The Effect of an Upstream Control Object in Low-Speed Rotation upon the Flow past a Long Plate*

Katsuya HIRATA**, Masahiro KONDO**, Rei OKUMA** and Jiro FUNAKI**

**Department of Mechanical Engineering, Doshisha University, Kyoto 610-0321, Japan
E-mail: khirata@mail.doshisha.ac.jp

Abstract
In the present study, the authors consider a control of the flow past a semi-infinite plate with a blunt front. The flow is one of the simplest separated-and-reattaching flows, and can be a model such as heat exchangers and flow straighteners commonly seen inside power plants, chemical plants and household appliances. As a control device, a rotating object, which is a small flat plate, is placed in the upstream of the semi-infinite plate. In a wind tunnel, the authors conduct flow-velocity-fluctuation measurements using a hot-wire anemometer for various control-object positions and rotation speeds, showing (1) root-mean-squared values near the leading edge of the semi-infinite plate and (2) dominant frequencies in the downstream. The present test range of the control-object rotation speed is low; specifically, the object’s tip velocity is less than the uniform mainstream velocity. Referring to such results, we can classify the controlled flow into four regions. Moreover, in order to clarify the characteristics for each region, the authors carry out (1) flow visualisations with particle-image-velocimetry analyses, and (2) velocity-profile measurements concerning time-mean and turbulence-intensity values.

Key words: External Flow, Flow Control, Flow Separation, Wind Tunnel, Oscillatory Flow

1. Introduction

Bluff bodies such as circular and square cylinders are the most basic structural members. And the flow around bluff bodies is much complicated by comparison with that around streamlined bodies, because of the existence of separated shear layers accompanying strong unsteadiness. As the bluff-body flow is very common in various aspects, it often bothers many engineers in designings.

Until now, various control methods for such flow have been proposed and developed. One of the methods is to place a small control object near the body. There have been many researches for streamwisly-short bluff bodies, such as a circular cylinder, a square cylinder, and short rectangular cylinders. Here, most of the above researches are concerned with the control of the forming position of the Karman vortex street behind a short bluff body, for its drag’s reduction. As well as the drag reduction, this small-control-object method is effective on mixing enhancement/suppression, vibration suppression and thermal control in practical problems.

However, among the bluff-body flows, the streamwisly-long-bluff-body flow is much different from the short-bluff-body one. Because, the separated shear layers are possible to reattach the afterbody surfaces of the long bluff bodies, namely, the...
separated-and-reattaching flow is formed. It is well known that a semi-infinite plate with a blunt front in uniform flow is one of the simplest configurations that realise the separated-and-reattaching flow, as well as the back-step flow. The flow can be a model such as heat exchangers and flow straighteners commonly seen inside power plants, chemical plants and household appliances. Then, we have desired to establish the smart and fine control methods upon the flow.

Kiya et al. (27) and Sasaki & Kiya (28) researched the effect of an upstream small object upon the flow past a semi-infinite plate with a blunt front. They reported (1) shorter reattachment length, (2) thinner separated shear layer and (3) weaker pressure fluctuation on the plate’s side surface. In their studies, they regard the above results as the effects of the mainstream turbulence introduced by a small and enough-upstream control object.

We might expect the possibility of the control object as an effective flow-control device in such long-bluff-body configurations, as well as short-bluff-body configurations (1)-(26). However, the above studies (27), (28) correspond to the experiments only in the limited ranges of governing parameters such as geometric parameters and the Reynolds number, according to their concern. So, we need further studies in order to get more useful results in much wider parameter ranges for flow controls. In addition, we introduce the rotation of the control object as another flow-control parameter, expecting the possibility of further effective flow control. In the present study, we restrict our concern within a lower range of the rotation speed, considering practical effectiveness. We can expect different effects of mixing or heat-transfer enhancement/suppression between two sides of the semi-infinite plate, because the control-object rotation might make the flow asymmetric. For example, those selective effects could be utilised in the electric generation by temperature difference. Complementarily speaking, we can consider applications of the autorotation of the control object, which is a self-rotational phenomenon without external mechanical driving forces. While the autorotation is well not revealed yet, such applications seem to have high potential in various fields.

More specifically, as a control device for the flow past a semi-infinite plate with a blunt front, a rotating control object, which is a small flat plate, is placed in the upstream of the semi-infinite plate. In a wind tunnel, we conduct flow-velocity-fluctuation measurements using a hot-wire anemometer (hereinafter, referred to as HWA) at various control-object positions and rotation speeds. Using the measured turbulence intensity and dominant frequency, we try to classify the flow into some kinds. Moreover, in order to clarify the characteristics in each classified flow, we carry out (1) flow visualisations with particle-image-velocimetry (hereinafter, referred to as PIV) analyses, and (2) velocity-profile measurements with HWA concerning time-mean and turbulence-intensity values.

