Experimental Study on the Wake Structure behind a Cylindrical Rotator with Asymmetric Protrusions in a Unidirectional Flow

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Abstract

Wake structures behind a cylindrical rotator with asymmetric protrusions were investigated through a laboratory experiment. Such a cylindrical rotator could prevent a flood disaster due to the accumulation of driftwood at bridges. In this study, a rotator composed of a cylinder with five quarter-cylindrical protrusions was placed in a unidirectional flow. The rotator could rotate freely under hydrodynamic forces. The results indicate that vortices shed from the rotator affected flow structures behind the rotator. The transverse distribution of the time-average longitudinal velocity of the flow with respect to the rotator was asymmetric about the longitudinal centerline. In the accelerating area with rotation of the rotator, five vortices were obviously shed from each quarter-cylindrical protrusion in each period. Where the flow and rotation were in opposite directions, vortices formation was disrupted. A longitudinal series of vortices merged downstream, ultimately becoming a single vortex. Therefore, the wake flow becomes asymmetric in an area behind the rotator where a significant torque acts.

Keywords: Cylindrical rotator; wake; vortex; Reynolds stress; driftwood

1. Introduction

In recent years, the frequency of torrential rains resulting in slope failure, bank erosion, and other problems has been increasing. In particular, there are many cases where driftwood flowing in medium and small rivers builds up against bridges that span the river, damming the river because the span length of the bridge is too small in some cases. As a result, overflow occurs that inundates nearby houses, shore areas, and other places resulting in massive damage, even when the flow discharge does not exceed the design high-water discharge.

Research into driftwood and measures for dealing with it have therefore become a pressing issue [1]. However, although there are examples of research into the accumulation of driftwood at bridges and houses [2-7], there are few examples of investigation into specific measures for reducing the damage caused by driftwood [1]. A detachable parapet of a bridge was proposed as a countermeasure to reduce the accumulation of driftwood and refuse during flooding [8].

Against this background, we previously proposed a method for preventing the buildup of driftwood and refuse at bridges by installing a rotating cylinder called the "rotator," which is an asymmetric structure set in front of the bridge piers, and a similar method for preventing the buildup of driftwood and refuse at bridges by wrapping the bridge piers in a rotating caterpillar fitted with an asymmetric structure [9]. These methods use the massive energy of the water flow during a flood to turn the flow direction of driftwood around a bridge pier by the rotator or the caterpillar and to promote the washing out of driftwood that would otherwise build up against the bridge pier. If there is no torque around a bridge pier without the rotator or the caterpillar, driftwood and refuse are likely to balance and accumulate there.

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In that research [9], we investigated the effectiveness of the rotating bodies for preventing driftwood from getting caught on the bridge by flowing driftwood models in an open water channel where a rotator was installed in front of a bridge model and comparing the results with those from other cases, such as when a non-rotating cylinder was installed. However, there is little research that treats water flow around a cylindrical rotator with an asymmetric shape, and there are almost no examples of research that can serve as references for the aim of putting this technology into practical use.

Accordingly, in this study we first experimentally investigated the basic wake structure of rotating bodies with the aim of understanding and improving the effectiveness of installing rotators to prevent the buildup of driftwood at bridge piers. Note that this investigation is also applicable to the flow around a cylindrical bridge pier wrapped in a rotating caterpillar of the type mentioned earlier [9].

Research related to this work, which treats cylinders rotating due to flow, includes research into vertical-axis wind turbines such as those of the Darrieus and Savonius types [10-14]. The shape of the Savonius wind turbine in particular is relatively similar to the shape of the rotator examined in this research. Although the knowledge gained from these previous studies will serve as a useful reference in some ways, the wake structure of the rotator examined in this research is greatly different than that of the wind turbine because the wind is a fluid introduced into and emitted from the interior of the cylinder in the wind turbine.

