18th Australasian Fluid Mechanics Conference
Launceston, Australia
3-7 December 2012

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

Y. Jodai[1]

[1]Department of Mechanical Engineering
Kagawa National College of Technology, Takamatsu, Kagawa 761-8058, Japan

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 $l / h \geqq 1$, 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_∞ : freestream velocity of wake

U_m : reference velocity (at $x = -1000$ mm, $y = 150$ 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

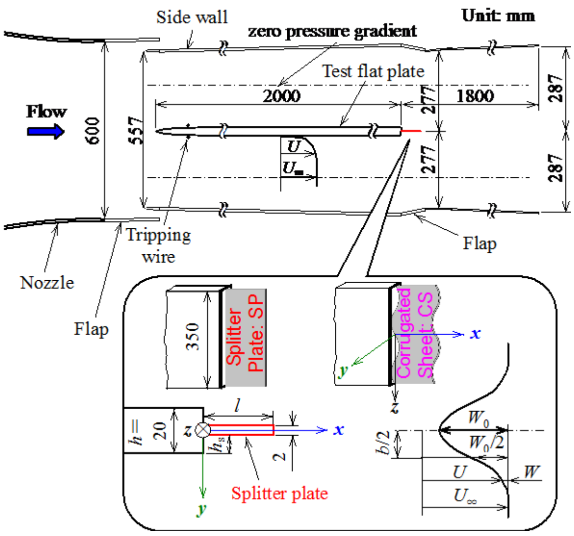

Figure 1. Configuration of flow field and coordinate system.

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 z=0 mm), experiments were made at unit Reynolds number U_m / ν of 9.93×10^5 m^{-1} (U_m≒15 m/s, ν 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 ～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.

	commer-cial	self-made (CS_a)		
acronym	**CS_p**	**CS_{a1}**	**CS_{a2}**	**CS_{a3}**
material	poly-carbonate	aluminum		
thickness	0.5～0.75 mm	2 mm		
wave length	32.3 mm	175 mm	35 mm	35 mm
amplitude	10.3 mm	20 mm	20 mm	10 mm
wave number	10.8	2	10	10

Table 1. Dimensions of corrugated sheets.

The length of the corrugated sheet was selected l=20 and 60 mm (l / h=1 and 3). The sinusoidal CS made of aluminum alloy, named CS_a, was made with an electric discharge machine. The flow field was controlled by changing l / h.

Measuring Techniques

Measurement of the instantaneous velocity in the wake was mainly conducted with a X-hot-wire probe (a pair of tungsten filaments 5 μm in diameter and 1 mm in sensor length arranged parallel to the other with a crossing angle of 91 deg) operated by a constant temperature anemometer. A I-hot-wire probe and Pitot tube (1.06 mm in diameter with static pressure holes 0.3 mm in diameter) were also used for the experiment with the corrugated sheet. Instantaneous velocity signals were converted into digital data sets with a sampling frequency of 10 kHz for 10 seconds, and the output data were calculated with a personal computer. Measurements are executed on the 24 cross sections for the case without the splitter plate and 8 cross sections for the cases with the splitter plate. As for the cases with the corrugated sheet, 4 cross sections of x / h=7.5, 30, 50 and 62.5 were measured.

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, 4 and 5 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 θ, 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≧3. In the downstream area after x / h=60, W_0 converged to less than 20% of freestream velocity U_∞ independent of the

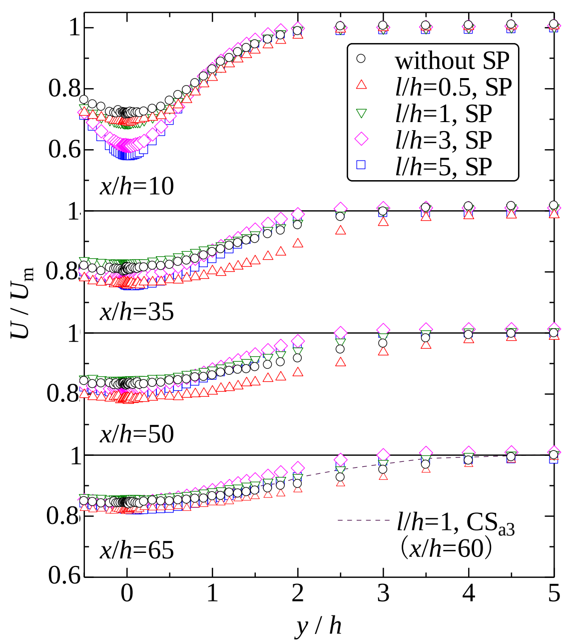

Figure 2. Mean velocity profiles.