**List of notations**

- \( b \) : breadth of a control object (m)
- \( f \) : dominant frequency of velocity fluctuation (Hz)
- \( H \) : height of a semi-infinite plate; characteristic length scale (m)
- \( L \) : length of a semi-infinite plate (m)
- \( l \) : length between a control-object centre and a semi-infinite-plate front (m)
- \( n \) : rotation speed of a control object (Hz)
- \( Re \) : Reynolds number, \( \equiv U_0H/\nu \)
- \( St \) : Strouhal number, \( \equiv fH/U_0 \)
- \( U_0 \) : flow velocity of uniform mainstream (ms\(^{-1}\))
- \( u \) : time-mean flow velocity (ms\(^{-1}\))
- \( u' \) : turbulence intensity (ms\(^{-1}\))
$W$ : width (span) (m)  
$x, y$ : coordinates (m)  
$y_{SL}$ : shear-layer thickness (m)  
$\alpha$ : inclination angle of a control object (rad)  
$\Omega$ : tip-speed ratio, $\equiv \pi nb/U_0$  
$\nu$ : kinematic viscosity (m$^2$s$^{-1}$)

**Subscripts**

LE : at a measuring position near a leading edge of a semi-infinite plate; at $x/H = 0$ and $y/H = 0.525$

MIN : minimum

SW : at a measuring position just above a side wall of a semi-infinite plate; at $y/H = 0.55$

2. Experimental Method

2.1 Model and coordinates

Figure 1 shows the present model with an enough streamwisly-long rectangular-cross-section plate, which is approximated as a semi-infinite plate. Table 1 summarises the present values of basic experimental parameters. The height $H$ of a semi-infinite plate is a characteristic length scale, which is fixed to 20 mm. The cross-section ratio $L/H$ of the plate is fixed to 37.5, where $L$ is the plate’s length. A control object is placed in the upstream of the plate, with a distance $l$ apart from the plate’s front face. The reduced length $l/H$ is 2.0, 3.0, 4.5 and 8.0. The plate’s width $W$, which is the same as the control-object width, is 290 mm. Then, the aspect ratio defined by $W/H$ becomes 14.5. The breadth $b$ and the thickness of the control object is 10 mm ($= 0.5H$) and 2 mm ($= 0.1H$), respectively. Then, the reduced breadth $b/H$ of the control object is 0.5. The control object is forced to rotate at a rotation speed $n$ in the clockwise direction. We non-dimensionalise $n$ as a tip-speed ratio $\Omega = \pi nb/U_0$, where $U_0$ denotes the mainstream velocity. The range of $\Omega$ is from 0.001 to 0.41. $\Omega$ has rather low values less than unity, because we suppose the efficiency and the applicability of the flow control in practical uses as mentioned above. All experiments are conducted at a Reynolds number $Re = 5000$.

The present coordinate system is shown in Fig. 1, as well. The origin $O$ is at the centre on the plate’s front face. The $x$- and $y$-axes are taken in the mainstream direction and the cross-mainstream direction, respectively.

2.2 Experimental apparatus

Experiments are conducted in a Gottingen-type wind tunnel, with an open test section of 1 m in height, 1 m in width and 2 m in length. Turbulence intensity at $U_0 = 5$ ms$^{-1}$ is less than 0.5 %. Two rectangular and thin end plates, with 10H in height, 37.5H in length and 1H in thickness, are fitted with the semi-infinite plate to ensure the two dimensionality of flow. The semi-infinite plate and the end plates are made of acrylic resin. As the blockage ratio of the semi-infinite plate is 0.0088, no corrections have been carried out on raw data. The control object is made of aluminum, which is forced to rotate by an election motor outside.

![Fig. 1 Model and coordinate system.](image-url)
Flow velocity is measured using an I-type HWA probe, which is vertically inserted up from the lower outside toward the lower side surface of the semi-infinite plate. Incidentally, we conduct all HWA measurements only on the lower side, namely, on half the \(x-y\) plane with positive \(y\). Concerning the upper side, we use the lower-side results with the control object rotating anti-clockwise. Strictly speaking, the measured flow velocity is the composite of \(x\)- and \(y\)-direction components. By fast-Fourier-transform analyses on HWA signals, we detect dominant frequencies \(f\)’s. Non-dimensional form of \(f\) is defined as the Strouhal number \(St \equiv fH/U_0\).