Furthermore, in recent years, spiral Magnus wind turbines, which utilize the Magnus effect, have increasingly come to be used in practice [15-18]. These wind turbines generate electricity in a highly efficient way, by applying electric power to rotate cylinders that have spiral-shaped fins attached, which makes the entire wind turbine rotate from the aerodynamic lift produced. However, it may be possible to generate power even more efficiently, using natural energy alone, by using the rotator from this research instead of the impermeable spiral cylinder blades corresponding to the fins in regular wind turbines. An experimental study was conducted by Ito et al. [17] on the technology for rotating spiral Magnus wind turbines without motors by combining them with the aforementioned Savonius wind turbines.

2. Methods

A linear open channel of length 1400.0 cm, width 60.0 cm and height 60.0 cm, as shown in Fig. 1, was used in the experiments. The experimental conditions are shown in Table 1, where \( Q \) is the flow rate, \( h \) is the water depth at a point A (refer to Fig. 1, 50.0 cm upstream of the lateral center of the cylinder), \( U \) is the cross-sectional mean flow velocity at the vertical cross-section containing the point A, \( Re \) is the Reynolds number, and \( Fr \) is the Froude number. \( Re \) is defined as \( UD/\nu \), where \( \nu \) is the kinematic viscosity coefficient of water and \( D \) the cylinder diameter. Note that \( D \) for the rotator is the diameter of the cylindrical part. \( Fr \) is defined as \( U/(\sqrt{gh}) \) for a given \( h \) where \( g \) is the gravitational acceleration.

![Diagram of experimental apparatus](image)

**Table 1. Experimental conditions**

<table>
<thead>
<tr>
<th>( Q ) (m³/hr)</th>
<th>( h ) (cm)</th>
<th>( U ) (cm/s)</th>
<th>( Re )</th>
<th>( Fr )</th>
</tr>
</thead>
<tbody>
<tr>
<td>75.0</td>
<td>12.0</td>
<td>29</td>
<td>1.4 X 10^4</td>
<td>0.27</td>
</tr>
</tbody>
</table>

The rotator is a cylinder of diameter \( D = 5.0 \) cm and length 12.0 cm, to which five quarter-cylindrical protrusions formed by dividing a cylinder of radius \( k = 1.0 \) cm into four equal parts have been attached at equal spacing (refer to Fig. 2), and the support post of the rotator, which is an axle of rotation, is fixed by an acrylic plate installed spanning the water channel. A cylindrical structure was installed laterally in the middle of the channel with longitudinally 950 cm downstream from a honeycomb to control water surface disturbance (refer to Fig. 1). The cylindrical structures used in the experiments were a rotator that is not controlled and rotates freely depending on the current and, for comparison, a non-rotating cylinder of the same size without the quarter-cylindrical protrusions attached.
Time-series data of the rotating phase and flow velocity for the rotator were synchronized by using a digital laser sensor installed under the rotator. The mean rotational frequency of the rotator was determined from the laser signal and was found to be $f_r = 0.84$ Hz. The tip speed ratio was therefore $\lambda = 2\pi f_r (D/2+k)/U = 0.64$. An ultrasonic flow velocimeter was used for measuring the flow velocity, and the horizontal distribution of the three components of flow velocity were measured at a height of 3.5 cm from the channel floor. The sampling frequency was 100 Hz, and the measurement duration was 6 min at each point.

Figure 3 shows the definitions of the O-xyz coordinate system and the directions of each of the three instantaneous flow velocity components ($u_0$, $v_0$, $w_0$). The measurement positions were at the intersections of 7 measurement lines ($x=7.5$, 10.0, 12.5, 15.0, 20.0, 30.0, 40.0 cm) in the $x$ direction and 11 measurement lines ($y=0$, ±2.5, ±5.0, ±7.5, ±10.0, ±15.0 cm) in the $y$ direction.

