Influence of Planar and Corrugated Sheet on Turbulent Wake behind Flat Plate with Thick Trailing Edge

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Abstract
The present experiments were conducted with a splitter plate and a corrugated sheet, fitted to the trailing edge along the wake center line, as a flow control device. Although the shape of the corrugated sheet changes spanwise, its streamwise length is constant. It is shown by a hot-wire experiment that the characteristics of the wake changes, such as momentum thickness and Reynolds shear stress, depend on the length of the splitter plate. The effects of the corrugated sheet on the wake are found by using a Pitot tube. The development of the wake remarkably changes with wave length and amplitude in addition to the length of the corrugated sheet.

Introduction
The characteristics of the turbulent wake behind a body with flow separation must be clarified in the light of the engineering application. This kind of study will provide useful engineering knowledge for the improvement of flow around airfoils with a blunt trailing edge (e.g., gas turbine blade with film cooling), noise reduction in a wind turbine blade with cut-off trailing edge, or enhancement of turbulent mixing/heat transfer in fluid machinery with flow separation. So far the author has shown that the development of the mean flow and fluctuating velocity field near a thick flat plate are different from that of the flat plate with a thin trailing edge in references [2-4]. These studies are important because they indicate the initial conditions in various fluid-related machinery or equipment (e.g., blade cascades) as well as they give information on flow control near the trailing edge itself.

In reference [2], the author and others investigated the base pressure and the properties in the boundary layer near the trailing edge of a long flat plate (100-h-long, h=thickness of flat plate) by changing the length of the splitter plate, l. The results revealed a remarkable difference in the base pressure between a long flat plate and a short flat plate in the case without the splitter plate, and the effect of l/h on the base pressure coefficient and the mean velocity field was classified into two categories, for the cases of l/h<1 and l/h≧1, respectively. Since the above effect of l/h is closely connected with the vortex structure formed behind the long flat plate, the vortex strength and scale, and its shedding frequency were investigated in reference [3]. Recently, control of turbulent quantities in addition to the mean flow, depending on the value of l/h, were reported in the follow-up paper [4].

In a related study, measurements of symmetric wake of a smooth flat plate 1829-mm-long were presented by Ramaprian, Patel and Sastry [5]. The last 670-mm length of the model was tapered at an included angle of 0.9 deg, and the last 50 mm was filed to terminate in a trailing edge of 1-mm nominal thickness. They showed that evolution of the upstream boundary layers into the classical asymptotic wake occurs in three quite distinct stages.

Tombazis and Bearman [6] investigated the three-dimensional aspects of vortex shedding from a bluff body with wavy trailing edge, and showed that the longest vortex formation length occurs unexpectedly at a valley of the wave. The streamwise length of their model changes spanwise, but its transverse thickness is constant. This is a great difference in shape from our corrugated sheets. Moreover, Werle, Paterson and Presz [7] studied the influence of the rippled trailing edge on the lift-and-drag characteristics of the airfoil and showed higher maximum lift and/or lower drag at high lift. These are one of the flow-control methods called “3D forcing by passive means” in the review article by Choi, Jeon and Kim [1].

In contrast, the fundamental study of a wake with flow separation at the thick trailing edge of a long flat plate or airfoil (friction drag is a major contributor to the total drag) has remained unsolved, unlike many experimental studies of the wake behind bluff bodies (pressure drag is the major parameter). Then, the objective of this work was to investigate whether or not the turbulent wake varies with the use of a planar splitter plate or corrugated sheet, attached to the thick trailing edge on a long flat plate. The effect of the length of the additional plate or sheet on the mean flow and turbulence is also discussed.