Flow is visualised by the smoke-wire method. As a smoke wire, we use a Nichrome wire with a diameter of 0.2 mm, which is placed in the upstream of the control object. A voltage of 50 V impressed by a direct-current power supply heats the liquid paraffin applied on the smoke wire, to generate white smoke. We observe the smoke motion on a mid-span \(x-y\) plane beneath the semi-infinite plate, which is lighten up by a sheet-like laser beam. We record the smoke motion using a high-speed video camera with a frame rate of 2000 frames/s, which is fixed outside the wind-tunnel test section. The recorded images are analysed on a personal computer with a PIV technique.

3. Results and Discussion

3.1 Turbulence intensity

At first, we consider the turbulence intensity at a certain position in space as an indicator of the control-object effects. Turbulence intensity is often a suitable indicator for heat/mass transfers and material mixings, because of its high sensitivity to local fluctuations. On the other hand, the measuring position for turbulence intensity should be determined carefully. Our probe position is almost the same as Kiya et al., (27) who supposed that the shear-layer turbulence near a flow-separation position is the most essential factor to dominate the separated-and-reattaching-flow characteristics. The present probe position \(LE\) is at \((x, y) = (0, 0.525H)\) near a leading edge. And, we define \(u_{LE}'\) as the turbulence intensity at the position \(LE\).

Figures 2-5 show \(u_{LE}'/U_0\) plotted against the tip-speed ratio \(\Omega\), where \(u_{LE}'\) is non-dimensionalised by \(U_0\). Figures 2, 3, 4 and 5 represent the results for \(l/H = 2.0, 3.0, 4.5\) and 8.0, respectively. And, open and solid circles denote the lower and upper sides, respectively. Each figure also includes the result at \(\Omega = 0\) (no-rotation case), for reference. Specifically speaking, an open diamond denotes an average over six time-mean values of \(u_{LE}'\) at inclination angles \(\alpha = 0, \pm 30, \pm 60\) and 90 deg. (hereinafter, referred to as a quasi-steady value). And, an error bar at \(\Omega = 0\) corresponds to the maximum and minimum among the six time-mean values.

We first consider Fig. 2 as an example, as Figs. 2-5 show common features. With increasing \(\Omega\) from zero, \(u_{LE}'/U_0\) shows various distinctive features on both the sides. So, we classify the tested range of \(\Omega\) into four regions, referring to such distinctive features. That is, regions I, II, III and IV are at \(\Omega \approx 0-0.03, 0.03-0.1, 0.1-0.2\) and 0.2-0.5, respectively.

Table 2 shows the definitions of the regions; namely, the distinctive features of \(u_{LE}'/U_0\) seen in each region. Specifically speaking, in the region I, \(u_{LE}'/U_0\) on the lower side is almost the same as that on the upper side. In the region III, \(u_{LE}'/U_0\) on the lower side is much smaller than that on the upper side. (The difference between the two sides is almost 30 %. Furthermore, \(u_{LE}'/U_0\) on the lower side is smaller than the quasi-steady one, which is denoted by an open diamond in the figure). The region II is the transition region between the regions I and III, showing a complex manner on \(u_{LE}'/U_0\). At larger \(\Omega\) than that for the region III, the region IV appears. \(u_{LE}'/U_0\) in the region IV is much larger than that in the region III on each side, showing the following features. (1) There often exists a...
Table 1  Experimental parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H ) [m]</td>
<td>( 2.0 \times 10^{-2} )</td>
</tr>
<tr>
<td>( b ) [m]</td>
<td>( 1.0 \times 10^{-2} )</td>
</tr>
<tr>
<td>( L ) [m]</td>
<td>( 4.0 \times 10^{-2}, 6.0 \times 10^{-2}, 9.0 \times 10^{-2}, 1.6 \times 10^{-1} )</td>
</tr>
<tr>
<td>( W ) [m]</td>
<td>0.29</td>
</tr>
<tr>
<td>( n ) [Hz]</td>
<td>( 0.1 ) – ( 50 )</td>
</tr>
<tr>
<td>( U_0 ) [m/s]</td>
<td>3.5 – 3.8</td>
</tr>
<tr>
<td>( b/H )</td>
<td>0.5</td>
</tr>
<tr>
<td>( l/H )</td>
<td>( 2.0, 3.0, 4.5, 8.0 )</td>
</tr>
<tr>
<td>( L/H )</td>
<td>37.5</td>
</tr>
<tr>
<td>( \Omega )</td>
<td>( 0.001 ) – ( 0.41 )</td>
</tr>
<tr>
<td>( AR(=W/H) )</td>
<td>14.5</td>
</tr>
<tr>
<td>( Re )</td>
<td>5000</td>
</tr>
</tbody>
</table>

Fig. 2 Turbulence intensity \( u_{LE}'/U_0 \) at a near-leading-edge position LE against tip-speed ratio \( \Omega \) for \( l/H = 2.0 \).