3. Results and Discussions

3.1. Mean flow velocity and turbulence structure

Figure 4 shows the distribution across the channel of the two horizontal components ($u$, $v$) of the mean flow velocity of the rotator and cylinder just behind each cylinder at $x/D = 1.5$. In the figures for the results of this experiment—except for the frequency spectra (Figs. 6 and 8)—the spatial coordinates, flow velocity, and so forth are represented as dimensionless quantities normalized by $D$ and/or $U$, respectively. It is clear that whereas the mean flow velocity distribution for the cylinder is left–right symmetric about the center line of the channel where $y = 0$, the flow velocity distribution for the rotator is asymmetric. This occurs because the rotator rotates in one direction, and the flow velocity $u$ is larger in the positive $y$ region than in the negative $y$ region, particularly in the area near the rotator (e.g., $y/D = ±0.5$). In the $y > 0$ region, since the rotator rotates in the direction that follows the main flow due to the orientation of the protrusions, it is understood that $u$ is larger than in the $y < 0$ region. On the other hand, in the $y < 0$ region, since the rotator rotates in the direction that opposes the flow, $u$ is smaller than in the $y > 0$ region.
Next, Fig. 5 shows the distribution across the channel of the turbulent flow energy, \( k \), and production of turbulence, \( P_r \), under the same conditions as for Fig. 4. In this research, \( k \) and \( P_r \) are expressed by Eqs. (1) and (2).

\[
k = \frac{1}{2} \left( \bar{u}'^2 + \bar{v}'^2 + \bar{w}'^2 \right) \tag{1}
\]

\[
P_r = -\bar{u}'\bar{v}' \frac{\partial u}{\partial y} - \bar{u}'\bar{v}' \frac{\partial v}{\partial x} \tag{2}
\]

Here, \( u' \), \( v' \), and \( w' \) are the fluctuating parts of \( u \), \( v \), and \( w \), respectively, and the overbars represent time averaging. The spatial derivatives in the equation for \( P_r \) are approximated by a difference method. In general, although \( P_r \) of the wake flow for any cylindrical two-dimensional structure is often approximated by the first term on the right-hand side of Eq. (2), in this research considering the distortion of the flow arising from the rotation, the spatial derivative of \( v \) was also considered because it was thought that \( v \) might also have an effect [19]. However, the first term was around one order of magnitude larger than the second term when we actually attempted performing calculations, and the contribution of the second term to \( P_r \) was small.

Similar to the mean flow velocity distribution in Fig. 4, the distributions of \( k \) and \( P_r \) for the cylinder were symmetric on \( y = 0 \), while those for the rotator were asymmetric, as shown in Fig. 5. Naturally, this is also because the rotator rotates in a single direction.

We also investigated the relation between the asymmetric mean flow velocity distribution in Fig. 4 and the asymmetric turbulent distribution in Fig. 5 around the rotator. For both \( P_r \) and \( k \) of the rotator in Fig. 5, asymmetric twin peak distributions with a maximum value at \( y/D = 0.5 \) and a local maximum at \( y/D = -1 \) are confirmed. In this figure, \( k \) at both points becomes larger than in the surroundings due to the production of turbulence. Furthermore, these points also match the points where the absolute value of the spatial gradient of the mean flow velocity becomes large in Fig. 4. Because of this left–right asymmetry of the distributions, a mean flow occurs in the \( y \) direction accompanying rotation and results in advective transport, which can be understood from the value of \( v \) at \( y = 0 \) being almost zero for the cylinder and considerably negative for the rotator.
3.2. Periodic variation characteristics of the flow

Figure 6 shows the frequency spectra \( F_u(f) \), \( F_v(f) \), and \( F_h(f) \) of the flow velocities \( u, v, \) and \( w \) at \( x/D = 1.5, \ y/D = 0.5 \) near the rotator, and Fig. 7 shows the time series of the phase-averaged dimensionless flow velocity \( u' \) and \( v' \), those are nondimensionalized by \( U \), at the same point with dimensionless time, \( tT \), which is nondimensionalized by the period \( T = 1/f \) of the rotation on the vertical axis. Time interpolation was performed and the phase-averaged horizontal velocities were calculated by using the rotation signal data from the laser and its synchronized normalized flow velocity data.

