the near wake of the rectangular generator was largest only at $\alpha = 10^\circ$, and when $l/h = 2$, it was largest at all angles of attack. When $\alpha = 20^\circ$, for the case of $l/h = 5$, the triangular generator produced the largest vorticity. The vorticity decay characteristics with downstream distance also depend strongly on the generator shape and angle of attack. This signifies that the initial peak vorticity strength in the near wake does not imply its strength tendency at further downstream stations.

Trajectories of vortex core (or center) along downstream distance for each case were presented. It was found that the vortex of the triangular generator was formed at lower position than those of the trapezoidal and rectangular generators. But the lateral position of the vortex center of the triangular case was closer to the trailing edge than the other two cases, all of them being located in the suction side in the near wake region.

Acknowledgements:

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References:

[18] PIVview 3C, PIVTEC, Gottingen, Germany; software available at http://www.pivtec.com/