Fig. 3 Turbulence intensity \( u_{LE}'/U_0 \) at a near-leading-edge position LE against tip-speed ratio \( \Omega \) for \( l/H = 3.0 \).

Fig. 4 Turbulence intensity \( u_{LE}'/U_0 \) at a near-leading-edge position LE against tip-speed ratio \( \Omega \) for \( l/H = 4.5 \).

Fig. 5 Turbulence intensity \( u_{LE}'/U_0 \) at a near-leading-edge position LE against tip-speed ratio \( \Omega \) for \( l/H = 8.0 \).
jump of \( u_{LE}'/U_0 \) between regions III and IV. (2) \( u_{LE}'/U_0 \) keeps an almost constant value, being independent of \( \Omega \).

In Fig. 6, we summarise turbulence-intensity measurements for \( l/H = 2.0-8.0 \); namely, the data in Figs. 2-5. The figure shows the boundaries between the regions I-IV on the \( l/H-\Omega \) plane. All the boundaries are almost parallel to the lateral axis, expect for small \( l/H \). Then, we see that the \( \Omega \) effect upon \( u_{LE}'/U_0 \) is much stronger than the \( l/H \) effect. –We should note that a gap between the regions III and IV corresponds to the jump of \( u_{LE}'/U_0 \) for example at \( \Omega = 0.2 \) in Fig. 2.–

In the region I, as \( \Omega \) decreases toward zero, we might expect an asymptote of \( u_{LE}'/U_0 \) to the quasi-steady value. However, we cannot find such an asymptotic trend in any of Figs. 2-5. For further discussion, we show Fig. 7, where the lateral axis has a logarithmic scale instead of a linear scale in Fig. 3 in order to make the observation at low \( \Omega \) easier. Both the values of \( u_{LE}' \) on the lower and upper sides well coincide with each other, in the region I. However, it seems difficult to confirm their asymptotic trends to the quasi-steady value (shown as an open diamond in the figure). Open and solid triangles in the figure show the remainders subtracted the control-object-rotation frequency components from \( u_{LE}'/U_0 \) on the lower and upper sides, respectively. Both the remainders asymptote to the quasi-steady value, as \( \Omega \) decreases. Then, we can regard the region I as in an asymptoting process toward the quasi-steady state. In other words, \( u_{LE}'/U_0 \) always involves the control-object-rotation component. And, if we subtract this component from \( u_{LE}'/U_0 \), the remainder is consistent with the result at \( \Omega = 0 \). –Incidentally speaking, this component becomes small, as \( l/H \) increases. For example, the component is merely 1-2 % in Fig. 5.–

Next, we consider the region IV with the largest \( \Omega \). In this region, \( u_{LE}'/U_0 \) tends to keep a constant value, being independent of \( \Omega \). Figure 8 shows such constant values of \( u_{LE}'/U_0 \) plotted against \( l/H \). For reference, we also plot the quasi-steady \( u_{LE}'/U_0 \) which is the value of \( u_{LE}'/U_0 \) averaged over six different inclination angles \( \alpha \)’s, as open diamonds in the figure. When \( l/H \) increases from zero to 4.5, the quasi-steady \( u_{LE}'/U_0 \) increases monotonically. For \( l/H > 4.5 \), the quasi-steady \( u_{LE}'/U_0 \) asymptotes to a constant value with increasing \( l/H \). The values of \( u_{LE}'/U_0 \) on the lower and upper sides are shown as open and solid circles in the figure, respectively. At \( \Omega = 0.3 \), namely, in the region IV, the lower-side \( u_{LE}'/U_0 \) is always less than the upper-side one for \( l/H < 3.0 \). For \( l/H \geq 3.0 \), both the lower-side and upper side ones almost agree with each other. And for \( l/H > 4.5 \), both asymptote to the same constant value, which is approximately equal to the quasi-steady \( u_{LE}'/U_0 \). Incidentally, we also plot \( (u_{LE}'/U_0)_{MIN} \) as open triangles, which represent the minimum values of \( u_{LE}'/U_0 \) in the region III. We can confirm that \( (u_{LE}'/U_0)_{MIN} \) is almost the same as the minimum among the values of \( u_{LE}'/U_0 \) at six different inclination angles \( \alpha \)’s.

### 3.2 Dominant frequency of velocity fluctuation

To detect dominant frequency \( f \), we observe the spectra of velocity fluctuations by Fourier-transform analyses. A HWA-probe position is at \( 10H \) downstream (in the \( x \) direction) and \( 0.55H-2.55H \) downward (in the \( y \) direction) from the origin, whose range covers the shear layer on the semi-infinite-plate side wall at \( 10H \) downstream. This measuring position is determined to get clear and stable spectrum peaks. –Incidentally, in the further downstream at \( x/H > 10 \), we have confirmed that detected \( f \) is the same as that at \( x/H = 10 \).– Hereinafter, \( f \) is non-dimensionalised as the Strouhal number \( St \).