![Fig. 6. Frequency spectra just behind the rotator (x/D=1.5, y/D=0.5)](image)

Fig. 6. Frequency spectra just behind the rotator (\( x/D=1.5, y/D=0.5 \))

![Fig. 7. Normalized phase-averaged horizontal velocity just behind the rotator (x/D=1.5, y/D=0.5)](image)

Fig. 7. Normalized phase-averaged horizontal velocity just behind the rotator (\( x/D=1.5, y/D=0.5 \))

There are five waves both \( u' \) and \( v' \) in Fig. 7, and the spectral power of each component dominates at the frequency of 4.2 Hz, which is 5 times the rotational frequency \( f_r = 0.84 \text{ Hz} \) of the rotator in Fig. 6. Since the rotator has five protrusions, the five waves in Fig. 7 are induced by the protrusions on the rotator. Note that since the rotator rotates freely depending on the current in this research and is not controlled, the rotational frequency also changes slightly around \( f_r = 0.84 \text{ Hz} \).

When the peak frequency of the flow velocity spectra around the cylinder was determined at the same point as Fig. 6, it was found to be 0.97 Hz (refer to Fig. 8), and since this is relatively close to the rotational frequency of the rotator \( f_r = 0.84 \text{ Hz} \), the rotational frequency of the rotator may be affected by vortex shedding from the fixed cylinder. However, the periodicity investigated in this work is based on the phase relationship in the rotation time-series data from the laser and its synchronized flow velocity, so it arises from the rotation of the rotator, regardless of whether this kind of vortex shedding effect exists.

![Fig. 8. Frequency spectra just behind the cylinder (x/D=1.5, y/D=0.5)](image)

Fig. 8. Frequency spectra just behind the cylinder (\( x/D=1.5, y/D=0.5 \))

Vertical flow velocity did not affect the horizontal wake structure of the cylindrical structure. The amplitude of fluctuation of vertical flow velocity \( w \) was small since \( F_w(f) \) around both the rotator and the cylinder was sufficiently small compared with \( F_u(f) \) and \( F_v(f) \) in Figs. 6 and 8. Therefore, the vertical flow structure around the cylinders is not discussed further.
Fig. 9. Normalized phase-averaged horizontal velocity component just behind the rotator at $x/D = 1.5$ (i): $u/U$; ii): $v/U$.

Fig. 10. Normalized phase-averaged horizontal velocity component behind the rotator at $x/D = 2.5$ (i): $u/U$; ii): $v/U$.

Fig. 11. Normalized phase-averaged horizontal velocity component behind the rotator at $x/D = 8.0$ (i): $u/U$; ii): $v/U$. 
For each of the $x/D$ measurement lines, the variation in dimensionless phase-averaged velocity was extracted by subtracting the dimensionless mean values ($u/U$, $v/U$) from each of the dimensionless phase-averaged flow velocities ($u’$, $v’$). The variation is indicated by $\langle \rangle$. The nondimensionalized results as representative measurement lines are shown in Figs. 9 to 11. The closed solid black curves in the figures represent the approximate positions and sizes of the individual vortices, and the arrows indicate the direction of vortex rotation, that is, the direction of flow. Furthermore, the dotted closed curves similarly show examples of vortices where there is a possibility of merging. Note that in each diagram, i) shows $\langle u \rangle/U$ and ii) shows $\langle v \rangle/U$. Although these diagrams show the periodic time lapse of the flow as detected on each of the measurement lines, this corresponds to drawing a plan view of the coherent flow structures, so-called vortices, for the case where the variations detected on the measurement lines are assumed to continue as they are by advection.