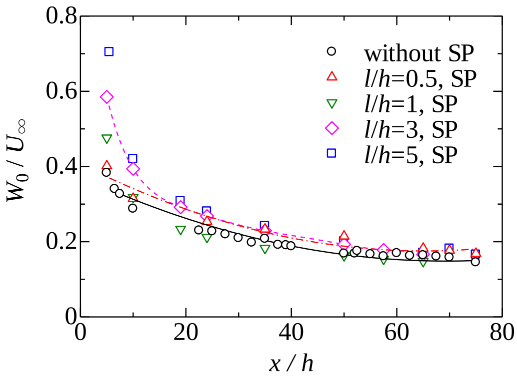

Figure 3. Maximum velocity defect.

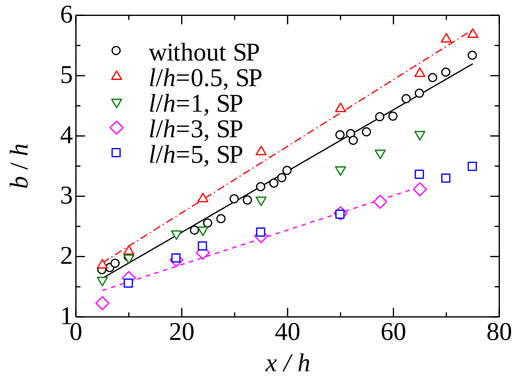

Figure 4. Full width at half maximum of velocity defect.

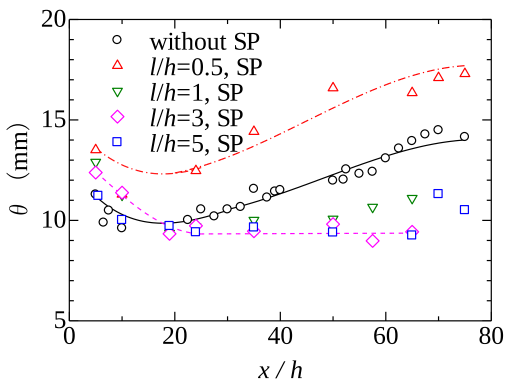

Figure 5. Momentum thickness.

installation of the splitter plate. Second, b increased streamwise but took smaller value with the splitter plate of $l / h \geqq 1$, especially in the case of $l / h \geqq 3$. In the exceptional case, however, b increased with the splitter plate of $l / h = 0.5$. Third, the converging tendency of θ 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 θ).

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 $l / h \geqq 1$ 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

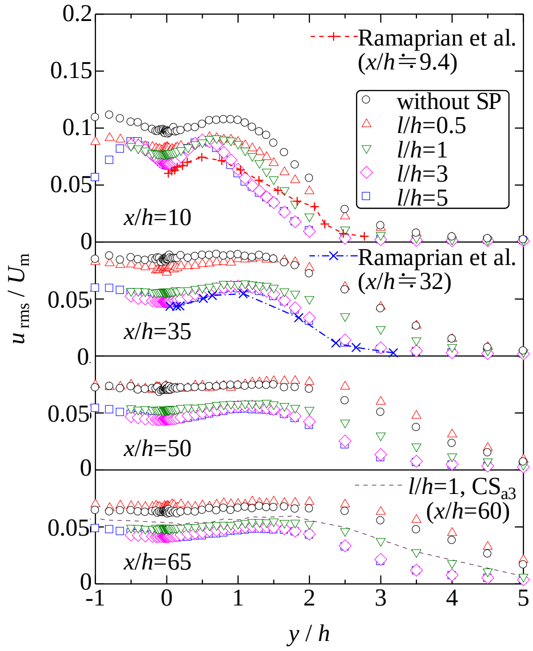

Figure 6. Streamwise turbulent intensity profiles.

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_m as in figure 2. u_{rms} / U_m in the vicinity of the trailing edge decreased with increasing the length of the splitter plate. At $x / h \fallingdotseq 35$, distribution of u_{rms} / U_m 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 $l / h > 1$.