Figure 9 shows \( St \) plotted against \( \Omega \) for \( l/H = 4.5 \). Figures (a) and (b) represent the lower and upper sides, respectively. For reference, the figure includes the result at \( \Omega = 0 \) (no-rotation case), which is the quasi-steady \( St \) defined by the same manner as the quasi-steady \( u_{LE}'/U_0 \).
Table 2  Definitions of regions I – IV.

<table>
<thead>
<tr>
<th>Region</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>$u_{LE}'/U_0$ on the lower side is almost the same as that on the upper side.</td>
</tr>
<tr>
<td>II</td>
<td>Transition region between the regions I and III.</td>
</tr>
<tr>
<td>III</td>
<td>$u_{LE}'/U_0$ on the lower side is distinctively smaller than that on the upper side.</td>
</tr>
<tr>
<td>IV</td>
<td>$u_{LE}'/U_0$ is much larger than that in the region III on each side, showing the following features. (1) There is a jump of $u_{LE}'/U_0$ between regions III and IV. (2) $u_{LE}'/U_0$ keeps an almost constant value, being independent of $\Omega$.</td>
</tr>
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</table>

Fig. 6 Boundary chart of regions I – IV.

Fig. 7 Turbulence intensity $u_{LE}'/U_0$ at a near-leading-edge position LE against tip-speed ratio $\Omega$ for $l/H = 3.0$ (logarithmic scale). $\triangle$, $\blacksquare$ denote $u_{LE}'/U_0$ without the control-object-rotation component.

Fig. 8 The constant value of $u_{LE}'/U_0$ in the region IV against $l/H$, together with the minimum value ($u_{LE}'/U_0)_{\text{MIN}}$ of $u_{LE}'/U_0$ in the region III.

Fig. 9 Strouhal number $St$ against tip-speed ratio $\Omega$ for $l/H = 2.0$. $\diamond$ denotes the quasi-steady result.
We can observe one or two distinctive spectrum peaks at $\Omega<0.23$, but no clear peaks at $\Omega \geq 0.23$. Here, the plots with $St=0$ in the figure denote no clear peaks.

At $\Omega<0.23$, all the plots collapse on any of three straight lines; namely, $St = nH/U_0$, $St = 2nH/U_0$ and $St = 4nH/U_0$. Specifically speaking, we see only a few plots on a straight line $St = 4nH/U_0$ on the lower side, and only a few plots on a straight line $St = nH/U_0$ on the upper side. However, most of plots are in such a linear relation as $St = 2nH/U_0$ on both the side. This linear relation, namely, the relation of $f = 2n$, is supposed to correspond to the vortex shedding which occurs twice a control-object rotation (see later). In addition, we can confirm the above features at different values of $l/H$ as shown in the next paragraph.

In Fig. 10, we summarise the boundaries between the flows with and without dominant frequencies, on the $l/H-\Omega$ plane. –The latter flow is represented as the plots with $St = 0$ in Fig. 9. Open and solid circles in Fig. 10 denote the upper and lower sides, respectively. We can confirm a good agreement between both the sides. Moreover, the boundary is almost parallel to the lateral axis, that is, $\Omega \approx 0.20$ being independent of $l/H$. Then, we see that the $\Omega$ effect upon $St$ is much stronger than the $l/H$ effect, as well as the effects upon $u_{LE}/U_0$.

If we compare the boundary between the regions with and without dominant frequencies with the boundaries of the regions I-IV based on $u_{LE}/U_0$ (dashed lines in the figure), we find out the boundary concerning dominant frequencies almost coincides with the boundary between the regions III and IV. Therefore, the flow in the regions I-III is strongly influenced by the vortex shedding related with the control-object rotation. On the other hand, the whole flow field in the region IV is not featured by the flow structures with any periodicities in time.

Figure 11 shows the range of $St$ plotted against $l/H$. Open and solid circles denote the lower and upper sides, respectively, as well as Fig. 10. For reference, we also plot the quasi-steady $St$, which is the value of $St$ averaged over six different $\alpha$’s as open diamonds in the figure. We can see that both the upper limits of $St$ on the lower and upper sides are approximately the same as the minimum value of $St$ for the stationary control object at various $\alpha$’s, where this minimum value is denoted as the lower limit of the error bar around the quasi-steady $St$. This fact suggests a strong influence of the range of quasi-steady $St$ upon the upper limit of $St$. –If we conduct the experiments with so wider range of $St$ as $2nH/U_0$ exceeds the maximum value of $St$ for the stationary control object at various $\alpha$’s, it might be possible to detect the non-dimensional dominant frequency of $2nH/U_0$ again.–

3.3 Flow visualisation and PIV analysis

Flow visualisations and PIV analyses are conducted in order to reveal spatial flow features in each region. Figures 12, 13 and 14 show visualised photographs (figure (a)) and the corresponding PIV results (figure (b)) for the regions II, III and IV, respectively. In figure (b), vorticity $\omega$ is non-dimensionalised as $\omega H/U_0$, whose value is shown by the
colour corresponding to a legend on the right hand in each figure.