In Figs. 7, 9, and 10, symbols are assigned to each of the 5 waves produced by the protrusions for convenience. Uppercase letters are assigned to the waves for $\langle u \rangle$ and lowercase letters are assigned to the waves for $\langle v \rangle$. Then the uppercase and lowercase letters are associated such that, for example, wave $A$ and wave $a$ refer to the same wave, that is a vortex, generated by the same protrusion. If we look at wave $B$ and wave $b$ at $x/D = 1.5$ near the rotator in Fig. 9, wave $b$ takes a positive peak where the variation in wave $B$ has a phase of zero ($\omega T = 0.27$) at $y/D = 0.5$, which is dominated by the amplitude of the variation. If we consider the general rotation direction of vortices separated from such a cylindrical structure, we can understand that vortices exist as shown by the solid lines in Fig. 9.

### 3.3. Region where the rotation direction and main flow direction are the same ($y > 0$)

First, we describe points such as that it can be seen that the features corresponding to the same vortex are different at a glance, as can be seen in the vortices that are significantly flattened in $\langle u \rangle$ but are not quite so distorted in $\langle v \rangle$ in Figs. 9 and 10. For example, if we investigate at $y/D = 0.5$ and 1.0, where five cyclic variations dominate, flattened vortices occur in $\langle u \rangle$ as a result of the vortices being stretched out in the $x$ direction because the mean flow velocity $u$ at $y/D = 1.0$ far from the cylinder is faster than $u$ at $y/D = 0.5$ (refer to Fig. 4). Note that although the flattened vortices in Fig. 9 i) appear to be tilted counterclockwise, the actual flattened vortices are tilted clockwise. For $\langle v \rangle$, mean velocity shear is small since the absolute value of mean velocity is small, as can also be seen from Fig. 4, so the distortion of the vortices is small. The shape of the actual vortices is significantly flattened—as can be envisioned by considering the combination of Fig. 9 i) and ii)—and they are also deformed in the $y$ direction, making the shape even further deformed at some point downstream, where the vortices become more like a crescent shape than a flattened ellipse.

We now discuss transformations accompanying downstream flow of the vortices by comparing Fig. 9, where $x/D = 1.5$, with Fig. 10, where $x/D = 2.5$. In Fig. 10 ii), the positive peaks of waves $a$ and $d$ become smaller. Therefore, waves $e$ and $a$ and waves $c$ and $d$ continue to progressively form single vortices, as indicated by the dotted lines in the figure. Furthermore, it can also be seen from Fig. 10 i) that the negative peak disappears from wave $A$, and the positive regions of waves $E$ and $A$ progressively form a single region. It was thus inferred that merging of the vortices occurred.

In Fig. 11 i) at the downstream position $x/D = 8.0$, a single set of positive and negative regions exists in $\langle u \rangle$, for example, at the period of one rotation that can be seen at $y/D = 1.0$. This also forms the same single set of variations in $\langle v \rangle$ in Fig. 11 ii). As a result, at a position somewhat downstream, at $x/D = 8.0$, a single wave corresponding to the period of one rotation was formed as a result of repeated merging of vortices. That is possibly the disappearance of weak vortices.

### 3.4. Region where the rotation direction and main flow direction are different ($y < 0$)

In the region of $y < 0$, where the rotation opposes the main flow, five clear waves organizing vortices were not observed even in Fig. 9 near the rotator, and the amplitudes of the waves were smaller than in the $y > 0$ region. In other words, the vortices that occur in the region of $y < 0$ are weaker than the vortices in the region of $y > 0$. It is inferred that either merging has already begun upstream of $x/D = 1.5$ or clear vortices do not necessarily occur from all five of the protrusions, and there may be cases where the passage of a protrusion is accompanied by only a weak perturbation not a vortex.

In the region of $y < 0$ slightly downstream in Fig. 10, both $\langle u \rangle$ and $\langle v \rangle$ have almost precisely a single variation in the period of one rotation. In other words, in the region of $y < 0$, the effect of the protrusions disappears even faster than it does in the $y > 0$ region.