Nomenclature

\( u_{rms} \): rms value of streamwise fluctuating velocity \( u \)

\( U \) : local streamwise mean velocity

\( U_\infty \) : freestream velocity of wake

\( U_m \) : reference velocity (at \( x=-1000 \text{ mm}, \ y=150 \text{ mm} \))

\( W \) : velocity defect

\( b \) : full width at half maximum of velocity defect

\( h \) : thickness of flat plate (≈20 mm)

\( l \) : streamwise length of splitter plate/corrugated sheet

\( x \) : streamwise distance from trailing edge

\( y \) : normal distance from wake center line

\( z \) : spanwise distance from plate center

Experimental Apparatus and Techniques

Configuration of Flow Field and Coordinate System

The configuration of the flow field is the same as in our previous paper [2-4]. A wind tunnel of open-circuit type has a 4000-mm-long rectangular working section with an inlet area approximately 560 mm-wide×350 mm-spanwise long. The test section is located downstream of the outlet nozzle. A test flat plate 20-mm-thick (h)×2000 mm-long made of polyvinyl chloride (PVC) is set vertically along the center line of the test section in the front position. Figure 1 shows the schematic flow field (xy plane), test flat plate, coordinate system and
nomenclature. The coordinates of \( x \) and \( y \) are determined as the streamwise distance from the trailing edge and the normal distance from the wake center line of the test flat plate, respectively. To establish a developed turbulent boundary layer, trip wires 1 mm in diameter were placed 100 mm downstream of the leading edge of the test flat plate on both sides of the plate. In order to maintain the constant freestream static pressure along the working section, the sidewalls and flaps, 100- and 200- mm-long, of the test section were adjusted (width of the working section slightly changed along \( x \)). Thus, the freestream zero pressure gradient could be maintained for all experimental conditions. Measurement of the freestream static pressure was conducted with wall static pressure holes (40 holes each) at \( y = 150 \) mm on the lower side wall as shown by the dash-dotted line in figure 1. At the spanwise center (cross section of \( x = 0 \) mm), experiments were made at unit Reynolds number \( U_m / \nu = 9.93 \times 10^5 \text{ m}^{-1} \) \( (U_m \approx 15 \text{ m/s}, \nu \) as kinematic viscosity). The turbulent intensity in the freestream is about 0.2%.

**Splitter Plate and Corrugated Sheet**

A splitter plate (SP) made of stainless steel (2 mm-thick×350-mm-long-spanwise) is set vertically in the center line of the test section just behind the trailing edge of the test flat plate. Since the thickness of the test flat plate, \( h \), is 20 mm, the step height, \( h_s \), formed by the splitter plate, becomes 9 mm. The length of the splitter plate was adjusted \( l = 10, 20, 60 \) and 100 mm \( (l / h = 0.5 \sim 5) \). Four types of corrugated sheet (CS) made of polycarbonate resin/aluminum alloy (2 mm-thick×350-mm-long-spanwise) are set vertically as in the splitter plate. The dimensions of the corrugated sheets are shown in detail in table 1.

<table>
<thead>
<tr>
<th>combercial</th>
<th>self-made (CS(_s))</th>
<th>material</th>
<th>thickness</th>
<th>wave length</th>
<th>amplitude</th>
<th>wave number</th>
</tr>
</thead>
<tbody>
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<td>CS(_p)</td>
<td>CS(_a1)</td>
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<td>32.3 mm</td>
<td>10.3 mm</td>
<td>10.8</td>
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<td></td>
<td>CS(_a2)</td>
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<td>175 mm</td>
<td>20 mm</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>CS(_a3)</td>
<td>aluminum</td>
<td>2 mm</td>
<td>35 mm</td>
<td>20 mm</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>35 mm</td>
<td>10 mm</td>
<td>10 mm</td>
<td>10</td>
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</table>

**Results and Discussion**

**Mean Flow Field**

In this section, we will investigate the development of the mean flow field in the wake behind a long flat plate with a blunt trailing edge in the case with/without the splitter plate. Figure 2 shows the local streamwise mean velocity profiles in the range of \( x / h = 10 \) to 65 with the splitter plate of \( l / h = 0.5 \) to 5. The mean velocity \( U \) on the ordinate are non-dimensionalized with the reference velocity \( U_m \). Normal distance from the wake center line \( y \) on the abscissa is non-dimensionalized with the thickness of the test flat plate \( h \). Figures 3 and 4 show the streamwise variation in the maximum velocity defect \( W_0 \), the full width at half maximum of velocity defect \( b \) and the momentum thickness \( \theta \), respectively.