In Fig. 12, which represents the region II, we can see two rows of large-scale vortical structures with such streamwise dimensions as several times of $H$, namely, one on the lower side and the other on the upper side of the semi-infinite plate. It is not easy to confirm those flow features directly from the photographs and vorticity-dense distributions recorded by still camera such as Fig. 12. However, by means of video-camera observations, we can recognise them more clearly. In addition, by means of this video-camera observations, we can recognise that the vortical structures are the results of a sequence of the vortex shedding from the control object and the following leeward advection. Furthermore, we can also recognise that the vortex shedding occurs twice a control-object rotation.

The spatial arrangement of the vortical structures is neither alternate like the Karman vortex street nor symmetrical. Strictly speaking, the arrangement depends upon the leeward position, due to the difference of the advection speed between the lower and upper sides.

Concerning the spatial sizes of the vortical structures, the sizes on the lower side seem to be the same as those on the upper side, although those on the lower side are slightly larger than those on the upper side in a strict sense. Then, we expect the symmetry on time-mean velocity profile. In fact, we will confirm the symmetry by HWA measurements in the following subsection. The symmetry well corresponds to the agreement of $u_{LE}'/U_0$ between both the sides, as well as in the region I (see Figs. 2-4).

In Fig. 13, which represents the region III, we can see two rows of large-scale vortical structures, clearly even in a still photograph. All the vortical structures in Fig. 13 are smaller than those in Fig. 12. As well, by means of video-camera observations, we can recognise that the vortical structures are the results of a sequence of the vortex shedding from the control object and the following leeward advection, and that the vortex shedding occurs twice a control-object rotation.

As well as Fig. 12, the spatial arrangement of the vortical structures is neither alternate like the Karman vortex street nor symmetrical. Strictly speaking, the arrangement depends upon the leeward position, due to the difference of the advection speed between the lower and upper sides.

In contrast to Fig. 12, concerning the spatial sizes of the vortical structure, the sizes on the lower side are smaller than those on the upper side. Then, we expect the asymmetry on

Fig. 12  Flow visualisation in region II ($\Omega=0.08, l/H = 4.5$).
time-mean velocity profile. In fact, we will also confirm the asymmetry by HWA measurements in the following subsection. On the other hand, as mentioned above, the asymmetry about the size is not so clear in the region II. The asymmetry well corresponds to the difference of $u_{LE}'/U_0$ between both the sides, as well (see Figs. 2-4).

In Fig. 14, which is in the region IV, it is difficult to observe any obvious large-scale vortical structures. Furthermore, it is difficult to observe any periodicities in time, even by means of video-camera observations. Such a less-periodicity matches well with the fact that there exist no dominant frequencies of velocity fluctuations in the region IV (at $\Omega \geq 0.23$ in Fig. 9).

If we focus upon the shear-layer size in the region IV, we can expect the symmetry on time-mean velocity profile. In fact, we will also confirm the symmetry by HWA measurements in the following subsection. The symmetry well corresponds to such another fact as $u_{LE}'/U_0$ on the lower side almost coincides with that on the upper side in the region IV and at $l/H \geq 3.0$ (see Fig. 8).

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**Fig. 13** Flow visualisation in region III ($\Omega =0.20$, $l/H = 4.5$).

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**Fig. 14** Flow visualisation in region IV ($\Omega =0.41$, $l/H = 4.5$).
### 3.4 Velocity profile on a semi-infinite plate

Figures 15, 16 and 17 show sample velocity profiles in the region I, III and IV, respectively. Open and solid circles in the figures represent the time-mean velocity and the turbulence intensity, respectively. Besides, the figures also show the outer edges and the centres of shear layers for reference (for their definitions, see Ref. [31]). We represent the outer edge by a solid line or a chain line, and the centre by a dashed line or a two-dot chain line, where the chain line and the two-dot chain line correspond to the case without the control object. In each figure, figures (a) and (b) represent the results on the lower and upper sides, respectively.