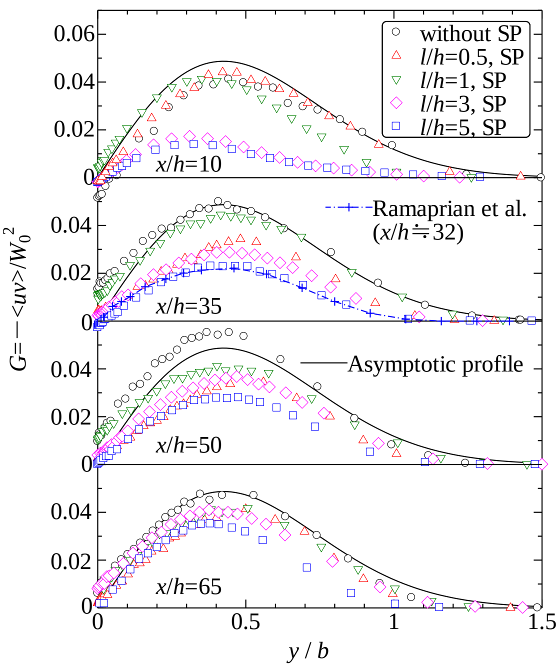

Figure 7. Reynolds shear stress profiles.

In the downstream area at $x / h ≒ 35$, 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.

$$G = -\frac{< uv >}{W_0^{\ 2}} \quad . \tag{1}$$

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

where, the assumptions [5] are: "self-preservation," "half-power laws for b and W_0," "constant eddy viscosity ν_T" and "$\nu_T / (U_\infty \theta_L) = 0.032$ (θ_L, 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 θ, 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 θ with the corrugated sheet of $l / h = 3$ is in contrast to the corrugated sheet of $l / h = 1$ (kept increasing θ). 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_m and u_{rms} / U_m took roughly the same distribution in both cases with SP and CS_{a3}, for $l / h = 1$ (see figures 2 and 6).

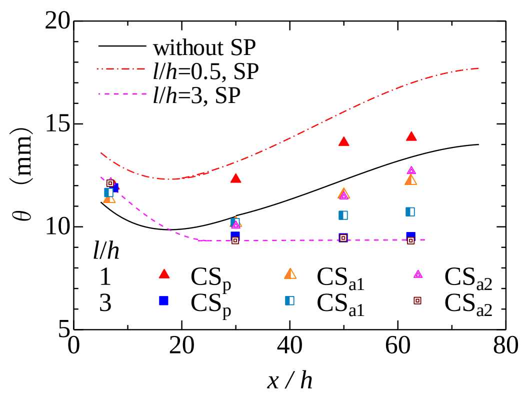

Figure 8. Effect of corrugated sheet on momentum thickness.

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 $l / h ≧ 3$. 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 $l / h ≧ 1$, especially in the case of $l / h ≧ 3$. In the exceptional case, however, b increased with the splitter plate of $l / h = 0.5$.

(3) The converging tendency of the momentum thickness θ 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 θ). The converging tendency of θ with the corrugated sheet of $l / h = 3$ is in contrast to the corrugated sheet of $l / h = 1$ (kept increasing θ).

(4) The streamwise turbulent intensity u_{rms} / U_m 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_m 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 $x / h ≒ 35$, 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. Ryohei Nakagiri, of the Advanced Course in Industrial and Systems Engineering is gratefully acknowledged.

References

[1] Choi, H., Jeon, W. P. & Kim, J., Control of Flow Over a Bluff Body, *Annual Review of Fluid Mechanics*, **40**, 2008, 113-139.

[2] Jodai, Y., Takahashi, Y., Ichimiya, M. & Osaka, H., The Effects of Splitter Plates on Turbulent Boundary Layer on a Long Flat Plate Near the Trailing Edge, *Transactions of the ASME-Journal of Fluids Engineering*, **130**, 2008, 051103-1-051103-7.

[3] Jodai, Y., Takahashi, Y., Ichimiya, M. & Osaka, H., The Effects of Splitter Plates on the Vortex Structure behind a Long Flat Plate with a Blunt Trailing Edge, *Transactions of the Japan Society of Mechanical Engineers, Series B*, **73**, 2007, 1183-1190.

[4] Jodai, Y., Ichimiya, M. & Osaka, H., Effects of Splitter Plates on Turbulent Quantities on a Boundary Layer Developing on a Flat Plate near the Trailing Edge, *Journal of Fluid Science and Technology*, **6**, 2011, 587-597.

[5] Ramaprian, B. R., Patel, V. C. & Sastry, M. S., The Symmetric Turbulent Wake of a Flat Plate, *AIAA Journal*, **20**, 1982, 1228-1235.

[6] Tombazis, N. & Bearman, P. W., A Study of Three-Dimensional Aspects of Vortex Shedding from a Bluff Body with a Mild Geometric Disturbance, *Journal of Fluid Mechanics*, **330**, 1997, 85-112.

[7] Werle, M. J., Paterson, R. W. & Presz Jr., W. M., Trailing-Edge Separation/Stall Alleviation, *AIAA Journal*, **25**, 1987, 624-626.