First, \( W_0 \) in the vicinity of the trailing edge increased with increasing the length of the splitter plate, especially in the case of \( l / h \geq 3 \). In the downstream area after \( x / h = 60, W_0 \) converged to less than 20% of freestream velocity \( U_m \) independent of the

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**Figure 1. Configuration of flow field and coordinate system.**

**Figure 2. Mean velocity profiles.**

Table 1. Dimensions of corrugated sheets.
As seen in figures 2 to 5, the properties in the mean flow field without splitter plates (kept increasing the converging tendency of however, especially in the case of installation of the splitter plate of $l/h=0.5$ to 5. The rms values of the streamwise fluctuating velocity $u_{rms}$ on the ordinate are non-dimensionalized with the reference velocity $U_{ref}$ as in figure 2, $u_{rms}/U_{ref}$ in the vicinity of the trailing edge decreased with increasing the length of the splitter plate. At $x/h \approx 3.5$, distribution of $u_{rms}/U_{ref}$ in the case of $l/h>1$ is roughly the same as with that obtained on the flow behind the sharp trailing edge (their thickness of the fore-body is 19 mm) [5].

The Reynolds shear stress is given by using the time average of the product of streamwise- and normal-fluctuating velocity $u$ and $v$, as $\langle uv \rangle$. As shown in figure 7, the normalized Reynolds shear stress $G$, equation (1), in the vicinity of the trailing edge remarkably decreased with the splitter plate of $l/h>1$.

安装了隔板后，第二，$b$ 增加了流线方向的速度，但取较小的值与隔板的 $l/h \geq 1$，特别是在 $l/h \geq 3$ 的情况下。在例外情况，然而，$b$ 增加了隔板的 $l/h=0.5$。第三，$\theta$ 在 $x/h\approx 20$ 与隔板的 $l/h=3$ 是相对于隔板的 $l/h=0.5$ 和无隔板时（kept increasing $\theta$）。

As seen in figures 2 to 5, the properties in the mean flow field can be roughly classified into three categories: without SP, $l/h < 1$ and $l/h \geq 1$ the same as in the boundary layer [2, 4].

**Turbulent Quantities**

In this section, let us examine the development of the fluctuating flow field in the wake in the case with/without the splitter plate. Figure 6 shows the local streamwise turbulent intensity profiles in the range of $x/h=10$ to 65 with the splitter plate of $l/h=0.5$ to 5. The rms values of the streamwise fluctuating velocity $u_{rms}$ on the ordinate are non-dimensionalized with the reference velocity $U_{ref}$ as in figure 2, $u_{rms}/U_{ref}$ in the vicinity of the trailing edge decreased with increasing the length of the splitter plate. At $x/h \approx 3.5$, distribution of $u_{rms}/U_{ref}$ in the case of $l/h>1$ is roughly the same as with that obtained on the flow behind the sharp trailing edge (their thickness of the fore-body is 19 mm) [5].