In the region I (see Fig. 15), both the time-mean-velocity and turbulence-intensity profiles on the lower side are approximately the same as those on the upper side. Then, we can confirm the symmetry on time-mean flow fields. Moreover, if we compare the present profiles with those in the case without the control object, we see that there exist little differences between them concerning the time-mean-velocity profiles. Specifically speaking, the outer edges are almost in the same positions as these in the case without the control object. However, concerning the turbulence-intensity profiles, there exist considerable differences between them. Specifically speaking, we cannot determine the centre from the present turbulence-intensity profiles.

Next, we consider the region III (see Fig. 16). On the lower side (in figure (a)), both the shear-layer thicknesses based on the outer edge and on the centre are smaller than those...
Fig. 16  Velocity profiles in region III ($\Omega = 0.17, \ell/H = 2.0$).

Fig. 17  Velocity profiles in region IV ($\Omega = 0.41, \ell/H = 2.0$).
in the case without the control object. On the upper side (in figure (b)), the shear-layer thickness based on the outer edge is slightly larger than that in the case without the control object, and the shear-layer thickness based on the centre is slightly smaller than that in the case without the control object.

Finally, we consider the region IV (see Fig. 17). As well as the region I (in Fig. 15), both the time-mean-velocity and turbulence-intensity profiles on the lower side are approximately the same as those on the upper side. Then, we can confirm the symmetry on time-mean flow fields, again. In contrast to the region I, the shear-layer thickness based on the outer edge is smaller than that in the case without the control object, on each side. However, concerning the centre, we cannot determine it on each side, as well as the region I.

Figure 18 summarises the shear-layer thickness $y_{SL}$ based on the outer-edge in the regions I-IV. More specifically, the figure shows the non-dimensional shear-layer thickness $y_{SL}/H$ at $x/H = 4.0$ plotted against tip-speed ratio $\Omega$. Open and solid circles in the figure represent the results on the lower and upper sides, respectively. A chain line denotes the result in the case without the control object. –Supplementarily speaking, we can see similar results with Fig. 18 even at $x/H = 2.0$ and 8.0, except for $x/H = 0$.–

Now, we compare the lower and upper sides in each region, namely, at $\Omega = 0.02, 0.17$ and 0.41. In the region I (at $\Omega = 0.02$), $y_{SL}/H$ on the lower side is almost the same as that on the upper side. In the region III (at $\Omega = 0.17$), $y_{SL}/H$ on the lower side is smaller than that on the upper side. In the region IV (at $\Omega = 0.41$), $y_{SL}/H$ on the lower side is almost the same as that on the upper side, as well as the region I. Thus, in the region III, the asymmetry about the semi-infinite-plate centre on time-mean-velocity profile becomes remarkable. On the other hand, both the lower-side and upper-side values of $y_{SL}/H$ in the region IV are much smaller than that in the case without the control object. –Incidentally, we can see that both the lower-side and upper-side values of $y_{SL}/H$ in the region I are slightly smaller than that in the case without the control object. This is in a good agreement with Kiya et al.\(^\text{27}\) and Sasaki & Kiya.\(^\text{28}\).–

In many practical aspects, the turbulence intensity near the semi-infinite-plate side walls often becomes a crucial factor for heat/mass transfers and material mixings. So, in Fig. 19, we summarises leeward distributions of the turbulence intensity $u'_{SW}$ near the plate’s side wall at $y/H = 0.55$ shown in Figs. 15-17, at various values of $\Omega$. More specifically, Fig. 19 shows the non-dimensional turbulence intensity $u'_{SW}/U_0$ plotted against $x/H$ for $l/H = 2.0$.$u'_{SW}/U_0$ on the lower side is almost equal to that on the upper side, expect for $x/H = 0$. Then, we cannot observe any obvious asymmetry expect for the results at $x/H = 0$, even in the region III where we have confirmed a clear asymmetry on the time-mean-velocity profile.

![Fig. 18](image_url)  Non-dimensional shear-layer thickness $y_{SL}/H$ at $x/H = 4.0$ against tip-speed ratio $\Omega$ ($l/H = 2.0$).
Incidentally, at $x/H \geq 4.0$, $u'_\text{sw}/U_0$ approximately coincides with that without the control object in all the regions. Those values of $u'_\text{sw}/U_0$ in all the regions are larger than that at $\Omega = 0$ (in no-rotation case). This is consistent with Kiya et al.\(^{(27)}\) and Sasaki & Kiya.\(^{(28)}\) However, in most of the regions, $u'_\text{sw}/U_0$ near the leading edge ($x/H \approx 0$) is much larger than both that without the control object and that at $\Omega = 0$. One exception is on the lower side in the region III (an open triangle in the figure), where $u'_\text{sw}/U_0$ is as small as that at $\Omega = 0$.