### 3.5. Overall structure of mean flow and turbulence

From Figs. 9 to 11, periodic velocity variations become significant in the longitudinal vertical cross-section at $y/D = 0.5$ in the region of $y > 0$ and in the longitudinal vertical cross-section at $y/D = -1.0$ in the region of $y < 0$. 

...
It is therefore thought that from the rotation of the rotator, the vortices occurring from each protrusion in the region of $y > 0$ flow downstream near $y/D = 0.5$ and those in the region of $y < 0$ flow downstream near $y/D = -1.0$.

Figure 12 shows the longitudinal transformation of the spanwise distribution of turbulent energy $<k>$ on the phase-averaged flow velocity, and Fig. 13 shows that of the mean flow velocity in the main flow direction. In this research, $<k>$ is expressed by Eq. (3).

$$< k > = \frac{1}{2} \left( < u ^2 > + < v ^2 > + < w ^2 > \right)$$  \hspace{1cm} (3)

![Fig. 12. Longitudinal transformation of lateral distributions of normalized $<k>$ behind the rotator](image)

![Fig. 13. Longitudinal transformation of lateral distributions of longitudinal mean flow velocity behind the rotator](image)

Figure 12 shows asymmetric twin peak distributions that have local maxima at $y/D=0.5$, -1.0 where the vortices pass as in the distribution of $k$ consisting of all frequency components shown in Fig. 5. Furthermore, as could also be expected from the results in Figs. 9 to 11, the local maxima is greatly attenuated toward the downstream direction. In Fig. 12, although the region where the effects of the vortices remain differs on both sides of $y = 0$, the vortices become weak at the position $x/D = 6.0$ since the peaks in $<k>$ have nearly disappeared. Also in Fig. 13, the mean flow velocity distribution has become nearly symmetric there. Note that in the longitudinal measurement range where $x/D \leq 8.0$, a velocity defect region remains in Fig. 13, that is, the characteristics of the wake flow separated from a cylinder are maintained [19].

Finally, Fig. 14 shows the longitudinal transformation of the spanwise distribution of the Reynolds stress behind the rotator on the $xy$ plane, which is particularly representative of the effects of the rotator, and Fig. 15 shows that behind the cylinder for comparison. The Reynolds stress around the cylinder in Fig. 15 is nearly pointwise symmetric about the origin, and the forces are nearly balanced on both sides of the central axis where $y = 0$, and so a torque does not act. In contrast in Fig. 14, the Reynolds stress around the rotator does not exhibit pointwise symmetry in the range of $x/D < 6$, corresponding to the mean flow velocity results described earlier. The points where the Reynolds stress has a positive peak for $y > 0$ at $y/D = 0.5$ and a negative peak for $y < 0$ at $y/D = -1.0$ are consistent with the turbulent energy distribution. From the above, it can be understood that a significant torque acts in the wake flow region of the rotator.
4. Conclusions

In this research, we conducted an experimental investigation of the wake structure of a cylinder that rotates due to flow as part of the development of technology for preventing the accumulation of driftwood at a bridge pier by installing a cylindrical rotator. The following results were obtained.

(1) Vortices are generated by each of the five protrusions as a result of rotation of the rotator.

(2) Vortices in the region where the direction of rotation of the rotator is the same as the direction of the main flow (y>0) flow near y/D = 0.5, and vortices that occur on the opposite side (y<0) flow near y/D =-1.0. Furthermore, the vortices merge as they flow downstream, eventually forming a single variation with a period corresponding to the rotational period of the rotator.

(3) The effect of the vortices extends down to around x/D = 6.0 with the asymmetric forces about the central axis accompanying the rotation of the rotator, and the mean flow velocity and characteristic turbulence quantities are asymmetric in this region where a significant torque acts.

In future research, it will be necessary to examine the appropriate installation position of a rotator based on the results of this research, and to ultimately understand and improve the effectiveness for preventing the accumulation of driftwood by using the rotator when taking into account the effects of driftwood and bridge piers.
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References