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The Reynolds shear stress is given by using the time average of the product of streamwise- and normal-fluctuating velocity $u$ and $v$, as $\langle uv \rangle$. As shown in figure 7, the normalized Reynolds shear stress $G$, equation (1), in the vicinity of the trailing edge remarkably decreased with the splitter plate of $l/h>1$.
In the downstream area at \( x / h \approx 35 \), distribution of \( G \) in the case of \( l / h > 1 \) almost coincided with that obtained on the flow behind the sharp trailing edge \([5]\) and greatly differed from the asymptotic profile in equation (2) indicated by the solid line.

\[
G = -\frac{< u' v' >}{W_0^2} \exp \left[ -4 \left( \frac{y}{b} \right)^2 \ln 2 \right] \tag{1}
\]

\[
G = 0.2728(\ln 2)^2 \exp \left[ -4 \left( \frac{y}{b} \right)^2 \ln 2 \right] \tag{2}
\]

where, the assumptions \([5]\) are: “self-preservation,” “half-power laws for \( b \) and \( W_0 \),” “constant eddy viscosity \( \nu_T \)” and “ \( \nu_T / (U_{\infty} \theta_1) = 0.032 \) ( \( \theta_1 \), the momentum thickness at the last measurement station).”

**Effect of Corrugated Sheet**

Finally, we will investigate the change in wake by use of the corrugated sheet. Figure 8 shows the streamwise variation in the momentum thickness \( \theta \), where the data obtained with the corrugated sheet are added to the lines with/without the splitter plate seen in figure 5. The converging tendency of \( \theta \) with the corrugated sheet of \( l / h = 3 \) is in contrast to the corrugated sheet of \( l / h = 1 \) (kept increasing \( \theta \)). It is found that the development of the wake remarkably changes with the wavelength and amplitude in addition to the length of the corrugated sheet. Regarding the velocity profiles, in the downstream area after \( x / h = 60 \), \( U / U_{\infty} \) and \( u_{rms} / U_{\infty} \) took roughly the same distribution in both cases with SP and CS\(_{a3}\) for \( l / h = 1 \) (see figures 2 and 6).

![Figure 8. Effect of corrugated sheet on momentum thickness.](image)

**Conclusions**

The influences of planar and corrugated sheets on turbulent wake developing behind a long flat plate with thick trailing edge were studied and concluded as follows:

(1) The maximum velocity defect \( W_0 \) in the vicinity of the trailing edge increased with increasing the length of the splitter plate, especially in the case of \( l / h \geqslant 3 \). In the downstream area after \( x / h = 60 \), \( W_0 \) converged to less than 20% of freestream velocity independent of the installation of the splitter plate.

(2) The full width at half maximum of velocity defect \( b \) increased streamwise but took smaller value with the splitter plate of \( l / h \geqslant 1 \), especially in the case of \( l / h \geqslant 3 \). In the exceptional case, however, \( b \) increased with the splitter plate of \( l / h = 0.5 \).

(3) The converging tendency of the momentum thickness \( \theta \) after \( x / h = 20 \) with the splitter plate of \( l / h = 3 \) is in contrast to the splitter plate of \( l / h = 0.5 \) and without splitter plates (kept increasing \( \theta \) ). The converging tendency of \( \theta \) with the corrugated sheet of \( l / h = 3 \) is in contrast to the corrugated sheet of \( l / h = 1 \) (kept increasing \( \theta \)).

(4) The streamwise turbulent intensity \( u_{rms} / U_{\infty} \) in the vicinity of the trailing edge decreased with increasing the length of the splitter plate. In the downstream area after \( x / h = 60 \), \( u_{rms} / U_{\infty} \) took roughly the same distribution in both cases with SP and CS\(_{a3}\) for \( l / h = 1 \).

(5) The normalized Reynolds shear stress \( G \) in the vicinity of the trailing edge remarkably decreased with the splitter plate of \( l / h > 1 \). In the downstream area at \( x / h \approx 35 \), distribution of \( G \) in this case coincided with that obtained on the flow behind the sharp trailing edge (great different from the asymptotic profile).

**Acknowledgments**

The experiment of the present work was conducted at Kagawa National College of Technology, and the assistance provided by the former students, Mr. Hirotaka Motoki and Mr. Ryohki Nakagiri, of the Advanced Course in Industrial and Systems Engineering is gratefully acknowledged.

**References**