4. Conclusions

We have considered a control of the flow past a semi-infinite plate with a blunt front. As a control device, a rotating object, which is a small flat plate, is placed in the upstream of the semi-infinite plate. In a wind tunnel, we have conducted flow-velocity-fluctuation measurements using a hot-wire anemometer for various control-object positions $l/H$'s and various control-object rotation speeds $\Omega$'s, in addition to flow visualisations with particle-image-velocimetry analyses. The tested range of $\Omega$ is low. Obtained results are as follows.

(1) We classify the tested range of $\Omega$ into four regions, referring to distinctive features on the turbulence intensity $u'_\text{LE}/U_0$ near a semi infinite-plate leading edge. That is, the regions I, II, III and IV are at $\Omega = 0-0.03$, 0.03-0.1, 0.1-0.2 and 0.2-0.5, respectively. The influence of $l/H$ upon the classification is small.

(2) In the region I, $u'_\text{LE}/U_0$ on the lower side is almost the same as that on the upper side. In the region III, $u'_\text{LE}/U_0$ on the lower side is much smaller than that on the upper side. The difference between the two sides is almost 30%. Furthermore, $u'_\text{LE}/U_0$ on the lower side is smaller than the quasi-steady one. The region II is the transition region between the regions I and III, showing a complex manner on $u'_\text{LE}/U_0$. At larger $\Omega$ than that for the region III, the region IV appears. $u'_\text{LE}/U_0$ in the region IV is much larger than that in the region III on each side, being independent of $\Omega$.

(3) We can regard the region I as in an asymptoting process toward the quasi-steady state. $-u'_\text{LE}/U_0$ always involves the control-object-rotation component. And, if we subtract this component from $u'_\text{LE}/U_0$, the remainder is consistent with result at $\Omega = 0$.

(4) Concerning flow-velocity fluctuations at $x/H = 10$, we can observe one or two distinctive spectrum peaks at $\Omega < 0.23$ (in the regions I-III), but no clear peaks at $\Omega \geq 0.23$ (in the region IV). At $\Omega < 0.23$, all the data are approximated by $St = nH/U_0$, $St = 2nH/U_0$ or $St = 4nH/U_0$. Most of the data are in such a linear relation as $St = 2nH/U_0$ on both the lower and upper sides. This linear relation, namely, the relation of $f = 2n$, is supposed to correspond to the vortex shedding which occurs twice a control-object rotation. Moreover, we have confirmed a relation between the upper limit of observed $St$ and the value of quasi-steady $St$.

\[ \begin{array}{c|c|c}
\hline
x/H & u'_\text{sw}/U_0 & \% \\
\hline
0 & 0 & 0 \\
1 & 10 & 10 \\
2 & 20 & 20 \\
3 & 30 & 30 \\
4 & 40 & 40 \\
\hline
\end{array} \]

Fig. 19 Leeward distribution of turbulence intensity $u'_\text{sw}/U_0$ near the side wall (at $y/H = 0.55$) against $x/H$ for $l/H = 2.0$.\[ \text{Fig. 19 Leeward distribution of turbulence intensity } u'_\text{sw}/U_0 \text{ near the side wall (at } y/H = 0.55) \text{ against } x/H \text{ for } l/H = 2.0.\]
The asymmetry of flow about the semi-infinite-plate centre is remarkable in the region III. In the other regions, the time-mean flow field is almost symmetrical. Incidentally, in the region IV, it is difficult to observe any obvious large-scale vortical structures.

The non-dimensional shear-layer thickness $y_{SL}/H$ on the semi-infinite-plate side wall is almost the same as that without the control object, except for the lower side in the region III and for both the sides in the region IV where $y_{SL}/H$ is much smaller than that in the case without the control object. In the region III, concerning $y_{SL}/H$, we have confirmed the asymmetry, again.

Apart from the leading edges, the non-dimensional turbulence intensity $u’_{SW}/U_0$ near the semi-infinite-plate side wall coincides with that without the control object in all the regions, having almost the same value on both the lower and upper sides. These values of $u’_{SW}/U_0$ approximately in all the regions are larger than that at $\Omega = 0$ (in no-rotation case). However, in most of the regions, $u’_{SW}/U_0$ near the leading edge is much larger than both that without the control object and that at $\Omega = 0$. One exception is on the lower side in the region III, where $u’_{SW}/U_0$ is as small as that at $\Omega = 0$.

As concluding remarks, we describe some practical suggestions involved in the present results. In the region III, the flow controls utilising the asymmetry might be effective. In the region IV, while we cannot expect such asymmetry flow controls, the heat/mass-transfer and material-mixing enhancements with high durability and high reliability can be effective owing to the lack of any dominant frequencies.

Acknowledgements

We appreciate technical supports by Mr Y. Uemura (Doshisha University).

References


